THE BIOMECHANICS OF THE FIELD HOCKEY DRAG FLICK

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ABSTRACT

The drag flick is important in field hockey as it gives a greater opportunity to score a goal at penalty corners than hitting does. However, there is a lack of scientific research conducted on this technique. The purpose of this research was therefore to undertake a technique analysis of the drag flick.

Given the paucity of research 10 field hockey coaches were recruited to synthesise expert opinions using a consensus-based, modified three-stage Delphi poll, comprising initial interviews and subsequent questionnaires. 28 physical and technical attributes were agreed and informed the biomechanical analyses. The four corners of the goal were agreed as the preferential target areas along with ball accuracy as the overall performance criterion.

Twelve mixed ability field hockey players (8 male and 4 female) (age 24.25 ± 4.83 years, height 1.75 ± 0.09 m and mass 77.29 ± 17.44 kg) were then recruited to perform 60 drag flick trials at a 1 m^2 target positioned in a standard field hockey goal at a distance of 14.63 m. The trials were split into three conditions: Self-selected target area, performance criterion ball accuracy; self-selected target area, ball velocity; and prescribed target area, ball accuracy. Three-dimensional kinematic data was recorded from a motion analysis system using a 15-segment model to compute performance and technique variables.

An analysis of the full time series of kinematic data was completed to determine the core movement strategy of the drag flick technique. The main findings showed that the task constraint of accuracy altered the kinematic sequencing of players from a throw like pattern to more of a push like pattern. The left and right hip and shoulder ab-/adduction and left and right elbow and wrist flex/-extension are the key joint angles which contribute to the core of the drag flick technique.

A dimensional reduction technique (PCA) was then applied to the same data to decompose the complex, but highly redundant set of postures into a comprehensible number of uncorrelated variables. Each of these variables represented multisegmented movements, which could be visualized. The main findings were that the left and right flex-/extension of the wrists are key to drag flick technique, in addition to the lowering of the thorax. Also, the lower body kinematics explain greater variance compared with the shoulder and elbow joints, as they dominate the principal components, accounting for most of the variance.

Although further work is required, this research has enhanced the understanding of the technique of the field hockey drag flick, particularly with respect to the core movement strategy.

DECLARATION

I confirm that the thesis is my own work and has not been submitted for any degree or comparable award. All published or other sources of material consulted have been acknowledged in the text or the reference list.

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ABBREVIATIONS

ACR	Acromion Process
ANN	Artificial Neural Networks
ASIS	Anterior Superior Iliac Spine
AV	Angular velocity
BH	Body Height
BL	Bottom left
BP	Ball pickup
BR	Bottom right
C7	7^{th} cervical vertebrae
CNS	Central nervous system
COM	Centre of mass
CRP	Continuous relative phase
CV	Coefficient of variation
DOF	Degrees of freedom
EV	Eigenvalues
FAL	Fibula medial malleolus
FB	Foot to ball distance at end of crossover step
FIH	International Hockey Federation
FLE	Femur lateral epicondyle
FME	Femur medial epicondyle
f-PCA	Functional Principal Component Analysis
GB	Great Britain
GCS	Global coordinate system
GHJ	Glenohumeral joint centre
GOM	Global Optimisation Method

H	Head marker
HEEL	Posterior surface of the calcaneus
Hz	Hertz
ISB	International Society of Biomechanics
Kg	Kilogram
KS	Kinematic sequence
LCS	Local coordinate system
LOE	Level of Evidence
LV	Linear velocity
M	Foot marker
m	Metres
$m \cdot s^{-1}$	Metres per second
m^2	Metres squared
MRI	Magnetic resonance imaging
MV	Movement Variability
N	Participants
P ACC	Prescribed target area – ball accuracy
PC	Eigenvectors
PCA	Principal Component Analysis
PC_k	Principal components
PM	Principal movements
PMA	Principal Movement Analysis
PP	Principal postural position
PSIS	Posterior Superior Iliac Spine
RCT	Randomized controlled trial
s	Seconds
S	Shank marker
SD	Standard deviation

SJN	Sternum Jugular Notch
SOM	Self-organising map
SRV	Stick resultant velocity
SS ACC	Self-selected target area – ball accuracy
SS VEL	Self-selected target area – ball velocity
ST	Stick marker
SW	Stance width
SXS	Sternum xiphisternal
T	Thigh marker
TAM	Tibia medial malleolus
TL	Top left
TPD	Thorax pelvis differential
TR	Top right
U	Upper arm marker
UCM	Uncontrolled Manifold

PUBLICATION, BOOK CHAPTER AND CONFERENCE PROCEEDING

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CHAPTER 1:
INTRODUCTION

1.1 Background

Field hockey is a popular team sport played by men and women around the world. According to the International Hockey federation (FIH), field hockey is played in five continents by a total of 137 nations (FIH, 2022). Field hockey is a fast-paced, skill-based sport. Players continually move into different positions at varying speeds and are required to rapidly assess changing situations and make decisions. The aim of a field hockey match is for players to score goals by hitting, pushing, or flicking the ball with hockey sticks into the opponent team's goal. In field hockey a penalty corner is awarded to the attacking team when the defending team commit a penalty in the circle. There are circumstances the umpire can award a penalty corner outside the striking circle and within the 23 m area, should the offence be severe. During a penalty corner, the ball is placed 10 m from the goalpost on the backline and a player pushes the ball along the surface towards the top of the striking circle. No attacking player can be inside the circle. To score, a player must stop the ball just outside the circle while a team-mate tries to either flick or shoot to score a goal. There are many strategies to score from a penalty corner (hit; slap; deflection from an on running attacker; and drag flick).

This thesis focusses on the drag flick technique within the penalty corner, no other penalty corner strategy or method of flicking within the game of field hockey will be considered within this thesis. A set of images can be referred to in Figure 1 which provides a visual of the drag flick technique. The combination of velocity and elevation achieved during this stroke makes it a very effective goal scoring method (McLaughlin, 1997). The penalty corner is deemed to be one of the most important game situations in field hockey and in recent years, the innovation of the drag flick has become an effective shooting technique and thus a vital part of a team's attack due to the goal scoring opportunities it provides (McLaughlin, 1997, Yusoff et al., 2008, Mosquera et al., 2007). The drag-flick is noted to be between 1.4 and 2.7 times more efficient (Mosquera et al., 2007) than hitting or push-shooting the ball at the goal from a penalty corner (McLaughlin, 1997, Yusoff et al., 2008, Mosquera et al., 2007) and this particular goal scoring technique produces one third of the goals scored from a penalty corner (Laird and Sutherland, 2003, Mosquera et al., 2007).

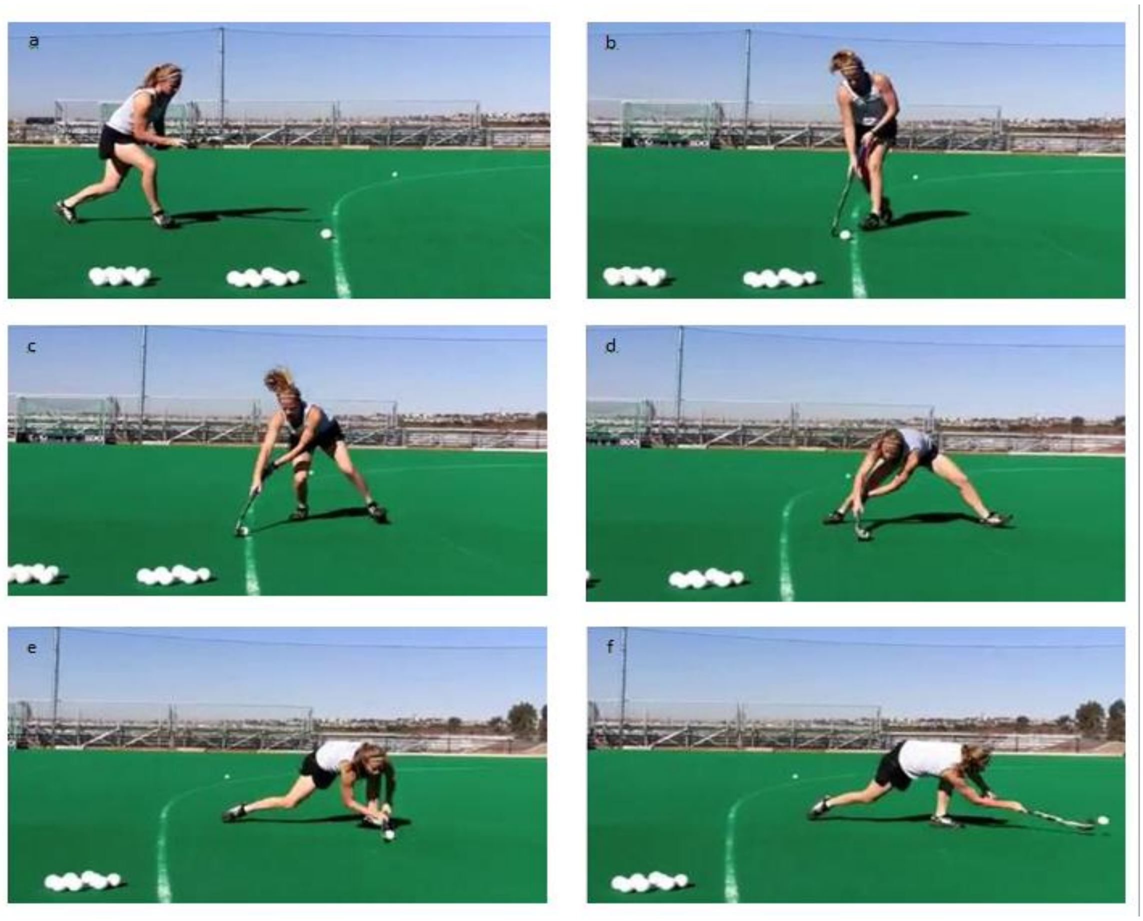


Figure 1: A sequence of still images to identify the drag flick technique. The sequence of images from a to f (USA Field Hockey, 2010).

The aim of a drag flick is to shoot the ball as accurately and as fast as possible to score a goal, which is like other single and double limb throwing and hitting tasks (e.g., golf swing, and penalty kick in football). The drag flick is different to a hit in field hockey, as the drag flick is permitted to elevate the ball at the goal, thus making it a much more aggressive alternative to hitting from the penalty corner, as direct hitting shots on goal are not allowed to be above backboard height of the goal (46 cm). The drag flick is a multi-joint coordination task that involves both upper limbs in a closed chain. The rules of field hockey require the player to drag the ball along with the stick head and then flick it, instead of just hitting it as in other closed-chain shooting tasks (e.g., baseball batting, golf swinging). The drag flick is learned and developed through training and feedback provided by the coach. Although the intention of training is to automate and hone an optimal technique through continual practice over time, and improve the deception of the drag flick technique, it may also stress the capacity to perform technical actions correctly.

1.2 Thesis context

Sport and exercise biomechanics is concerned with the analysis of the mechanics of human movement. A movement pattern is a general series of anatomical movements that have common elements of spatial configuration, examples being, walking, running, jumping, throwing, and striking (Kreighbaum and Barthels, 1996). Put more simply such patterns show how movements are coordinated to produce the desired outcome (Bartlett, 2014). Consequently, biomechanics has emerged as an important area of scientific investigation in human movement. 'Technique analysis' is the term given to an analytical method that is used to understand the way in which sports skills are performed, which considers individual style (Lees, 2002). Chapter 2 within this thesis provides an extensive literature review on what is already known about technique analysis and the drag flick technique which is the focus of this thesis. Chapter 3 provides a conceptual framework of the position of this thesis and a rationale for decisions taken in the planning of the studies within this thesis.

The drag flick has become an extremely important aspect of field hockey because it gives a greater opportunity to score a goal than hitting does. However, there is still a lack of scientific research conducted on field hockey when compared to other sports, and even less on the specific technique of the drag flick. To date, the studies that have analysed field hockey have mainly focused efforts on issues related to training and injury, e.g., endurance (Manna et al., 2009, Chapman et al., 2009); general physical condition (Astorino et al., 2004, Spencer et al., 2004); velocity (Bloomfield et al., 2007); strength (Cochrane and Stannard, 2005) and injury prevention (Barboza et al., 2018). Consequently, while these studies have provided an insight into training and injury prevention there are still many unanswered questions regarding the biomechanical analysis of the drag flick and any variability which may occur within or between players performing this technique.

The small number of studies that have focused on the drag flick technique have provided kinematic information about players from different levels of performance (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010, De Subijana et al., 2011, de Subijana et al., 2012, Gómez et al., 2012, Hussain et al., 2012). In all these studies, authors reported and agreed on the common cues that indicate a successful drag-flick: a wide stance, a whipping action of the stick before the hips and shoulders were rotated, and a final acceleration of the stick. However, all these papers have focused on the performance of the drag flick and do not provide a technique analysis on the drag flick. Since embarking on this PhD journey there have been a further seven papers that have been identified within the literature (Ansari et al., 2014, Bari et al., 2014, Ibrahim et al., 2017, Eskiyecek et al., 2018, Palaniappan and Viswanath, 2018, Ladru et al., 2019, Rosalie et al., 2017). These studies have extended the body of knowledge as they have focussed on constraints around the drag flick linked to accuracy that impact on ball velocity and a deeper analysis on the kinematic sequencing of the drag flick. However, no study to date has provided a full technique analysis and a deeper understanding on the core movements of the drag flick. This is the purpose and focus of this thesis, to undertake a technique analysis of the drag flick and contribute to the knowledge, understanding and application of the core movement strategy of the drag flick technique.

1.3 Research aims, questions, and study objectives.

A biomechanical analysis of the drag flick will have a positive impact on sports scientists' understanding of the technique, as well as potentially improving the understanding of hockey coaches and hockey players with an interest in learning and improving the execution of the drag flick. The aim of this thesis is two-fold:

- To evaluate biomechanically the movement involved in performing the field hockey drag flick.
- To establish the extent of similarity and difference in the movement variability of the field hockey drag flick technique.

As such, this study aims to analyse and evaluate the movement characteristics, and their variability, of the field hockey drag flick by considering the following research questions:

- What physical and technical attributes do hockey coaches feel determine the success of the drag flick technique?
- What are the biomechanical characteristics and variability of the hockey drag flick?

To achieve the study aims and answer the research questions, three principal objectives have been established:

- To conduct a Delphi Poll with expert coaches regarding what attributes contribute to a successful drag flick technique.
- To determine the variability of individuals undertaking the drag flick and establish the effects of task constraints on the movement pattern and variability utilising complete time-series kinematic data.

- To apply Principal Component Analysis (PCA) to kinematic data of the drag flick technique to establish a biomechanical analysis of the entire time-series of kinematic data.

1.4 Overview of chapters

The thesis comprises nine chapters, eight following on from this first chapter which has introduced the thesis by outlining the background and study context of the thesis, along with an overview of the research aims, questions, and study objectives. Chapter 2 provides an evaluative literature review, covering published literature on the biomechanics of the field hockey drag flick and other material pertinent to the study aim, research questions and objectives.

Chapter 3 presents the underpinning conceptual framework for the thesis. The chapter aims to position the thesis and justify the three main studies within the thesis by conceptualising an overarching framework for the thesis. It also outlines what will be measured and evaluated within the thesis and what is out of scope.

Chapter 4 sets out the Delphi Poll as an appropriate methodological process to gather qualitative opinions from the perspective of an expert panel of field hockey coaches with a consensus-based method. The data collected from the Delphi Poll study is used to inform the subsequent biomechanical analyses and test out the areas of consensus from the expert panel of coaches.

Chapter 5 presents the Biomechanics Methodology. This chapter describes the equipment, protocols and procedures used to collect and analyse the time series of kinematic data, to achieve a thorough analysis of the field hockey drag flick.

Chapter 6 presents a Biomechanical Analysis which builds on the current body of literature around the drag flick. Performance and technique variables have been analysed to establish what effect selected task constraints have on the drag flick technique. The Chapter also provides an analysis of the entire time series of kinematic data for the drag flick.

Chapter 7 adopts a more novel contemporary methodological approach to quantitative analysis to consider the entire time series of kinematic data of the drag flick and to also consider the coordination of a complex multi-joint movement. Principal Movement Analysis (PMA) has been applied to provide a qualitative analysis of the drag flick driven by a contemporary quantitative analysis of the biomechanical time series data of the movement that extends the more traditional analysis completed in Chapter 6.

Chapter 8 presents a general discussion, synthesising the findings from the Delphi poll with the traditional and more contemporary movement analysis, evaluating them against the extant literature and discussing the overall insights and reflections on the whole study.

Chapter 9 contains a summary of the original contributions from the work, limitations to the study, conclusions, and recommendation for further study.

CHAPTER 2:
LITERATURE REVIEW

2.1 Chapter introduction

Biomechanical analysis in sport involves the evaluation of movement patterns and specific techniques. Qualitative methods of analysis describe movement without the use of numbers. In contrast, quantitative analytical methods involve the collection, measurement, and evaluation of numerical data. According to Teferi and Endalew (2020) athletes and coaches can only recall 30% of performance correctly. Performance analysis helps with the remaining 70% by providing accurate performance data. This chapter addresses the key debates within sports biomechanics, as a part of performance analysis literature, which are deemed both important and necessary to help fulfil the research aims of this study.

The objective of the literature review is to critically review relevant research on the broader areas of technique analysis, movement variability, and the specific topic area of the biomechanics of the field hockey drag flick. The literature review will evaluate the theory and investigations pertinent to the studies that are reported in the main body of the thesis.

2.1.1 A review of key terms

The term 'technique' is a commonly used concept within sports biomechanics literature, however the nature and scope of this term is seldom defined, which can leave the term subject to widespread and inconsistent interpretation (Lees, 2002). Therefore, this section defines the key concepts central to this thesis and outlines the nature and importance of the drag flick technique in the sport of field hockey.

2.1.2 Technique

The term 'technique' is widely used but it is rarely defined. A sport related definition of a 'technique' can be defined as "the pattern and sequence of movements" (Carr, 1997, p.5). More precisely technique has been defined as, "a specific sequence of movements or parts of movement in solving movement tasks in sports situations" (Dictionary of Sports Science, 1992). Lees (2002) suggested that a technique involves the relative position and orientation of body segments as they change during the performance of a sport task to perform that task effectively. While it is important to acknowledge that the definitions of 'technique' do not indicate how a technique can be measured, they do imply that technique is characterised by variables that can be visually observed and recorded. Technique is important as it is a crucial component for successful performance, which is a combination of achieving the primary objective of the performance and, where possible, preventing acute and chronic injuries. Specifically, understanding the way in which athletes technically execute a movement (i.e., technical characteristics and postures) is integral for optimising team-sport performance. Thus, good performance requires good technique, but good technique does not guarantee good performance (Lees, 2008).

Analysing a technique can be achieved through qualitative and quantitative analysis, with both approaches widely used in contemporary biomechanics and reviewed in turn in the following section.

2.2 Qualitative approaches to technique analysis

Qualitative analysis is formed from non-numerical data and is characterised by the subjective interpretation of movements based on observations. Knudson and Morrison (2002) defined qualitative analysis of motor skills as the,

> "Systematic observation and introspective judgement of the quality of human movement for the purpose of providing the most appropriate intervention to improve performance".
>
> (Knudson and Morrison, 2002 p. 4).

Lees (2017, p.4) defined qualitative analysis as:

> "a method used to evaluate technique in the performance of sports (or exercise) skills. It uses observation and can be supplemented with a visual recording, such as video. It relies on a knowledge of the relevant sport and sports skill, as well as an in-depth knowledge of 'principles of movement'."
>
> (Lees 2017, p.4)

Since observation, intervention and performance are used in these definitions, it is necessary to also define these terms. 'Observation' is defined by Knudson and Morrison (2002) as the "process of gathering, organising and giving meaning to sensory information about human movement" (p.4). Knudson and Morrison also defined 'intervention' – in the context of qualitative analysis – as the "administration of feedback, corrections, or other change in the environment to improve performance" (p.4). Finally, 'performance' is considered by Knudson and Morrison (2002) as a broad term to mean both the short-term and long-term effectiveness of a person's movement in achieving a goal.

Technique analysis is commonly identified in the literature as a prerequisite to improve an athlete's performance (Knudson and Morrison, 1996, Luttgens and Hamilton, 1997, Bartlett, 1999, Elliott, 1999). Though, only a few authors (Adrian and Cooper, 1995, Elliott, 1999) have specified that technique analysis is used to improve technique and it is only through such analysis that improved performance may result. These subtle differences are summarised by Lees (2002, p.814) who suggested that technique analysis is:

> "Concerned not only with establishing `how movements are made' (a descriptive goal), but also with studying the `most effective way movements are made' and `their effect on performance' (analytical goals). Thus, several goals can be identified for technique analysis."
>
> (Lees 2002, p.814)

In the case of this study, the technique analysis conducted is concerned with the core movement strategy of the field hockey drag flick (a descriptive goal) and also to establish to what extent different task constraints affect this core movement strategy (analytical goal). To date, many generic skills (throwing, catching, jumping) and sport specific skills (e.g., soccer instep kick, javelin throw, hurdle jumping, golf swing) have been qualitatively analysed. However, as yet no scientific literature exists that examines the field hockey drag flick technique using qualitative analysis.

Qualitative analysis has been developed as an analysis which is based on scientific principles but applied through subjective observation. As outlined in this section, a qualitative approach to technique analysis is typically based on the observation of a specific movement, evaluating individual technique in comparison to an expert model template, whereby any deviations from this model highlight any faults that could be modified through intervention methods (i.e., coaching) (Lees, 2002). Observational models serve to assist a systematic observation of a qualitative technique analysis. A popular approach to observe and evaluate a technique qualitatively is to use the ideas of phase analysis; a descriptive process that divides up a movement into relevant parts so that attention can be focused on the technique of each part (Lees, 2002). Phase analysis can also reveal the specific timing sequence, a coordination pattern observed in a process known as temporal analysis (Lees, 2008).

To date, a specific phase analysis model has not been developed for the field hockey drag flick, so the following paragraphs will offer a general overview of the nature and component parts of a phase analysis model.

2.2.1 Phase analysis

Some phase analysis literature (Knudson and Morrison, 1996, Bartlett, 1999) identified three main phases to perform a skill or technique (preparation, action, and follow-through), however, others suggested four or more phases to perform a skill or technique (retraction, preparation, action, and follow through) (Hay and Reid, 1982, Lees, 2008). There is a consensus that phases can be further broken down into sub-phases and that the distinction between one phase or sub-phase and another is subjective and determined by the skill or technique being analysed and the needs of the analyst. Nevertheless, this process of breaking a movement down into its functional parts is an important initial analytical step (Lees, 2002).

A phase analysis model is a representation of the ideal form of a movement in each phase, depicted in written, diagrammatic, or pictorial form (Lees, 2002). Such models tend to offer a descriptive process by dividing up a movement into relevant smaller segments allowing attention to be focused on each part of the performance (Lees, 2008). Coaching manuals used by National Governing Bodies as part of Coach Education programmes tend to utilise phase analysis as it offers a sequential breaking down of a skill or technique into its various phases (see Hughes (1994), as an example for soccer skills) and provides a descriptive (often visual) template for relevant parts of the skill or technique based on expert performance. This approach is readily used at the highest standard of performance and detailed phase analyses as model templates have been presented in coaching journals (see Hucklekemkes 1992, for the hurdles; Tidow 1990, for the long jump). at the time of writing there was no evidence that England Hockey, the National Governing Body for Hockey in England uses a phase analysis model template as part of its coaching journal/coach education programme for hockey coaches to identify the sequential parts of the drag flick technique. This is surprising, given that the drag flick is the most common and effective offensive goal scoring technique in field hockey – both indoor and outdoor (Piñeiro et al., 2007, McLaughlin, 1997, Yusoff et al., 2008). As a result of this situation, any coaching of the drag flick will be subjective and remain primarily qualitative, relying heavily on the personal experiences of the coach educators. As a result, this may lead to inconsistent or poor coaching of the field hockey drag flick technique.

The description of phases and sub-phases should identify 'key moments' and 'critical features' for each of the phases in relation to the performance of each body segment. A key moment is defined by Lees (2008, p.165) as "those points in time in which an important action is performed related to the 'way of doing'". Lees (2008) went on to suggest that a key moment in striking sports is impact; he named a few examples such as toe off, foot strike, maximum knee flexion, or minimum elbow angle which define key moments of a technique. Critical features, according to Lees (2008), are observable aspects of a movement and refer to a body or limb position. McPherson (1990, p.2) defined critical features as "components of movement that are essential to the performance of a technique". Knudson and Morrison (1996) offered a useful example of the generic skill of overarm throwing and suggested that critical features are general statements that refer to position (e.g., angle of release; leg drive and opposition; sequential coordination; inward rotation of the arm). These critical features then appear to relate to the very general characteristics of the technique, some of which may be expressions of selected underlying biomechanical principles of movement. Once these descriptions of performance have been identified and noted, movement principles relating to performance are included to offer a comprehensive overview of the performance.

To complete a qualitative phase analysis model, the movement principles associated with the phase or sub-phase, key moments and or critical features need to be identified. An advantage of employing qualitative analysis is that it can be used by a wide range of people and can be useful in an instructional (teaching) and/or clinical (movement rehabilitation) setting. Using qualitative analysis techniques such as phase analysis, critical features and principles of a movement can also provide a detailed insight into the important characteristics of sports technique without using complex and detailed biomechanical data (Davids et al., 2000).

Despite having advantages, several authors have identified the limitations of a qualitative approach, which are linked to the myth that success equates to a model template and high technical skill (Bartlett, 1999; Lees, 2002). Furthermore, subjective evaluation of a complex technique such as the field hockey drag flick presents a difficult challenge to the individual observing and evaluating technique, especially considering the numerous variables related to the performance (i.e., speed of approach, length of step, placement of support foot from the approach phase etc.). Therefore, qualitative analysis also requires a range of experience and knowledge of the technique being analysed, in this case the field hockey drag flick, and associated underlying biomechanical principles.

2.3 Quantitative approaches to technique analysis

In contrast to qualitative approaches, quantitative approaches to technique analysis are formed from numerical data. Given the advancement in data collection methods in recent decades, the normal approach to quantitative analysis uses instrumentation. Consequently, most biomechanical texts describe a range of instrumented data collection methods for quantifying performance skills and usually include motion analysis, force analysis and electro-myography (Lees, 2002). Teferi and Endalew (2020) highlighted that Sports Biomechanists often quantitatively study kinematic features that characterise elite performance of a particular athlete; often constructing a model that details the kinematic characteristics of sound performance for practical use by coaches and athletes. As scientific analysis methods have developed and are more widely available, the level of detail of kinematic and temporal variables that can be measured in the analysis of technique has increased and the understanding of movement patterns characterising techniques has improved. However, quantitative analysis provides a different challenge for researchers and coaches as the level of small details being measured needs to be relatable and understandable in the context of the whole movement and the overall technique being measured. Therefore, as with qualitative analysis, quantitative analysis still requires a range of experience and knowledge of the technique being analysed. Furthermore, criticism of quantitative analysis has been its lack of ecological validity, where the focus should be on the whole movement in an applied setting.

Quantitative analysis has evolved into a powerful tool for supporting clinical decision making in the laboratory (Lees, 2002). Traditionally technique analysis has been used to present data that represents an ideal technique; this approach assumes that within or between participant variability has little or no importance. Variability is an inherent component within and between all biological systems (Newell and Corcos, 1993) and therefore movement variability and its relevance for technique analysis will be discussed in the next section.

2.4 Movement Variability and Human Movement Control

To date, quantitative approaches to analysing the drag flick have presented ball velocity as the overall performance outcome of the drag flick and have indicated the need for coordination and control of the rigid body segments to optimise the speed and position of the stick at ball release (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010, Hussain et al., 2012).

The relationship between sports biomechanics and motor control has been suggested to provide a more detailed understanding of coordination and control (Davids et al., 2006). However, this interdisciplinary approach to technique analysis is currently limited in both field hockey and the drag flicking literature.

Motor control is the process by which humans activate and coordinate the muscles and limbs involved in the performance of an action via the central nervous system (CNS) and interact with the environment during the performance of a specific task (Gollhofer et al., 2012). The biomechanical degrees of freedom (DOF) within the human system can enable each person to control their movement and accurately vary and adjust their coordination patterns with respect to the performance of a specific task. The term DOF has been defined as:

"The number of independent coordinates required to completely characterise a body, or system, position."

(Zatsiorsky, 1998, p.104)

The motion of rigid segments in space can be fully described by measuring three independent translational degrees-of-freedom (position of the origin) and three independent rotational degrees-of-freedom (orientation – the rotation about each principal axis of the segment) referred to as the 6 degrees of freedom method. Therefore, when looking at a complex movement patterns such as the drag flick with multiple segments and the kinematic chain of these segments there is a theoretically infinite set of joint positions which could result in the same end position of the stick at ball release.

The understanding and approach to variability in the analysis of human movement has changed dramatically over time. Traditionally, in motor control inter- and intra-individual variability have been viewed as system noise or error that must be reduced. This view of variability stems from the assumption of a single perfect technique (Bartlett et al., 2007). Bernstein (1966) suggested that, for coordinated movement to arise, the numerous functional degrees of freedom of the body must be organised in time and sequence to form a functional movement pattern. Bernstein (1967) viewed any surplus degrees of freedom (DOF) (i.e., DOF in excess of the DOF required to perform a specific task successfully) as redundant and a source of problems for the central nervous system (CNS). This posed the question in the motor control literature of how the CNS manages all these apparent problems of choice, when there are excess DOF for the task in question? (Latash, 2008). Latash (2012) claimed that the classical problem of motor redundancy presented by Bernstein (1967) was misleading and presented an alternative view of the principle of abundance. This considers the apparently redundant DOF as useful and even vital for many aspects of motor behaviour. The idea of 'good variance' helps an abundant system to deal with secondary tasks and unexpected perturbations, with variance considered as adaptive across a variety of conditions (Latash, 2012). Surplus DOF provide a luxury for each individual to vary joint coordination patterns to stabilise task relevant performance / outcome variables (Latash, 2012). Therefore, it should be expected that variability will be evident in repetitions of all movements and there is no single identical movement pattern for the same movement task.

2.4.1 Movement Variability in technique analysis

Variability is a characteristic of all human movement, regardless of task familiarity and it plays a functional role in movement coordination (Langdown et al., 2012, Preatoni et al., 2013). It is typical in research to analyse an athlete's best performance when trying to capture the biomechanics of the technique. However, Dona et al. (2009), identified the need to analyse an individual's "typical" mode of performance. It is the focus of this thesis to capture the core movement strategy of the drag flick acknowledging and measuring the variations that emerge by repeating the same technique. Variability in movement patterns plays a fundamental role in sports skills and its influence on the analysis of biomechanical data should be considered (Bartlett et al., 2007). The analysis of the best trial approach may be arbitrary and the results from such analyses could be misleading. Therefore, a full analysis of an individuals' movement pattern should include analysis of an appropriate number of repetitions together with an analysis of movement variability (Dona et al. 2009). Quantitative biomechanical analysis often involves the assessment of discrete measures of kinematic and kinetic variables involved in a particular movement task to outline the differences between populations and to evaluate performance, enhance performance or prevent injury (Preatoni et al., 2013). This has been a criticism of Sports Biomechanists, that too much focus is placed on discrete data, such as ball to foot distance, stance width, or durations of movement phases such as length of drag, thereby discarding much of the richness of information contained in the time-series data. This becomes more relevant when we consider movement coordination (Lamb and Bartlett, 2017).

Movement Variability (MV) has traditionally been quantified using the size of the standard deviation (SD) (Fleisig et al., 2009) and coefficient of variation (CV) (Bradshaw et al., 2007). However, the use of these methods relies on the assumption that the data being analysed are normally distributed, and this is not always the case or may not be easily assessed (Preatoni et al., 2013). Nevertheless, the use of discrete variables in biomechanics means a large amount of data is discarded and important information lost (Ryan et al., 2006). Repeated movements generate a family of curves of kinematic/kinetic data that do not perfectly overlap and may differ in magnitude and timings but consist of a large number of highly correlated time-varying variables (Dona et al. 2009). Dona et al. (2009) expressed the need to find structure in the data, to identify the most characteristic features and predict whether a pattern is representative for an athlete or not, therefore, satisfying two main needs of data reduction and data interpretation. Data reduction seeks to remove collinearity and to simplify data, whereas data reduction seeks to obtain a meaningful summary of the data, without overlooking the information that movement variability conveys (Dona et al. 2009). To deal with this problem, methods need to be undertaken that are aimed at identifying functional units of coordination in the form of synergies, as well as methods to distinguish functional form from random fluctuations. These methods should allow for the detection of time-varying coherent patterns of coordination (Daffertshofer et al., 2004). Functional Principal Component Analysis (f-PCA) has been presented as being effective for the study of human motion (Ormoneit et al., 2005), providing an understanding of the motor development process (Ryan et al., 2006), and analysing joint coordination data in the motor development process (Harrison et al., 2007). Pattern recognition methods used to extract features from large data sets or to classify and determine group differences have been applied in sport biomechanics. Principal Component Analysis (PCA) is a multivariate statistical technique, which aims to reduce the dimensionality of highly dimensional data sets (Dona et al. 2009).

2.5 Measuring movement variability

2.5.1 Methods commonly used in Sports Biomechanics

Methods of assessing the potential importance of movement variability (MV) and its functionality in sport have used several mathematical techniques across a range of sports (Preatoni et al., 2013). Examples of these include: vector coding in running (Heiderscheit et al., 2002); cross-correlation ratios and angle-angle plots (Button et al., 2003), Confidence Intervals 2 (CI2) (Mullineaux, 2017) and continuous relative phase (CRP) techniques in basketball (Robins et al., 2006) and running (Hamill et al., 1999).

2.5.2 Cross-correlations

Higher cross-correlations indicate a stronger joint coupling and dependent control between two joints, whereas a low correlation indicates little coupling and independent control between joints (Button et al., 2003). Button et al. (2003) measured MV in basketball free throw shooting using mean cross-correlations to evaluate the coordination or coupling between the elbow and wrist joints. Cross-correlation functions can determine aspects of coordination that show whether one joint lags behind another. This can be useful to study proximal-to-distal kinematic sequencing which is typical in throwing actions. Although the calculation of cross-correlation functions is driven by quantitative analysis the interpretation of them is partially qualitative, due to the time lags and correlation coefficients (Lamb and Bartlett, 2017). Button et al. (2003) used the associated cross-correlation time lags to determine that better players used a proximal-to-distal sequence coordination pattern, where the elbow was initially released, before the wrist.

Cross-correlations are also useful for analysing changes in coordination if the data is linear as there should be a meaningful relationship between the two variables to be correlated. Human movement dynamics are not normally linear, but if we wish to test hypotheses about the statistical significance of the correlation coefficient, we can, logarithmically transform the data (Howell, 2012).

The cross-correlation method is also limited to measuring the coordination between two joints and cannot measure the synergistic properties across a wider of range of joints. As the drag flick technique involves the coordination of multiple joint angles this method is not suitable for analysing the coordination patterns present.

2.5.3 Angle-angle plots

Button et al. (2003) also used the method of angle-angle plots to examine variation in the elbow joint angles with the wrist joint for basketball free throw shooting. An average curve was established with variability presented from the mean curve, to present simultaneous joint angle differences from the mean curve thorough the free throw motion. The changes in standard deviations over time reveal that the angle-angle plots show greatest variability toward the end of the action. Furthermore, this feature is consistent regardless of skill level.

Many attempts have been made to quantify angle-angle diagrams, such as vector coding (Glazier et al., 2006); and normalised root mean squared difference method (NoRMS), as proposed by Sideway et al. (1995). Both these methods reduce the qualitative pattern to a few numbers and provide a measure of the coordination variability over the entire duration of the movement (Davids et al., 2006). Therefore, these methods could be problematic when analysing MV in coordination during movement where the variability changes throughout different phases.

The angle-angle plots method is also limited to measuring the coordination patterns between two joints, therefore, showing a similar limitation to the cross-correlations approach in being unable to measure the synergistic properties between three or more joints, which again is problematic for the drag flick technique.

2.5.4 Confidence Intervals 2 (CI2)

Another method which has been presented within the literature during the development of this thesis is the CI2 method proposed for calculating and comparing confidence intervals of two bivariate time-series (Mullineaux, 2017) allowing for assessment of variability within an individual’s data. This approach involved the construction of an area surrounding the mean bivariate time series through a series of steps. Initially, ellipses were generated around each data point after normalising the time. Subsequently, vertices were positioned at the intersection points where a line, perpendicular to the direction of the mean bivariate time series, met the boundary of the respective ellipse at each time instance. Using these vertices, convex quadrilaterals were then formed. This methodology served the purpose of establishing 95% confidence intervals around a dataset consisting of bivariate information.

The application of this technique allowed for the assessment of dissimilarity or similarity between two sets of bivariate data (such as using two joint angle variables). The criterion for differentiation was the absence of overlap between the convex quadrilaterals formed from each dataset at the same time point within the movement. Conversely, when overlap occurred between these quadrilaterals, it indicated similarity between the datasets. The magnitude of the convex quadrilaterals' area served as a measure of variation within for example an angle-angle plot. Importantly, this specific approach did not consider information derived from vectors connecting the data points. Therefore, it falls outside the realm of traditional 'vector coding' techniques. Given the complexity of the movement being analysed for this thesis this methodology was not suitable to analyse such a multi-joint movement.

2.5.5 Continuous relative phase (CRP)

CRP throughout movement captures the changing constraints affecting the performance of the whole movement, which is central to dynamical systems theory incorporating consideration of the continuous interaction between many constraints (performer, environment, and task).

The principal of subtracting the proximal from the distal allows the detection of which segment is leading the other through the phase space (Stergiou et al., 2001). CRP plots the angular velocity of a joint or body segment against its angular position and in a ‘phase plane’ (Figure 2) (Bartlett, 2014).

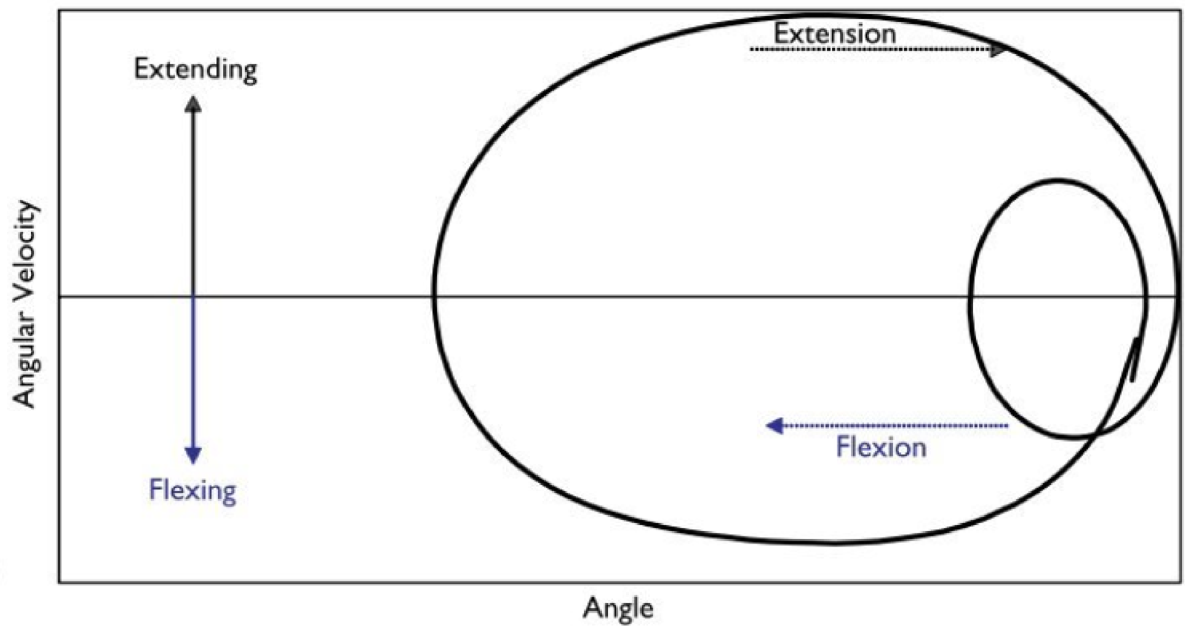


Figure 2: Continuous Relative Phase plane of the knee joint: angular velocity against angular position for one running stride cycle (Bartlett, 2007, p.105).

CRP contains both temporal and spatial information, which provides a more comprehensive analysis of the movement being analysed (Hamill et al., 1999, Robins et al., 2006). Davids et al. (2006) suggested CRP to be more sensitive in measuring coordination and variability within coordination. Furthermore, CRP has an advantage over angle-angle plots as it allows for a measure of coordination over the variability across the whole movement.

However, the CRP method is again restricted to measuring the spatial-temporal coordination patterns between two joints or segments, therefore, being unable to identify and quantify synergistic properties between three or more joints which are involved in complex movements such as the drag flick.

2.5.6 Vector coding

Heiderscheit et al. (2002) used a modified vector coding to compare the MV in joint coordination during a treadmill running task in participants with and without patellofemoral pain, to compare the variability of stride characteristics and joint coordination. Within-limb couplings were created to define an angle as the orientation of the vector to the right horizontal between two adjacent data points on the angle-angle plot within the stride cycle. The vector coding analysis also provided a measure of CV. These were obtained averages across the whole gait cycle and more locally at key phases across the cycle (such as early stance, mid stance, and swing) (Heiderscheit et al., 2002).

Similar to CRP, vector coding allows continuous measurement of MV in coordination throughout the entire movement (Davids et al., 2006). However, unlike CRP, a disadvantage of vector coding is that it does not provide temporal information; it only provides spatial information, which could limit the sensitivity to MV in coordination over the movement cycle (Hamill et al., 1999).

2.5.7 Artificial Neural Networks (ANN) and Cluster Analyses

Techniques within sport movements normally involve the coordination of many segments. All the methods of analysis considered so far are limited to studying coordination of the coupling of two joints (angle-angle plots) or two joint angular velocities (cross-correlation functions) and two joints and their angular velocities (phase planes and continuous relative phase). ANNs is a method that can allow analysis of more segments within the movement in question in the assessment of coordination (Lamb and Bartlett, 2017).

The most common ANN used in technique analysis is Kohonen's (2012) self-organising map (SOM), useful for visualising and clustering data. A SOM can compress redundant high-dimensional data to a simple low-dimensional map, whilst retaining the original relationships within the data (Lamb and Bartlett, 2013). The techniques analysed using SOMs include discus throwing (Bauer and Schöllhorn, 1997), javelin (Schöllhorn and Bauer, 1998), and golf shots (Lamb et al., 2011).

Bauer and Schöllhorn (1997), and Schöllhorn and Bauer (1998) used a cluster analysis approach to quantitatively evaluate the differences in discus and javelin throwers within and between training and competition trials. Both studies presented similar movements during a session, while the movements differed by a larger degree between sessions suggesting a high day to day variability compared to within-day variability. Lamb et al. (2011), analysed the coordination patterns between golfers performing short and long chip shots. The SOM trajectories showed changes in coordination between movement patterns used for short chip shots and movement patterns used for long chip shots.

Methods such as ANN and cluster analysis have been used to show that each performer can vary their technique and exploit within- and between-individual differences. Kohonen (1995) developed the application that maps input variables onto a two-dimensional graphical matrix or ANN. This approach has been shown to be a repeatable and sensitive measure of differences within and between individuals and tasks, which provides an alternative method for measuring MV from quantitative data (Bauer and Schöllhorn, 1997, Schöllhorn and Bauer, 1998, Lamb et al., 2011). However, there is difficulty in interpreting what regions and shapes of the graphs and or clusters represent specific characteristics of movement techniques. Therefore, from a practical perspective, it is difficult to identify the mechanical links to techniques based on two-dimensional maps.

2.5.8 Uncontrolled Manifold (UCM)

The “Uncontrolled manifold” (UCM) is based on the dynamical systems approach to movements and the principal of abundance (Latash, 2012). The approach is based on the hypothesis that movement organisation can be described in terms of motor tasks being controlled by the CNS. In this context, the stability of the motor solution is evaluated in terms of inter-trial motor variability across repetitions. The variability of elemental variables from a reference behaviour (e.g., the mean joints configuration) that alters the nominal task achievement or performance variable can be expressed by mapping the space of elemental variables to the motor task space (Scholz et al., 2000). The UCM technique attempts to separate variability into what variability influences the outcome of a technique and what variability does not (Latash et al., 2002). UCM technique can be used to assess the possible presence of synergies; families of motor patterns which all produce the desired endpoint trajectory (Rosenblatt et al., 2014). Research has found synergies to be present in pistol shooting (Scholz et al., 2000), a sit to stand task (Scholz and Schoner, 1999) and the golf swing (Morrison et al., 2016). Synergies allow flexibility, adaptability, and robustness to perturbation whilst minimising endpoint deviation (Scholz and Schoner, 1999). However, the UCM technique investigates stability control and does not aim to quantify overall sharing patterns. There is also the risk of including elemental variables in the UCM analysis that have no effect on the hypothesised performance variable, as this will artificially inflate the range of solutions index; therefore, artificially inflating the strength of the synergy index (Latash et al., 2007).

2.5.9 Statistical Parametric Mapping (SPM)

Statistical Parametric Mapping (SPM) is a powerful method used for analysing spatially distributed data, particularly when spatial patterns are of interest. SPM enables the assessment of variability in joint kinematics by quantifying and visualising spatial differences, facilitating the identification of patterns and distinctions between trials, conditions, or groups (Pataky et al., 2019). SPM was originally used for neuroimaging, particularly functional magnetic resonance imaging (fMRI) (Friston et al, 1995), however, it has more recently been used to analyse kinematic data (Pataky et al, 2013 & Li et al, 2016).

This method considers where data deviates from typical patterns and assumes that the data follow certain statistical properties, such as normality. If the data violate these assumptions, the results may be misleading. Therefore, as the variability of the drag flick technique was unknown in this instance, SPM may not identify the core movement pattern. Consequently, if the participants analysed were consistently making similar movement patterns, SPM would not highlight the variability within the data in relation to the performance outcome. Although SPM provides statistical maps showing significant differences in spatial patterns, it may not directly offer insight into the mechanical links to the technique and be easily relatable to coaches. In the context of technique analysis, combining SPM with other methods or techniques may be necessary to gain a deeper understanding of the sources of variability in the drag flick technique.

2.5.10 Principal Component Analysis

Principal Component Analysis (PCA) is a statistical pattern recognition technique, used to extract features from large data sets, which makes it ideally suited to dimension reduction and examination of the modes of variation in experimental data (Preatoni et al., 2013). PCA reduces the dimensionality of data by converting a large number of measures into a newer smaller set of uncorrelated variables called principal components (PCs) which best represent the original dataset (Preatoni et al., 2013). Each new variable is a linear combination of the original variable. The first principal component (PC1) is the linear arrangement of the original variables which accounts for the greatest amount of variance. The second principal component (PC2) is orthogonal to PC1 and explains the maximum amount of the remaining variance in the data. All the principal components are orthogonal to each other, so there is no redundant data. All remaining principal components are defined alike, so that the lowest order PCs normally explain very little variance and can usually be ignored (Dona et al. 2009). PCA techniques have been modified and used in biomechanics research in various applications including gait (Landry et al., 2007, Muniz and Nadal, 2009); balance (Pinter et al., 2008); ergonomics (Wrigley et al., 2006), and surface electromyography (Perez and Nussbaum, 2003, Hubley-Kozey et al., 2006). Warmenhoven (2021) has made significant advancements in PCA within the field of Biomechanics and is renowned for his work in PCA derivatives. His research goes beyond traditional PCA by focusing on derivatives and higher-order statistics derived from PCA, which enables a deeper understanding of the underlying variability within datasets. This approach proves highly useful for studying complex and multidimensional datasets, particularly when aiming to capture subtle variations in the data and explore relationships among variables.

2.5.11 Function Principal Component Analysis (f-PCA)

Functional Principal Component Analysis is an extension of the traditional PCA, where the principal components are represented by functions rather than vectors (Ramsay and Silverman, 2002, Ryan et al., 2006, Harrison et al., 2007). Functional data analysis (f-PCA) uses a family of curves of the entire observed function rather than a string of numbers with the assumption that data are supposed to have underlying functional relationships central to them. f-PCA analysis demonstrates the way in which a set of functional data varies from its mean, and, in terms of these modes of variability, quantifies the discrepancy from the mean of each individual functional datum (Dona et al. 2009).

f-PCA was used to test the effects of in-shoe orthoses on lower limb kinematics in participants with previous Achilles' tendon injury (Donoghue et al., 2008). Using f-PCA Donoghue et al., (2008) provided evidence that in-shoe orthoses constrained movement patterns but restored some aspects of variability in other movements. Dona et al. (2009) applied f-PCA bilaterally to sagittal knee angle and net moment data in national and international racewalkers. Technical differences and asymmetries between participants were evident following f-PCA even when traditional analysis (M ^ SD curves) was not effective. Dona et al. (2008) concluded that f-PCA was sensitive enough to discover potentially important technical differences between different skills levels of athletes, and therefore f-PCA might present a useful aid for the analysis of sports techniques.

2.5.12 Principal Component Analysis to quantify technique.

Federolf et al. (2013) used PCA analysis to quantify movement techniques in sport based on a methodology first presented by Troje (2002) in an analysis of human gait. Troje (2002) separated whole-body movements into sets of principal movement directions (eigenpostures) and then linearized the principal movements by approximating them with sinusoidal functions (Federolf et al., 2013). Numerous studies have used this methodology to investigate human movement (Troje and Westhoff, 2006, Provost et al., 2008, Chang and Troje, 2009, Schouten et al., 2010). However, few researchers have used this methodology to investigate techniques in sport. Federolf et al. (2013) suggested that the principal components of a movement, determined like Troje's "eigenpostures" in gait, can be used to quantify the "technique" of individual athletes and might thus provide a methodology to scientifically assess "technique" in sports, and bridge the gap between researchers and practitioners in sport. Federolf et al. (2013) presented the applicability of PCA for the objective determination of the "principal movements" (PMs) that comprise technique in sport.

Following the work of Federolf et al. (2013), PCA has been well documented for technique analysis (Witte et al., 2010). PCA has been applied for technique analysis in dance (Bronner and Shippen, 2015), diving (Young and Reinkensmeyer, 2014), gymnastics (Williams et al., 2016), skiing (Federolf et al., 2014), soccer (Diaz et al., 2012), and tennis (Huys et al., 2008, Smeeton and Huys, 2011). However, it was not until the work of Gløersen et al., (2018), that a PCA analysis was undertaken on techniques for groups of participants. Earlier studies calculated separate PCAs for each individual participant. Gløersen et al., (2018), described a novel data normalisation approach to allow data from all participants to be combined thus facilitating a direct comparison of the postural movement components between athletes.

2.6 Summary

A range of methods have been used to investigate MV in sports biomechanics, such as vector coding (Heiderscheit et al., 2002), cross-correlation ratios (Button et al., 2003), and cluster analyses techniques (Chow et al., 2008). Each method has been applied to provide a greater understanding of MV and its functionality in a wide range of movement tasks.

However, each technique presented in this chapter has limitations that have provided a basis for rejection in this thesis. For example, techniques such as cross-correlations, angle-angle plots, CRP, and vector coding are limited to measuring the MV in coordination between only two joints. The field hockey drag flick is a complex movement which includes coordination of multiple joints. The data reduction methods used in approaches such as artificial neural networks and cluster analysis are also problematic to interpret and do not clearly represent the mechanics of the technique being analysed. The UCM technique has been shown to be a powerful tool for recognising and quantifying synergies in a holistic way across a wide range of joint angles. However, the UCM method presents the stability of a movement pattern without confirmation of what the core movement strategy is. A participant may be consistent, but they may have a consistent movement pattern which is not representative of the core movement of, in this study, the drag flick technique.

The study completed in chapter 7 of this thesis is therefore based on the work of Gløersen et al. (2018) and the use of the novel data normalisation process to allow a PCA analysis to be undertaken on a group of mixed ability drag flickers with a view to determining the core movement strategy of the drag flick technique. This normalisation was designed to remove anthropometric differences while conserving the differences in marker movement to ensure that each participant equally affects the PCA output (Federolf et al., 2013). The PCA and principal movements analysis will determine, along with other studies within this thesis, the core movement strategy of the drag flick technique.

2.7 Quantitative analysis in drag flicking

There are quantitative biomechanical studies in the scientific literature that focus on the field hockey drag flick, yet the number of such studies is relatively small (n=14). This is despite the drag flick being one of the most fundamental and most used scoring techniques in the game. The application of biomechanics to the field hockey drag flick is of benefit to both coaches and players and is essential to establishing the key mechanical factors of physical performance (Gómez et al., 2012). Of the studies that exist, several have analysed the drag flick using a variety of quantitative techniques , including: two-dimensional video (Hussain et al., 2010, Palaniappan and Viswanath, 2018), three-dimensional motion capture (De Subijana et al., 2011, De Subijana et al., 2012, Gómez et al., 2012, Ladru et al., 2019) three-dimensional motion capture and force plate (Ibrahim et al., 2017, De Subijana et al., 2010); three-dimensional video (Yusoff et al., 2008, McLaughlin, 1997, Hussain et al., 2012, Ansari et al., 2014, Bari et al., 2014, Rosalie et al., 2017). These various techniques provide measurable numerical data that indicate how certain variables could influence a drag flick technique and performance outcome.

Table 1 presents an overview of these papers and an evaluation of the methods used within these papers. In addition to these selected studies, other studies have focused on shooting techniques in field hockey (Chivers and Elliott, 1987, Kerr and Ness, 2006, Brétigny et al., 2008) and reviewed the biomechanical model of the drag flick in a search for the best performance. The reviewed studies in Table 1 focus on literature concerning the kinematic data describing the drag flick and the performances of players of different levels. An overview of each paper has been presented including the measures used to undertake each biomechanical analysis along with an evaluation of each paper. As can be seen by the evaluation of each paper there are a number of limitations with each study on the biomechanics of the field hockey drag flick.

Table 1: Comparisons and evaluations of published work of the drag flick technique using Quantitative methods.

Authors(s) and date	Title	Participants	Measures	Evaluation
McLaughlin (1997)	Three-dimensional biomechanical analysis of the hockey drag flick: full report	15 participants (all male, 14 sub-elite and 1 elite)	Three-dimensional video	Justification of variables from pilot work which used only one participant. Focus on performance outcome ball velocity. Successful trials analysed of scored goals; no smaller target identified. Data of DV's not normalised. Time discrete points analysed. Means presented. No three-dimensional analysis only two-dimensional data presented.
Yusoff et al., (2008)	Three-dimensional biomechanical analysis of the hockey drag flick performed in competition	Five participants (all male, elite)	Three-dimensional video of drag flick performed in competition.	Only 19 drag flicks analysed in total and only five of these drag flicks resulted in a goal being scored. Same variables as McLaughlin (1997). Time discrete points analysed. Performance outcome was ball velocity. As in competition, large variability of position of the ball due to accuracy of the injector and stopper. Means presented.
De Subijana et al., (2010)	Biomechanical analysis of the penalty-corner drag-flick of elite male and female hockey players	13 participants (seven male and six females, all elite players only 1 was considered elite drag flicker)	Three-dimensional motion capture laboratory conditions Force data collected of front foot. 20 good trials of contact with the force plate.	No justification of selected variables. Good trials considered good contact with force plate not accuracy of drag flick. Means presented.

De Subijana et al., (2011)	The application of biomechanics to penalty corner drag-flick training: a case study	One participant (male elite)	Three-dimensional kinematics motion capture	Pre and post intervention to develop and apply a training method for the drag flick. Successful trial was a goal scored; no specific target areas were used.
De Subijana et al., (2012)	Training-induced changes in drag-flick technique in female field hockey players	Four female drag-flickers with 2.45 ± 1.79 years of experience of drag flicking	Three-dimensional kinematic motion capture, Training induced changes	Pre and post intervention to develop and apply a training method for the drag flick for female players. Successful trial was a goal scored no specific target area used. Means presented.
Hussain *et al*., (2012)	Biomechanical study on drag flick in field hockey.	Five male sub elite and elite players	Three-dimensional video	Author did not present any previous literature on drag flick. Participants only performed three trials. Only one trial from each participant selected for analysis. Comparison made between groups of sub elite and elite but no clarity in how many in each group. No justification of what a successful trial was. No justification on why variables selected. Means presented.
Gómez *et al.*, (2012)	Kinematic pattern of the drag-flick: a case study	One participant (female elite)	Three-dimensional motion capture Analyse individual differences in the drag flick pattern	15 trials to the left and 15 trials to the right Only goals scored accepted as successful trials. No specific target within goal. Nonparametric statistic used for analysis. Focus is on aiding the goal keepers to detect the direction of the drag flick not on the drag flicker. Not clear if participants aimed bottom left/right or top left/right.

				Main differences between right and left drag-flicks were the position of the stick and the ball at the beginning of the shot.
Ansari *et al*., (2014)	Three-Dimensional Biomechanical Analysis of the Drag Flick in Penalty Corner Drag Flick Performance,	Four male university drag flickers	Three-dimensional video 50 Hz. Target 1 m diameter circle top right position of the goal.	10 trials each participant 6 best trials selected for analysis no justification on what the 6 best trials are. Two participants in each group No justification of selected variables Time discrete variables analysed. Means presented.
Bari *et al.,* (2014)	Three-Dimensional Analysis of Drag-flick in The Field Hockey of University Players	Two male university drag flickers	Three-Dimensional video 50 Hz Target 1 x 1 square inch at top left corner	6 best trials selected with no justification of what constitutes best trial. Variables not normalised to body height. No justification of selected variables. Time discrete variables analysed. Means presented.
Ibrahim *et al.,* (2017)	Kinematic analysis of the drag flick in field hockey	Ten participants (all male, elite)	Three-dimensional motion capture (150 Hz) and force plate (two 1 x 1 m force plates used to measure timing of right and left foot touch down) Ball speed measured by three-dimensional video	No justification for position of target. 20 trials completed by each player. Average of all participants best trials presented. No justification of what is best trial. No justification of selection of angular velocity variables being above 300 deg/s Angular velocities only presented for best trial of each participant. Tried to analyse entire time series but results focus on peak angular velocities. No statistically significant results, assumes close to proximal to distal sequencing.
Rosalie *et al.,* (2017).	Does skill specialisation influence individual differences in	16 elite field hockey players, 8 classed as elite drag flickers and 8 as elite players but not drag flickers.	Three-dimensional video (120 Hz) 16 trials 4 to each target area of top right, top left,	Nonparametric tests used to analyse data. Success of trials measured based on mm distance from the target area. Therefore, trials still measured that were over 1 m away from target area.

	drag flicking speed and accuracy?		bottom right and bottom left.	Presents data to suggest flicking to the left is more challenging than to the right. Ball speed measured by estimate of distance travelled by ball.
Palaniappan, R., & Viswanath, S. (2018).	Biomechanical analysis of penalty corner drag flick in field hockey.	50 participants (all male, university players)	Two-dimensional video 100 Hz	Calibration volume was only 1 m x 1 m. 10 trials performed; only the trial which resulted in a goal with the highest ball velocity was selected for analysis. No justification of selected variables.
Eskiyecek *et al.*, (2018).	3D biomechanical analysis of targeted and non-targeted drag flick Shooting technique in field hockey	11 participants (all male, sub-elite)	Three-dimensional video 120 Hz Sports radar gun used to measure Ball velocity	Six drag flick trials Performed at a distance of 9.15 m from the goal post. Three trials at a target provided of 40 x 40 cm positioned in the middle of the crossbar. Three trials were non targeted so aimed only at the goal. Force calculated for the stick by weight of the stick x the acceleration of the stick.
Ladru *et al.,* (2019).	Lead knee extension contributes to drag flick performance in field hockey	19 elite players mixed gender and age.	Three-dimensional motion capture 240 Hz	Target positioned 1.3 m above ground in the middle of the goal. Target had different scoring areas with the middle of the target being the highest scoring. Ball velocity measured with radar gun. 15 trials of player's optimal speed. Higher maximal angular velocity of lead knee joint results in higher ball speeds.

Note: Data were extracted from peer-reviewed articles published between 1997 and 2019, accessed through databases such as PubMed and SPORTDiscuss.

Previous studies have identified the position of the foot relative to the ball at ball pick up; a wide stance, drag length and a whipping action of the stick followed by explosive sequential rotations of the pelvis, upper trunk and stick as determinants of a successful drag flick (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010, Gómez et al., 2012, Ibrahim et al., 2017). Table 2 presents an overview of results of quantitative research of the drag flick technique. McLaughlin, (1997) was the earliest of these studies that undertook a biomechanical analysis on selected time discrete variables on 14 sub elite and 1 elite participant. As with all studies presented in Table 2 (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010, Gómez et al., 2012, Ibrahim et al., 2017, Rosalie et al., 2017, Palaniappan and Viswanath, 2018, Eskiyecek et al., 2018, Ladru et al., 2019) ball velocity was determined as the overall performance variable of the drag flick technique, with little or no focus or consideration of ball accuracy.
However, none of the studies presented in Table 2 provided a clear justification or rationale for the choice of selected performance outcome and the choice of discrete dependent variables. There are similar variables reported throughout the selected studies, but it is only De Subijana et al., (2010) and Gómez et al., (2012) who reported normalised variables where relevant to compare across participants. McLaughlin (1997), Yusoff et al., (2008), Palaniappan and Viswanath (2018) and Ladru et al., (2019), all reported results that were not normalised even though comparisons were made between participants and other studies. Other papers presented in Table 2 did not present variables that required normalising (Ibrahim et al., 2017, Rosalie et al., 2017, Eskiyecek et al., 2018) e.g., ball velocity, joint angles, and angular velocities. Participant sample size ranged from 1 to 50 participants, with most studies recruiting between 11 and 19 participants. The gender of participants is male dominated throughout the literature, only Gómez et al., (2012), De Subijana et al., (2010), and Ladru et al., (2019) recruited female participants (1, 6, and 7 respectively). In contrast, this thesis included twelve participants, four of which were female with ability ranging from novice to elite.

Number of trials performed by participants also ranged from one to a total of 30 trials per participant, with a range of target areas. McLaughlin (1997), (best trial analysed), Yusoff et al., (2008), (between two and five trials per participant) and De Subijana et al., (2010), (20 good trials per participant) all accepted a good trial as one that was scored in a standard size hockey goal, with Yusoff et al., (2008) being unique in that drag flicks were performed in competition with defenders and other elements of the penalty corner being performed such as: the dragging out and stopping outside the circle (high ecological validity). Gómez et al., (2012), allocated the scoring of a goal as a successful trial but instructed participants to aim 15 trials at the left-hand side of the goal and 15 trials at the right-hand side of the goal. Ibrahim et al., (2017), analysed 20 trials aiming at an unspecified target size positioned 1.5 m off the ground central to the goal. It appears that all trials were analysed regardless of successfully hitting the target or scoring a goal. Rosalie et al. (2017), required participants to complete a total of 16 trials aimed at an unspecified target area positioned at each of the four corners of the goal (top left, top right, bottom left and bottom right). Given the aim of this thesis is to establish the core movement strategy of the drag flick technique, it is in contrast to all the studies presented in Table 2, as they aimed to establish the variables that contributed to ball velocity. Therefore, a relatively large number of trials were performed for the purpose of this thesis, with each participant performing 20 trials in three different conditions focussed on ball velocity, ball accuracy and self-selected vs prescribed target areas of a 1 m x 1 m target.

The quantitative research to date on the drag flick as presented in Table 2 has followed the habitual reduction of data to time discrete points within the drag flick technique and the averaging of kinematic data to establish a criterion technique. No consideration has been given to how body segments move in relation to each other throughout the technique, considered as the pattern of coordination. The quantitative analysis to date has made progress in identifying the factors that affect performance, however, a clear distinction has yet to be made between 'technique' factors and those due to other influences (Lees, 2022). Most studies presented in Table 2 presented a kinematic sequencing of participants, providing overall group means. McLaughlin (1997), Yusoff et al., (2008), De Subijana et al., (2010), Gómez et al., (2012), all presented a kinematic sequence of proximal to distal, from hips to stick. However, it is not until Ibrahim et al. (2017), where a more thorough analysis of the kinematic sequencing is provided. Ibrahim et al. (2017), presented joint angular velocities of the trunk, right and left shoulder, right and left elbow, and right and left wrist. It is reported that participants presented close to proximal to distal kinematic sequencing, with the torso and left upper limb movements sequencing torso lateral rotation, left shoulder internal rotation, left wrist radial deviation, and left wrist extension and the torso and right upper limbs following a pattern of torso lateral rotation, right shoulder flexion, right wrist flexion and right elbow extension kinematic sequencing. Ibrahim et al. (2017) presented trunk motions (lateral and axial) right wrist flexion, and left wrist extension being the main contributors to stick velocity at ball release. Shoulder and elbow motions insured a straight ball trajectory and elongated the trunk moment arm to stick point. It is the intention of this thesis to develop beyond the current body of literature and analyse three dimensional joint angles and joint velocities for both lower and upper limbs.

Regarding the form of data analysis used, existing studies have adopted a biomechanical analysis of analysing time discreet events recognised in the drag flick, such as ball pick up, stance width, drag length, and ball release (e.g., Table 2). There is a limitation to this approach in that by only using time discreet points, a substantial amount of data is made redundant in the movement. As presented earlier in the literature review the contemporary biomechanics literature has moved to a position where the coordination of joint angles should be considered for a complete technique analysis to be undertaken. The current body of drag flicking literature presents a gap in the literature for a study which uses the entire time series of data to undertake a quantitative analysis. This thesis intends to fill this literature gap and provide an important contribution towards the field of technique analysis within sports biomechanics by measuring the entire time series of data of a field hockey drag flick technique followed by the completion of a contemporary analysis which allows the reduction of data to a more manageable form without any data becoming redundant.

Table 2: Comparisons and results of published drag flick technique literature using Quantitative methods.

Author(s) and date	Title	Participants	Methods	Results
McLaughlin (1997)	Three-dimensional biomechanical analysis of the hockey drag flick: full report	15 participants (all male, 14 sub-elite and 1 elite)	3D Video analysis 25 Hz Best trial analysed, performed no. of flicks until optimal performance Target goal	**Ball velocity (m·s^{-1})** 19.1 ± 1.84 **Position of right foot from the ball at right foot placement (m)** -0.24 **Kinematic sequence** Max AV of hips – Max AV of shoulders – Max LV of right hand – Max LV toe of stick Angular Velocity (AV) Linear Velocity (LV)
Yusoff et al., (2008)	Three-dimensional biomechanical analysis of the hockey drag flick performed in competition	Five participants (all male, elite)	3D Video analysis 50 Hz All trials analysed in competition from one end of the pitch. P1 = 5 trials, P2 = 4 trials, P3 = 2 trials, P4 = 3 trials, P5 = 5 trials	**Ball velocity (m·s^{-1})** P1 22.97 ± 1.43; P2 27.83 ± 3.78; P3 24.02 ± 0.29; P4 24.91 ± 7.87; P5 19.61 ± 3.65 **Position of right foot from the ball at right foot placement (m)** P1 -0.88 ± 0.06; P2 -0.65 ± 0.03; P3 -0.31 ± 0.01; P4 -0.14 ± 0.21; P5 -0.71 ± 0.01 **Kinematic sequence** Hip rotation leading the shoulder rotation. **Stick displacement (m)** Low style – 0.67 ± 0.42 Upright style – 1.27 ± 0.11
De Subijana et al., (2010)	Biomechanical analysis of the penalty-corner drag-flick of elite male and female hockey players	13 participants (seven male and six females, all elite players only 1 was considered	Motion capture 250 Hz 20 good trials analysed. Results normalised. Force plate data captured front	**Ball velocity (m·s^{-1})** Skilled player 25.4 ± 1.3; Male group 21.9 ± 1.7; Female group 17.9 ±1.7 **Stance width (BH)** Skilled player 0.88 ± 0.03; Male group 0.88 ± 0.05; Female group 0.80 ± 0.04 **Kinematic sequence** Skilled player and male group: Peak neg AV of stick; Peak pelvis AV; Peak upper trunk AV; ball release

		elite drag flicker)	foot placement 250 Hz. Target goal	Female group: Peal pelvis AV; Peak neg AV of the stick; Peak upper trunk AV; ball release
Gómez *et al.*, (2012)	Kinematic pattern of the drag-flick: a case study	One participant (female elite)	Motion capture 250 Hz 15 trials each side left and right. Target area goal	**Ball velocity (m·s^{-1})** Right 22.20 ± 0.80; Left 22.49 ± 0.68. **Position of right foot from the ball at right foot placement normalised (BH)** Right -0.93 ± 0.03; Left -0.88 ± 0.04. **Stick angle at front foot heel contact (°)** Right; -90.62 ± 22.96 Left -77.28 ± 31.80. **Stick angle at min AV of the stick (°)** Right -96.47 ± 26.50; Left -74.50 ± 33.57. **Kinematic sequence** Same for right and left. Max AV pelvis; Max AV upper trunk; Min AV stick; Ball release; Max AV stick
Ibrahim *et al.,* (2017)	Kinematic analysis of the drag flick in field hockey	Ten participants (all male, elite)	Motion capture 150 Hz 20 trials ball 13 m centrally in front of goal Target area 1.5 m off the ground 2 x force plates used to measure front and rear foot placement. 2 x video capture 140 Hz	**Ball velocity (m·s^{-1})** 31.7 ± 2.5 **Kinematic sequence** Left upper limb: Torso lateral rotation; shoulder internal rotation; wrist radial deviation; wrist extension. Right upper limb: Torse lateral rotation; shoulder flexion; wrist flexion; elbow extension Trunk axial and lateral rotations and right wrist flexion and left wrist extension were main contributors to stick endpoint speed.

Rosalie *et al.,* (2017).	Does skill specialisation influence individual differences in drag flicking speed and accuracy?	16 elite field hockey players 8 classed as elite drag flickers 8 and elite players but not drag flickers. All males.	Video analysis 120 Hz Ball positioned 14.63 m centrally from the goal. 16 trials performed to four target area's top left, top right, bottom left and bottom right.	**Ball velocity (m·s^{-1})** TL ranged from 27.17 to 18.89; TR ranged from 29.00 to 19.34; BL ranged from 30.07 to 20.87; BR ranged from 30.05 to 20.84. Drag flicks to the left side of the goal are more challenging than to the right side of the goal.
Palaniappan, R., & Viswanath, S. (2018).	Biomechanical analysis of penalty corner drag flick in field hockey.	50 participants (all male, university players)	Two-dimensional video 100 Hz 10 trials performed highest all velocity trial used for analysis	**Ball velocity (m·s^{-1})** 28.65 ± 1.69 **Position of right foot from the ball at right foot placement (1/100th Sec)** -0.69 ± 0.11 **Stance width (m)** 1.37 ± 0.08 **Stick angle at front foot heel contact (°)** 73.72 ± 3.69 **Drag length (1/100th Sec)** 2.31 ± 0.07 **Stick velocity (m/s)** 26.18 ± 2.39
Eskiyecek *et al.*, (2018).	3D biomechanical analysis of targeted and non-targeted drag flick	11 participants (all male, sub-elite)	Motion capture 120 Hz 6 trials performed 9.15 m from goal post 3 trials at target of 40 x 40 cm in middle of crossbar and	**Ball velocity (m·s^{-1})** Non targeted: 11.42 ± 3.58; targeted: 9.97 ± 3.80 **Force applied to the stick (N)** Non-targeted: 135.56 ± 123.32; targeted: 131.64 ± 107.34

	Shooting technique in field hockey		three targeted at goal	
Ladru *et al.,* (2019).	Lead knee extension contributes to drag flick performance in field hockey	19 elite players mixed gender and age. 7 female and 12 male participants.	Motion capture 240 Hz Ball position centrally 14.63 to goal Target positioned 1.30 m above ground in middle of goal. Target had additional accuracy measures on target which resulted in different scoring methods. 15 trials capture per player	**Ball velocity ($m \cdot s^{-1}$)** Female: 19.50 · 2.18; Male: 25.62 ± 2.18; Junior: 20.87 ± 1.71; Senior: 36.45 ± 2.23 **Stance width (m)** Female: 1.58 ± 0.71; Male: 1.68 ± 0.77; Junior: 1.62 ± 0.91; Senior: 1.66 ± 0.87 **Drag length (m)** Female: 2.22 ± 0.48; Male: 2.73 ± 0.32; Junior: 2.51 ± 0.46; Senior: 2.58 ± 0.30

Note: Data were extracted from peer-reviewed articles published between 1997 and 2019, accessed through databases such as PubMed and SPORTDiscuss.

2.8 Application of biomechanics in coaching

Sport coaches naturally want the best for their athletes to help them improve performance and reduce their risk of injury. These two objectives are also the focus of sports biomechanics (Knudson, 2007). Coaches use biomechanics to analyse technique, determine appropriate conditioning, and rehabilitate from injuries (Elliott, 1999, Bartlett, 1999, Knudson, 2007). The following section explores the literature concerning the biomechanics of offensive shooting skills in coaching.

In football, players kick the ball to score goals; in track and field, athletes throw a javelin, shot put, or discus as far as possible to win; in field hockey, players perform a drag flick or hit to score goals. An important aspect of these skills is to accelerate the distal end segment and implement/ball to achieve high “end-point” velocity (Bartlett, 2014). In these examples it is the projectile, for example the ball within the drag flick, which needs to achieve a high “end-point” velocity, if not maximal velocity, while maintaining, in most of these skills, high accuracy. The distal end is considered to be any point on the most distal segment or object for which the direction and speed of motion are useful in describing the outcome of the skill, e.g., the hand in a throwing skill or the racket in a tennis serve. A drag flick is unique compared to other offensive shooting skills such as baseball pitching, spikes in volleyball, or hits in tennis, as unlike most hitting and throwing tasks the drag flick does not start with a back swing; the drag flick is also undertaken in a crouched position which is not common in other hitting and striking actions. In addition, in most other double hand actions the position of the hands is close together allowing a similar movement in both limbs. However, in the drag flick the left hand is positioned at the top of the stick and the right hand relatively low on the stick. Although there are other constraints around the drag flick compared with other striking actions, there are many similarities mechanically to achieve the distal acceleration, in this case the ball. Therefore, it Is the aim of this section of the literature review to establish the principles of the coaching literature for striking actions and establish the relevant phases of the drag flick technique. The aim of this thesis is to gain an understanding of this complex multi-joint technique and establish the core movement strategy of the drag flick.

2.8.1 Coaching analysis of striking actions

At the time of writing there has been no peer reviewed coaching literature published on the drag flick technique. In addition, there are no coaching literature resources available from either Great Britain (GB) Hockey or England Hockey, the two governing bodies for Field Hockey in GB and England. However, most striking and throwing movements are characterised by sequential motions of the segments comprising an open-linked system of rigid segments in which the distal end moves freely through space, with the movement progressing from the most proximal segment to the most distal segment (including any handheld implement) (Putnam, 1993). This was based on Bunn's (1972) summation of speed principle, which stated the speed at the distal end of a linked system, should start with the more proximal segments and progress to the more distal segments such that each segment starts its motion at the instant of greatest speed of the preceding segment and reaches a maximum speed greater than that of its predecessor. In the example of the drag flick technique, it could be considered that the drag flick is a throw like movement of an open kinetic link system, where the system has a base (the feet position) and a free open end (the stick). In throw like examples external torque is applied to the base segment to initiate the system's motion and give the entire system, angular momentum. Therefore, initial rotation may occur in the base which is the most stable part of the system in the drag flick technique and is followed by the forward rotation of the next distal segment (the pelvis, thorax, shoulder, arms, hands). Each segment initiates movement as the movement of the proximal segment reaches its greatest angular velocity. This kinetic link principle may be likened to the motion of a whipping action (Kreighbaum and Barthels, 1996). Many investigators have demonstrated proximal-to-distal sequencing in tennis serve (Plagenhoef, 1971, Van Gheluwe et al., 1987, Elliott et al., 1986, Elliott et al., 1989), the tennis forehand (Elliott et al., 1989) and in throwing (Vaughn, 1985, Jöris et al., 1985, Ishii et al., 1986). There has however, been literature published which suggests that there are aspects of throwing and striking activities where modifications are seen in the proximal-to-distal pattern. Feltner and Dapena (1986), Van Gheluwe et al. (1987), Sakurai et al., (1993) and Woo and Chapman (1992) have all reported cases of throwing or striking motions where peak internal rotation velocity of the humerus follows the movements of the forearm and hand segments. This was also replicated in the drag flick literature by Ibrahim et al. (2017), presented earlier in the literature review with the close to proximal-to-distal sequencing.

Elliott et al., (1995, 1996), studied 11 male tennis players performing a high-speed tennis serve and eight male and female squash players performing a forehand drive. The results show that the noteworthy contributions of upper arm internal rotation and forearm pronation both occur late in the movement. While forearm pronation typically occurs after elbow extension and before, or simultaneously with, wrist flexion, the rotation that seems to differ from previous proximal-to-distal sequencing descriptions is upper arm internal rotation. This movement occurs simultaneously with, or after, wrist flexion in both the tennis serve and squash forehand, being much later than predicted. The results of these two studies clearly demonstrate that an explanation of proximal-to-distal segmental sequencing based upon two-dimensional information is insufficient. Results from the studies quoted indicate the relative importance of these two long-axis rotations. It would seem that most previous research investigating the pattern of segmental sequencing in throwing and upper limb striking skills has simplified the movement by disregarding motion about the longitudinal axis. It is the intention in this thesis to ensure each joint angle is analysed for movement around all three axes.

In this thesis a method to study the whole-body movement patterns and establish the core movement strategy of the drag flick technique will be presented, taking into consideration the entre time series of data. The aim is to bridge the gap between researchers and coaches and present an analysis that is easily interpreted by coaches and athletes but driven by quantitative data.

2.9 Chapter summary

A range of literature has been evaluated in relation to the field hockey drag flick, MV and sports biomechanics and the different methods that have been used to measure MV in sports biomechanics. A summary of the key messages from the literature is provided below:

- At the time of writing there was no qualitative published literature on the drag flick technique or the performance of the drag flick.
- There are quantitative biomechanical studies in the scientific literature that focus on the field hockey drag flick, yet the number of such studies is relatively small (n=14). Ball velocity has dominated the performance criterion of the published literature. Previous studies have identified the position of the foot relative to the ball at ball pick up; a wide stance, drag length and a whipping action of the stick followed by explosive sequential rotations of the pelvis, upper trunk and stick as determinants of a successful drag flick (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010, Gómez et al., 2012, Ibrahim et al., 2017).
- No studies at the time of writing have considered MV in the drag flick. Sports biomechanics research has used a range of methods for investigating MV (Preatoni et al., 2013). Gløersen et al., (2018) proposed the use of data

normalisation to undertake PMA on a group of athletes. PMA would allow consideration of how body segments move in relation to each other throughout the technique. This method was selected as an appropriate procedure to determine the core movement strategy of the drag flick technique.

CHAPTER 3:
CONCEPTUAL FRAMEWORK

Chapter 3. CONCEPTUAL FRAMEWORK

The purpose of this chapter is to present the conceptual framework that underpins the approach to data collection, analysis and evaluation of the hockey drag flick taken in this thesis. The thesis is focussed on the biomechanical analysis of the field hockey drag flick. Therefore, it is important to define the key terms used extensively throughout this thesis before moving on to the position of this thesis followed by the justification of why this approach was selected for the thesis.

3.1 Definition of terms

The term technique and skill are often used within the literature interchangeably. For the purpose of this thesis the definition of technique has been taken from the Dictionary of Sports Science:

`a specific sequence of movements or parts of movement in solving movement tasks in sports situations' (Dictionary of Sport Science, 1992).

The technique of the drag flick within this thesis is focussing on the movement pattern and sequencing of movements that occur within the drag flick as part of the overall skill of shooting within field hockey. A skill is defined as:

'When a general movement pattern is adapted to the constraints of a particular task or sport' (Kreighbaum and Barthels, 1996) p 300.

There will be instances throughout this thesis, in particular the results, where the style of the drag flick will be reported. Kent, (2006) defined style as "An individual adaptation of a technique". The style is clearly distinct from the other terms as it relates to the individual specifically, not what could be considered as the core strategy that governs the movement, regardless of the deviation on technique due to variations across repetitions, or task constraints. As this thesis is concerned with the specific movement that occurs for the drag flick the term technique will be used throughout this thesis. This conceptual framework outlines the position of this thesis as a technique analysis not an analysis of performance of the drag flick.

3.2 Position of thesis

During the 1950's and 1960's qualitative analysis of sports skills was the main approach used within Biomechanics to understand the technique of sports skills (Lees, 2017). This was mostly due to the lack of equipment and methods to investigate techniques.

Qualitative analysis for the purpose of this thesis has been taken from Knudson and Morrison (2002) and defined as the,

"Systematic observation and introspective judgment of the quality of human movement for the purpose of providing the most appropriate intervention to improve performance" p31.

Before a suitable framework for qualitative analysis was developed the biomechanics literature moved into a body of research based around quantitative analysis (Lees, 2017). This quantitative analysis took a reductionist approach and the popularity of 'biomechanical analysis of performance' emerged which in many cases attempted to measure aspects of technique (Lees, 2017). When a single measurement is extracted from a continuous variable, a large amount of data is discarded and potentially useful information may be unaccounted for (Preatoni et al., 2013). However, the increasing number of laboratory-based research reports in sports biomechanics did not result in substantial improvements in the theoretical bases or frameworks used in sports biomechanics research (Knudson, 2007). In fact, Hudson (1997) reported how students and colleagues often considered sports biomechanics an irrelevant discipline.

3.3 Deterministic models

Chow and Knudson, (2011) suggested that deterministic models serve a purpose within biomechanics to promote the use of theoretical models in sports and exercise biomechanics research. They suggested that the deterministic model approach provides a strong theoretical or mechanical basis for examining the relative importance of factors that influence the outcome of a movement. However, Glazier and Robins (2012) believed their main weaknesses are the limitation of practical application, specifically the inability to provide substantive information about coordinative movement patterns or 'technique', and the practical application of deterministic models in that they are models of performance and not models of technique. The field of sports biomechanics perhaps needs to explore alternative methodological approaches that are based on qualitative analytical techniques (Glazier and Robins, 2012). It is suggested that for meaningful applications of biomechanical interventions to be effective biomechanical quantification must be combined with a qualitative analysis of the movement with the coach (Lees, 1999, McPherson, 1996).

3.4 Technique analysis

The field of biomechanics has moved more recently towards a more holistic, process orientated approach, rather than relying on a reductionist approach, and within that attempt to understand more about underlying coordinative movement patterns (Glazier and Robins, 2012). Chow and Knudson (2012) also argued that the field of biomechanics would benefit from research focusing on technique as opposed to performance. This thesis is positioned as a technique analysis to establish the core movement strategy of the drag flick technique and therefore is contemporary research within the field of biomechanics. Although the focus of the thesis is a technique analysis it is generally accepted that an understanding of how a technique is performed can provide the basis for improved performance (Lees, 2002). The approach taken within this thesis and outlined in the remainder of this chapter is a rarity in the applied biomechanics field and has the potential to impact the methods for investigating sport skill techniques. It is hoped that such an approach, reflecting how the field of biomechanics has moved, will bridge the gap between researchers and practitioners (Ae, 2020).

Ae (2020) suggested that preparing motion models for sports technique, i.e., the averaged motion patterns, also referred to as standard motion, creates a standard motion of refence that is appropriate for practical use. Three steps are used to create a standard motion in Ae's (2020) paper: 1. Collect kinematic coordinate data; 2. Normalise coordinate data relative to a reference point such as centre of mass; and 3. Average the normalised data which creates an averaged motion pattern known as the standard motion. The concept of standard motion, which has been applied within this thesis to identify a core movement strategy of the drag flick technique, also has the potential to provide a biomechanical understanding of the whole movement which may also inform the basis of athlete technique. The remainder of this chapter presents a conceptual and analytical justification that underpins the approach taken in this thesis, specifically in relation to how the three studies were designed in order to undertake a technique analysis of the drag flick technique.

3.5 Justification

3.5.1 The Delphi Poll

The level of evidence related to the understanding of the drag flick technique that existed in the literature prior to the start of this study was poor in quality and quantity. The levels of evidence based on Ackley et al. (2008) was used to establish the position of the literature within the public domain around the drag flick technique (Table 3). At the time of embarking on this study the literature within the public domain totalled five studies. McLaughlin (1997) produced a research report published by the National Sports Research Centre of Australia (Level of Evidence (LOE) – VII, Table 2). The remaining four studies were all evaluated as LOE IV (Table 3) as all four are either case or cohort studies (De

Subijana et al., 2009, De Subijana et al., 2010, De Subijana et al., 2011, Yusoff et al., 2008).

Table 3: Levels of evidence which can be assigned to studies based on the methodological quality of their design. Adapted from (Ackley et al., 2008).

Level of evidence (LOE)	Description
Level I	Evidence from a systematic review or meta-analysis of all relevant RCTs (randomized controlled trial) or evidence-based practice guidelines based on systematic reviews of RCTs or three or more RCTs of good quality that have similar results.
Level II	Evidence obtained from at least one well-designed RCT
Level III	Evidence obtained from well-designed controlled trials without randomisation (i.e., quasi-experimental).
Level IV	Evidence from well-designed case-control or cohort studies.
Level V	Evidence from systematic reviews of descriptive and qualitative studies (meta-synthesis).
Level VI	Evidence from a single descriptive or qualitative study.
Level VII	Evidence from the opinion of authorities and/or reports of expert committees. Such as England Hockey or coaches that coach the drag flick technique.

The studies identified within the drag flicking literature at the time, were a combination of either individual or small groups of participants. No paper identified a rationale for the variables measured and presented. All papers discarded a large amount of data by only analysing time discrete points within the drag flick technique, with again no sound rationale to establish why these had been selected. For these reasons, the published literature did not provide a sound basis to proceed with the experimental work of this thesis. Without sufficient evidence at an appropriate level there was a need to gather some evidence prior to conducting any biomechanical studies.

In the absence of a definitive technique for the drag flick, and scientific evidence to provide a sound basis for the present study it was felt that given the role of coaches and their close working relationships with athletes learning and improving their technique, they would be best placed as experts to inform the approach taken in this work. A group was established to gain some consensus and common ground to inform the scientific studies presented within this thesis, as well as understanding coaches views on the common elements of the drag flick technique. This was undertaken by a formalised approach within research using the Delphi Poll Methodology. This provided a strong starting point for informing the biomechanical studies within this thesis. It also provided the initial process of producing a thorough technique analysis on the drag flick technique. Knudson (2007) suggested analysis should start with coaches compiling relevant information on the movement to identify the critical features of the movement in question.

Following the results from the Delphi Poll, there were a number of both independent and dependent variables identified by the expert coaching panel which were taken forward as part of the biomechanical analysis chapters:

- Centre of Mass height
- Thorax/pelvis differential angle
- The joint angles for Wrists, elbows, shoulders, hips, knees, and ankles
- A Principal Component Analysis to look at the coordination of joint angles.

In addition, the following variables previously reported within the literature were also analysed:

- Position of back foot at ball pick up.
- Length of drag of the ball.
- Time taken to drag the ball.
- Distance of wide stance width.
- Linear velocity of the stick.
- Ball velocity.
- Kinematic sequence.

3.5.2 Biomechanical Methodology

Two biomechanical analyses were performed on the same set of multiple trials of the hockey drag flick to simulate a real-world data capture of training environments. Trials were performed at a target area selected by participants but with two constraints in the form of performance outcomes of ball accuracy and ball velocity that were informed by both the quantitative and qualitative results of the Delphi Poll Method. A separate set of trials were also completed where participants were given a prescribed target area. Given the procedures for data capture were designed following the Delphi Poll study it is important to note that the experimental chapters within this thesis are not hypothesis driven, and do not form a typical experimental design.

It was not the purpose of this thesis to establish what contributes to a successful performance within the drag flick technique. The purpose of this thesis was to undertake a technique analysis to establish the core elements and sequencing of movements of the field hockey drag flick. Therefore, throughout the thesis the focus is not analysing only those trials that hit a target successfully but all trials. All trials were representative of a drag flick technique, and therefore facilitate an interpretation of what is the core movement strategy and sequencing of movements involved within a drag flick technique. As the focus was to establish the core movement strategy, decisions were made around the design which did not follow a true experimental design. A sample was collected from a range of participants that were of mixed playing level and mixed level of experience of the drag flick. However, all participants were able to perform the drag flick technique.

Participants were able to self-select target areas and were also prescribed target areas. Prescribed target areas were selected based on the results from the Delphi poll study and expert coaches agreeing that the four corners were the preferred target areas with the top left and right being favoured due to difficulty for the defence to save the shot. However, coaches identified that top left and right are difficult for the drag flicker to successfully achieve and therefore bottom left and right are the next preferred target areas. Participants were asked to complete 20 trials in each condition and all trials were analysed to establish movement consistency and variability across trials. These aspects of study design were based on the use of constraints around the drag flick technique to determine what changed and what remained in the movement pattern, as a result of these constraints (Kreighbaum and Barthels, 1996). It aims to identify and understand how the constraints affect the movement. Constraints provide boundaries within which the performer is challenged to search for the most effective solutions through self-organisation (Fetisova et al., 2021). The approach of applying constraints facilitates the possible recognition of more than one model of technique of the drag flick and that there is also the possibility that every participant has a unique technique with a range of variability, or a technique with similar common elements combined with differences in style. The application of the constraints within the technique analysis methodology facilitates an understanding of what changes within the movement pattern as a result of the specific constraints.

3.5.3 Biomechanical Analysis

Turning now to the analytical elements of this conceptual framework, a biomechanical analysis was undertaken, to evaluate the variables that had been previously reported in the literature to establish their comparability with the results of the data within this thesis. Variables that had emerged from consensus amongst the expert coaching panel in the Delphi Poll were also evaluated. Secondly, to analyse and determine variables which made original contributions to the literature. Due to the dearth of existing literature at the start of this study a three-dimensional analysis was undertaken to establish the movement patterns and the variability of individual joint angles and what impact the task constraints have on these joint angles.

Movement variability has previously been presented within the literature as ‘noise’ within the data (Bartlett et al., 2007). Bartlett et al., (2007), provided an overview of research into the variability of movement and coordination patterns. However, it is now generally considered within the literature that movement variability deserves attention as a potential source of useful information to aid understanding through the processes of analysing movement patterns (Preatoni et al., 2013). Variability has provided a measure of coordination as the functional link between the muscles and joints used to produce the desired movement (Mullineaux and Wheat, 2018). As part of the technique analysis of this thesis the degree of departure from the central score will be presented and analysed to determine what are the core components of movement during the drag flick technique.

3.5.4 Principal Movement Analysis

The final study within this thesis was designed to consider the nature of the drag flick technique as a multi-joint movement. When a movement involves multiple degrees of freedom there is a need to analyse inter-joint coordination (Mullineaux and Wheat, 2018). Therefore, a more contemporary Principal Component Analysis (PCA) was undertaken. PCA has emerged as a method to study whole-body movement patterns (Federolf, 2013). As the traditional PCA can be difficult to interpret and explain to the athlete or coach, a more contemporary methodology was used to determine principal movements (PMs). PMs have been used as a mathematical method to break down a complex movement pattern into its main components to determine the main variance from a mean posture (Federolf et al., 2014). Both these analyses were applied in the current study to contribute any new knowledge regarding the movement patterns of the hockey drag flick to the existing body of literature, and support coaches and athletes to develop their understanding of the movement pattern, the core sequencing and where changes can be seen based on the influence of different constraints.

3.6 Chapter Summary

The three studies of this thesis (Delphi poll; three-dimensional biomechanical analysis; and PCA analysis) address the conceptual framework defined in this chapter which underpins the overall approach taken in this thesis. This combination resulted in a technique analysis to establish the movement pattern of the field hockey drag flick. In summary, the particular conceptual framework described here was devised due to dearth of literature on the biomechanics of the drag flick at the time of embarking on this PhD journey, and the need for a contemporary technique analysis to support coaches' understanding of the movement. The following bullet points summarise the conceptual framework and justify why particular decisions were taken for each of the studies and the nature of the methodological design of the biomechanical analyses:

- A Delphi poll was undertaken to seek a consensus of opinion from expert hockey coaches due to the relatively poor quality and quantity of the drag flick literature available at the time.
- The Delphi poll identified the need to investigate both ball accuracy and ball velocity as performance outcomes of the drag flick, with both adopted as constraints within the data capture and biomechanical analyses.
- The Delphi poll also identified a range of dependent variables that had not been reported within the literature previously which were analysed within the study.
- The procedure for collection of the biomechanical data was designed to create constraints around the performance of sets of trials of the drag flick (different target areas – self-selected and prescribed, and different performance outcomes of accuracy and maximum velocity). This approach facilitated an investigation of the effects these constraints had on the movement pattern of the drag flick.
- Whole movement sequences of joint angles were used to analyse and establish the core movement strategy of the drag flick, to build on the previous analyses of discrete events typically reported in the existing literature.
- The PCA and identification of principal movements were undertaken to analyse the coordination of joint angles and establish the core movement strategy of the drag flick.
- The focus of this thesis was to establish the core movement strategy of the drag flick not to analyse and improve the performance of the drag flick. However, some of the findings of this work may improve our understanding of the components, sequencing and variability of the movement, which in turn may support coaches in their practice to improve the performance of their players.

CHAPTER 4:
STUDY 1: DETERMINING THE KEY FACTORS FOR A SUCCESSFUL FIELD HOCKEY DRAG FLICK TECHNIQUE THROUGH EXPERT CONSENSUS USING THE DELPHI POLL METHOD

4.1 Introduction

In sports such as field hockey, the successful utilisation of the drag flick technique is a vital skill used to score goals. The aim of this study was to identify and clearly define the components that determine a successful drag flick from the perspective of an expert panel of field hockey coaches. This study was needed as part of the thesis as there was a lack of clear, generalizable evidence obtained using robust methods in the literature and lack of clarity in the coaching or national governing body literature.

Through gathering expert opinion with a consensus-based method (the Delphi method), the data collected can be used (in addition to data from the two Biomechanical studies within this thesis) to identify, assess and develop technical and tactical competency in field hockey players undertaking the drag flick technique. This will provide an original contribution to the research literature and assist those involved in coaching and playing hockey who wish to understand more about the drag flick technique and its core movement pattern.

The three-round modified Delphi procedure incorporated semi structured interviews and the repeated circulation of a questionnaire to a select panel of field hockey coaching experts. The Delphi panel members were asked to consider the key components of the field hockey drag flick technique which informed the development of the questionnaire used by the expert panel to rate each questionnaire item in terms of importance and relevance to determine the makeup of a successful drag flick. The data collected during the third round of questioning were employed to provide a final measure of consensus regarding the key components of the field hockey drag flick. The results of this study provide empirical evidence that can assist coaches with useful information that can be utilised during the coaching process to develop and improve player performance.

The chapter begins by setting the study context by reviewing key literature, following which details of the procedures used for the Delphi study are presented, specifically the recruitment of participants, the research design and development of the two rounds of questionnaires, and the pilot study. Finally, the data analysis, results and discussion are presented.

4.2 Background to the study

The importance of evidence-based practice in field hockey coaching underpins coaching practitioners' ability to make judgments regarding the successful coaching of the execution of the penalty corner drag-flick, as well as when coaching the defence of a penalty corner. This is important because coaches structure practice and preparation as well as game play, so their views on both aspects are integral to understanding the key components and sequential parts of a successful drag flick technique.

The Delphi method is used in the iterative investigation on a critical issue, with the aim of reaching a consensus among the experts (Beech, 1991). It mainly motivates the experts to exchange views several times by using their professional knowledge, experience, and suggestions anonymously through a series of questionnaire distributions and collections until all experts reach a consensus to resolve a complicated issue (Green et al., 1990). Being a group decision-making method, the Delphi method has such characteristics as anonymity, consensus, feedback control and statistical group response (Lewis-Beck et al., 2003). The Delphi Method is predicated on the underlying assumption that the informed judgment from a group of experts is likely to be more reliable and accurate than the judgment of a single individual or group of non-experts (Adler and Ziglio, 1996). (Murry Jr and Hammons, 1995) reported that the Delphi Method could be implemented as a valid research technique in situations where: 1) the logistical constraints make repeated multiple group meetings infeasible; 2) the heterogeneity of the participants must be maintained to ensure validity of results; 3) the individuals needed to contribute have diverse backgrounds and no established history of communication; 4) the group process may incorporate too many individuals for a face-to-face group exchange; and 5) the disagreements among individuals may be so severe or politically unpalatable that the communication process must be refereed and/or anonymity assured.

The Delphi Method in sport coaching has been used previously to develop evidence-based practice and to establish policies and procedures when none were in existence, or it was difficult for one individual to make a decision (Coombe et al., 2020). As outlined above, there is a lack of academic and coaching pedagogical literature detailing the physical and technical components of the drag flick technique, which is a gap that this study seeks to fill. In this regard, the Delphi Method should not be viewed as a scientific method for creating new knowledge, but rather a set of processes for making the best use of available information, be that scientific data or the collective wisdom of experts.

Sandrey and Bulger (2008) outlined three research objectives which are commonly associated with the Delphi method that remain connected to the rationale that underlies this group decision-making process: 1) development of a range of responses to a problematic issue; 2) the ranking of a range of responses in order to provide an indication of significance; and the 3) establishment of consensus regarding a range of responses. Similarly, Stahl and Stahl (1991) identified the following possible objectives of a Delphi investigation: 1) identifying and investigating underlying assumptions that contribute to divergent judgments or opinions; 2) ascertaining information that may help to generate a consensus of opinion from a selected panel of experts; 3) establishing relationships between expert judgments in the form of rankings on a topic that pertains to a number of disciplines; and 4) educating the respondent group to the diverse and multi-disciplinary nature of the topic in question.

The advantage of the Delphi method is that it can motivate the experts to propose a collective opinion thoroughly and systematically (Adler and Ziglio, 1996), which can achieve quick convergence of the forecasting opinions as desired by the decision-makers. This method not only collects ideas widely, but also obtains the independent opinions of the experts. As an inherently flexible approach, the Delphi method affords researchers numerous advantages when identifying the research question, planning the research design, collecting, and analysing data, and documenting the research process (Skulmoski et al., 2007). The distinct characteristics of the Delphi method contribute to its usefulness as a research instrument in evidence based decision-making and long-range forecasting. When conducted properly, the Delphi method enables the research participants to assume ownership of a particular problem and its accompanying solution (Sahakian, 1997). Additional advantages of the Delphi method include the improvement in the accuracy of the decision-making process due to the use of controlled-feedback and anonymity; elimination of the geographical and logistical impediments inherent in face-to-face group meetings; establishment of consensus based on the group's systematic evaluation, reflection, and re-evaluation of the pertinent issues, and statistical description of the group responses (Skulmoski et al., 2007). Ziglio (1996) further summarised the strengths of the Delphi method and its ability to focus attention on the most relevant issues by minimising the psychological and professional barriers to communication that are inherent in face-to-face meetings, provide an equal opportunity to respond for all the participants, and produce a detailed record of the decision-making process and the resultant informed judgment.

Despite the proposed benefits of this group decision-making process, critics have raised concerns related to the sampling and data analysis techniques associated with the Delphi method (Sackman, 1974). Clayton (1997) stated that while most of these criticisms regarding the scientific rigor of the Delphi method have been addressed in the literature, it is essential that researchers acknowledge and account for the following limitations in the research design:

1. The personal backgrounds and experiences of the panel members are generally beyond the control of the researcher.
2. The panel members' personal and professional responsibilities may limit the amount of time and effort that each individual can invest in the decision-making process.
3. The process by which the panel arrives at consensus remains largely unknown. It is uncertain whether the panel members alter their decision-making process as a result of careful reconsideration or respond to the pressure to conform.

In addition, critics suggest that the results of a Delphi method are difficult to generalize beyond the specific panel of experts that participated in the study. As with other forms of survey research, participant motivation and non-response rate or sample attrition remain primary concerns. McKenna (1994) recommended the use of face-to-face interviews during the first round of a study to help increase response rates throughout the Delphi process, a technique which was adopted for this study and is outlined later in the chapter.

The aim of the study was to identify and clearly define what attributes contribute to a successful drag flick technique. The objectives of the Delphi method within this thesis were to: 1) ascertain information that may help to generate a consensus from a selected panel of experts; 2) establish a consensus regarding a range of responses on what contributes to a successful drag flick; and 3) establish a consensus on the overall performance criterion of the drag flick technique. Through gathering expert opinion with a consensus-based method (the Delphi method), a list of technical and physical characteristics can be agreed and used to inform the biomechanical analysis of the field hockey drag flick for this thesis.

The Delphi method process used in this study included three rounds and Table 1 describes each step of the process, which has been adapted from McKenna (1994). The methodology describes the first Delphi round, recruitment of participants, and the design and implementation of the next two rounds of questionnaires. Finally, the methodology used to analyse data and results for each round of the questionnaire are presented.

Table 4 The steps undertaken of the Delphi process adapted from (McKenna, 1994).

1	Defining the research project
2	Recruitment of participants
3	Development of first round for interviews
4	Analysis of round one of data
5	Development of second round questionnaire
6	Dissemination of second round questionnaire and data collection
7	Analysis of round two data
8	Development of third round questionnaire
9	Dissemination of third round questionnaire and data collection
10	Analysis of round three of data
11	Final report fed back to participants
12	Participants were asked to confirm agreement of final report

4.3 Methods

4.3.1 Philosophical assumptions

Qualitative research offers a means to unearth and help explain a critical issue. To do this, it is imperative that researchers decode the meaning and interpretation of words and circumstances within specific social contexts to gain an understanding of the situation from the perspective of those involved in the issue being studied (Liamputtong, 2008).

According to Guba and Lincoln (1994), it is the responsibility of the researcher to consider their world view and basic beliefs that deal with three fundamental interconnected questions about ontology, epistemology, and methodology, (p.108):

- The ontological question – what is the form of and nature of reality and therefore, what is there that can be known about it?
- The epistemological question – what is the nature of the relationship between the knower or would-be knower and what can be known?
- The methodological question – How can the inquirer (would be knower) go about finding out whatever he or she believes to be known?

In short, ontology and epistemology are philosophical assumptions presumed by the researcher about how research problems should be understood and addressed (Kuhn, 1970). To capture the coaches' beliefs and attitudes to determine the key components of the field hockey drag-flick, this study adopted a qualitative approach, which was underpinned by interpretivism and framed ontologically by relativism and epistemologically by constructivism. Relativism accepts that there are multiple and subjective realities, whereby contradictory, but equally valid accounts of the world can exist, while constructivism considers knowledge as subjective and socially constructed (Smith et al., 2014).

4.3.2 The Expert Panel

4.3.2.1 Recruitment of participants

Participants were requested to provide informed consent prior to participation (Example **Appendix** A). Ethical approval was obtained for this research from Leeds Beckett University following the university policy and procedure (Appendix B). Recruitment focused on practising field hockey coaches at an elite level in the United Kingdom (UK) and Europe. As drag flicking is a technique successfully utilised within both men’s and women’s field hockey the recruitment of participants was open for coaches who had previous and current experience of coaching either men’s or women’s field hockey. However, given the gender imbalance of coaches within field hockey, with men dominating the demographic, it was anticipated that the expert panel would replicate this imbalance and recruit more male than female participants. However, the recruitment of participants would seek to ensure female representation within the expert panel through snowball sampling.

Snowball sampling was used to recruit participants, which is an outreaching strategy that starts with an individual, or a few individuals, as primary contacts and uses the contact’s social and professional networks to recruit similar participants in a multistage process (Sadler et al., 2010). These key individuals are typically known as ‘gatekeepers’ and are recognised by (Lavrakas, 2008), p.299 as people/organisations who:

> “Stand[s] between the data collector and a potential respondent. Gatekeepers, by virtue of their personal or work relationship to a respondent, are able to control who has access, and when, to the respondent”.

In regard to identifying key gatekeepers for this thesis, field hockey clubs competing in the Men’s and Women's National League were approached in (2014). Field Hockey clubs are considered to be the key gatekeeper within the domestic league in England. In addition, field hockey clubs were asked to pass recruitment materials on to any coaches they had worked with previously. Ten expert field hockey coaches (aged 39.2 ± 8.29 years) were recruited as the expert panel. The essential inclusion criteria were:

1. Be willing to complete an individual interview and two rounds of follow up questionnaires.
2. Hold 10 years' experience of working within field hockey.
3. Completed a minimum of five years of coaching at National League or equivalent level.

4.3.3 Procedures of the Delphi process

4.3.3.1 Pilot testing

The first draft of the questionnaire was piloted with a group of four hockey coaches who were not part of the expert panel. Piloting of rounds is considered important because it supports the involvement of stakeholders and guides the Delphi process (Clibbens et al., 2012). The aims of the pilot study were to highlight any ambiguity in the wording; to ensure that respondents would be able to navigate easily through the online medium of Kwik Surveys (an online application that enables users to create and analyse surveys) (Problem Free Ltd, Bristol, UK); to expose any software or hardware problems. A fourth aim of the pilot study was to find out how long it took to complete the interviews and questionnaires, to advise the expert panel of this information prior to them consenting to participate. Feedback received from individuals involved in the pilot study led to some small changes of wording for the questionnaires.

4.3.3.2 Development of the semi structured interview schedule

Vromen (2010), p.258 has offered a convincing case for the use of interviews as a useful data collection method:

> "Interviews conducted in-depth rather than through formal survey mechanisms tend to be exploratory and qualitative, concentrating on distinct features of situations and events, and upon the beliefs and personal experiences of individuals."

Semi-structured, in-depth interviews were chosen to fulfil the aim of the first round of the Delphi study. The experts were guided by the broad question; "what makes a successful drag flick technique?" Semi-structured interviews were selected because they allow the main questions in the interview guide to remain constant through all interviews (Patton, 2002), but also enable the researcher to alter the sequence of the questions and probe for more information if necessary (Alexander et al., 2008).

An inductive qualitative semi structured interview was undertaken with each of the participants in the expert panel lasting between 56 and 92 minutes. The semi structured nature allowed the researcher to probe the participants as and when needed to elaborate on their rationale and opinion, through engaged conversation. Semi structured interview questions were devised using coaching literature around the field hockey drag flick (Mitchell-Taverner, 2005). Questions were specifically designed to ensure coaches could respond freely and explain in their expert opinion what attributes a successful drag flick technique contained. The coaching literature was used to guide the researcher for appropriate prompts to engage each participant. Indicative questions and prompts can be found in Appendix C. To devise an appropriate questionnaire for rounds two and three, open coding was used as a method of analysis following the transcription of each individual interview (Example Appendix D). A range of indicators broadly forming four distinct themes of: technical, psychological; physical and anthropometric attributes were identified for the development of a questionnaire for the following rounds of the Delphi process.

4.3.3.3 Development of questionnaire for round two and three.

The round two questionnaire was devised based on the results of the interviews with the expert panel. The questionnaire was disseminated via the online medium of Kwik Surveys. It asked participants to evaluate, rate, or delete indicators that had been highlighted as contributing to the drag flick technique. During this stage of the research, participants were invited to comment on each indicator and to add, modify or disagree with the performance attributes identified. Participants rated each attribute using a 5-point Likert scale (5: Strongly agree; 4: Somewhat agree; 3: Neutral or undecided; 2: Somewhat disagree; 1: Strongly disagree). In addition to the attributes which contributed to a successful drag flick technique, the expert panel were also asked to identify in their opinion what was the most important overall performance criterion for the drag flick technique. The results of this question were used to inform not only this study but the remainder of the thesis.

4.3.3.4 Data Analysis

To recap, the overall aim of the study was to produce a list of attributes that contribute to a successful drag flick technique which were agreed upon by the experts. Following round one, the interview data was analysed using thematic analysis. The following six steps were undertaken as outlined by Braun and Clark (2006): familiarisation; generating initial codes; searching for themes; reviewing themes; defining and naming themes and producing the report (Braun and Clarke, 2006). Following this iterative process, the qualitative responses from interviews were transcribed verbatim. The audio recording was repeatedly listened to, and the transcripts read multiple times to ensure familiarity. Raw data themes with similar meaning were combined into groups. These groups were named lower order themes and represented the basic unit of analysis. Then, the lower order themes with similar meaning were combined into higher order themes. The results are presented later in the chapter.

The aim of the analysis for round two and three was to reach a level of consensus. This involved decreasing the larger list of attributes into a smaller, more refined list, with only the most important attributes included. The process for editing the attributes and refining the list of indicators is explained below.

Each indicator identified within the questionnaire was analysed to meet the following essential criteria:

1. The item received a mean rating of at least four or higher (This was either 'somewhat agree' or 'strongly agree' on the Likert scale).
2. The item received at least 75% of all individual ratings at level four or higher.

Any item that failed to meet the essential criteria was considered not to be critical in nature and was removed creating a revised questionnaire for round three of the Delphi process. This final questionnaire was then disseminated to the expert panel. Following completion, round three underwent the same data analysis as round 2. Any items that remained following the essential criteria explained above were considered to be of critical importance and were used to form the results of this study.

4.4 Delphi poll results

A summary of results from each Delphi round and how these led to the development of the subsequent Delphi round questionnaire are included in this section. A summary of participant demographic characteristics is presented in Table 5.

Table 5 Elite Coach participant demographic information of the Delphi Poll Expert Panel. Source: Created by the author.

Participant	Gender	Position	Experience at elite level
1	Male	Head coach for National League team	11 Years
2	Female	Head coach for National team	6 years
3	Male	Head coach for National team	6 years
4	Male	Assistant coach for National League team	5 years
5	Male	Head Coach for National League team.	6 years
6	Male	Head Coach for National League team.	7 years
7	Male	Assistant Coach for National League team	10 years
8	Male	Talent development coach for National team and Head Coach for National League team.	5 years
9	Male	Head coach for National League team	6 years
10	Female	Assistant Coach for National team and head coach for National League team.	5 years

4.4.1 Attributes

Four dimensions representing key attributes needed to perform a successful drag flick emerged from interviews with coaches, these were: i) Technical, ii) Psychological, iii) Physiological and iv) Anthropometric. In addition, 16 higher order themes and 30 lower order themes were identified and can be viewed in Table 6. Technical attributes were defined as a specific sequence of movements or parts of movement (Lees, 2002). All attributes identified by any coach or coaches were added to the second-round questionnaire. Following round one, 40 attributes were rated as being of critical importance for circulation in round two. Following analysis of Round 2, 13 attributes were removed due to not meeting the essential criteria for analysis. Two attributes were added to round 3 which did not appear in round 2 due to qualitative comments made by coaches in round 2. Following the third and final round, 28 attributes met the previously described criteria, which represents the consensus of the group. The list of attributes identified for both round 2 and 3 along with the associated percentage agreement and response means have been summarised in Table 7.

Table 6: Thematic analysis from coach interviews of the key dimensions of a successful field hockey drag flick. Source: Created by the author.

Dimension

a. Higher order themes
   1. Lower order themes

Technical

a. Approach to the ball
   1. Enough steps on the approach to adapt to where the ball is stopped.
   2. Timing with the trapper to enable early release of the ball.

b. Gathering the ball
   1. Timing of ball pick up.
   2. Pick up of ball on the left foot before cross-over step or skip.
   3. Cross-over step into pick up.
   4. Skip step rather than cross over allows weight transfer to be quicker.
   5. Picking the ball up behind the body
   6. Lateral distance of the ball from the body
   7. Position of right hand on the stick.

c. The drag
   1. Rotation of body
   2. Length of drag.
   3. Speed of transition / drag.
   4. Timing / balance in the drag phase
   5. Power driven by leg drive and hip rotation.
   6. Transfer of weight
   7. Large drag distance to get closer to the goal.
   8. Do not over stretch with final left foot placement.
   9. Large step leading with left foot to increase drag length.
   10. Drag the ball on a straight line towards the goal, rather than pushing the ball away from the body as this will lose power.
   11. Drag the ball close to the body so not to over stretch and stay within your base of support.
   12. Low position
   13. Hands at shin height whilst dragging the ball to get the ball to travel up and down the shaft and get the whip.

d. Release of the ball
   1. Balance of release, two feet on the floor at release – right foot used to add to the final push and acceleration.
   2. Head position, not looking up too early.
   3. Relative height of upper body and head on release**
   4. Left hand forward on release**
   5. Wrist position on release**
   6. Angle of stick for direction and height of the ball
   7. Point of release for direction of target area
   8. Right hip follows through.

Psychological

a. Mentally tough

b. Ability to focus and shut out irrelevant information

Physiological

a. Upper body strength
b. Upper arm strength
c. Forearm strength
d. Core strength / Stability
e. Flexibility
f. Explosive power in the legs
g. Strength around hips (Gluteal & hip flexors)
h. Quadriceps strength

Anthropometric

a. Height

b. Long Levers

4.4.2 Performance criterion

As part of the Delphi Method the expert panel were also asked for their opinion on what is the overall performance criteria of a successful field hockey drag flick. This was to inform this study and the wider thesis. During round 1 of interview's the expert panel identified three different performance criteria: Accuracy; Speed; Disguise. Following both round 2 and 3, 60% of participants rated Accuracy as the most important performance criterion. However, this did not meet the previously described essential criteria for consensus, but qualitative comments identified the need for all three performance criteria to be considered together as important. The following quotes are examples of two of the expert panel in relation to the overall performance criterion: "All three of the above. No good being fast but inaccurate, or accurate and slow. But at the top-level deception is also key!" (Participant 3: head coach for National age group women's team) and "There have to be elements of all three. However, without accuracy, routines cannot be relied upon and there is a chance that the target will be missed." (Participant 10: Assistant Coach for National team and head coach for National League team). Although specific answers regarding the most important performance criterion did not reach consensus, analysis of the qualitative data showed that all coaches agreed that accuracy was the most important performance criterion, as without accuracy there was little chance of a goal being scored. Two example quotes are: "Accuracy has to be the most important due to the fact that if the drag is not accurate then even if it is hard it cannot go in (Participant 4: Assistant coach for National League team) and "accuracy first as needs to be on the goal: speed from power and coordination between taker and trapper and of course speed of injection" (Participant 7: Assistant Coach for National League team).

4.4.3 Target areas

Finally, the expert coaching panel were also asked for their opinion on the most effective target areas for players to aim at for success at scoring from a drag flick penalty corner. 100% of participants agreed that the preferred target area for highly skilled players is either top left or top right, with no coach specifically favouring top right or top left. In addition, 100% of the expert panel agreed that for players with a lower skill level bottom left or bottom right are the preferred target areas, again with no preference over the left- or right-hand side.

Table 7: Attributes and results of round 2 and 3 of the Delphi method to gain a consensus of what makes a successful field hockey drag flick. Source: Created by the author.

Attribute	% Agreement Round 2	Mean Round 2	% Agreement Round 3	Mean Round 3
Technical - Approach to the ball				
Enough steps on the approach to adapt to where the ball is stopped	90%	4.1	100%	4.8
Timing with the trapper to enable early release of the ball*			90%	4.4
Technical - Gathering the ball				
Timing of ball pick up	90%	4.3	100%	4.7
Pick up of ball on the left foot before cross-over step or skip.**	60%	3.3		
Cross-over step into pick up	80%	4.2	90%	4.4
Skip step rather than cross over allows weight transfer to be quicker**	20%	2.9		
Picking the ball up behind the body	80%	4.9	100%	4.2
Lateral distance of the ball from the body	80%	4.0	100%	4.4
Position of right hand on the stick.	60%	3.5		
Technical - The drag				
Rotation of body	100%	4.7	100%	5.0
Length of drag	80%	4.2	90%	4.4
Speed of transition / drag	100%	4.4	100%	4.9
Timing / balance in the drag phase	100%	4.5	100%	4.9
Power driven by leg drive and hip rotation	100%	4.8	100%	5.0
Transfer of weight	90%	4.5	100%	4.9
Large drag distance to get closer to the goal**	40%	3.1		
Do not over stretch with final left foot placement**	70%	3.9		
Large step leading with left foot to increase drag length**	60%	3.2		
Drag the ball on a straight line towards the goal, rather than pushing the ball away from the body as this will lose power.**	50%	3.5		
Drag the ball close to the body so not to over stretch and stay within your base of support.**	50%	3.3		
Low position	80%	4.0	100%	4.5
Hands at shin height whilst dragging the ball to get the ball to travel up and down the shaft and get the whip.**	50%	3.5		
Technical - Release of the ball				
Balance of release, two feet on the floor at release – right foot used to add to the final push and acceleration	80%	4.0	100%	4.2
Head position, not looking up too early	80%	4.4	100%	4.5
Relative height of upper body and head on release**	70%	3.9		
Left hand forward on release**	40%	3.7		
Wrist position on release**	30%	3.9		
Angle of stick for direction and height of the ball	80%	4.0	100%	4.4
Point of release for direction of target area	90%	4.0	100%	4.6
Right hip follows through	80%	4.2	100%	4.7
Psychological				
Mentally tough	90%	4.3	90%	4.3
Ability to focus and shut out irrelevant information*			100%	4.6
Physiological				
Upper body strength	90%	4.3	100%	4.8
Upper arm strength	90%	4.0	100%	4.7
Forearm strength	80%	4.0	90%	4.3
Core strength / Stability	100%	4.8	100%	4.8
Flexibility	100%	4.7	100%	4.8
Explosive power in the legs	90%	4.3	100%	4.9
Strength around hips (Gluteal & hip flexors)	90%	4.4	100%	4.8
Quadriceps strength	90%	4.1	100%	4.7
Anthropometric				
Height**	30%	3.1		
Long Levers**	70%	3.9		

*Attributes added following qualitative comments in round 2.

** Attributes removed following analysis of round 2.

4.5 Discussion

The primary aim of this study was to use expert knowledge to develop a clear understanding of the attributes that contribute to a successful drag flick technique within field hockey. Furthermore, the study aimed to gain a consensus of the overall performance criterion of the drag flick technique. Following three rounds of consultation with field hockey experts, consensus was reached for 28 attributes which were all deemed important aspects of the field hockey drag flick. However, consensus was not reached for an overall performance criterion.

Technical attributes dominated the expert opinion of the group of coaches, with 18 of the agreed 28 attributes considered as key to the performance of the drag flick. Physiological attributes were also considered to influence the success of a drag flick technique, with eight attributes agreed. The influence of psychological attributes was limited to mental toughness and the ability to focus. Accuracy was rated as the most important overall performance criterion; however, this did not meet the previously described criterion of consensus (75%). As presented in the results accuracy was rated as the most important performance outcome with 60% consensus. However, upon analysis of the qualitative comments all coaches identified accuracy as key to the success of the drag flick technique. 90% of the expert panel agreed that accuracy and ball velocity were the two most important performance outcomes and therefore both performance outcomes were introduced as constraints in the biomechanics data capture outlined in chapter 5 so that their influence on the drag flick technique could be evaluated. These results and the proposal of including both ball accuracy and ball velocity into further testing were presented to the expert panel and all participants approved findings to complete the Delphi poll study.

4.5.1 Technical attributes

The group of expert panellists identified four clear stages of the drag flick technique (Approach to the ball; gathering the ball; the drag; and release of the ball). This supports the current biomechanical body of literature for the drag flick technique in that four time discrete positions have been identified within the literature to be of significance in the drag flick technique: right foot contact with the ball (approach to the ball); stick contact with the ball (gathering the ball); left foot contact with ball (the drag); and ball release (release of the ball) (Yusoff, 2008 & De Subijana, 2010). However, it may well be that key information to achieve these discrete aspects of technique may well be contained in the preceding continuous data characterising the movement pattern.

4.5.1.1 Approach to the ball

The panellists identified both timing of the run and the ability to adapt the run to where the ball is stopped as key to the approach to the ball. This is something the Biomechanical literature had not identified due to findings of such studies being based on laboratory type simulations with no goal keepers, defenders or ball trappers involved. However, given the paucity of research on the drag flick technique it is not surprising that there is limited research with ecological validity. Yusoff (2008) did undertake an analysis of the drag flick technique within competition over a multi-team tournament and gained a good insight into different styles of the drag flick technique. Although the expert coach panel identified the importance of the approach to the ball, the restrictions of the experimental set up in chapter 5 prevented the approach to the ball being analysed. This is a part of the drag flick technique which should be analysed in future biomechanical research but is testament to the value of the Delphi method to identify factors which are considered important to ecological validity and are part of the consensus of an expert group of coaches.

4.5.1.2 Gathering the ball

Timing, position of the right foot in relation to the left foot and the ball (cross-over step - Figure 3), and the lateral distance of the ball from the body were all identified as important technical characteristics of this phase of the drag flick technique by the expert panel. The cross-over step allowing players to position their right foot in front of the ball prior to collecting the ball has been identified within the literature as a key component of the drag flick technique to maximise drag distance and angular velocity of both the pelvis and the shoulders (De Subijana et al., 2010, Gómez et al., 2012, McLaughlin, 1997, Yusoff et al., 2008).

Figure 3: Image of the cross-over-step at ball pickup (USA Field Hockey, 2010).

4.5.1.3 The drag

The drag was identified by the expert panel as having the biggest influence on the overall ball velocity. A consensus was reached that: the rotation of the body, length of the drag, the speed generated during the drag by the timing, balance, power of the legs and hips, the transfer of weight, and the low body position were all key components of this phase of the drag flick technique. Many of these attributes are also identified with the current literature. As previously mentioned in the section above (gathering of the ball), the position of the right foot in relation to the ball on pick up, allows a player to reach behind when collecting the ball. This, in combination with a wide stance width, allows the length of the drag to be increased to produce a greater impulse of the drag flick, which affects the overall ball velocity (Bartlett, 2014) (Figure 4). Foot to ball distance, stance width, drag distance, and position and velocity of the stick, pelvis and trunk are all variables which are consistently identified in the literature (De Subijana et al., 2010, Gómez et al., 2012, McLaughlin, 1997, Yusoff et al., 2008). The low position of the player was deemed important to ensure the ball can travel up and down the players stick during this drag phase to support the biomechanical principle of impulse and ensure the player is able to maximise stance width and drag distance. One expert panellist described this as a sling action:

> “What is key is the position of the ball on the stick itself: the drag is in effect a sling action and so the ball needs to be held fractionally on the stick about 4 to 5 inches up from the toe and then slide down the stick to gather speed”.

However, this is not always supported in the current literature. Yusoff (2008) identified two variations of stick angle amongst participants. The low style as identified above, and an upright style. The paper identified the low style having a reduced stick displacement compared to the upright style (0.67 m vs 1.27 m). However, there is a 19% difference between the ball speeds of the two styles (22.97 $m \cdot s^{-1}$ ± 1.43 - Low style vs 27.83 $m \cdot s^{-1}$ ±

3.78 - upright style) of drag flick technique presented in the paper. Although the lower style has a reduced stick displacement the upright style was able to generate a higher ball speed. It is possible that the lower style drag flick can generate ball velocity with lesser stick displacement providing less opportunities for the defenders to read the shot direction, however, the higher ball velocity from the upright drag flick style will also create less time for defender to react to the shot.

Figure 4: Image of the drag phase during the drag flick technique (USA Field Hockey, 2010).

4.5.1.4 Release of the ball

The expert panel identified attributes within this stage of the drag flick technique predominately related to the accuracy of the shot itself. Balance on ball release; head position; angle of the stick; point of release; and right hip follow through were all agreed as a consensus of the key attributes of the ball release in the drag flick. Similar to the findings of the approach to the ball no published literature to date has looked at variables which are identified as important for the release of the ball.

In addition to the technical attributes which the panellists agreed by consensus, both physiological and psychological attributes were also identified.

Figure 5: Image of ball release of drag flick technique (USA Field Hockey, 2010)

4.5.2 Physiological attributes

The expert panel identified eight physiological attributes that are important for the drag flick (Table 6). These were a combination of upper and lower body strength; core strength; explosive power and flexibility. To date the current body of literature around the drag flick technique has not considered physiological differences amongst participants. However, the general field hockey literature has identified physiological and skill-related tests for talent identification within female field hockey. Keogh, et al. (2003) identified greater lower body power conditioning with higher level players which supports the expert panellist's consensus in relation to the drag flick technique. No literature has been found on core strength; explosive power or flexibility in relation to field hockey players, and therefore these attributes need further investigation within field hockey.

The final grouping the expert panel agreed was important for the drag flick was psychological attributes.

4.5.3 Psychological attributes

Mental toughness and the ability to shut out irrelevant cues were the only psychological factors on which the expert panel reached a consensus. This is supported by Gould et al., (2002) in a study of psychological characteristics of Olympic champions. Mental toughness was identified as the mental skill factor most frequently cited as a significant contributor to sports performance enhancement. Shutting out irrelevant cues has long been identified within the motor learning literature and the impact on performance of an inability to do so has been demonstrated (Schmidt and Wrisberg, 2008). It is perhaps surprising that these are the only two psychological attributes that reached a consensus within this study, but this is possibly representative of the coaching knowledge around sport psychology and the focus on the performance of the drag flick. In sports psychology studies coaches have expressed views that technical and physiological aspects of performance are issues that they are able to deal with whereas issues of sport psychology were areas in which coaches had limited knowledge and needed assistance (Williams and Kendall, 2007).

4.6 Summary

The use of a modified Delphi format incorporating initial interviews ensured that the subsequent round of questions presented in the form of questionnaires was based on the views of the expert panel members rather than those of the researcher. In addition, the use of interviews promoted a more in-depth analysis of participant's opinions and therefore improved the trustworthiness of the data.

Two rounds of questionnaires were undertaken to reach a consensus in which 28 attributes were identified, falling into three broad categories of technical; physiological; and psychological attributes.

The technical category was further broken down into different stages of the drag flick technique which was supported within the current research literature around the drag flick: approach to the ball; gathering the ball; the drag and the ball release. Overall, the expert panel identified a range of attributes according to their perceived impact on performance of the drag flick. These attributes were carried forward as dependent variables to be analysed in the biomechanical analysis in chapter 6. Positions of foot to ball at pickup; length of the drag; time of the length of the drag; stance width; centre of mass height; the kinematic sequencing and the thorax/pelvis differential were all dependent variables that were identified through the Delphi poll which were used to inform the methodological procedures for the biomechanical analysis presented within this thesis.

Other aspects of the Delphi Poll which were carried forward for the biomechanical testing procedures are the preferred target areas based on the consensus from the expert panel and the performance outcome of the drag flick technique. In summary, the expert coaching panel agreed the top two corners (left and right) were the preferred target areas for success. If on target, the defence has the lowest chance of saving the ball, however, all coaches agreed that these two target areas were also the most challenging for the attacking players. The two bottom corners (left and right) were the easiest target areas for the drag flickers and these target areas also increased the possibility of deflections into the goal from other players. However, in contrast, compared with top left and top right these target areas were easier for the defenders and goalkeeper to save the ball. For the purpose of the biomechanical methodological procedures within this thesis the four corners of the goal were used for the prescribed target areas, with more emphasis placed on the two bottom target areas due to the ability of the participants and their experience with the drag flick technique.

For the overall performance criterion, accuracy did not reach the specified level of agreement for consensus, but it was identified, through qualitative analysis, as the most important overall performance criterion for the drag flick technique. This lack of consensus of the overall performance criteria will be factored into the biomechanical testing as both accuracy and velocity will feature in the constraints placed on participants regarding different conditions that participants are asked to comply with as part of their drag flick trials during data collection.

The following bullet points summarise the Delphi poll study presented in this chapter and how the Delphi poll informed the biomechanical methodology presented in Chapter 5:

- A panel of 10 expert field hockey coaches was established.
- An initial interview with the expert panel to inform the questionnaire produced for subsequent rounds.
- Two rounds of questionnaires gained a consensus between the expert panel of field hockey coaches on 28 attributes of the drag flick technique.
- Following the consensus, the following dependent variables were used to inform the methodological procedures in Chapter 5:
    - Foot to ball distance at ball pickup
    - Length of drag distance
    - Length of time of drag flick
    - Stance width
    - Height of Centre of Mass
    - Kinematic sequence
    - Thorax/pelvis differential angle
- Top right/left and bottom right/left were used as target areas in Chapter 5.
- Both ball accuracy and ball velocity were used as overall performance criterion for procedures within Chapter 5.

CHAPTER 5:
BIOMECHANICAL METHODOLOGY

5.1 Introduction

This chapter describes the equipment and protocols used to collect and analyse the time series of kinematic data to achieve a thorough quantitative analysis of the field hockey drag flick technique. A robust methodology was established to ensure the validity and accuracy of the data collected. This included calibration of the motion capture system to quantify error, the methodology used to process the kinematic data and the filtering processes applied. Ethical approval was obtained for this research from Leeds Beckett University following the university policy and procedure.

5.1.1 Participants

Twelve field hockey players (8 male and 4 female) were recruited initially via convenience sampling and then via snowball sampling. The researcher requested potential volunteer participants through hockey networks; coaches in the Delphi method study were asked if they could recommend any potential participants; and recruitment materials were sent to local hockey clubs within the Yorkshire area. Twelve participants were selected based on availability and proximity to Leeds Beckett University for data collection. Twelve was also representative of number of participants used within the drag flick literature (McLaughlin, 1997, De Subijana et al., 2010, Ibrahim et al., 2017, Eskiyecek et al., 2018, Rosalie et al., 2017) and the Principal Movement Analysis literature (Gløersen et al., 2018, Werner et al., 2021).

Each participant was tested in one data collection session, and all were able to perform a drag flick, with the sample reflecting varying ability from novice to expert performer. Due to the difficulty of assessing a participant's level of performance of the drag flick technique, participant level was based on playing experience taking into consideration the following factors:

1. Highest level of current affiliated team the participant competes for in field hockey at time of testing
2. How long participants had been performing the drag flick
3. Highest level in which participants have performed the drag flick in a competitive environment.

Twelve players participated in this investigation (age 24.25 ± 4.83 years, height 1.75 ± 0.09 m and mass 77.29 ± 17.44 kg).

All players at the time of testing were free from injury and not in any recovery phase returning from an injury. The testing procedures were explained verbally and in writing to each participant in accordance with Leeds Beckett University's ethical procedures and written informed consent was provided (Appendix E and F). All participant data was stored on a password protected computer and backed up on a secure file on the cloud; participants were assigned a code number to assure anonymity, with a separate secure file containing the identification of the participants and code number.

5.1.2 Procedures

Data were collected in the Biomechanics Laboratory of the Carnegie School of Sport at Leeds Beckett University (Appendix E & F). The layout for data capture specified below allowed participants to undertake a drag flick replicating a setup with dimensions corresponding to England Hockey specifications. All participants were asked to undertake drag flick trials using a field hockey ball (an International Hockey Federation (FIH) approved hockey ball; mass = 160 g; circumference = 23 cm) and their own FIH approved hockey stick.

All participants were required to undertake their drag flicks aiming at a standard field hockey goal, 3.66 m wide and 2.14 m high. The ball was positioned 14.63 m from the goal target, which is representative of the top of the circle where players undertake the drag flick from in a game (Figure 6 a). The position at the top of the circle was selected based on the results of the Delphi poll study in Chapter 4. Coaches identified the top of the circle as the best position when a team only has one drag flicker as this gives the widest angles available at the goal for the drag flicker. Only two participants involved within this study play in teams where more than one drag flicker is available, therefore the top of the circle was considered the position that has the best ecological validity for participants included within this study. Participants were asked to complete 20 drag flick trials within three different conditions. Each condition was limited to 20 trials regardless of success so as not to unduly fatigue the participants. RPE data was collected after every five trials to ensure players were not becoming unduly fatigued throughout the testing protocol. It is normal for a player to repeat 100 to 150 trials in training and therefore the participants were not being asked to exceed their regular training intensities. Players were informed in advance of the testing so they could factor in the extra repetitions of drag flicks into their training schedules.

Each test condition was based on a target area within the goal provided and whether the researcher had given the instructions to achieve ball accuracy or ball velocity as the primary objective (Figure 6 b). Ball accuracy was explained to the participants as putting more emphasis on hitting the target than overall ball velocity. Ball velocity was explained to participants as putting more emphasis on the overall ball velocity whilst still aiming for the specified target area. The specified 0.5 m^2 target area was positioned in the field hockey goal. The conditions utilised ball accuracy and ball velocity as primary objectives due to the sparsity of research within this area. Study 1 of this thesis identified, through the Delphi Poll Method with expert field hockey coaches, that there was no agreement as to what is the most important objective of the field hockey drag flick. Self-selected and prescribed target areas were incorporated into the conditions to establish whether different target areas had any effect on the kinematic data of each participant, and whether any patterns could be identified within the data. Prescribed target areas were selected randomly by the researcher based on ability of players and identified preferred target areas by coaches in study 1. Coaches identified the four corners as the preferred target areas with bottom left and bottom right being preferred for novice players. Therefore, the allocation of prescribed target areas was given following the self-selection process and consideration of the ability of each player.

The three conditions were:

- Condition 1 - Participants were asked to self-select a preferred 0.5 m^2 target area within the goal and were given ball accuracy as the primary objective.
- Condition 2- Same target as condition 1 but with ball velocity as the primary objective.
- Condition 3- Participants were given a 0.5 m^2 target area selected by the researcher and given ball accuracy as the primary objective.

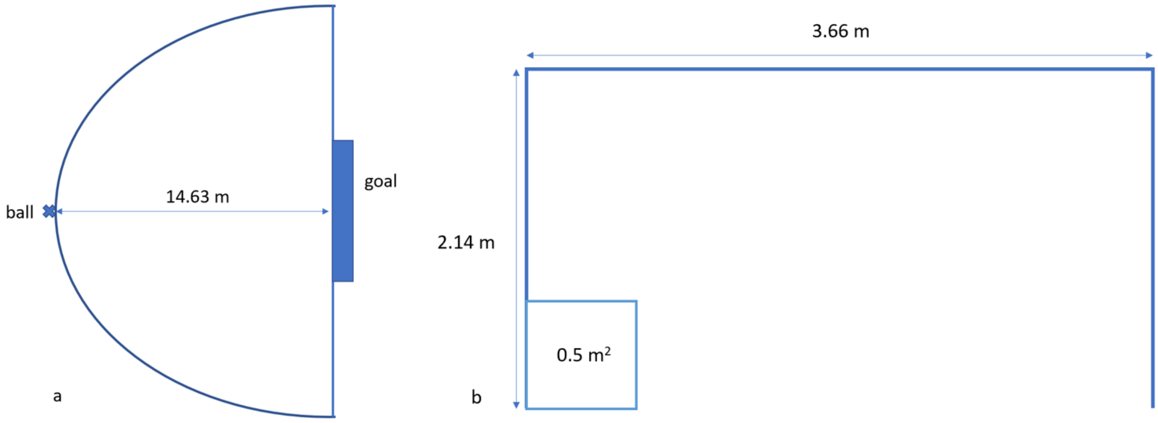


Figure 6: Experimental set up of data collection. (a) position of ball in relation to the goal (14.63 m from goal), (b) example of position of 0.5 m2 target area positioned within goal. Source: Created by the author.

5.1.3 Data Capture

A Qualisys Track Manager system (Qualisys AB, Gothenburg, Sweden) captured the drag flicks with 10 cameras, sampling at 250 Hz, which was the same capture rate used in the other drag flick studies of three-dimensional analysis using motion capture (De Subijana et al., 2009, De Subijana et al., 2010, De Subijana et al., 2011, Gómez et al., 2012). The drag flick is a fast-paced complex technique and therefore a high sampling frequency is required to ensure important time discrete events were visible throughout the movement (ball pick-up, foot to ball distance, stance width and ball release). To minimise occlusion of markers on the participants six cameras were positioned high on a rig pointing downwards and four cameras were positioned lower outside the four corners of the capture volume (Figure 7). The Qualisys system was calibrated at the start of each data collection period.

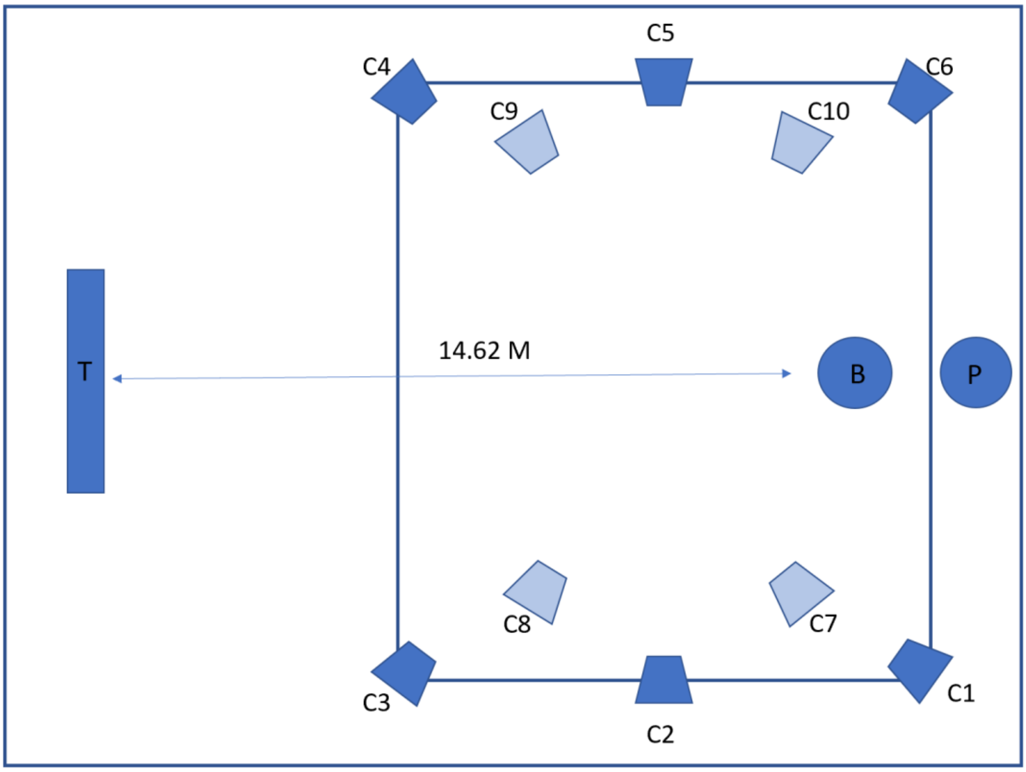


Figure 7: Representation of the experimental set-up: C1-C6 = Six infrared camera attached to an overhead rig; C7-C10 = four infrared cameras positioned lower on tripods; P = Participant; B = Ball; T = Target. Source: Created by the author.

A video camera (Casio EX-ZR700 Casio Computer Co., Ltd. Tokyo, Japan) was also used to capture whether the drag flick was successful or not. The camera was set to record at 240 Hz with a shutter speed of 1/1000 and an aperture of f/3.5. The camera was positioned to the side and behind the active participant and zoomed and focussed onto an area slightly larger than the target area. This data was used to confirm post data collection that the records collected of hit and missed shots were accurate.

For the purpose of analysis, the drag flick movement was deemed to have commenced once the left foot left the ground to initiate the step before the cross-over step and was completed ten frames after ball release from the stick in order to measure ball speed (De Witt and Hinrichs, 2012). The time of the left foot leaving the ground was determined by the velocity of the left heel marker increasing above 0.1 $m \cdot s^{-1}$ in the vertical Z-axis of the global coordinate system (GCS). Once the start event was determined, a cubic spline interpolation was used to normalize all movement trajectories to 101 samples using Visual3D (x64 Professional v6.01.18, C-Motion, Germantown, USA) to align each trial for further analysis (Gløersen et al., 2018).

5.1.4 Calibration

A capture volume 3 m long, 2.5 m wide and 2 m high was calibrated with an error of less than 1.5 cm. This was based on guidelines provided by Payton and Burden (2017) with the capture volume being a compromise between capturing the movement being studied and the resolution of the system by using the smallest volume possible.

Calibrating the Qualisys system enables the image coordinates on each individual camera to be converted to the real-world three-dimensional coordinates of each marker (Payton and Burden, 2017). The Qualisys system uses a two-stage process for calibration: the static and dynamic calibration using the L frame and the wand (Figure 8).

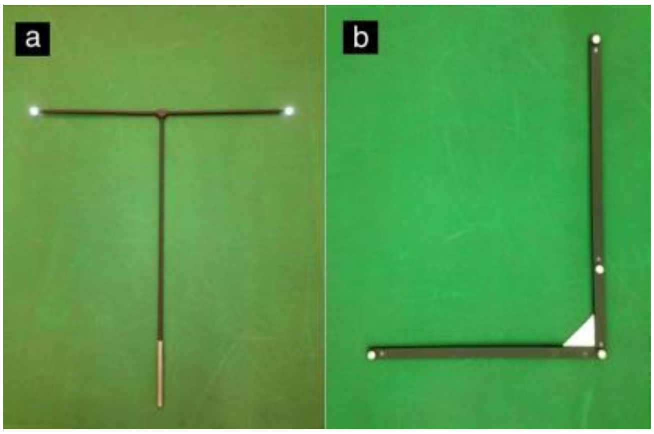


Figure 8: The wand and L frame structure used in the calibration process. Source: Created by the author.

The L Frame with four fixed markers in known locations was used to determine the location of the GCS. The X axis was aligned with the direction of travel of the ball towards the goal, the Z axis vertically and the Y axis orthogonal to X and Z to create a right-hand orthogonal coordinate system.

The dynamic wand calibration was conducted to register the cameras to the whole of the capture volume (Payton and Burden, 2017). The wand was moved around in a sporadic manner to cover the whole capture volume in all three planes of movement. Qualisys provided the mean residuals of each camera and calibration was only accepted if the mean residual for each camera was less than 1.0 mm, therefore indicating that the wand was within 1 mm of it’s true position.

5.1.5 Coordinate systems.

For each segment, a local coordinate system (LCS) was created using predominately a default x-y-z Cardan rotation sequence to determine the orientation of the LCS in space. This sequence has been widely used within the biomechanics literature and more specifically is the sequence used by the other published papers around the biomechanics of the field hockey drag flick (De Subijana et al., 2009, De Subijana et al., 2010, De Subijana et al., 2011, Gómez et al., 2012). The exceptions to the use of this methodology are described below. Each LCS was positioned at the proximal joint centre of the segment when standing in an anatomical position. The z-axis pointed upwards along the longitudinal axis of the segment (representing axial rotation), the positive x axis pointed to the subject’s right (representing the flexion/extension axis of the joint) and the positive y axis pointed forwards (representing the abduction/adduction axis of the joint) (Figure 9). A series of three rotations, one about each of the coordinate axes is then calculated that places the joint in the same final orientation as the true movement.

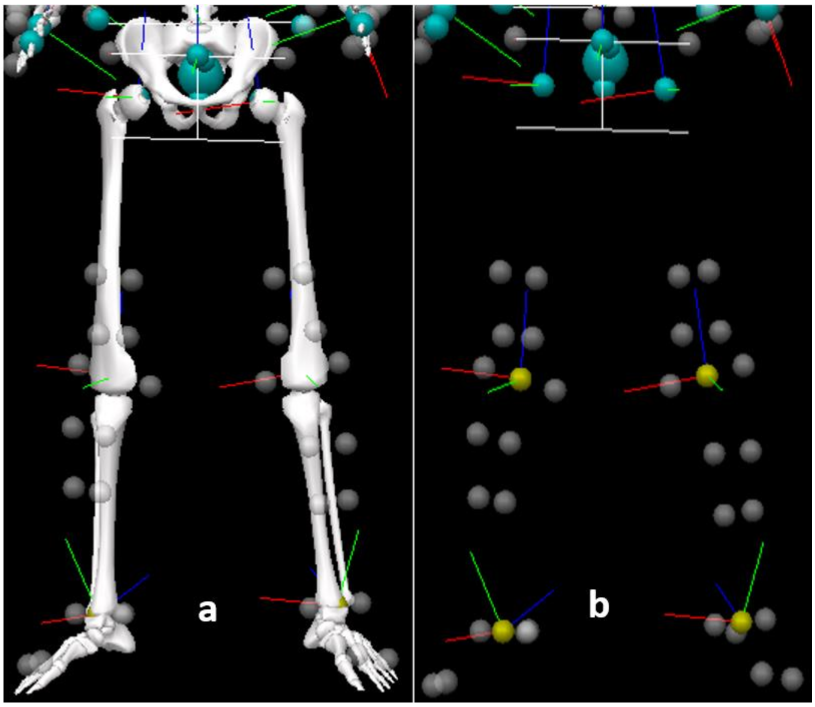


Figure 9 - LCS's represented by z axis (blue line), x axis (red line) and y axis (green line) for the pelvis, hips, knees, and ankles. (a) with segments, (b) without segments displayed. Figures generated using Visual 3D software.

However, within the drag flick movement the shoulder joint angle is greater than 40 degrees and therefore, it is recommended that a z-y-z Euler rotation sequence is used (Wu et al., 2005). Using this sequence for the shoulder joint: the first rotation is about the z axis of the humerus (angle = internal/external rotation); the second rotation is about y-axis in the anterior direction (angle = abduction/adduction); and the third rotation is about the trunk's vertical z-axis (angle=horizontal flexion/extension). Therefore, for the purpose of this research the z-y-z rotation sequence was used for the shoulder joints and the x-y-z rotation sequence was used for all the other joints.

For the biomechanical analysis in Chapter 6, the coordinate data taken from the moving markers was expressed in the GCS. However, for the purpose of the Principal Movement Analysis in Chapter 7 the coordinates of the markers were expressed in a reference system originating in the centre of mass position of the participant, with the X-axis pointing in the lateral direction compared to the direction of travel of the ball, the Y-axis in anterior direction of the travel of the ball, and the Z-axis in vertical direction. This was to enable an analysis to be undertaken on the variability of the participants isolated movement as opposed to the variability of their movement in relation to the GCS of the lab.

5.1.6 Inverse kinematics

5.1.6.1 Six Degrees of Freedom

Visual 3D has two distinctive approaches to computing the position and orientation of a segment. The first (six degrees of freedom) is to assume independence of all segments, where each segment has three non-collinear tracking markers where the position and orientation of these markers are estimated and there is no explicit linkage connecting segments; the endpoints of the proximal and distal segment move relative to each other based directly on the recorded markers (Robertson et al., 2013). As six degrees of freedom does not constrain the endpoints of the proximal and distal segment to remain fixed relative to each other this can result in apparent dislocations at joints predominately because of skin movement artefact (Lu and O'connor, 1999). Skin movement artefact is the discrepancy between the movement of the marker and the movement of the actual skeleton (Payton and Bartlett, 2008). For example, Lu and O'Connor (1999) noted that joint dislocation at the hip and knee were 3.88 and 3.24 cm, respectively. Therefore, it was deemed that the six degrees of freedom approach was not ideal for measuring the positions and orientations of a multilink model due to the possible joint dislocations and the associated unreliable kinematics.

The second method Visual 3D used to compute pose estimation is Lu and O'Connor's (1999) Global Optimisation Method (GOM) i.e., Inverse kinematics which assumes a linked chain of segments, such as the joint properties that define the connection between segments and minimise the effect of skin movement artefact and measurement error.

5.1.6.2 Global Optimisation Model (GOM)

Global optimisation computes the pose of a model that best matches the motion-capture data of the optimal pose of a multilink model using a least squares approach. Lu and O'Connor (1999) described a global optimization process where physically realistic joint constraints can be added to the model to minimize the effect of the soft tissue and measurement error. The difference between six degrees of freedom and Lu and Connor's (1999) approach is that constraints can be added between segments that restrict the relative motion between the segments. One or more kinematic chains are created to determine the parameters of a jointed flexible object in order to achieve the desired pose, therefore minimising the effects of skin movement artefact and measurement error.

The GOM approach has been shown to provide an efficient and reliable method for the calculation of the poses of multilink models from marker coordinates. The consideration of joint constraints can largely reduce the effects of skin movement artefacts, therefore, the GOM approach was used for this research.

5.1.7 Marker set

For the purpose of this research, guidelines provided by Cappozzo et al. (1995) were used to create a marker set that tracked the movements of the underlying bone segments. A minimum of three non-collinear markers were used to track each rigid segment, allowing a custom marker set to be created for the drag flick. This permitted markers to be placed that were more visible to each of the cameras. Where necessary additional markers were placed on segments to reduce occlusion. This was particularly relevant for the trunk due to the nature of the movement captured and markers on the front of the trunk being occluded (Payton and Burden, 2017). A total of 81 retro reflective markers were attached to the athlete's skin and equipment and were tracked.

A static calibration trial of each participant in the motorbike pose was captured with all anatomical and tracking markers placed on the participant (Figure 10). This enabled the Qualisys software to calculate the relationship between segment tracking markers and anatomical landmarks (Payton and Burden, 2017).

Some markers on anatomical landmarks were used for segment definition and were removed for the movement trials so as not to inhibit the movement patten of each participant. Some markers were used for tracking only and were positioned on the rigid segment in clusters. These were mounted to thermoplastic shells that were placed on the middle regions of each segment and had a known relationship to the anatomical landmarks where markers were positioned. The shells were attached to participants with neoprene wrap to secure them to each segment. This method of cluster markers has been shown to better reflect motion of the underlying bone compared to individual markers placed directly on the skin (Manal et al., 2000). Finally, some markers were used for both segment definition and tracking.

The individual markers were 19 mm in diameter and attached to the skin. Due to the gross movement of the drag flick and the perspiration of participants, taped markers either moved or dropped off in pilot testing.

For the duration of testing participants wore their own playing shoes and shorts/underwear that did not occlude the markers placed.

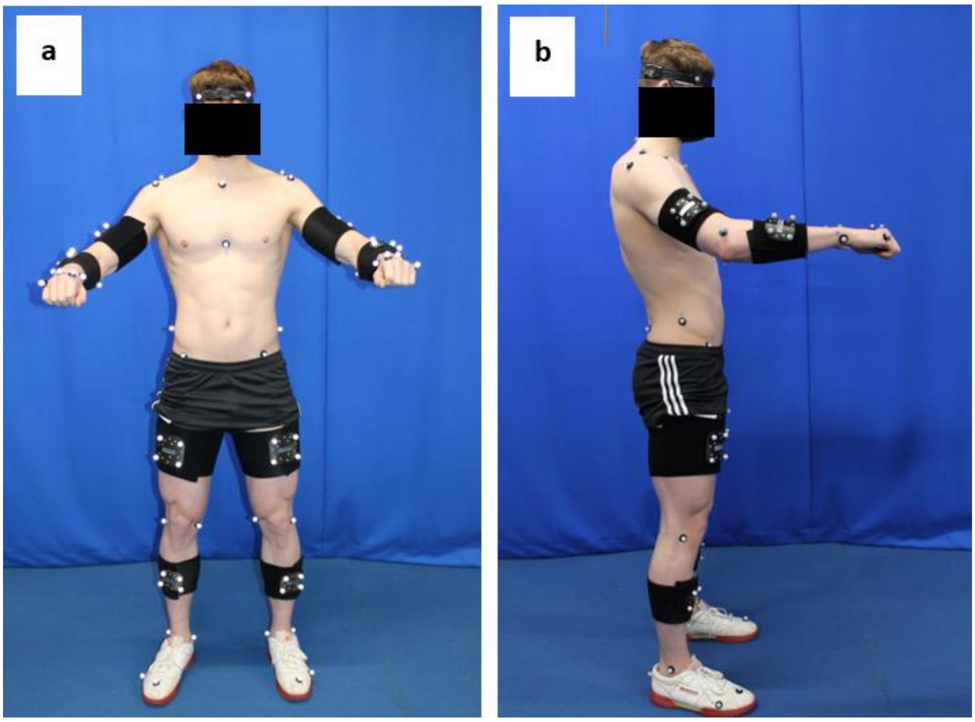


Figure 10: (a) Front view and (b) side view photos of the static calibration pose with markers. Source: Created by the author.

5.1.8 Segment definitions

5.1.8.1 Head

The proximal end of the head was defined by the triad of left and right acromion markers. The left and right anterior head markers (HI and H2) were placed just above each eyebrow and used to define the distal end of the head segment, which were vertically above the acromion at the level of the ear. (Figure 11) (C-Motion, USA). Left and right posterior markers (H3 and H4) were placed on the same transverse plane as H1 and H2. H1 to H4 were all used as tracking markers throughout the movement.

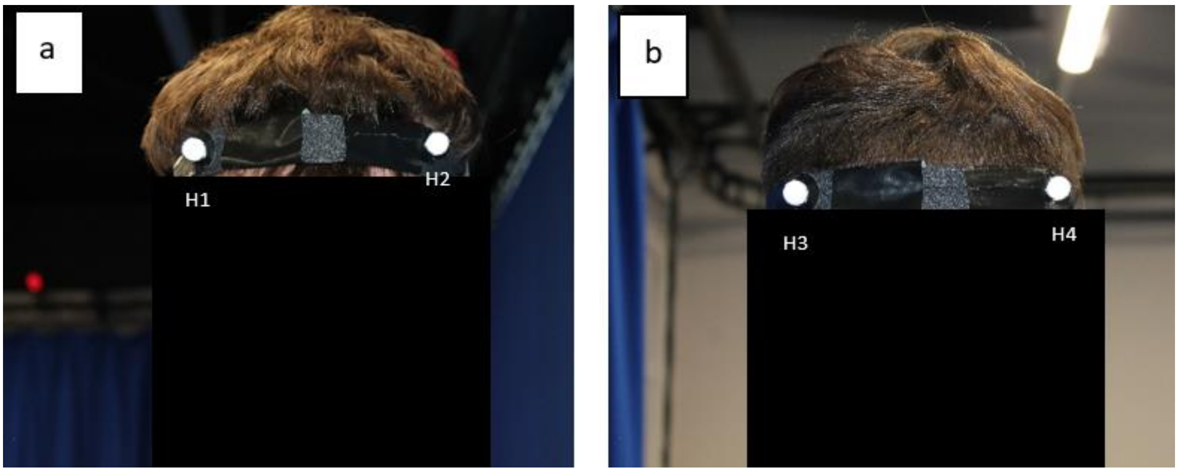


Figure 11: (a) Front view and (b) back view markers of the head. Source: Created by the author.

5.1.8.2 Upper arm

In order to identify the glenohumeral joint centre (GHJ) for the proximal end of the upper arm a method proposed by Campbell et al., (2009) was adopted. Magnetic resonance imaging (MRI) was used to validate this method as superior to six other established predictive methods. The inter-tester and within-tester reliability results showed an average of 6 ± 3 mm and 6 ± 4 mm that was significantly less ($p < 0.01$) than any other predictive method (9 -22 mm) (Campbell et al., 2009). MRI images of 15 participants were used to create a stepwise linear regression analysis to create the following three regression equations to estimate the x, y and z coordinates of the GHJ:

$$x = 96.2 - 0.302 \times (SJN - C7\ mm) - 0.364 \times height\ (cm) + 0.385 \times mass\ (kg)$$

$$y = -66.32 + 0.30 \times (SJN - C7\ mm) - 0.432 \times mass\ (kg) \quad (1)$$

$$z = 66.468 - 0531 \times (AcrLR - CP\ mm) + 0.571 \times mass\ (kg)$$

SJN is the Sternum Jugular Notch, C7 is the 7th cervical vertebrae, CP is the centre point between SJN and C7 markers and AcrLR is the midpoint between the most posterior and anterior points of the lateral ridge of the acromion process (Campbell et al., 2009).

The distal joint centre of the left and right upper arm was defined as the midpoint between the medial and lateral epicondyle markers of the humeri.

The acromion triad of markers and the medial and lateral epicondyle markers of the humeri were used for segment definition (Figure 12). C7, SJN and a thermoplastic of non collinear markers placed on the centre region the upper arm segments were used for tracking (Figure 13).

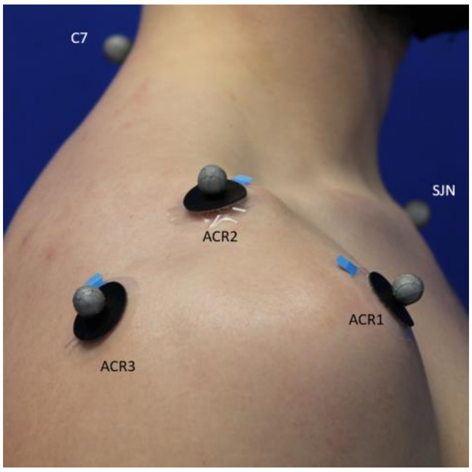


Figure 12: Photo of the right shoulder showing five markers used to define the GHJ using the regression model: SJN, C7, anterior (ACR1), central-medial (ACR2) and

posterior (ACR3) acromion markers (i.e., acromion triad). Source: Created by the author.

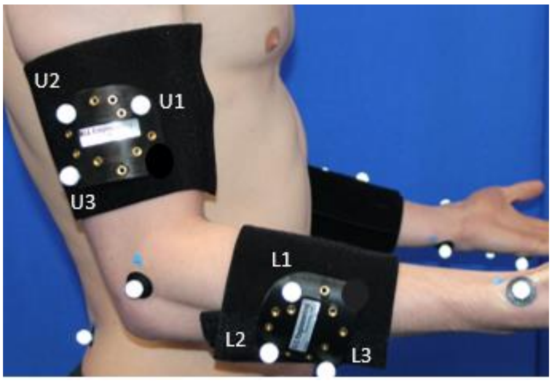


Figure 13: Photo of the upper arm (U1-3) and lower arm (L1-3) tracking markers. Source: Created by the author.

5.1.8.3 Lower arm

For the static trial, the midpoint between the medial and lateral epicondyle markers were used to define the proximal joint centre of the lower arm segment. Markers on the radius-styloid processes and the ulna-styloid processes were used to define the distal joint centre of the lower arm segment. A thermoplastic cluster of three non-collinear markers were placed on the lower arm segments for tracking purposes. These markers were repeated for both left and right lower arms (Figure 13).

5.1.8.4 Hand

For the static trial, markers on the left and right radius-styloid processes and the left and right ulna-styloid processes were used to define the proximal joint centre of the hand segment. Markers on the heads of metacarpals 1 and 5 was used to define the distal end of the hand segment. A third triad marker was placed on the hand segment. All markers were replicated for both left- and right-hand segments. These markers were used for both the segment definition and for tracking.

5.1.8.5 Pelvis

The pelvis segment was defined using the anatomical landmarks of the Left Ilium Crest Tubercle (LICT) and Right Ilium Crest Tubercle (RICT) as static markers and the Anterior Superior Iliac Spine (ASIS) and the Posterior Superior Iliac Spine (PSIS) as both static and tracking markers.

The right ASIS marker was removed for tracking to avoid movement patterns being altered by participants when undertaking the drag flick (Figure 14).

The origin of the pelvis segment coordinate system was defined as the mid-point between the ASIS markers using Visual 3D's CODA pelvis. The LCS of the pelvis was defined as the plane passing through the left and right ASIS markers, and the mid-point of the left and right PSIS markers.

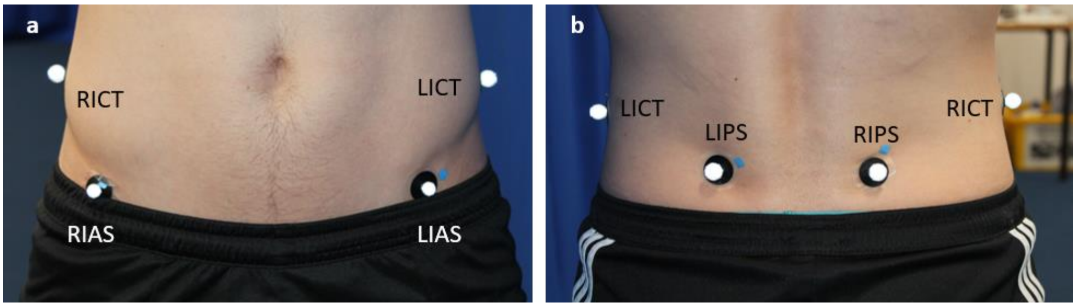


Figure 14: Static and tracking markers used for the CODA pelvis in Visual 3D. Source: Created by the author.

5.1.8.6 Thorax/Ab

The thorax segment was defined using the midpoint between the right and left iliac crest on the pelvis to define the proximal joint centre of the thorax/ab segment. The mid-point between the right and left shoulder joint centres was used to define the distal joint centre of the thorax/ab segment. Four additional tracking markers were placed onto the Thorax (sternum xiphisternal (SXS), 8^{th} thoracic vertebrae (T8), sternum jugular notch (SJN), and C7) (Figure 15). Additional tracking markers were used as the nature of the movement and the flexion of the thorax segment during the technique were likely to occlude markers.

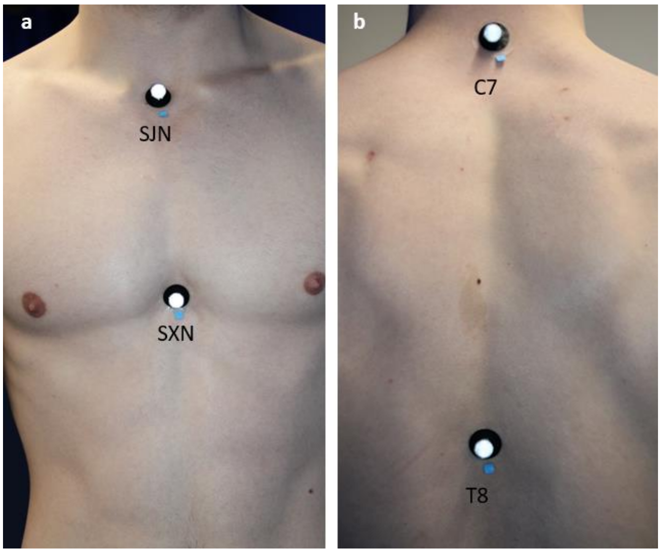


Figure 15: Front and rear-view photos of tracking markers for the thorax/ab segment. Source: Created by the author.

5.1.8.7 Thigh

For the static trial, the left and right hip joint centres were used to define the proximal joint centres of the left and right thigh segments. Estimates for the right and left hip joint centre are represented as landmarks that are created automatically when the CODA pelvis segment is created.

The location of the landmark is defined as:

RHJC=(0.36*ASIS_Distance, -0.19*ASIS_Distance,-0.3*ASIS_Distance)

LHJC=(-0.36*ASIS_Distance,-0.19*ASIS_Distance,-0.3*ASIS_Distance)

These estimates are based on a "prediction" method developed by Bell et al. (1990) and represented as landmarks that were created automatically when the CODA pelvis segment was created in Visual 3D. The same segment markers were used to define both the pelvis segment and the proximal end of the left and right thigh segments.

These estimates are adapted from the articles that compared the accuracy of hip joint centre locations using several prediction methods (Bell et al., 1989, Bell et al., 1990).

The mid-point between the medial (FME) and lateral (FLE) epicondyle markers on the femur was used to define the distal joint centre of the left and right thigh segment. A thermoplastic cluster of markers were placed on the centre region of the left and right thigh segments for tracking purposes (Figure 16).

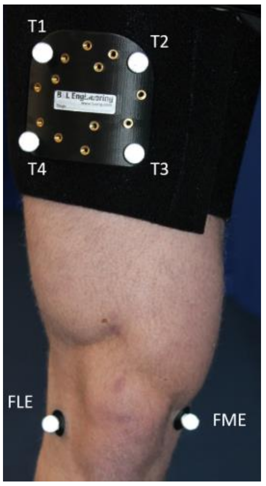


Figure 16: Photo of the tracking markers for the thigh segments. Source: Created by the author.

5.1.8.8 Shank

The mid-point between the medial and lateral epicondyle markers of the left and right femur was used as the proximal joint centre of the shank segments. The mid-point between the medial and lateral malleoli markers of the left and right tibia and fibula respectively was the distal joint centre of the shank segments. In addition, a thermoplastic cluster of markers were placed on the centre region of the left and right shank segments and used as tracking markers (Figure 17).

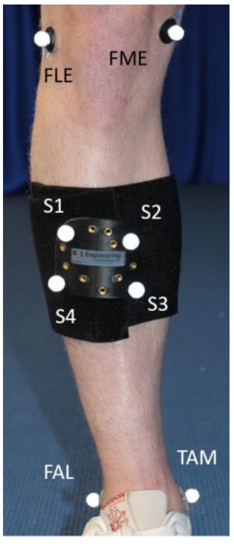


Figure 17: Photo of the static and tracking markers for the shank segments. Source: Created by the author.

5.1.8.9 Foot

The mid-point between the medial and lateral malleoli markers of the left and right tibia and fibula respectively were used for the proximal joint centre of the left and right foot segments (Figure 18).

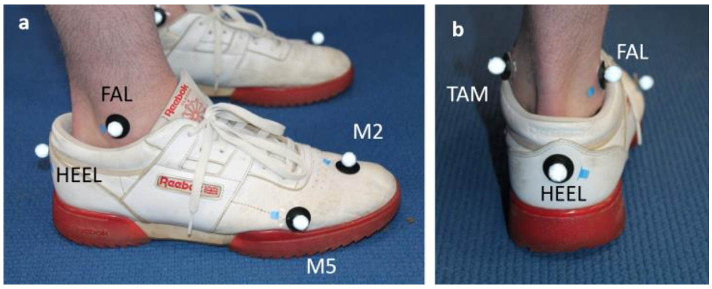


Figure 18: Side (a) and back (b) view of markers for the foot segment. Source: Created by the author.

The mid-point between the 5th metatarsal head and 1st metatarsal head was used as the distal joint centres of the left and right foot segments. All four markers (TAM, FAL, M5 and M1) were all used as static and tracking markers. An additional tracking marker was placed on the posterior surface of the calcaneus (HEEL).

5.1.8.10 Stick

The mid-point between the head of metacarpal 1 and 5 markers were used as the proximal head of the stick. A marker was placed at the end of the toe of the stick as the distal end of the stick (ST2). Two additional markers for tracking were placed just above the toe of the stick (ST1) and at the end of the stick (ST3) (Figure 19).

Figure 19 Static and tracking stick markers. Source: Created by the author.

5.1.8.11 Ball

Four 2 cm^2 markers (BL1-4) were attached to the ball using reflective tape to calculate linear and angular ball velocity for each drag flick trial. These markers were also used during the static trial to create a model of the ball in Visual 3D (Figure 20).

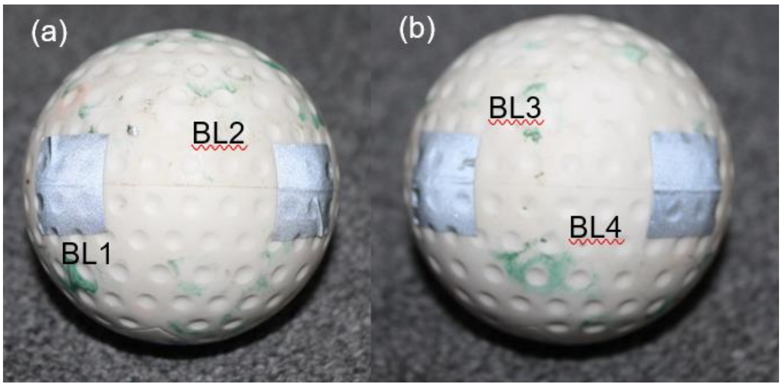


Figure 20: (a) Top view and (b) bottom view photos of markers (BL1-BL4) for the hockey ball. Source: Created by the author.

5.1.9 Body segment parameters.

The centre of mass (COM) of the participant (including equipment) was estimated from a 15-segment model using Visual3D (C-Motion, Inc., Germantown, MD, USA). The segment masses are based on regression equations by Dempster (1955) using data from eight cadavers.

5.1.10 Building a model

For the purpose of this research a static trial was recorded for each participant and a three-dimensional 15-segment model was created in Visual3D using this marker set, segment definitions and body segment parameters (Figure 21).

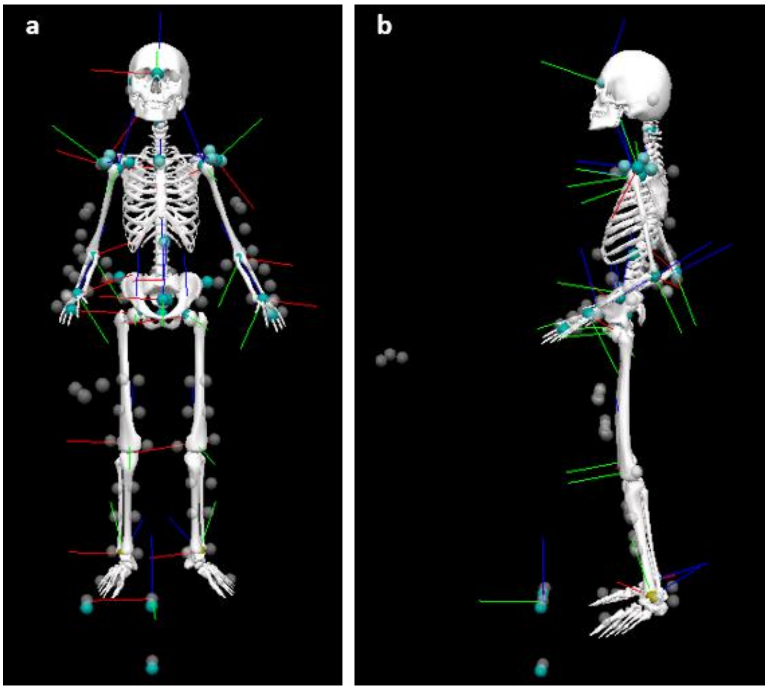


Figure 21: Front view (a) and side view (b) images of a three-dimensional, 15-segment model created in Visual 3D using the static trial. Figures generated using Visual 3D software.

Prior to assigning the static calibration model to the motion drag flick trials it was necessary to process the signal to remove random noise (Payton and Burden, 2017).

5.1.11 Data processing

Data processing was undertaken in Cortex (Motion Analysis Corp., Rohnert Park, California, USA). Very few gaps were present during the movement trials, the maximum duration of gaps was 24 frames (0.096 s). Initially all gaps in the marker trajectories were filled with either a cubic join or the virtual join function within the software. Cubic join calculates the values to place in the gaps with a cubic spline. A spline is fitted to the data either side of the gap and interpolated to estimate the missing values (Figure 22). When possible, gaps were filled using a virtual join function. However, this can only be used when there are four or more markers with fixed locations relative to each other. If one of these markers had a gap in its trajectory, the coordinate system of the missing marker was interpolated using the other three fixed markers. Once the data had been filled a manual inspection took place of the data to check the gap filling was sensible.

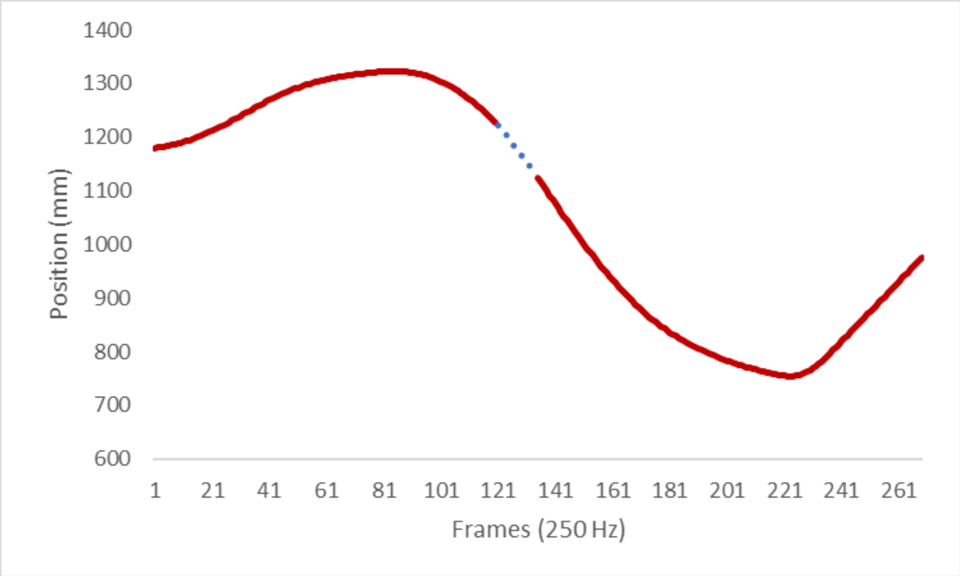


Figure 22: Example of the filling of a small gap in a marker trajectory using "cubic spline fill". The filled data is represented by the dashed line. Source: Created by the author.

5.1.11.1 Low pass filter

It is necessary to remove noise from kinematic data collected which contaminates the sampled data. There are various filters that can be applied, and these differ depending on the nature of the data collected. Image-based motion requires a low pass filter to be applied to allow the low frequencies within the data to pass through the filter and the higher frequencies than the specified cut-off to be reduced (Payton and Burden, 2017, Robertson et al., 2013). There are various low pass filters that are used within biomechanics, such as digital filters (e.g., the Butterworth filter), splines (e.g., the generalised cross-validated quintic spline), and frequency domain-based techniques (e.g., such as truncated Fourier series). As noise exists across the frequency of the data there will always remain some noise in the data, but it is important to select the appropriate amount of signal reduction. For example, if the cut-off frequency is too high the signal will contain too much noise, in contrast if the cut-off frequency is too low some data will be discarded (Payton and Burden, 2017). Two studies analysing the drag flick kinematics (Ibrahim et al., 2017, Yusoff et al., 2008) have used a Butterworth low-pass filter method to process the data with a cut-off frequency of 10 and 15 Hz at a capture rate between 50 and 150 Hz.

As identified above the selection of frequency cut-off is very important when filtering data. For the purpose of this research residual analysis was applied which compares the difference between filtered and unfiltered signals over a wide range of cut-off frequencies (Wells, 1980). The term residual refers to the signal content that remains when the filtered data is subtracted from the raw data (Robertson et al., 2013). The residuals of each filtered signal are then analysed graphically (Figure 23). According to Winter (2009) the projection of residual and filter cut-off frequencies provide a profile of a curve with a sudden increase. This sudden increase in the graphical representation between residuals and cut-off frequencies determines the theoretical cut-off frequency which should be applied.

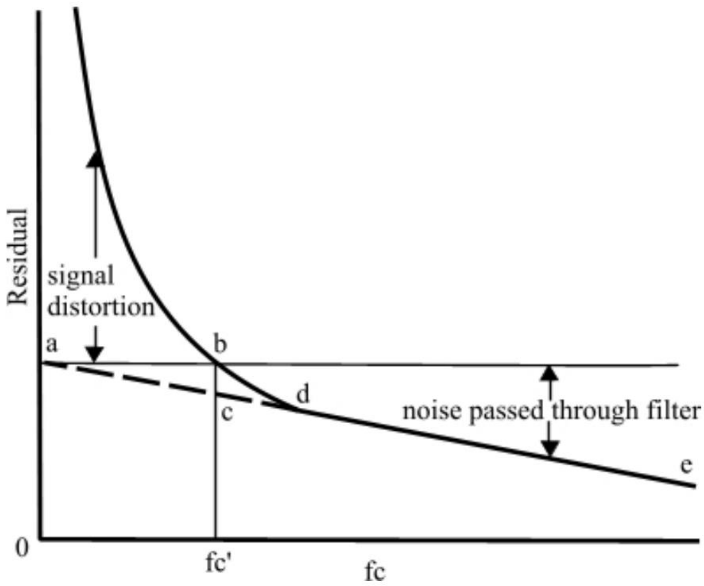


Figure 23 - Illustration of residual analysis method used to identify an appropriate cut-off frequency. The cut-off frequency is shown on the horizontal x-axis (fc). The residual (mm) is shown on the vertical y-axis (Winter, 1990).

Figure 23 shows that the area above the line 'de' (extended to 'a') represents the noise residual and the intercept 'a' of the vertical y-axis (at 0 Hz) is the root mean square error of the noise for the data set (Winter, 2009). The curved line represents the signal distortion that is taking place as the cut-off is reduced. According to Winter (2009), the final decision is what cut-off frequency should be chosen by estimating the amount of noise and signal distortion that is acceptable (point fc' in Figure 23). To estimate this, a line is projected from 'a' to intersect the residual line at 'b'. fc is the frequency on the abscissa which represents the balance point. Signal distortion is represented by 'bc', this is also an estimate of the noise that is passed through the filter (Winter, 2009).

A residual analysis was performed on the x, y, and z coordinates for a tracking marker on each of the 16 segments modelled for each participant. A comparison was made between two drag flick trials from two separate participants, and different stages of the drag flick trials. As front foot placement and ball pick up were moments in the movement pattern that were likely to have increased noise in the data these time discrete points were analysed to ensure appropriate cut-off frequencies were applied. The cut-off frequencies for all three axes were similar for each segment (i.e., within 2 Hz for each marker). Therefore, the highest cut-off frequency was identified from each axis, and each participant for the individual segments and applied for all participants. Table 8 - Cut-off frequencies estimated for each segment from two trials of two participants and applied cut-off frequencies performing a drag flick with maximal velocity. The table indicates a cut-off range between 9 – 12 Hz for all body segment markers showing that the segments for the placement of front foot had a higher cut-off frequency compared to those segments with limited impact with the ground.

Table 8 - Cut-off frequencies estimated for each segment from two trials of two participants and applied cut-off frequencies performing a drag flick with maximal velocity. Source: Created by the author.

Segment	P1 cut-off Frequency (Hz)		P2 cut-off Frequency (Hz)		Applied cut-off frequency for all participants (Hz)
	Trial 1	Trial 2	Trial 1	Trial 2	
Head	10	11	11	10	11
Thorax	11	11	11	9	11
Pelvis	10	10	9	11	11
Right Upper Arm	10	10	10	10	10
Right Lower Arm	10	10	11	11	11
Right Hand	10	10	11	11	11
Left Upper Arm	9	10	10	10	10
Left Lower Arm	11	10	11	10	11
Left Hand	10	9	11	10	11
Right Thigh	10	11	10	10	11
Right Shank	11	11	11	10	11
Right Foot	10	10	11	11	11
Left Thigh	12	10	12	12	12
Left Shank	11	11	12	10	12
Left Foot	10	10	11	11	11
Stick	10	10	10	11	11
Ball	9	10	11	10	11

The data collected was then analysed in two separate procedures. A typical traditional biomechanical analysis and a more contemporary Principal Movement Analysis both of which are outlined below.

5.1.12 Biomechanical analysis variables

Kinematic variables were selected for this research based on previous literature within the field of biomechanical analysis of the drag flick (De Subijana et al., 2010, Ibrahim et al., 2017, Yusoff et al., 2008), and the results of the Delphi poll study. Table 9 indicates which variables were selected from published research and the Delphi poll and how they were defined. Variables were calculated at various time discrete points within the drag flick: (Start of movement – pick up of left foot prior to cross-over step; stick and ball contact; placement of right foot at start of cross-over step; stance width at left foot placement; ball release).

Table 9 - Drag flick dependent variables measured and how they were defined. Source: Created by the author.

DependentVariables	Definition	How variables were identified
Ball Accuracy	Success of hitting 0.5 m^2 target	Delphi poll
Ball release velocity ($m \cdot s^{-1}$)	Velocity of the ball at release relative to the lab.	Published research and Delphi poll
Stick linear velocity ($m \cdot s^{-1}$)	Linear velocity of stick at ball release.	Published research
Length of time of drag flick time (s)	Time from back left foot pick up to ball release.	Published research
Normalised Drag Distance (BH)	Total ball drag distance normalised to participant height.	Published research and Delphi poll
Normalised Foot to Ball Distance (BH)	Distance from back foot to ball at pick up normalised to participant height.	Published research and Delphi poll
Normalised Stance Width (BH)	Distance between front and back foot at double foot contact.	Published research and Delphi poll
Thorax/pelvis differential position 1 (°)	Joint angle created by the Thorax relative to the pelvis at right foot contact with the ground.	Published research
Thorax/pelvis differential position 2 (°)	Joint angle created by the Thorax relative to the pelvis at stick contact with the ball.	Published research
Thorax/pelvis differential position 3 (°)	Joint angle created by the Thorax relative to the pelvis at left foot contact with the ground.	Published research
Thorax/pelvis differential position 4 (°)	Joint angle created by the Thorax relative to the pelvis at ball release.	Published research
COM Height	COM height from GCS at stance width and ball release.	Delphi poll
Kinematic Sequence	Kinematic sequence of peak velocities of peak negative linear velocity of the stick; peak pelvis angular velocity; peak upper trunk angular velocity; peak positive linear velocity of the stick.	Published research and Delphi poll

5.1.13 Principal Movement Analysis procedures

This research describes a novel data normalisation approach based around analysing the kinematic data using Principal Component Analysis (PCA). As referred to in the literature review this method was selected due its capability to reduce a large data set and analyse the coordination of joint angles throughout the technique. The data was concatenated for all participants, allowing a direct comparison of the postural movement components between participants based on the work by Gløersen et al. (2018). All calculations were computed using MatLab (Mathworks, Inc., USA) software. Data of each trial was normalised by subtracting mean posture and dividing by the trials mean Euclidean distance (Federolf et al., 2013, Federolf, 2016). Finally, the marker coordinates were weighted according to the relative body mass, which they represent (Federolf, 2016, Gløersen et al., 2018). This normalisation was designed to remove anthropometric differences while conserving the differences in marker movement to ensure that each participant equally affects the PCA output (Federolf, 2013, Federolf, 2016). If individual participants have varying body sizes and proportions these differences can lead to disparities in marker coordinate data. For example, a taller participant may have markers placed further apart than shorter participants, leading to a larger spatial spread in the marker data. By normalising the marker coordinates to the relative body mass, these anatomical variations are accounted for. While the normalisation equalises the influence of different markers, it still preserves the relative differences in marker movements. This is crucial for capturing individual and functional movement patterns within the PCA, as the goal is to analyse how different body parts move in relation to each other. Following these procedures, a matrix was created for each participant, N [N = 1…12], which was then pooled into a 24,240 x 60 pooled matrix. A PCA was conducted on this matrix resulting in one set of eigenvalues (EV) and one set of eigenvectors (PC), which are common to all participants across all conditions and all trials. From this, postural movements were quantitatively compared between participants. Following this the normalised data of each successful trial for each individual condition was projected onto the PC basis vectors to create a principal postural position (PP) for each time point and how much this PP deviates from the mean posture according to the movement pattern defined by the associated PC vector (Federolf et al., 2013, Haid et al., 2018, Daffertshofer et al., 2004). The results of this analysis were characterised qualitatively as movements of an animated stick figure. The full code can be viewed in Appendix P.

Mean line density plots of the time evolution coefficients were generated which allowed a comparison of participants using a colour coded system of red = low ability, orange = middle ability and green = high ability. Ability was determined for each condition using number of successful shots within the 20 trials of each condition (

Table 10).

Table 10 – Participant ability classification based on number of successful shots for each condition. Source: Created by the author.

Participant	SS ACC	SS VEL	P ACC
1	Middle (5)	High (7)	Low (1)
2	High (9)	Low (2)	Middle (5)
3	Middle (5)	Middle (3)	Low (2)
4	High (8)	High (6)	High (7)
5	Middle (4)	Middle (3)	High (7)
6	High (10)	High (5)	Middle (5)
7	Low (3)	Low (1)	High (9)
8	Middle (4)	Low (2)	Middle (4)
9	Low (3)	Low (1)	High (9)
10	Low (3)	Middle (3)	Low (1)
11	High (7)	High (5)	Middle (5)
12	Low (1)	Low (1)	Low (3)

Note: (n) = Number of successful shots within 20 good trials. Ability ranking based on successful shots of all participants across each individual condition. Condition 1: 1-3 successful shots = Low; 4-6 = Middle and 7-10 = High. Condition 2: 1-2 = Low; 3-4 = Middle and 5-7 = High. Condition 3: 1-3 = Low; 4-6 = Middle and 7-9 = High. SS ACC (self-selected target area – ball accuracy); SS VEL (self-selected target area – ball velocity); P ACC (prescribed target area – ball accuracy).

5.2 Summary

This chapter has described the processes undertaken to ensure high quality data was collected and analysed appropriately. A 15-segment model was created based on ISB recommendations and C-Motion guidelines. A residual analysis approach was used to produce filter cut-off frequencies as recommended by Winter (2009). Cut-off frequencies were used for each individual segment across the whole movement pattern. Study 2 the biomechanical analysis will utilise full time series of kinematic data to establish what kinematics are important for the drag flick technique and what joint angles are part of the core strategy of the drag flick technique. This has not been considered in the published literature to date at the time of writing and will be a novel analysis of this technique. However, the biomechanical analysis will not consider the coordination of joint angle this will be considered in the Principal Component Analysis (study 3). The PCA will use the entire time series of kinematic data to establish what principal movements within the drag flick technique account for the greatest variance in the data ensuring that the coordination of joint angles is considered as part of the core movement strategy of the drag flick technique. Two primary objectives will also be fulfilled by applying Principal Component Analysis to the kinematic data of the drag flick technique to explore the variability across participants and conditions through the entire time-series of data.

CHAPTER 6:
STUDY 2: BIOMECHANICS OF THE FIELD HOCKEY DRAG FLICK TECHNIQUE: EXPLORING THE KINEMATICS OF PERFORMANCE AND TECHNIQUE VARIABLES UNDER TASK CONSTRAINTS

6.1 Introduction

It is evident in the literature that all studies produced to date have focussed on a biomechanical analysis which could be considered more traditional, analysing time discrete moments within the drag flick technique. For this reason, the analysis of data within this chapter has taken the approach of analysing the entire time series of data through joint angle analysis and consideration of degree of departure from the mean score as a way to undertake a technique analysis on the drag flick technique. In using variability to analyse the data it prevents the reduction of data for statistical purposes, as reporting discrete values alone has been criticised, given that such an approach fails to account for the dynamic nature of movement (Mullineaux and Wheat, 2018). The nature of the analysis which follows is an original contribution to the body of literature, which has not been presented before for the drag flick technique.

Technique and performance variables were identified in Chapter 4 from the results of the Delphi Poll Method. The expert panel split the drag flick into three distinct phases (gathering the ball; the drag; and the release). The key aspects identified by the panel in the gathering phase were the timing, the foot to ball distance, the crossover step, and the lateral distance to the ball. The foot to ball distance and the stance width are regularly reported variables within the literature (Palaniappan and Viswanath, 2018, De Subijana et al., 2010, Gómez et al., 2012). However, there is limited literature which identified the lateral distance to the ball as a key variable. It is worth noting in the Delphi poll that the lateral distance to the ball was identified as being key to ensure the body can get low for the drag phase of the drag flick which is identified as one possible technique in (Yusoff et al., 2008). The expert panel identified the rotation of the body, length of drag, low body position and the wide stance width as the key variables for the drag phase of the technique. Again, these variables, with the exception of the low body position, are regularly reported within the body of literature (Palaniappan and Viswanath, 2018, De Subijana et al., 2010, De Subijana et al., 2011, Ibrahim et al., 2017). Finally, balance on ball release, angle of stick and right hip follow through were all identified as key variables for the release phase of the drag flick technique in the Delphi Poll study. Table 11 presents a summary of the dependent variables measure in the current body of literature. These technique and performance variables have been identified in drag flicking literature which characterise the way in which the drag flick is performed and contribute to the overall performance outcome of ball velocity (Yusoff et al., 2008, De Subijana et al., 2010). Limited literature has focused on the accuracy of the drag flick technique and predominately presented ball velocity as the key performance outcome.

The expert coaching panel agreed that ball accuracy was the key performance outcome, although accuracy did not reach the specified level of agreement for consensus in the Delphi poll. However, the coaches did identify the difficulty in having only one overall performance outcome, as it is important to have both accuracy and ball velocity to achieve the desired outcome. This informed the experimental design and methods for this current chapter to ensure both ball accuracy and ball velocity were considered as variables and conditions within the biomechanical analysis.

Table 11: Selected dependent variables measured for biomechanical analysis. Source: Created by the author.

Dependent variables measured that were identified within literature and Delphi poll	Additional joint angles measured (°).
Ball Accuracy	Ankle (Left and Right) x, y & z axis
Ball Velocity ($m{\cdot}s^{-1}$)	Knee (Left and Right) x axis
Stick resultant velocity ($m{\cdot}s^{-1}$)	Hip (Left and Right) x, y, & z axis
Length of time of drag flick (s)	Shoulder (Left and Right) x, y & z axis
Normalised ball drag distance (BH)	Elbow (Left and Right) x, y & z axis
Normalised foot to ball distance (BH)	Wrist (Left and Right) x axis
Normalised stance width (BH)	
Thorax and pelvis differential position at each of 4 time points* (°)	
Normalised height of centre of mass at stance width (m)	
Normalised height of centre of mass at point of release (m)	
Kinematic sequencing	

**Four time points: 1-Right foot contact with the ground; 2-stick contact with the ball; 3-left foot contact with the ground; 4-ball release*

The data presented within this chapter show the variability of technique for the drag flick across participants and conditions and will be used to address the primary research aim of this thesis (to evaluate the technique of the field hockey drag-flick). More specifically the following two objectives were considered:

1. To identify the core movement strategy of a field hockey, drag flick.
2. To identify the elements of technique that are modified to produce different outcomes.

6.2 Methods

The methodological procedures were presented in Chapter 5. All participants undertook 60 drag flicks in total. 20 in each of the three conditions, all participants completed the conditions in a randomised order within the same testing session: (Table 12):

- ball accuracy as the performance criterion (ACC) using a self-selected target area,
- ball velocity as the performance criterion (VEL) using a self-selected target area,
- ACC was also used as a performance criterion for a prescribed target area.

Participants self-selected one target area which was used for ball accuracy and ball velocity. Table 12 identifies the different target areas for each participant, participants were randomly prescribed target areas that coaches identified as ideal target areas presented in chapter 3 (i.e., all four corners of the goal). Variability is compared using a kinematic analysis undertaken on the entire data set and each individual target area.

Table 12: Target areas for each participant for all conditions: Self-selected accuracy (SS ACC); self-selected velocity (SS VEL) & prescribed accuracy (P ACC). Source: Created by the author.

		Condition	
Participant	SS ACC	SS VEL	P ACC
1	Bottom Left	Bottom Left	Top Right
2	Bottom Left	Bottom Left	Top Right
4	Bottom Left	Bottom Left	Bottom Right
5	Bottom Left	Bottom Left	Bottom Right
7	Bottom Left	Bottom Left	Bottom Right
10	Bottom Left	Bottom Left	Bottom Right
3	Bottom Right	Bottom Right	Bottom Left
6	Bottom Right	Bottom Right	Bottom Left
8	Middle Right	Middle Right	Top Left
9	Middle Right	Middle Right	Bottom Left
11	Bottom Right	Bottom Right	Top Left
12	Middle Left	Middle Left	Bottom Right

The main focus of this chapter is to analyse and present the continuous kinematic data of joint angles. This facilitates the understanding of kinematic sequencing and core strategy of the drag flick technique. An understanding of both the intra and inter participant variability across the whole movement and the impact of task constraint on this kinematic data will provide a significant contribution to the current body of literature. Other kinematic variables have also been presented for this research based on previous literature within the field of biomechanical analysis of the drag flick and the Delphi poll and have been split into performance and technique variables (De Subijana et al., 2010, Ibrahim et al., 2017, Yusoff et al., 2008). Table 13 indicates the dependent variables analysed within this study and whether they have been included based on previous literature or the Delphi Poll Method findings. Variables were calculated at various time discrete points within the drag flick: Start of movement – pick up of left foot prior to cross-over step; stick and ball contact; placement of right foot at start of cross-over step; stance width at left foot placement; ball release. These variables have been presented to support the analysis of the continuous kinematic data.

Table 13 - Drag flick performance related dependent variables measured for study 2 and how they were defined. Source: Created by the author.

Dependent Variables	Definition	How variables were identified
Ball Accuracy	Success of hitting 0.5 m^2 target	Delphi poll
Ball release velocity ($m \cdot s^{-1}$)	Velocity of the ball at release relative to the lab.	Published research and Delphi poll
Stick linear velocity ($m \cdot s^{-1}$)	Linear velocity of stick at ball release.	Published research
Length of time of drag flick time (s)	Time from back left foot pick up to ball release.	Published research
Normalised Drag Distance (BH)	Total ball drag distance normalised to participant height.	Published research and Delphi poll
Normalised Foot to Ball Distance (BH)	Distance from back foot to ball at pick up normalised to participant height.	Published research and Delphi poll
Normalised Stance Width (BH)	Distance between front and back foot at double foot contact normalised to body height.	Published research and Delphi poll
Thorax/pelvis differential position 1 (°)	Joint angle created by the Thorax relative to the pelvis at right foot contact with the ground.	Published research
Thorax/pelvis differential position 2 (°)	Joint angle created by the Thorax relative to the pelvis at stick contact with the ball.	Published research
Thorax/pelvis differential position 3 (°)	Joint angle created by the Thorax relative to the pelvis at left foot contact with the ground.	Published research
Thorax/pelvis differential position 4 (°)	Joint angle created by the Thorax relative to the pelvis at ball release.	Published research
Normalised COM Height	COM height from GCS at stance width and ball release normalised to body height.	Delphi poll
Kinematic Sequence	Kinematic sequence of peak velocities of peak negative linear velocity of the stick; peak pelvis angular velocity; peak upper trunk angular velocity; peak positive linear velocity of the stick.	Published research and Delphi poll

Initial analysis will provide a qualitative assessment of pattern variation of both performance and technique variables. The means of all participants across all conditions and all target areas will be analysed to identify what are the core performance and technique strategies of the drag flick technique. Following this, groups of participants who shared the same target areas across all three conditions will be analysed and compared, then finally the remaining individual participants will be considered.

Firstly, the successful and unsuccessful hits of the specified target and any patterns within these data will be considered. This will also include an analysis of the speed accuracy trade off identified within Chapter 3, looking at the ball velocity of each individual participant in relation to the success rate of the hit targets. Secondly, individual dependent variables will be analysed for each participant which have been identified within previous drag flicking literature (Table 2). These technique and performance variables have been identified in drag flicking literature which characterise the way in which the drag flick is performed and contribute to the overall performance outcome of accuracy (Yusoff, 2008; and De Subijana 2010). Finally, the entire time series of data will be considered for each joint angle measured (Table 2) through variable time graphs with joint angles across all three conditions and by combining conditions to look at the variability within the data. Selected data will be presented where there are patterns identified either within or between the participants.

For the kinematic sequencing, a method proposed by De Subijana et al. (2010) was used to determine the pelvis, thorax and stick angle velocities. These were calculated using a planar angle based on the line of double foot contact as the y-axis and the x-axis 90° from the y-axis to the right, the z-axis as the vertical axis.

The results initially report the findings from the performance variables, followed by the technique variables across all participants. Finally, both the core movement strategy and adaptations to the constraint of velocity will be presented which is an original contribution to the body of knowledge as such information has not previously been reported on the drag flick. Performance variables are variables which are related to the movements of the participant that contribute to the successful execution of the technique (Hughes and Bartlett, 2002).

6.3 Results

6.3.1 Performance Variables

6.3.1.1 Hit and Missed Targets

Total hit and missed targets are presented in Table 14. On examining the data for patterns of hit and missed targets there was no pattern which identified any individual fatiguing throughout any condition. All participants hit the target at least once within each condition however, participant 12 only hit a total of four successful targets out of 60 drag flick trials over three conditions which is less than 10%. Therefore, participant 12 had a high proportion of unsuccessful trials and so the data for this participant has not been included in the analysis for this chapter. The study is concerned with performance and technique variables and the core movement strategy of the drag flick technique and what impact the change in overall performance outcome and alterative target areas has on relevant dependent variables. The purpose of this study is not to compare hit and missed flicks but to establish what impact target area and overall performance criterion has on those successful drag flick trials.

Table 14: Hit and Missed targets of trials across all conditions for all participants (SS ACC: self-selected target area – ball accuracy; SS VEL: Self-selected target area – ball velocity; P ACC prescribed target area – ball accuracy). Source: Created by the author.

	SS ACC Condition		SS VEL Condition		P ACC Condition		Overall Hit/Missed targets	
Participant	**Hit**	**Missed**	**Hit**	**Missed**	**Hit**	**Missed**	**Hit**	**Missed**
1	5	15	7	13	1	19	13	47
2	9	11	2	18	5	15	16	44
3	5	15	3	17	2	18	10	50
4	8	12	6	14	7	13	21	39
5	4	16	3	17	7	13	14	46
6	10	10	5	15	5	15	20	40
7	3	17	1	19	9	11	13	47
8	4	16	2	18	4	16	10	50
9	3	17	1	19	9	11	13	47
10	3	17	3	17	1	19	7	53
11	7	13	5	15	5	15	17	43
12	1	19	1	19	2	17	4	56
Total	**62**	**178**	**39**	**201**	**58**	**182**	**159**	**561**

Overall, the SS ACC condition had the greatest success in terms of hit targets with a 26% success rate. This was followed by P ACC condition (24%) and SS VEL condition had the smallest success rate with 16%. Participant 4 achieved the greatest overall success rate over all three conditions with 35%. The highest number of successful trials within a condition was achieved by participant 6 in condition SS ACC with 10 successful hit targets. Discounting participant 12's results, condition SS ACC ranged from 15% to 50% success rate, with SS VEL from 5% to 35% and P ACC condition from 5% to 45%. These observations suggest that participants had the greatest success in hitting the self-selected target area with a focus on ball accuracy.

6.3.1.2 Ball Velocity

Mean ball velocities ± standard deviation (SD), and range are presented in Table 15 for all conditions. The individual participant data for each condition can be viewed in Appendix G.

Table 15: Mean peak ball velocity for all participants, standard deviation, and range ($m \cdot s^{-1)}$; of all conditions: SS ACC (self-selected target area – ball accuracy); SS VEL (self-selected target area – ball velocity); P ACC (prescribed target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Conditions	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
SS ACC	20.47	2.73	10.24	20.06	2.87	12.62	20.19	2.82	12.62
SS VEL	21.19	3.03	12.43	20.59	3.40	18.05	20.72	3.33	18.05
P ACC	20.36	2.98	13.70	20.13	3.08	15.08	20.19	3.04	15.68

On average participants produced higher ball velocities for hit targets in comparison to missed targets within condition SS ACC and SS VEL. On average the ball velocities presented for hit targets and overall, in condition SS VEL, are greater than the other two conditions (Table 15) which is perhaps to be expected as the overall performance criterion for this condition was ball velocity. These findings suggest that the participants did comply with the requirements of the conditions imposed in terms of ball velocity. P ACC is the only condition where participants on average produced a greater mean ball velocity for missed targets, compared to hit targets skill

6.3.1.3 Stick resultant velocity.

Stick resultant velocity (SRV) at ball release for all conditions is presented in Table 16. The individual participant data can be viewed in Appendix H. The SRV data supports the ball velocity data, as would be expected. Condition SS VEL has the greatest mean for hit targets (19.40 ± 3.07 $m \cdot s^{-1}$) and overall (19.10 ± 2.92 $m \cdot s^{-1}$), which focused on a requirement for ball velocity. The overall mean for all participants for hit targets is the smallest for condition P ACC across conditions (18.32 ± 3.45 $m \cdot s^{-1}$).

Table 16: Mean peak stick resultant linear velocity for all participants, standard deviation, and range ($m \cdot s^{-1}$); of all conditions: SS ACC condition (self-selected target area – ball accuracy); SS VEL condition (self-selected target area – ball velocity); P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Conditions	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
SS ACC	18.43	2.95	14.59	18.09	2.91	14.48	18.19	2.92	17.18
SS VEL	19.40	3.07	11.66	19.02	2.89	14.71	19.10	2.92	14.71
P ACC	18.32	3.45	13.76	18.29	3.50	17.80	18.30	3.48	18.16

6.3.1.4 Length of time of drag.

The length of time of the drag flick is considered as the time taken from ball pick up to ball release. The mean data for all conditions is presented in Table 17, individual participant data can be viewed in Appendix I. SS VEL has the smallest mean for hit targets (0.47 ± 0.03 s), compared with other conditions, followed by condition SS ACC (0.49 ± 0.05 s). Condition P ACC has the greatest mean for hit targets with 0.51 ± 0.04 s.

Table 17: Mean length of time of drag for all participants, standard deviation, and range (s); of all conditions: SS ACC condition (self-selected target area – ball accuracy); SS VEL condition (self-selected target area – ball velocity); P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Conditions	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
SS ACC	0.49	0.05	0.12	0.49	0.05	0.19	0.49	0.05	0.21
SS VEL	0.47	0.03	0.06	0.49	0.05	0.16	0.49	0.05	0.16
P ACC	0.51	0.04	0.09	0.51	0.05	0.16	0.51	0.05	0.17

6.3.1.5 Normalised drag distance

Normalised drag distance is presented as a percentage of body height to allow comparison across participants (Table 18). The individual participant data can be found in Appendix J. Condition SS ACC had the smallest mean for normalised drag distances across conditions (1.45 BH), and was consistent across hit, missed and all trials. SS VEL has a greater mean for hit targets (1.52 BH) than missed (1.48 BH) and all trials (1.49 BH) and has the greatest mean for hit targets across all conditions. Condition P ACC has a smaller mean for hit targets (1.48 BH) compared with missed targets (1.52 BH) within this condition.

Table 18: Mean normalised to body height drag distance for all participants, standard deviation, and range (BH); of all conditions. SS ACC condition (self-selected target area – ball accuracy); SS VEL condition (self-selected target area – ball velocity); P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Conditions	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
SS ACC	1.45	0.27	1.09	1.46	0.31	1.47	1.46	0.29	1.47
SS VEL	1.52	0.27	1.15	1.48	0.29	1.23	1.49	0.29	1.38
P ACC	1.48	0.09	0.22	1.52	0.13	0.47	1.51	0.13	0.52

6.3.1.6 Normalised foot to ball distance

Normalised foot to ball distance was normalised to participants body height. Foot position in front of the ball towards the goal is positive. Negative values mean the position of a participant's foot placement is behind the ball and further away from goal. Table 19 presents the normalised foot to ball distance for all participants across all conditions. Individual data across all conditions can be viewed in Appendix K. The position of the right foot with respect to the ball for condition SS ACC ranged from -0.17 BH to 0.57 BH for hit targets and -0.40 BH to 0.61 BH for all trials. Nine of the 11 participants on average positioned their foot in front of the ball for hit targets and all trials in condition SS ACC. The other two participants for hit targets and all trials (both target area bottom left) positioned their foot either level or behind the ball within this condition.

A similar pattern was followed for mean normalised foot to ball distances for condition SS VEL. Distances ranged from -0.17 BH to 0.57 BH for hit targets and -0.19 BH to 0.65 BH for all trials. Ten participants of the 11 positioned their foot in front of the ball for hit targets. The mean for all participants was positioned furthest in front of the ball for condition P ACC for hit targets and all trials. Again, nine of the 11 participants positioned their foot in front of the ball for hit targets and all trials. Participants 4 and 10 consistently position their foot either level with or behind the ball throughout all conditions. The foot to ball distance within condition P ACC ranged from -0.17 BH to 0.72 BH for hit targets and -0.23 BH to 0.72 BH for all trials.

Table 19: Mean normalised to body height foot to ball distance for all participants, standard deviation, and range (BH); of all conditions. SS ACC condition (self-selected target area – ball accuracy); SS VEL condition (self-selected target area – ball velocity); P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Conditions	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
SS ACC	0.27	0.20	0.74	0.23	0.25	1.01	0.24	0.24	1.01
SS VEL	0.25	0.23	0.74	0.27	0.25	0.84	0.27	0.24	0.84
P ACC	0.31	0.24	0.89	0.30	0.22	0.93	0.30	0.23	0.95

6.3.1.7 Normalised Stance Width

Stance width was normalised as a percentage of body height. Table 20 presents the normalised stance widths for all conditions. The normalised stance widths are consistent both across participants and across conditions (individual data can be viewed in Appendix L). There is little difference between the overall means for hit targets (SS ACC: 0.79 BH / SS VEL: 0.81 BH / P ACC: 0.81 BH) and all trials across (SS ACC: 0.79 BH / SS VEL: 0.80 BH / P ACC: 0.79 BH) all three conditions. Participant 11 has the greatest stance width across all conditions for both hit targets (0.91 BH) and all trials (0.92 BH) and participant 8 has the smallest stance width across all conditions for both hit targets (0.65 BH) and all trials (0.66 BH).

Table 20: Mean normalised to body height stance width for all participants, standard deviation, and range (BH); of all conditions. SS ACC condition (self-selected target area – ball accuracy); SS VEL condition (self-selected target area – ball velocity); P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Conditions	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
SS ACC	0.79	0.07	0.30	0.78	0.06	0.29	0.79	0.06	0.31
SS VEL	0.81	0.07	0.30	0.80	0.06	0.34	0.80	0.06	0.35
P ACC	0.81	0.07	0.38	0.79	0.07	0.36	0.79	0.07	0.37

6.3.2 Technique Variables

6.3.2.1 Thorax pelvis differential

Table 21, 22, and 23 present the thorax pelvis differential for all three conditions across all four time points (1, right foot contact with the ground; 2, stick contact with the ball; 3, left foot contact; and 4, ball release). A consistent pattern for all conditions is at right foot contact (1) the mean thorax pelvis differential position for all participants is rotating anticlockwise in reference to the pelvis but with minimal separation. At stick contact with the ball (2) the mean thorax pelvis differential position for all participants is neutral and little separation is occurring. As participants reach back for the ball during left foot contact with the ground (3) the mean thorax pelvis differential position overall for all participants is negative as the thorax is rotating in a clockwise direction in reference to the pelvis and a larger separation occurs. The separation then reduces again overall for all participants across all conditions as they release the ball.

Table 21 presents the mean thorax pelvis differentials for condition SS ACC. Most participants follow the pattern identified above across the four time points, however, there are some participants who present a different pattern. Participant 2 presents larger anticlockwise separation compared to other participants at time point 2 (at stick contact with the ball), which means this participant is reaching back for the ball at an earlier time point. Participants 5 and 8 are both rotating their thorax in a clockwise manner in relation to their pelvis at time points 1 and 2. Participant 4 has very little change in their thorax pelvis separation throughout the four time points. All participants within this condition follow a consistent pattern for the means for both hit and missed targets.

The mean values for all participants within condition SS VEL are presented in Table 22**.** Similar patterns occur with individual participants 2, 5, 8 and 4 as with condition SS ACC. In addition, participant 11 presents a greater anticlockwise separation compared to other participants at time point 1 (right foot contact with the ground) for both hit and missed targets and a smaller separation occurring at time point 3 compared to other participants.

Table 23 presents the mean data for all participants within condition P ACC. Again, as with the other two conditions participants 2, 5, 8 and 4 continue with the same pattern. In addition, participant 10 follows a similar pattern to both participants 5 and 8, with a greater positive separation at time point 1 for both hit and missed targets.

Table 21: Mean thorax pelvis differential position (degrees) for all participants for position 1 a) right foot contact with the ground; position 2 b) stick contact with the ball; position 3 c) left foot contact; and position 4 d) ball release of all participants for SS ACC condition (self-selected target area – ball accuracy). Source: Created by the author.

	Hit targets				Missed Targets				Overall			
Participant	1	2	3	4	1	2	3	4	1	2	3	4
1	5.6 ± 3.3	2.8 ± 3.2	-20 ± 2.2	-0.8 ± 12.2	8.2 ± 3	-2.1 ± 4.7	-19.4 ± 1.6	-8.8 ± 3.8	7.2 ± 3.2	-0.2 ± 3.2	-19.6 ± 1.8	-5.7 ± 8.6
2	3.4 ± 3	-14.9 ± 4.3	-20.7 ± 5	3.6 ± 9.9	4.1 ± 3.5	-16.7 ± 3.8	-19.4 ± 2.5	8.9 ± 3.9	3.8 ± 3.1	-15.7 ± 3.1	-20.1 ± 4	6.1 ± 8
3	-3.6 ± 1.9	1.8 ± 7.4	-24.3 ± 5.4	2.8 ± 5.2	-2.7 ± 7.3	2.5 ± 13	-11.6 ± 15.3	3.1 ± 8.7	-2.9 ± 6.3	2.3 ± 6.3	-14.9 ± 14.4	3 ± 7.8
4	2 ± 2.6	-4 ± 2.8	-4.8 ± 2.7	-4.1 ± 2.5	2.2 ± 5	-3.9 ± 2.4	-6.8 ± 3	-7.6 ± 3.9	2.1 ± 4.1	-4 ± 4.1	-6 ± 3	-6.2 ± 3.8
5	10.6 ± 2.3	15.1 ± 2	-6.1 ± 1.9	-5.8 ± 1.9	11 ± 2.2	13.7 ± 1.8	-7.5 ± 3.1	-6.4 ± 3.6	10.9 ± 2.1	14 ± 2.1	-7.2 ± 2.9	-6.3 ± 3.3
6	6.6 ± 4.6	0.8 ± 4.7	-16 ± 10.8	0.4 ± 11.4	4.2 ± 2.4	-1 ± 4.1	-18.2 ± 8	2.3 ± 6.9	5.5 ± 3.9	0 ± 3.9	-17 ± 9.5	1.3 ± 9.4
7	8.4 ± 5	1.9 ± 7.8	-11.4 ± 1.1	3.6 ± 1.8	6.9 ± 4.2	7.3 ± 4.5	-9.2 ± 1.8	3.3 ± 7.7	7.1 ± 4.2	6.5 ± 4.2	-9.5 ± 1.8	3.4 ± 7.1
8	11.1 ± 3.6	11.5 ± 5.3	2.2 ± 1.6	14.8 ± 1.7	8.3 ± 4.3	8.2 ± 3.1	-0.9 ± 5.7	11.6 ± 10.6	9.1 ± 4.2	9.1 ± 4.2	-0.1 ± 5.1	12.5 ± 9.1
9	0 ± 6.8	-3.9 ± 9.9	-7.4 ± 0.7	13.4 ± 2.9	0.4 ± 11.2	-4.4 ± 5.2	-10.9 ± 4.3	9.2 ± 13.9	0.3 ± 10.6	-4.4 ± 10.6	-10.5 ± 4.2	9.7 ± 13.1
10	-6.1 ± 1.5	-6.1 ± 15.1	-31.4 ± 3	-24.4 ± 1	-5.2 ± 2.8	-11.4 ± 7.2	-32.6 ± 2.4	-26.9 ± 3.9	-5.4 ± 2.6	-10.3 ± 2.6	-32.4 ± 2.5	-26.4 ± 3.6
11	-5.3 ± 3.1	-3 ± 1.7	14.6 ± 3.1	15.2 ± 6.9	-4 ± 5.1	-3.5 ± 2.7	9 ± 7.6	6.9 ± 13.3	-4.6 ± 4.2	-3.3 ± 4.2	11.6 ± 6.4	10.7 ± 11.2
Overall	3.8 ± 5.8	-0.8 ± 9.7	-13.1 ± 11.9	0.7 ± 11.1	3.3 ± 7.6	0.3 ± 10.1	-11.7 ± 11.3	-0.7 ± 13.4	3.3 ± 7.1	0 ± 9.9	-11.7 ± 11.8	0 ± 12.8

Table 22: Mean thorax pelvis differential position (degrees) for all participants for position 1 a) right foot contact with the ground; position 2 b) stick contact with the ball; position 3 c) left foot contact; and position 4 d) ball release of all participants for SS VEL condition (self-selected target area – ball velocity). Source: Created by the author.

	Hit targets				Missed Targets				Overall			
Participant	1	2	3	4	1	2	3	4	1	2	3	4
1	5.1 ± 4.3	3.3 ± 4.4	-17.6 ± 18	-13.7 ± 2.4	0.8 ± 3.8	1.1 ± 7.7	-23.8 ± 1.1	-12 ± 8.8	3.8 ± 4.5	2.6 ± 5.2	-19.4 ± 15	-13.2 ± 4.7
2	-3.3 ± 2.5	-16.9 ± 0.2	-24.9 ± 0	1.9 ± 25.9	-2.2 ± 3.3	-17.3 ± 3	-20.1 ± 2.4	6.1 ± 3.1	-2.4 ± 3.1	-17.2 ± 2.8	-20.8 ± 2.8	5.5 ± 8.1
3	-6.4 ± 1.1	-7.6 ± 4.9	-23.6 ± 4.1	-6.9 ± 5.3	-5.1 ± 3.1	-11.4 ± 6.2	-19.4 ± 12.9	-0.1 ± 5.5	-5.3 ± 2.9	-10.8 ± 6.1	-20.1 ± 11.9	-1.3 ± 5.9
4	-0.9 ± 5.4	0.1 ± 6.6	-6.8 ± 2.3	-2.6 ± 5.5	2.5 ± 3.6	-3.6 ± 2.6	-7.8 ± 3.1	-5.7 ± 4.1	1.5 ± 4.4	-2.5 ± 4.4	-7.5 ± 2.9	-4.7 ± 4.6
5	12.7 ± 0.7	15.3 ± 3	-7.3 ± 0.9	-9.9 ± 2.4	11.7 ± 1.9	17.4 ± 2.8	-6.5 ± 3.1	-8.2 ± 2.7	11.8 ± 1.7	17.1 ± 2.9	-6.6 ± 2.9	-8.5 ± 2.7
6	5.3 ± 2.8	-4.4 ± 4.2	-24.8 ± 1.9	-5.1 ± 3.7	4.9 ± 3.8	-5.9 ± 2.5	-24.4 ± 2.7	-3 ± 3.9	5.1 ± 3.5	-5.5 ± 3	-24.5 ± 2.4	-3.6 ± 3.9
7	4.5 ± 0	5.9 ± 0	-8 ± 0	1.9 ± 0	7.6 ± 1.7	5.4 ± 5.9	-8.9 ± 6	2.8 ± 3.7	7.4 ± 1.8	5.5 ± 5.7	-8.9 ± 5.8	2.8 ± 3.6
8	10.6 ± 1.2	9.5 ± 2	-4.4 ± 16.1	11 ± 1	10.9 ± 3.3	8.9 ± 2.5	-1.2 ± 3.2	5.4 ± 3.6	10.9 ± 3.1	9 ± 2.4	-1.5 ± 4.9	6 ± 3.8
9	2.8 ± 0	-9.5 ± 0	-2.7 ± 0	19.2 ± 0	1 ± 4.8	-7.3 ± 3.5	-12.4 ± 4.6	16.3 ± 5.5	1.1 ± 4.7	-7.4 ± 3.4	-11.9 ± 5	16.5 ± 5.4
10	-9.2 ± 2.4	-7.7 ± 8.2	-30.5 ± 1.1	-23.4 ± 3.4	-8.4 ± 5.1	-8.3 ± 9.8	-30.4 ± 2.1	-21.4 ± 2.5	-8.6 ± 4.6	-8.1 ± 9.1	-30.5 ± 1.8	-21.9 ± 2.7
11	-11.1 ± 2.6	-0.8 ± 2.7	2.7 ± 1.8	4.6 ± 10.8	-10.4 ± 2.2	-3.4 ± 4.9	8.9 ± 3	4.7 ± 10.3	-10.7 ± 2.2	-2.4 ± 4.3	6.7 ± 4	4.7 ± 9.9
Overall	0.7 ± 7.9	-0.5 ± 8.7	-14.3 ± 13.1	-5.2 ± 11.3	2.6 ± 7.6	-1.3 ± 11	-12.3 ± 11.1	0.2 ± 10.5	2.2 ± 7.7	-1.1 ± 10.6	-12.7 ± 11.5	-1 ± 10.8

Table 23: Mean thorax pelvis differential position (degrees) for all participants for position 1 a) right foot contact with the ground; position 2 b) stick contact with the ball; position 3 c) left foot contact; and position 4 d) ball release of all participants for P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit targets				Missed Targets				Overall			
Participant	1	2	3	4	1	2	3	4	1	2	3	4
1	6.9 ± 0	3.8 ± 0	-30.4 ± 0	-14.4 ± 0	4.1 ± 3.9	1.4 ± 5.7	-21.1 ± 2.9	-8.9 ± 2.9	4.4 ± 3.7	1.6 ± 5.4	-22 ± 3.9	-9.4 ± 3.2
2	-1.7 ± 2	-18.1 ± 3.7	-26.6 ± 10.9	9.4 ± 11	-0.9 ± 3.2	-13.4 ± 5.6	-16.6 ± 7.8	9.2 ± 6.8	-1.1 ± 2.9	-14.5 ± 5.5	-19.1 ± 9.4	9.2 ± 7.7
3	-7.7 ± 3	-1.5 ± 4.1	-22.3 ± 0.6	0.3 ± 5.7	-5.8 ± 3.2	-5.9 ± 5	-22.5 ± 2.2	1.3 ± 2.8	-6 ± 3.2	-5.5 ± 5	-22.4 ± 2.1	1.2 ± 3
4	1.6 ± 5.6	-0.4 ± 2.4	-2.4 ± 2	3.6 ± 2.6	-2.1 ± 6.4	-0.7 ± 3.6	-2.2 ± 2.5	5.1 ± 4.2	-0.8 ± 6.3	-0.6 ± 3.2	-2.3 ± 2.3	4.6 ± 3.7
5	10.8 ± 1.6	11.3 ± 2.2	-9.2 ± 1.4	-8.3 ± 3.5	11.7 ± 2.4	12 ± 2	-9.2 ± 1.5	-10.6 ± 1.9	11.4 ± 2.1	11.8 ± 2	-9.2 ± 1.4	-9.8 ± 2.8
6	1.6 ± 5.6	-1.4 ± 5.7	-15.1 ± 1.2	-1.4 ± 5.7	3.1 ± 2.4	-0.5 ± 3	-17.6 ± 3.6	1 ± 3.4	2.8 ± 3.4	-0.7 ± 3.7	-17 ± 3.4	0.4 ± 4.1
7	7.5 ± 0.7	4.5 ± 3.6	-7.4 ± 1.9	3.3 ± 2.7	6.2 ± 3	5.8 ± 1.8	-7.9 ± 3.2	3.9 ± 2.3	6.8 ± 2.2	5.2 ± 2.8	-7.7 ± 2.6	3.6 ± 2.5
8	11.6 ± 1.9	10.1 ± 3.5	-1.2 ± 1.7	4.8 ± 5.1	10.6 ± 4	8.8 ± 3.2	-2.2 ± 3	3.6 ± 3.1	10.8 ± 3.7	9 ± 3.1	-2 ± 2.8	3.9 ± 3.4
9	0.1 ± 6.2	-6.2 ± 3.3	-11.9 ± 3.5	16.8 ± 7.8	2 ± 3.1	-8.4 ± 3.4	-11.8 ± 6.1	16.2 ± 2.7	1.1 ± 4.7	-7.4 ± 3.4	-11.9 ± 5	16.5 ± 5.4
10	-3.9 ± 0	-12.3 ± 0	-29.4 ± 0	-29.6 ± 0	-2.8 ± 5.2	-2 ± 4.7	-30.1 ± 1.7	-23.8 ± 2.7	-2.6 ± 4.7	-5.8 ± 7.2	-30.6 ± 2	-25.3 ± 2.9
11	-0.1 ± 4.1	-7.3 ± 2.7	10 ± 3.7	10.4 ± 7.2	0.8 ± 7.7	1.6 ± 9.6	9.2 ± 9.6	17.3 ± 10.2	0.5 ± 6.6	-1.4 ± 8.9	9.5 ± 7.9	15 ± 9.6
Overall	3.4 ± 6.3	-0.8 ± 9	-10 ± 10.5	3.5 ± 10.6	2 ± 6.8	-0.9 ± 8.8	-13.4 ± 11.2	0.4 ± 12.1	2.4 ± 6.7	-0.9 ± 8.8	-12.4 ± 11	1.2 ± 11.8

6.3.2.2 COM height

The normalised centre of mass height at both stance width and ball release for all conditions is very consistent across hit and missed targets and all trials (Table 24). Individual participant data for each condition can be viewed in Appendix M. The greatest change from stance width to ball release is 2%. Participants have a stable normalised height of COM between the two events across all conditions ranging from 0.33 ± 0.02 BH to 0.34 ± 0.03 BH. The mean normalised COM height for hit targets for both stance width and ball release for all participants is slightly higher (P ACC: 0.34 ± 0.02 BH for stance width and ball release) for condition P ACC compared to the other two conditions (SS ACC: 0.33 ± 0.02 BH / SS VEL: 0.33 ± 0.02 BH for both stance width and ball release). Similar to the other two conditions, this variable remained consistent for both time points and for individual participants.

Table 24: Mean normalised to body height centre of mass (COM) height for all participants at stance width and ball release, standard deviation (BH) for all conditions. SS ACC condition (self-selected target area – ball accuracy); SS VEL condition (self-selected target area – ball velocity); P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit targets		Missed Targets		Overall	
Condition	Stance Width	Ball Release	Stance Width	Ball Release	Stance Width	Ball Release
SS ACC	0.33 ± 0.02	0.33 ± 0.02	0.34 ± 0.03	0.34 ± 0.03	0.34 ± 0.03	0.34 ± 0.02
SS VEL	0.33 ± 0.02	0.33 ± 0.02	0.34 ± 0.03	0.34 ± 0.02	0.34 ± 0.02	0.34 ± 0.02
P ACC	0.34 ± 0.02	0.34 ± 0.02	0.34 ± 0.02	0.34 ± 0.02	0.34 ± 0.02	0.34 ± 0.02

6.3.2.3 Kinematic sequence

Due to the amount of data collected the kinematic sequence of the peak velocities has been presented below for all trials. The kinematic sequence of the peak velocities altered between participants and conditions. The percentage of normalised event times for hit targets are presented in Table 25 to 27. The overall means for all three conditions presented a kinematic sequence of T1-T4-T3-T2-T5-T6 (T1: foot contact; T2: peak negative linear velocity of the stick; T3: peak pelvis angular velocity; T4: peak upper trunk angular velocity; T5: peak positive linear velocity of the stick; T6: ball release). However, there are a number of participants within each condition which did not follow this sequence. In condition SS ACC participants 1, 4, and 10 followed a sequence of T1-T3-T4-T2-T5-T6. Participant 7 followed a sequence of T1-T4-T2-T3-T5-T6, and participant 6 followed a sequence of T1-T3-T2-T4-T5-T6. Participant 11 followed a sequence of T1-T2, T3 and T4 occurring simultaneously followed by T5-T6. It is noteworthy that significant variations exist among participants in terms of the peak negative linear velocity of the stick. Specifically, Participant 11 exhibits an early occurrence of the average peak negative linear velocity of the stick, at 16.67% ± 5.65% during the initial stages of the drag flick movement, before ball pick-up. In contrast, Participants 5 and 10 demonstrate, on average, a late peak negative linear velocity of the stick, (Participant 5 at 86.75% ± 0.5% and Participant 10 at 86% ± 1.0% of the movement respectively). This late peak occurs during the wide stance width phase. Figure 24 illustrates the temporal progression of stick linear velocity for a representative trial of Participant 11. Despite the peak negative linear velocity occurring at 17% for this trial, a noteworthy observation is the occurrence of a second peak at 61% of the trial. This secondary peak is more in line with the patterns observed in the broader dataset, as presented in Table 25.

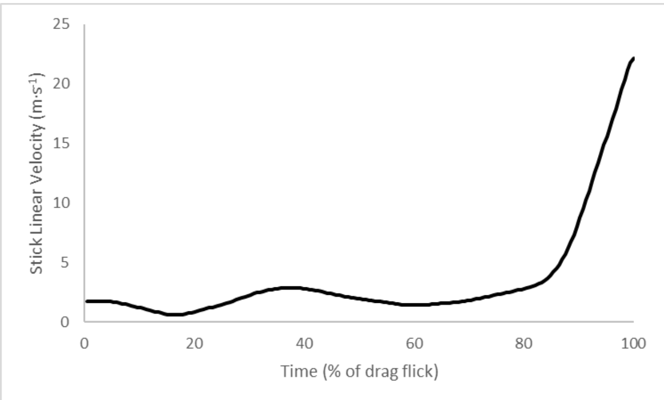


Figure 24: Time Course of Stick Linear Velocity in Participant 11, Condition 2, Trial 1: A Representative Example of Peak Negative Stick Linear Velocity. Source: Created by the author.

Figure 25 and Figure 26 depict the stick linear velocity of Participants 5 and 10, respectively. In Participant 5's representative trial, the peak negative linear stick velocity occurs at 87% (Figure 25). However, mirroring the observation in Participant 11's data, a second peak in negative stick linear velocity is noted at 68% aligning more closely with the broader dataset. Similarly, Participant 10 exhibits a peak negative stick linear velocity at 90%, but the second peak occurs at 70%, once again reflecting a pattern more representative of the overall dataset.

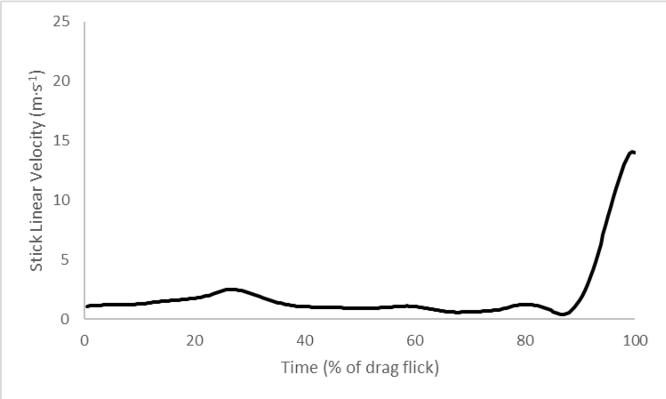


Figure 25: Time Course of Stick Linear Velocity in Participant 5, Condition 1, Trial 3: A Representative Example of Peak Negative Stick Linear Velocity. Source: Created by the author.

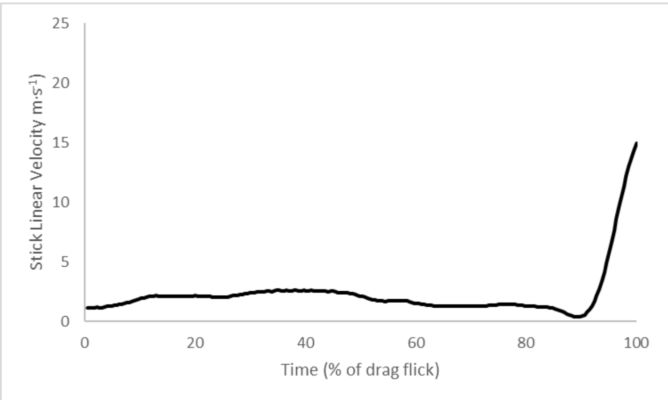


Figure 26 Time Course of Stick Linear Velocity in Participant 10, Condition 3, Trial 4: A Representative Example of Peak Negative Stick Linear Velocity. Source: Created by the author.

Table 25: Summary (M ± SD) of the normalised event times for all trials (as % of T1 – T6 time) for all participants for condition SS ACC (self-selected target area and ball accuracy). Source: Created by the author.

	Event			
Participant	T2	T3	T4	T5
1	54.8 ± 23.61	44.0 ± 5.83	49 ± 25.21	101 ± 0.0
2	64.75 ± 4.1	38.75 ± 6.5	25.13 ± 21.9	100.88 ± 0.35
3	67 ± 1.73	48.8 ± 22.42	18.2 ± 21.28	100.6 ± 0.89
4	73 ± 6.28	44.75 ± 12.67	46.13 ± 2.53	100.75 ± 0.71
5	86.75 ± 0.5	50.75 ± 9.18	15.5 ± 27.01	101 ± 0.0
6	48.89 ± 11.26	39.33 ± 2.96	51.89 ± 3.26	100.33 ± 1.32
7	63.67 ± 5.0	50.0 ± 0.58	20.67 ± 22.94	100.67 ± 0.58
8	56.75 ± 22.88	54.25 ± 6.13	27.5 ± 21.02	98.75 ± 0.96
9	69.5 ± 4.95	41.5 ± 13.44	30.0 ± 22.63	101 ± 0.0
10	86 ± 1.0	24.67 ± 2.08	55.33 ± 1.15	100.33 ± 1.15
11	16.67 ± 5.65	43.83 ± 3.19	43.83 ± 3.19	100.83 ± 0.41
Overall	61.83 ± 7.90	44.94 ± 7.72	34.83 ± 15.65	100.56 ± 0.58

Abbreviations: T1, foot contact (0%); T2, peak negative linear velocity of the stick; T3, peak pelvis angular velocity; T4, peak upper trunk velocity; T5, peak positive linear velocity of the stick; T6 ball release (100%).

Within condition SS VEL participants 2 and 7 followed a kinematic sequence of T1-T2-T3-T4-T5-T6. Participants 4, 9 and 10 followed a sequence of T1-T3-T4-T2-T5-T6, participant 8 followed a sequence of T1-T4-T2-T3-T5-T6 and participant 11 again, followed a sequence of T1-T2, T3 and T4 occurring simultaneously followed by T5-T6.

Table 26: Summary (M ± SD) of the normalised event times for all trials (in % of T1 – T6 time) for all participants for condition SS VEL (self-selected target area and ball velocity). Source: Created by the author.

	Event			
Participant	T2	T3	T4	T5
1	51.14 ± 23.7	43.86 ± 10.92	37.86 ± 26.78	101 ± 0.0
2	31.5 ± 43.13	36,0 ± 4.24	47 ± 4.24	100.5 ± 0.71
3	64.33 ± 1.53	56.67 ± 0.58	5.67 ± 0.58	101 ± 0.0
4	67.33 ± 15.12	37.33 ± 6.41	46.17 ± 3.13	99.67 ± 1.51
5	88.67 ± 1.53	50.33 ± 5.86	46 ± 23.39	101 ± 0.0
6	45.2 ± 4.97	43.8 ± 3.42	32.2 ± 26.72	101 ± 0.0
7	48 ± 0.0	58 ± 0.0	65 ± 0.0	101 ± 0.0
8	55.5 ± 0.71	59.5 ± 0.71	17.5 ± 0.71	99.5 ± 0.71
9	78 ± 0.0	31 ± 0.0	42 ± 0.0	101 ± 0.0
10	84.33 ± 3.79	27.67 ± 2.08	54.0 ± 1.0	99.0 ± 2.0
11	33.25 ± 44.59	40.5 ± 3.0	40.5 ± 3.0	100.25 ± 0.96
Overall	59.75 ± 12.64	43.15 ± 3.38	39.44 ± 8.14	100.45 ± 0.52

Abbreviations: T1, foot contact (0%); T2, peak negative linear velocity of the stick; T3, peak pelvis angular velocity; T4, peak upper trunk velocity; T5, peak positive linear velocity of the stick; T6 ball release (100%).

Condition P ACC again, presented overall means for hit targets with a kinematic sequence of T1-T4-T3-T2-T5-T6. However, participants 1, 2, and 10 followed a sequence of T1-T3-T4-T2-T5-T6, participant 6 followed a sequence of T1-T2-T3-T4-T5-T6. Participant 8 followed a sequence of T1-T4-T2-T3-T5-T6, and participant 11 again, replicated the same kinematic sequence of the other two conditions of T1-T2, T3 and T4 occurring simultaneously followed by T5-T6. Within this section the events T5 and T6 are consistently reported in that order, however, T5 often occurs after T6 for participants, but this is marginal and therefore the decision was taken to consistently report these events in this order as there was little difference between the timings of these events.

Table 27: Summary (M ± SD) of the normalised event times for all trials (in % of T1 – T6 time) for all participants for condition P ACC (prescribed target area and ball accuracy). Source: Created by the author.

	Event			
Participant	T2	T3	T4	T5
1	63.0 ± 0.0	37.0 ± 0.0	58.0 ± 0.0	101.0 ± 0.0
2	63.4 ± 0.55	38.2 ± 1.1	48.8 ± 1.1	101.0 ± 0.0
3	64.5 ± 2.12	55.0 ± 2.83	21.0 ± 26.87	100.5 ± 0.71
4	79.14 ± 3.02	42.71 ± 9.39	32.29 ± 21.06	99 ± 1.41
5	86.29 ± 0.95	53.57 ± 7.79	25.86 ± 27.65	101.0 ± 0.0
6	38.2 ± 6.69	39.0 ± 5.1	41.4 ± 22.23	101.0 ± 0.0
7	48.22 ± 26.88	44.78 ± 1.09	31.56 ± 30.36	99.67 ± 1.41
8	26.0 ± 6.08	60.0 ± 2.0	18.0 ± 0.0	97.67 ± 2.31
9	75.88 ± 4.36	42 ± 10.7	32.13 ± 20.64	100 ± 1.07
10	88.0 ± 0.0	25.0 ± 0.0	54.0 ± 0.0	101.0 ± 0.0
11	15.75 ± 0.96	43 ± 0.82	43 ± 0.82	100.75 ± 0.5
Overall	58.94 ± 4.69	43.66 ± 3.71	36.91 ± 13.70	100.23 ± 0.67

Abbreviations: T1 (0%), foot contact; T2, peak negative linear velocity of the stick; T3, peak pelvis angular velocity; T4, peak upper trunk velocity; T5, peak positive linear velocity of the stick; T6 ball release (100%).

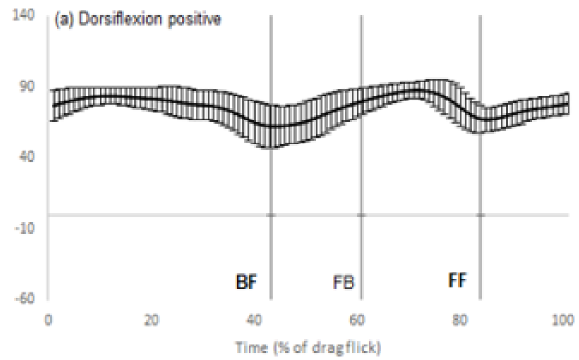
6.3.3 Core strategy

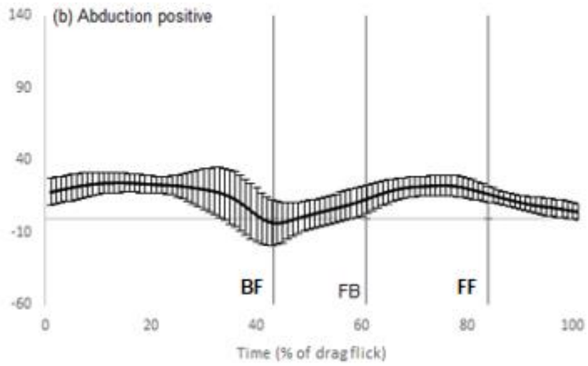
Left Ankle (°)

Flexion/Extension

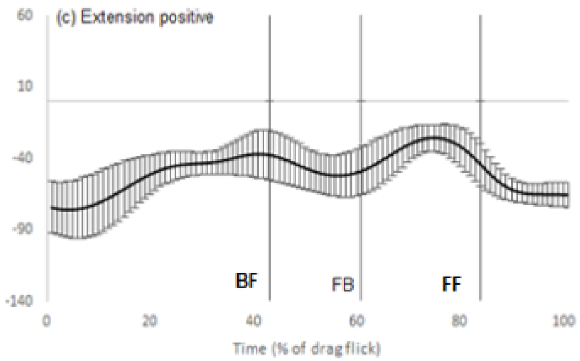
Abduction/Adduction

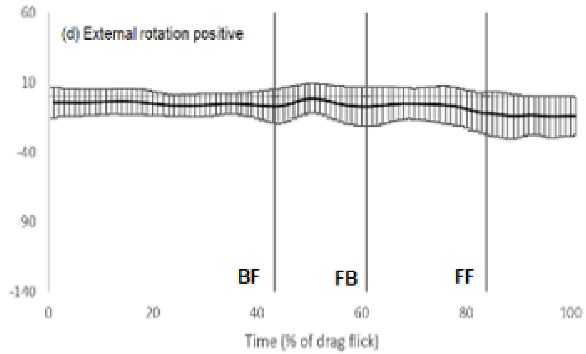
Internal/External Rotation





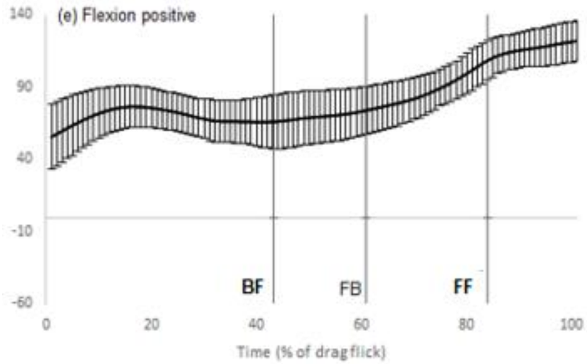
Left knee (°)

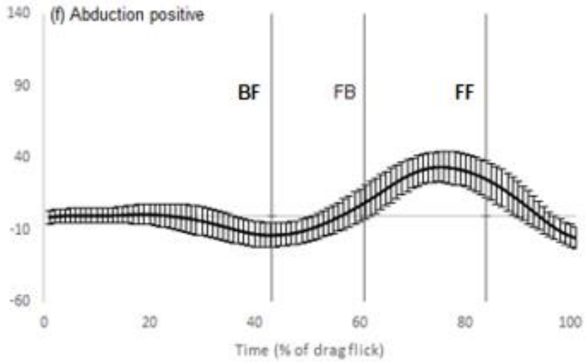


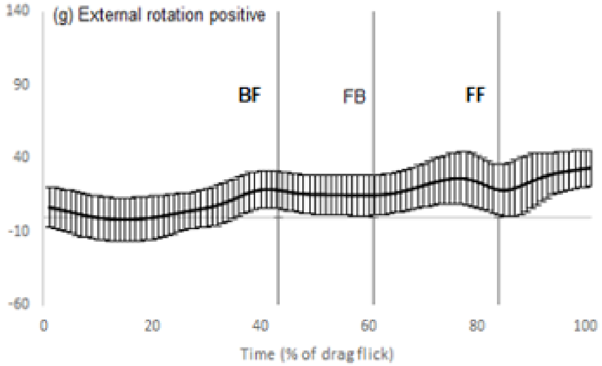


Flexion/Extension | Abduction/Adduction | Internal/External Rotation

Left Hip (°)

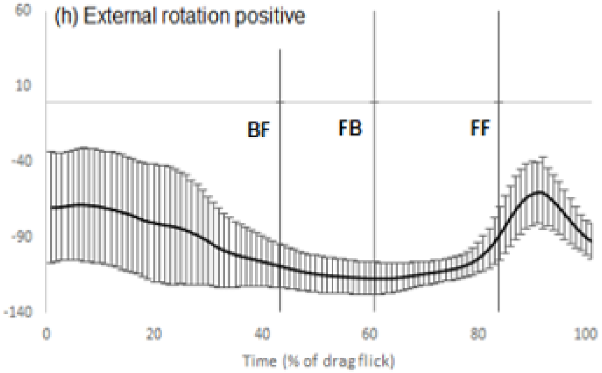


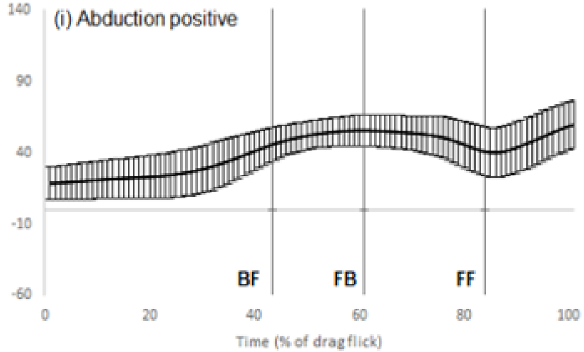


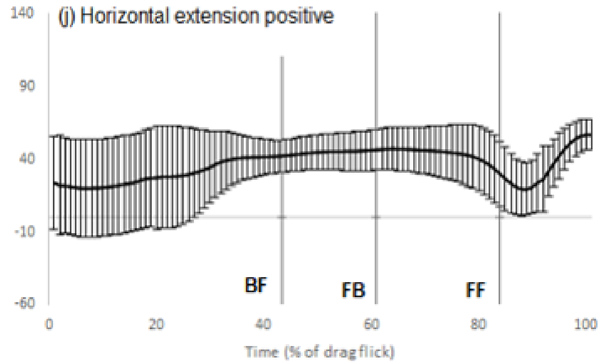


Internal/External Rotation | Abduction/Adduction | Horizontal Flexion/Extension

Left Shoulder (°)





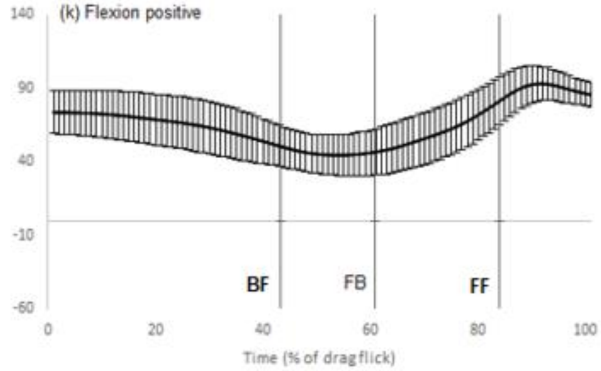


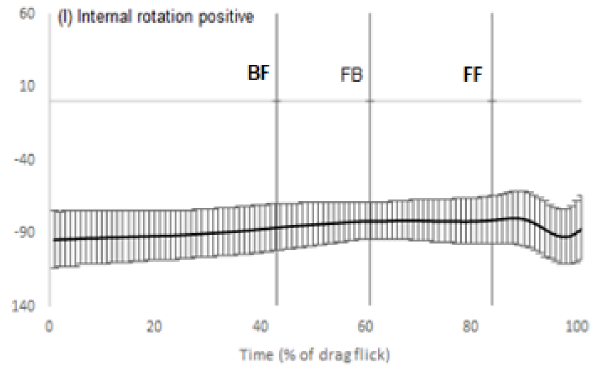
Flexion/Extension

Abduction/Adduction

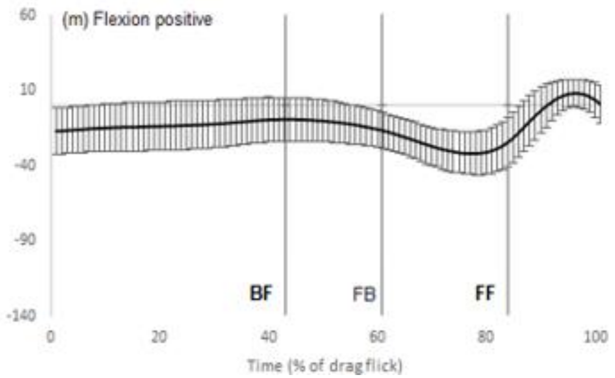
Internal/External Rotation

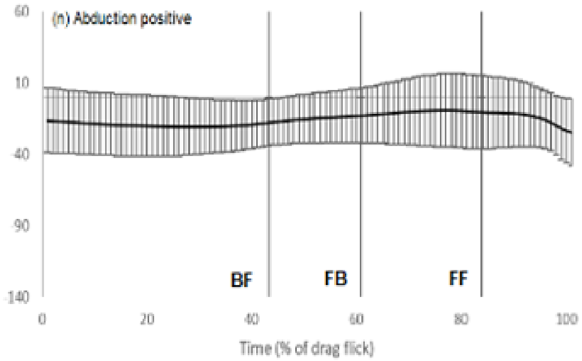
Left Elbow (°)





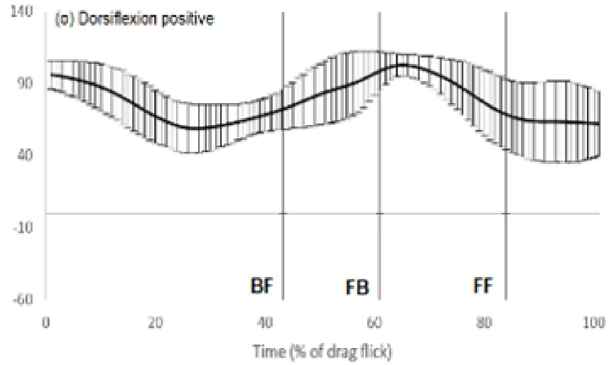
Left Wrist (°)

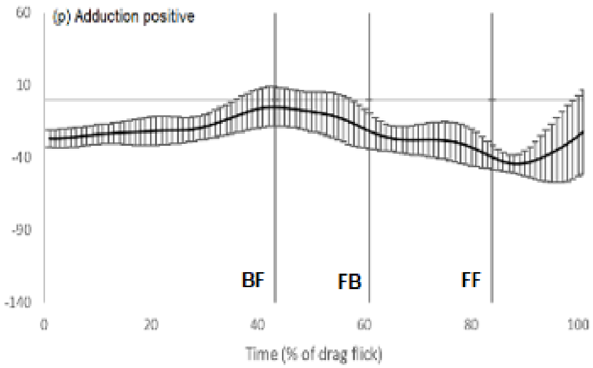




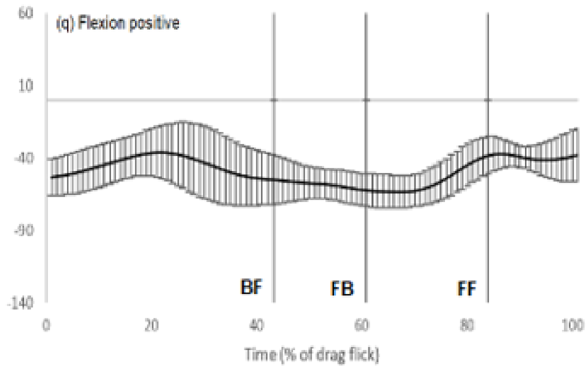
Flexion/Extension | Abduction/Adduction | Internal/External Rotation

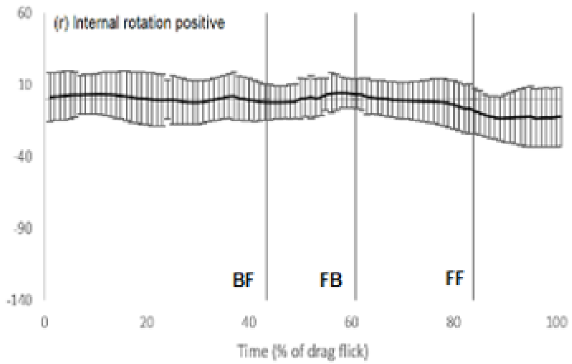
Right Ankle (°)





Right knee (°)



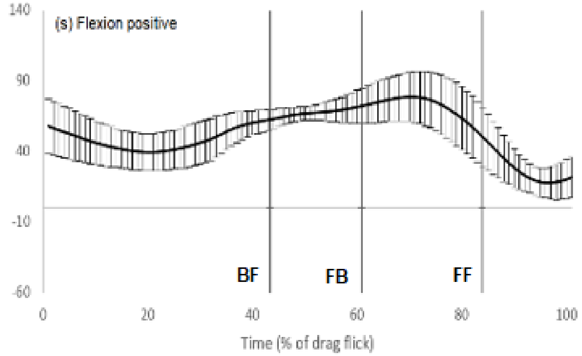


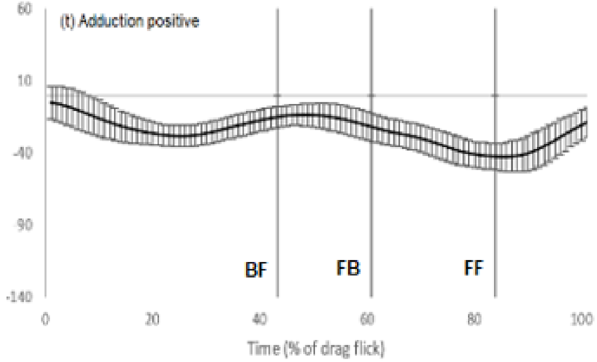
Flexion/Extension

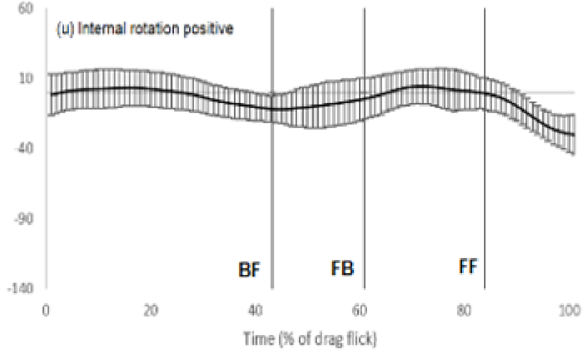
Abduction/Adduction

Internal/External Rotation

Right Hip (°)





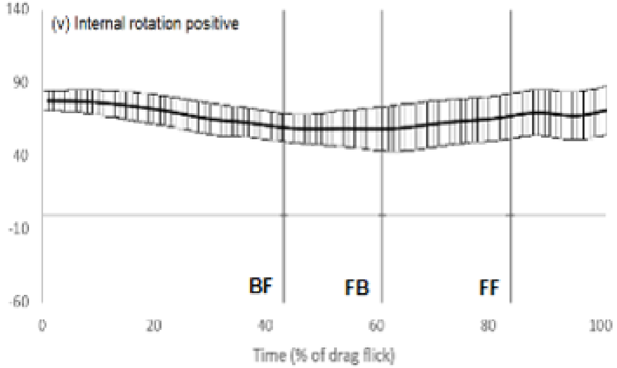


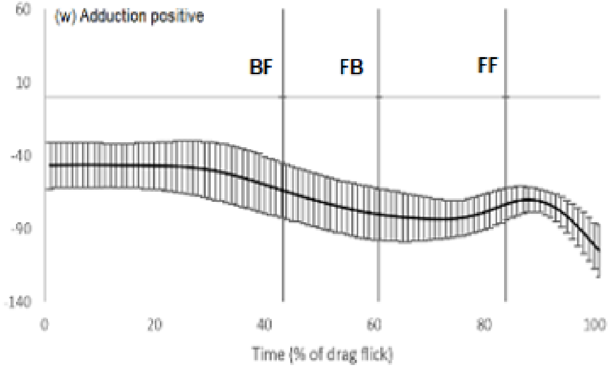
Internal/External Rotation

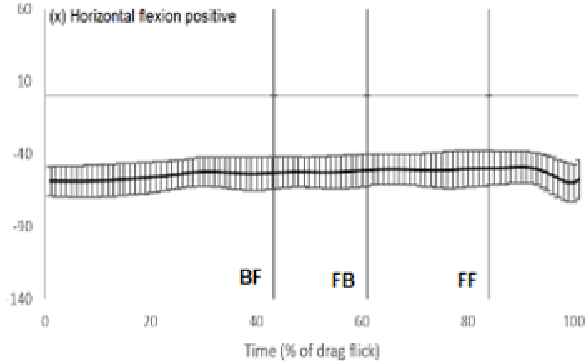
Abduction/Adduction

Horizontal Flexion/Extension

Right Shoulder (°)





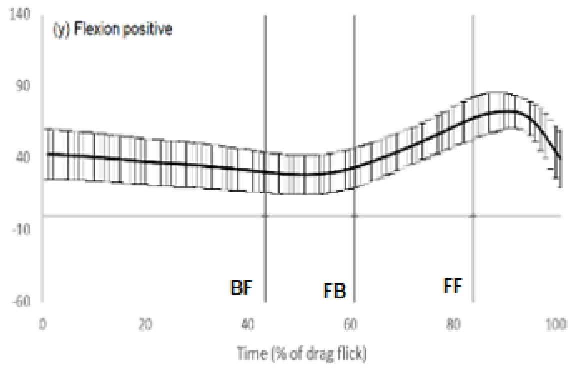


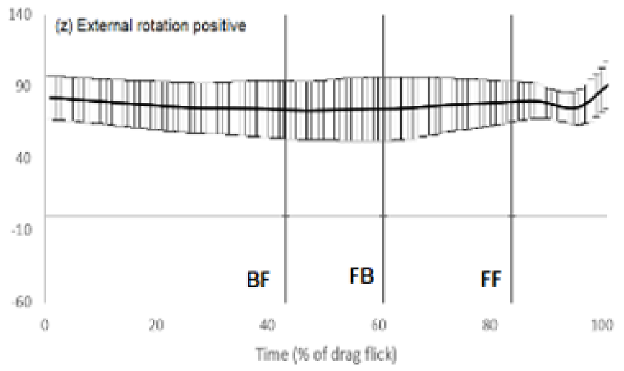
Flexion/Extension

Abduction/Adduction

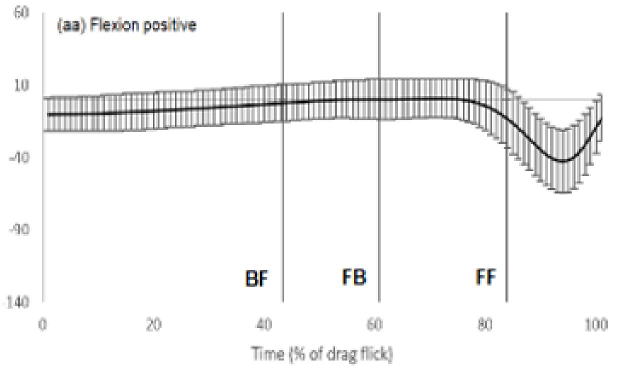
Internal/External Rotation

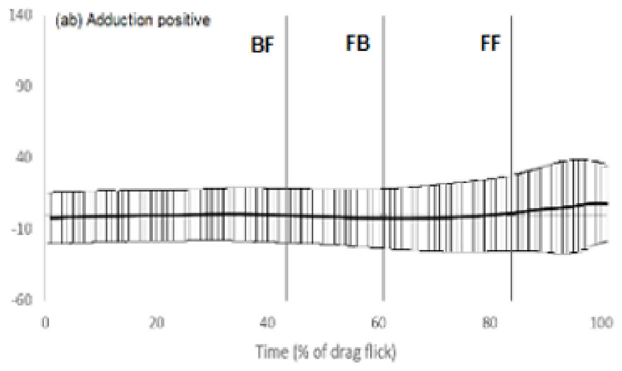
Right Elbow (°)





Right Wrist (°)





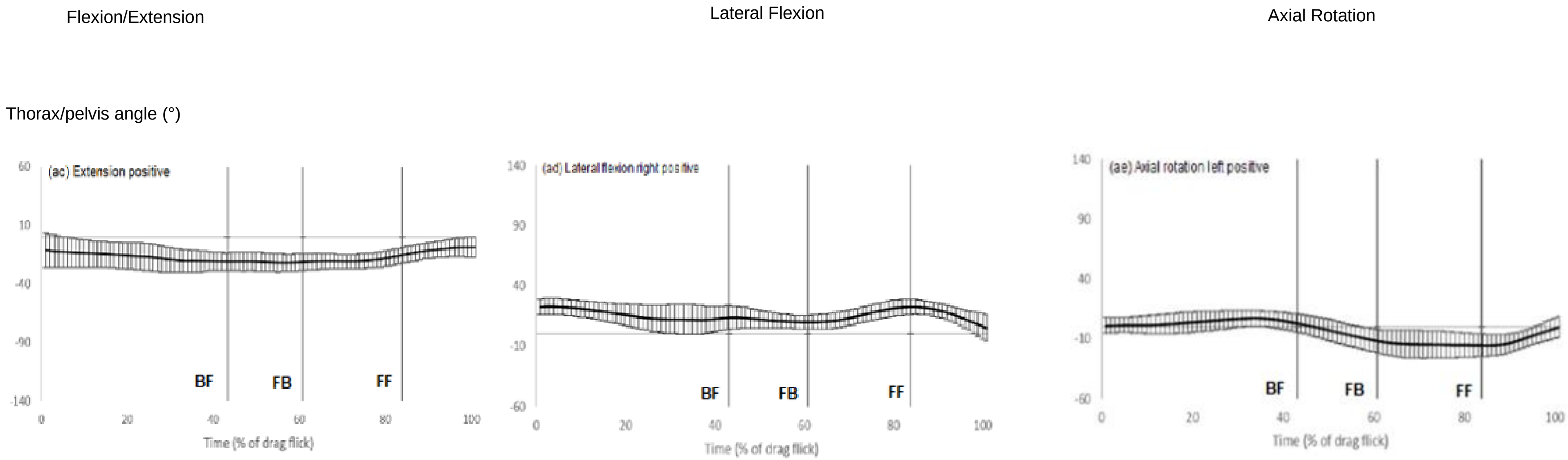


Figure 27: Mean joint angles (degrees) of each joint for all participants across all conditions. Vertical lines indicate back foot position at ball pick up (BF); foot to ball distance at end of crossover step (FB); and front foot position at stance width (FF). Source: Created by the author.

Figure 27 presents the mean data for all participants across all conditions and target areas and are based on the individual data which will be presented later in this chapter. Each joint angle and variability of the joint angle will be presented to identify the key movement pattern of the drag flick technique using a three-dimensional biomechanical analysis. In general, the joint angles of the lower body present less variability than the joint angles of the upper body for both the left- and right-hand sides (Lower body joint angles standard deviation ranged from 9.1° to 17.8°; upper body joint angles standard deviation ranged from 13.9° to 37.3°). Only the elbows and wrists present consistent variability, all other joint angles present inconsistent variability throughout the entire drag flick technique, which will be presented below.

6.3.3.1 Left ankle (Figure 27 a and b).

The left ankle dorsiflexes and abducts at the start of the drag flick, as the left leg is lifted from the floor in preparation for the wide front foot contact. The ankle then moves to a plantarflexion position at back foot contact up and then returns to a dorsiflexion position as the front foot plants to create the stance width and finishes in a dorsi flexion position as the participants release the ball. The ankle adducts at back foot contact and then abducts as the front foot is planted for the wide stance width. At full stance width and ball release the ankle adducts.

6.3.3.2 Left knee (c and d)

The left knee shows two peaks of extension (-36.9°; -25.7°) throughout the drag flick technique, which match the two steps taken by all participants through the technique (Figure 27 c). The first step with the front foot is taken in preparation for the cross-over step. As the front foot reaches forward the knee extends peaking at 41%, followed by flexion as the front foot becomes weight bearing for the beginning of the cross-over step. The knee continues to flex as the right foot is lifted from the ground to start the cross-over step. Following the cross-over of the right foot the left knee begins extending again for the second peak (75%) in preparation for front foot contact to create the wide stance width identified within the left ankle movement. As the knee contacts the ground, flexion movement occurs again as the front foot becomes weight bearing and ball release occurs. The mean data for left knee internal/external rotation ranges from -14.6 ° to 13.4 °. As participants move towards ball release the left knee internally rotates (Figure 27 d).

6.3.3.3 Left hip (Figure 27 e, f and g)

The left hip predominately moves in a flexion movement throughout the entire drag flick technique. There is a short period from 20% to 30% of the drag flick technique where the hip extends to an average value of 66.2° as the participants are reaching forward with the front leg to prepare for the cross-over step. For the remainder of the drag flick technique the hip flexes. Although the front foot again reaches forward for the wide stance width the thorax also flexes to move lower towards the ball and therefore flexion still occurs at the hip and continues through to ball release (Figure 27 ac). The variability of the mean data for all participants is consistent throughout the entire drag flick technique. Like the ankle there are two peaks of abduction (0.9°; 33.8°) for the mean data for all participants for the hip. As the first step occurs with the left foot in preparation for the cross-over step there is a peak of abduction (0.9°) in the mean data. The greater peak of abduction (33.8°) occurs as the front foot reaches to contact the ground at the end of the cross-over step to create the wide stance width. As the participants drag the ball through towards the front foot and ball release occurs the hip adducts to finish at an average of 15.5°. The left hip internally rotates at the start of the movement peaking at -1.7° as the left foot is reaching to contact the ground for the first step. As the foot contacts the ground for the first step in preparation for the cross-over step, the hip externally rotates to reach the first peak (19°). Similar to the flexion and abduction angles the hip predominately externally rotates throughout the drag flick technique with a second peak occurring on average at 76% (26.4°) as preparation for front foot contact for the wide stance width. Again, the variability within the mean data is consistent throughout the entire drag flick technique.

6.3.3.4 Left shoulder (Figure 27 h, i, and j)

The shoulder initially internally rotates as the participants reach behind for the ball and drag the ball from the back foot to the front during the wide stance width peaking at (-116.9°) 62%. As the participants drag the ball to the front foot and move to ball release the left shoulder starts to externally rotate peaking at (-59.9°) 91%, followed by a sudden internal rotation (-92.2°) 100%. There is larger variability at the start of the drag flick technique (64.6%) followed by less variability during the drag phase through to ball release (23.6%). The ab-/adduction angle is following a similar pattern. From the start of the drag flick through to back foot contact the left shoulder is abducting peaking at (55.6°) 61%. As the ball moves from the back foot to the front the left shoulder starts to adduct peaking at (40.1°) 86%, followed by a sudden abduction movement at ball release (59.7°) 100%. The variability for ab-/adduction is more consistent throughout the whole drag flick (34.2%). The movement pattern for the horizontal flex-/extension moves following the same pattern as ab-/adduction but there is greater variability particularly before back foot contact (82.1% compared with the rest of the movement pattern 42.1%).

6.3.3.5 Left elbow (Figure 27 k and l).

The elbow starts in a flexed position and as the participants move to front foot contact and reach behind for the ball the elbow shows, on average, one peak of extension (44.6°) at 55%. As the participants drag the ball and move the ball forwards towards ball release the elbow flexes and peaks at an average of 93° (92%). There is a small period of extension at the end of the drag flick as the participants release the ball (85.6°). The elbow interna/external rotation angle has limited movement throughout the drag flick technique with less than a 15° average range. The elbow gradually internally rotates for 88% of the drag flick technique peaking at an average of -79.2°, and during the last 12% there is a sudden external rotation movement of the elbow as the ball is released (-92°). The elbow angles have consistent variability throughout the entire drag flick technique.

6.3.3.6 Left wrist (Figure 27 m and n).

The left wrist starts in an extended position (-16.7°), as the participants reach back to pick the ball up at back foot contact and start the drag movement of the ball the wrist flexes peaking at -9.1°. As the foot reaches for front foot contact with the ground at the end of the wide stance width the wrist starts to extend which peaks at -31.8° at 77% of the drag flick technique. The wrist angle then changes to a flexion movement as the ball is dragged towards the front foot and again peaking at 8.3° (96%) then finally extends as the ball is released (0.8°). As with the elbow angles the variability of the mean data for the left wrist for all participants is consistent throughout the entire drag flick technique. The left wrist ranges from -24.3° to -8.9°. As participants reach behind for the ball at back foot contact, plant the feet and begin the dragging motion of the ball the left wrist remains abducted. As the ball is dragged to the front foot and moves to ball release the left wrist begins adducting.

6.3.3.7 Right ankle (Figure 27 o and p).

The right ankle initially plantarflexes as the foot leaves contact with the ground at the start of the movement peaking at 59.2° (27%). As the right foot contacts the ground during the cross-over step (FB on Figure 27 n) the ankle dorsiflexes (103.2°; 67%). As the wide stance width occurs the ankle extends and continues to extend for the remainder of the drag flick, peaking at 62.8°. The right ankle adducts as the foot leaves the ground during ball pick up, peaking at 4.8°, as the foot contacts the ground the ankle abducts as the right foot becomes weight bearing during the stance width, peaking at -44.4° (88%). As the right foot then begins to lift from the floor the ankle adducts through to ball release (-21.9°).

6.3.3.8 Right knee (Figure 27 q and r).

Replicating the left knee angle the right knee has two peaks of extension throughout the drag flick technique, which match the two steps taken by all participants through the technique. The first extension peak is the as the right foot leaves the ground in preparation for the cross-over step (-35.7°; 22%). The knee then extends as the right foot is brought behind the left leg for the cross-over step (-63°; 67%). The final peak of extension occurs as the weight is transferred from the right to left foot at stance width and continues to extend peaking at -36.7° (86%). At ball release the knee slightly flexes (-40.8°; 95%) followed quickly by a slight extension (-37.5°; 101%).

The knee internal/external rotation has a small range of movement (<20°). The main rotation occurs during the right foot placement at the end of the cross-over step externally rotating (Figure 27 r) and the transfer of weight from the right foot to the left foot at stance width. The variability of the mean data changes throughout the drag flick technique, there is a greater range of variability following the stance width through to the ball release.

6.3.3.9 Right hip (Figure 27 s, t and u).

The right hip initially extends as the right foot leaves the ground (39.7°; 20%), in preparation for the cross-over step. As the right foot is placed behind the left foot and the thorax is lowered towards the floor to allow ball pick up the hip flexes (Figure 27 ac) (78.8°; 70%). There is further extension as the left foot reaches for ground contact at the stance width and the weight is transferred to the left foot (18.0°; 96%). The hip begins flexing again at ball release (21.8°; 101%). A similar pattern occurs for the right hip abduction/adduction angle. As the right foot leaves contact with the ground abduction occurs, peaking at 25% of the drag flick technique (-28.2°). As weight transfers onto the left foot the hip adducts whilst the right foot moves behind for the cross-over step (-13.5°; 38%). As right foot contact happens at the end of the cross-over step the hip again begins to abduct to allow for a wide stance width peaking at -42.5° (86%). Finally, the hip adducts as the ball is released (-18.7°). The hip is externally rotating as the right foot is leaving contact with the ground and placed behind for the cross-over step at ball pick up (-11.8°; 44%). As the right foot contacts the ground to prepare for stance width, the hip internally rotates peaking at 4.5° (72%), followed by externally rotating as the ball is dragged and transfer of weight occurs on to the left foot through to ball release (-29.8°). The variability for ab-adduction and Internal-External rotation is consistent throughout this joint angle, however, the flexion-extension angle has smaller variability during the cross-over step compared to the start of the drag flick and stance width through to ball release.

6.3.3.10 Right shoulder (Figure 27 Error! Reference source not found. **v, w, and x).**

The mean right shoulder angle initially externally rotates until foot to ball distance as participants reach behind for the ball (58.8°; 60%). Following this the right shoulder internally rotates through to ball release as the ball is dragged towards the front foot and released (71.5°, 100%). The right shoulder abducts from start through to 72% (-83.3°), followed by a short movement adducting at the wide stance width (-69.8°, 88%) and then returning to abducting at ball release (-104.9°, 100%). There is limited range of motion for the right shoulder horizontal flex-/extension (10.68°). The only real movement occurs at the end during ball release where the right shoulder suddenly horizontally extends (-59.5°, 99%). The variation is consistent throughout all three axes for the right shoulder.

6.3.3.11 Right elbow (Figure 27 y and z).

The mean right elbow angle initially extends until back foot placement (28.5°; 51%). As the ball is dragged the elbow starts to flex until the ball reaches level with the thorax (72.9°; 91%) and the elbow starts to extend again as it is moved towards the front foot and through to ball release (38.5°). The variability of the flexion/extension data is greater than for other joint angles but is consistent throughout the drag flick technique. The internal/external rotation angle has limited movement throughout the drag flick technique with less than 13° of movement. There is limited movement until 87% of the drag flick technique, during the final 13% there is a sudden internal rotation (75.5°; 95%) followed by a sudden external rotation as the ball is released (91.2°). All participants follow the same elbow pattern but there is variation in amplitude of data and timing of peaks.

6.3.3.12 Right wrist (Figure 27 aa and ab).

The right wrist produces the opposite pattern to the left wrist. From the start of the drag flick the wrist angle begins flexing as the ball is picked up and dragged through towards the front foot (1.2°; 72%). As the ball crosses the thorax and moves towards the front foot the wrist extends (-42.2°; 94%) and then quickly flexes again at ball release (-12.5°). The variability of the mean data for all participants is consistent throughout the entire drag flick technique. There are <11° of movement in the right wrist for abduction/adduction. The right wrist moves adducting from start to ball release of the drag flick technique, but there is more variability towards the end of the movement at ball release.

6.3.3.13 Thorax pelvis (Figure 27 ac, ad and ae).

There is limited movement of the thorax in relation to the pelvis throughout the drag flick technique. There is only 13.5° of flexion/extension of the thorax throughout the entire drag flick. From the start of the drag flick through to 57% the thorax is flexing in relation to the pelvis, peaking at -21.9°. The thorax is flexing up until the participants have dragged the ball to mid stance width following front foot placement. As the participants prepare for dragging the ball to the front foot and to ball release the thorax starts to extend in relation to the pelvis, peaking at -8.4 ° at ball release. There is a larger range of movement of the thorax in relation to the pelvis for lateral flexion with a range of 17.9°, however, through the entire drag flick the thorax remains laterally flexed to the right in relation to the pelvis. The thorax laterally flexes to the left at left foot placement prior to the cross-over step (11.9°; 37%), followed by lateral flexion to the right, as the left foot leaves the ground in preparation for the start of the cross-over step with the right foot being placed behind the left foot (14.1°; 44%). As the right foot contacts the ground and the transfer of weight begins the thorax again laterally flexes to the left, peaking at 10.1° (61%). At front foot placement with both feet in contact with the ground the thorax laterally flexes to the left, peaking at 22.8° (85%). There is a final movement of lateral flexion to the left from front foot placement through to ball release, peaking at 5.2°.

The axial rotation of the thorax in relation to the pelvis presents the greatest range of movement for this joint angle with a range of 22.6°. As the participants are approaching the ball the mean thorax angle is rotated to the left, peaking at 7.2° (35%). As the participants pass level with the ball and begin the cross-over step to reach behind for the ball the thorax is rotated to the right and remains rotated to the right until the ball is dragged to the front foot (-15.4°; 85%). For the final 15% of the drag flick technique the thorax rotates to the left through to ball release (-0.2°). The variability of the thorax pelvis joint angle is consistent throughout the drag flick technique.

6.3.4 Variation in kinematics between the constraints of performance outcomes accuracy and velocity movement,

To compare the effects of the two constraints of maximum ball velocity and maximum accuracy on individual movement kinematics a sub-sample of participants who all self-selected target area bottom left were selected as this was the largest group for any given target area. In using this sub-sample all variability due to target area and prescription was eliminated. A total of six participants self-selected this target area and their individual kinematic sequences and overall mean ball velocity across all 20 trials under each constraint are presented in Table 28.

Table 28: Individual kinematic sequences and overall mean peak ball velocity of participants that self-selected target area bottom left for both condition SS ACC (self-selected target area – ball accuracy) and SS VEL (self-selected target area – ball velocity). Source: Created by the author.

Participant	SS ACC				SS VEL			
	KS	BV ($m \cdot s^{-1}$)	NFB (% BH)	NSW (% BH)	KS	BV ($m \cdot s^{-1}$)	NFB (% BH)	NSW (% BH)
1	3	22.27	0.26	0.77	2	23.93	0.34	0.81
2	2	22.98	0.18	0.84	1	25.32	0.14	0.86
4	3	17.81	0.08	0.77	3	17.88	-0.05	0.77
5	2	16.89	0.19	0.81	2	16.61	0.08	0.80
7	2	23.37	0.48	0.84	1	23.89	0.52	0.83
10	3	17.52	0.21	0.74	3	18.33	-0.11	0.75

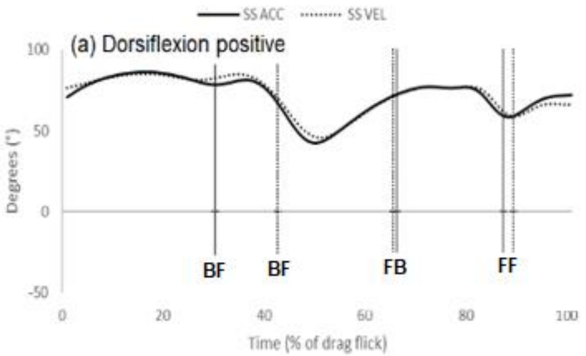
Abbreviations: Kinematic sequence (KS) 1 (T1-T2-T3-T4-T5-T6); Kinematic sequence 2 (T1-T4-T3-T2-T5-T6); Kinematic sequence 3 (T1-T3-T4-T2-T5-T6); T1, foot contact; T2, peak negative linear velocity of the stick; T3, peak pelvis angular velocity; T4, peak upper trunk velocity; T5, peak positive linear velocity of the stick; T6 ball release. BV (Ball Velocity); NFB (Normalised Foot to Ball Distance; NSW (Normalise Stance Width)

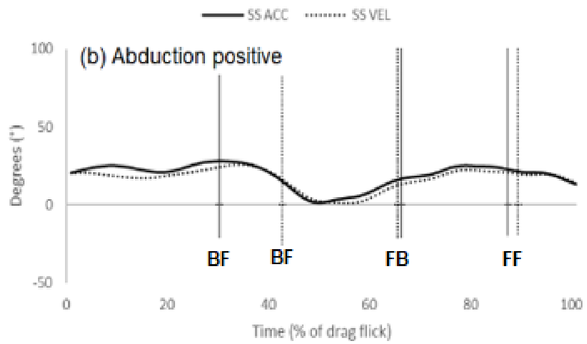
Kinematic sequence 1 is the preferred kinematic sequencing to achieve ball velocity according to published literature (McLaughlin, 1997, De Subijana et al., 2010, Gómez et al., 2012, Ibrahim et al., 2017). These papers all referred to a proximal to distal kinematic sequencing pattern as the preferred movement pattern to achieve high ball velocity. This is also supported theoretically as identified within chapter 2 the hockey drag flick is a throw like movement and therefore is likely to benefit from a proximal to distal kinematic sequencing. However, it is clear from the data presented in Table 29 that only three out of six participants used this sequence under the maximum velocity constraint, with the other three participants using two other sequences. It is also noteworthy that none of the six participants used sequence 1 when performing under the accuracy constraint, with four using sequence 2 and two using sequence 3. Whilst the focus of this thesis has been to establish whether or not there is a common movement strategy underpinning the technique of the drag flick, these findings of sequence and ball velocity variability under the constraints of maximum velocity and accuracy warrant further consideration at the individual level to better understand consistencies and differences in movement strategy.

The decision to extensively report and interpret individual patterns, particularly for Participants 2 and 7, is rooted in the aim of this study to gain insights into the complexities of the drag flick technique under different constraints, specifically maximum velocity and accuracy. While the literature has provided a general consensus on the preference for a proximal to distal kinematic sequencing pattern in achieving high ball velocity in the drag flick, the data presented in this chapter revealed a remarkable divergence from this expected norm. Three participants were selected for further analysis of the kinematic data to establish any differences between the movement patterns used for the constraints of accuracy and velocity. Participant 2 was chosen for analysis due to the significant change in ball velocity between the two conditions. With a 10% greater velocity under the velocity constraint compared to the accuracy constraint, Participant 2 demonstrated the potential for substantial adaptation in response to different performance demands. This choice allows for a comprehensive examination of what specific kinematic changes may have contributed to this notable variation in ball velocity. Participant 7 was selected because they followed the same kinematic sequences as Participant 2, yet only exhibited a 2% change in ball velocity between the two constraints. This participant provides a unique opportunity to explore how individuals with similar kinematic patterns might adapt differently in response to varying constraints. The small change in velocity suggests that other factors, such as timing or coordination, may have played a role. Participant 5, who demonstrated no change in kinematic sequencing and a 2% difference in ball velocity between constraints, adds an additional layer of complexity to the analysis. This selection provides insight into participants who maintain relatively consistent kinematic patterns despite changing constraints, highlighting the stability of their technique and potential individual differences in how they optimise their movements. The in-depth analysis of these participants, therefore, serves to explain the extent of individual-level variation in response to distinct constraints and the complexities of the drag flick technique. It aims to provide a more nuanced perspective beyond the overarching generalisations in the literature and highlights the importance of individualised coaching strategies to enhance performance in Drag Flick Technique. It also contributes to a richer understanding of the interplay between kinematics, performance, and constraints in the context of the drag flick, which is valuable for both practical coaching applications and future research in the field.

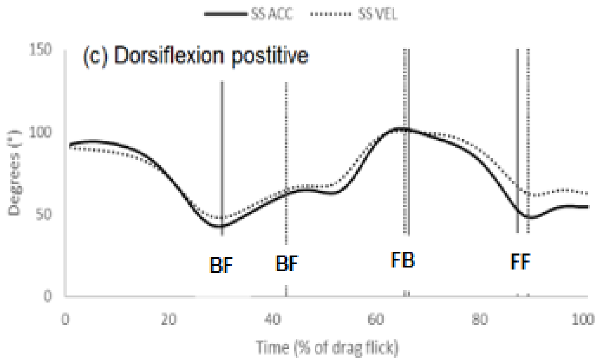
Flexion/Extension | Abduction/Adduction | Internal/External Rotation

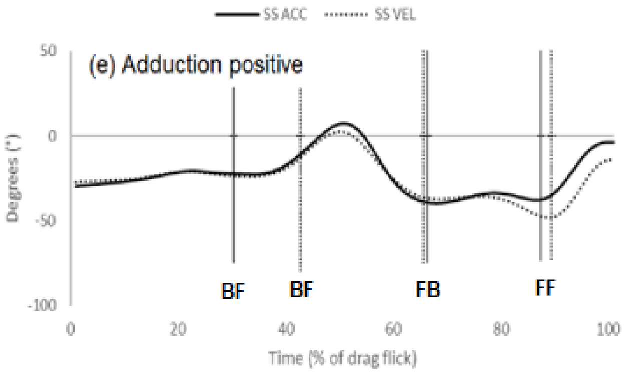
Left ankle





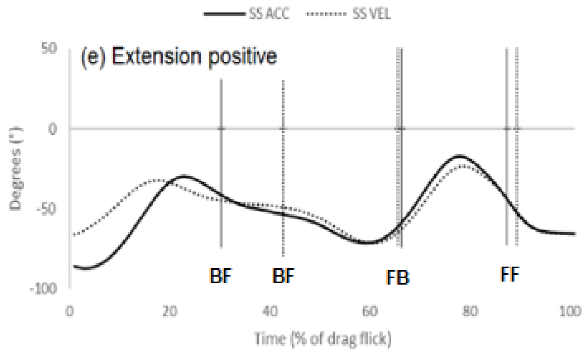
Right ankle

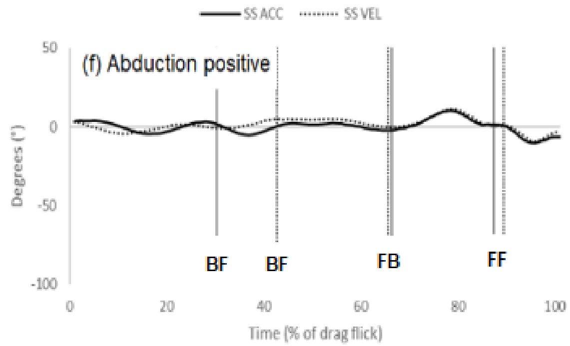




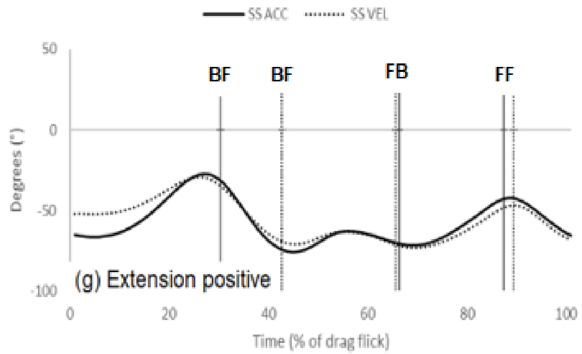
Flexion/Extension Abduction/Adduction Internal/External Rotation

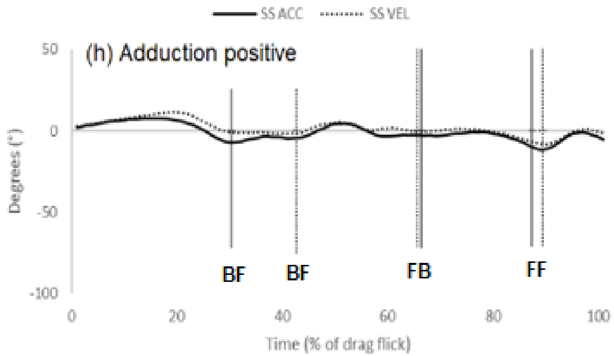
Left knee





Right knee



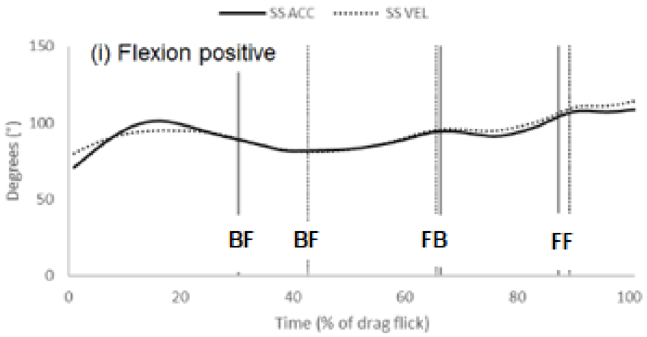


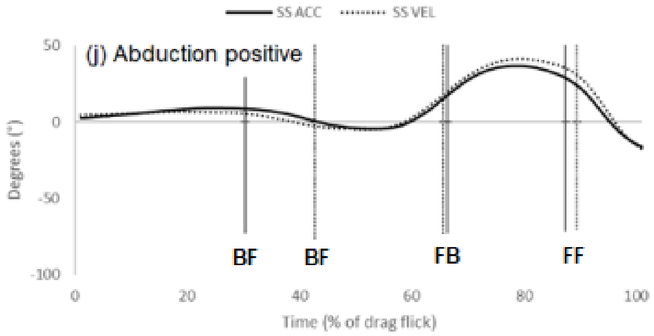
Flexion/Extension

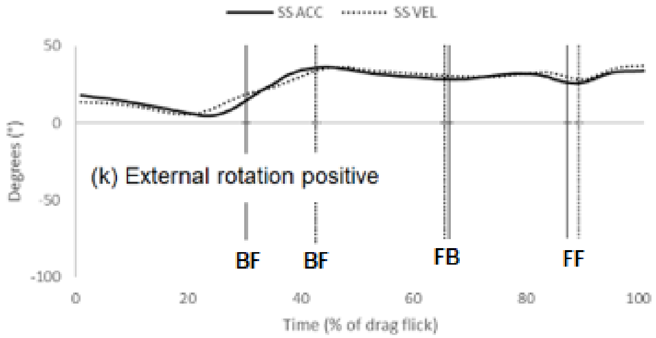
Abduction/Adduction

Internal/External Rotation

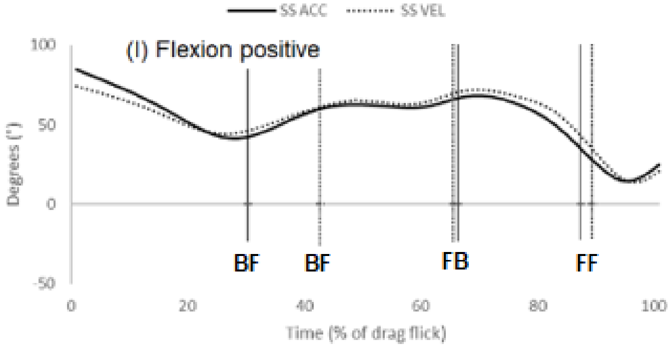
Left hip

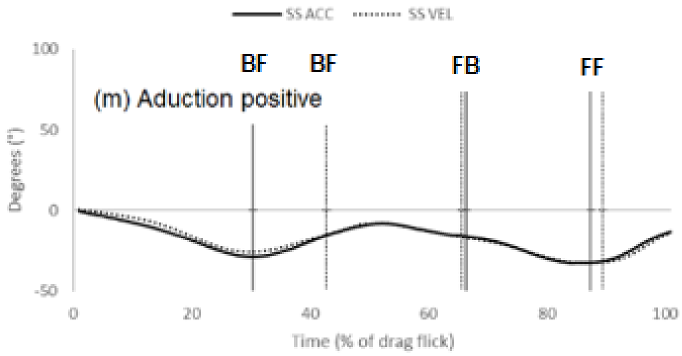


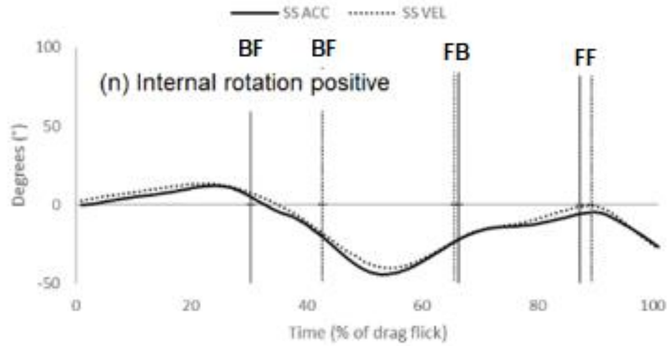




Right hip





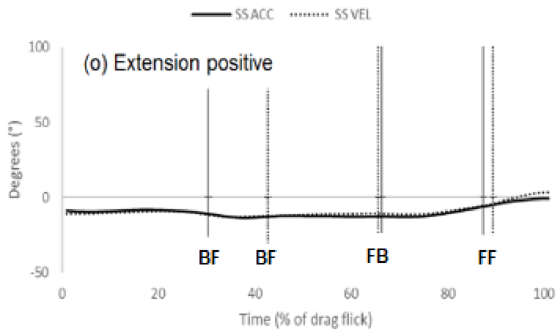


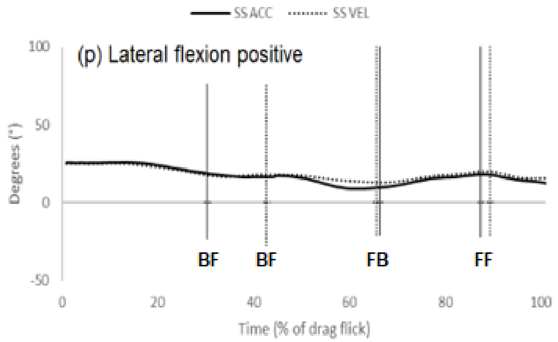
Flexion/Extension

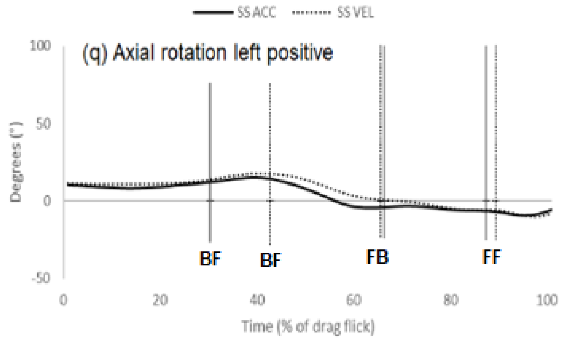
Lateral Flexion

Axial Rotation

Thorax Pelvis Differential





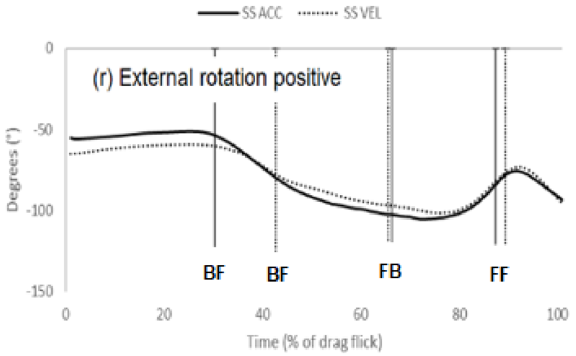


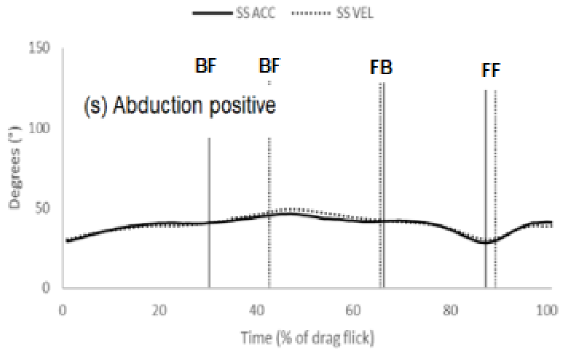
Internal/External Rotation

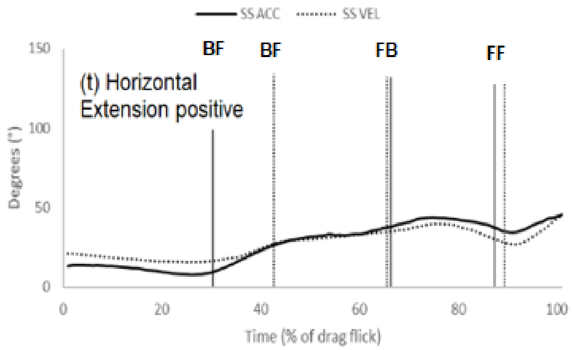
Abduction/Adduction

Horizontal Flexion/Extension

Left Shoulder





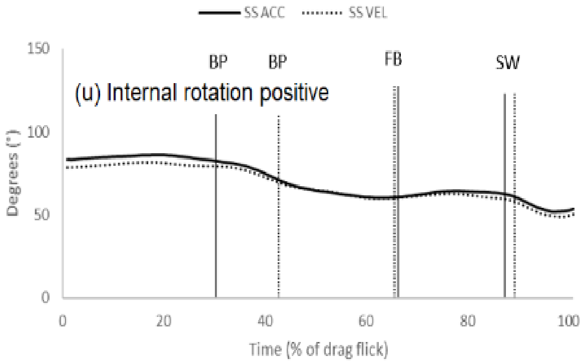


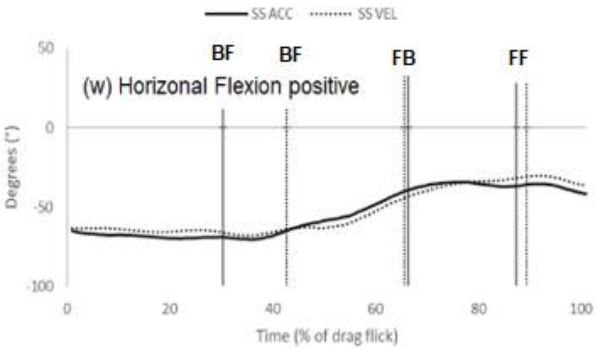
Flexion/Extension

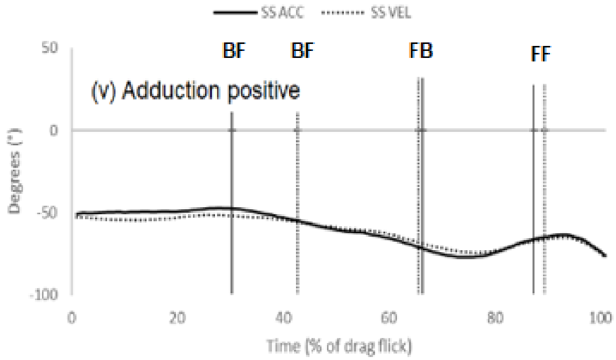
Abduction/Adduction

Internal/External Rotation

Right Shoulder

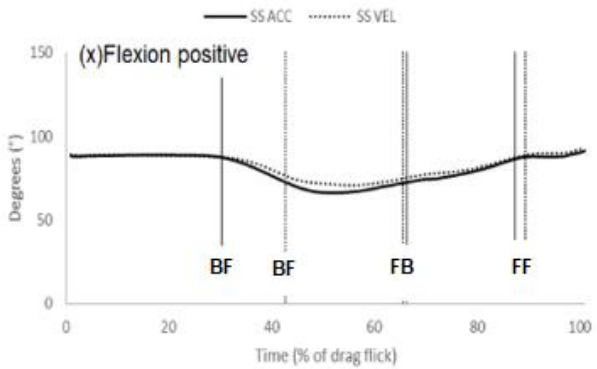


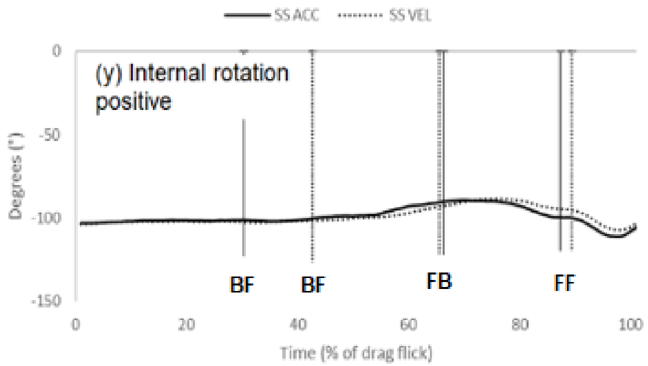




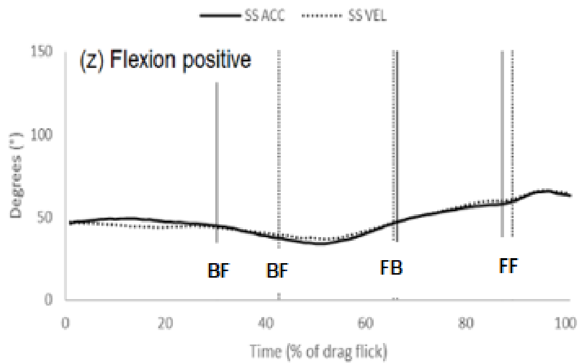
Flexion/Extension | Abduction/Adduction | Internal/External Rotation

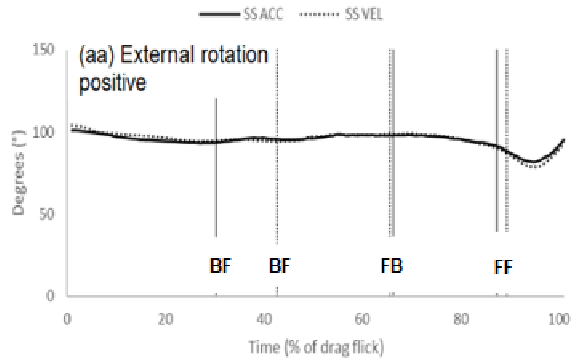
Left elbow





Right elbow





Flexion/Extension | Abduction/Adduction | Internal/External Rotation

Left Wrist

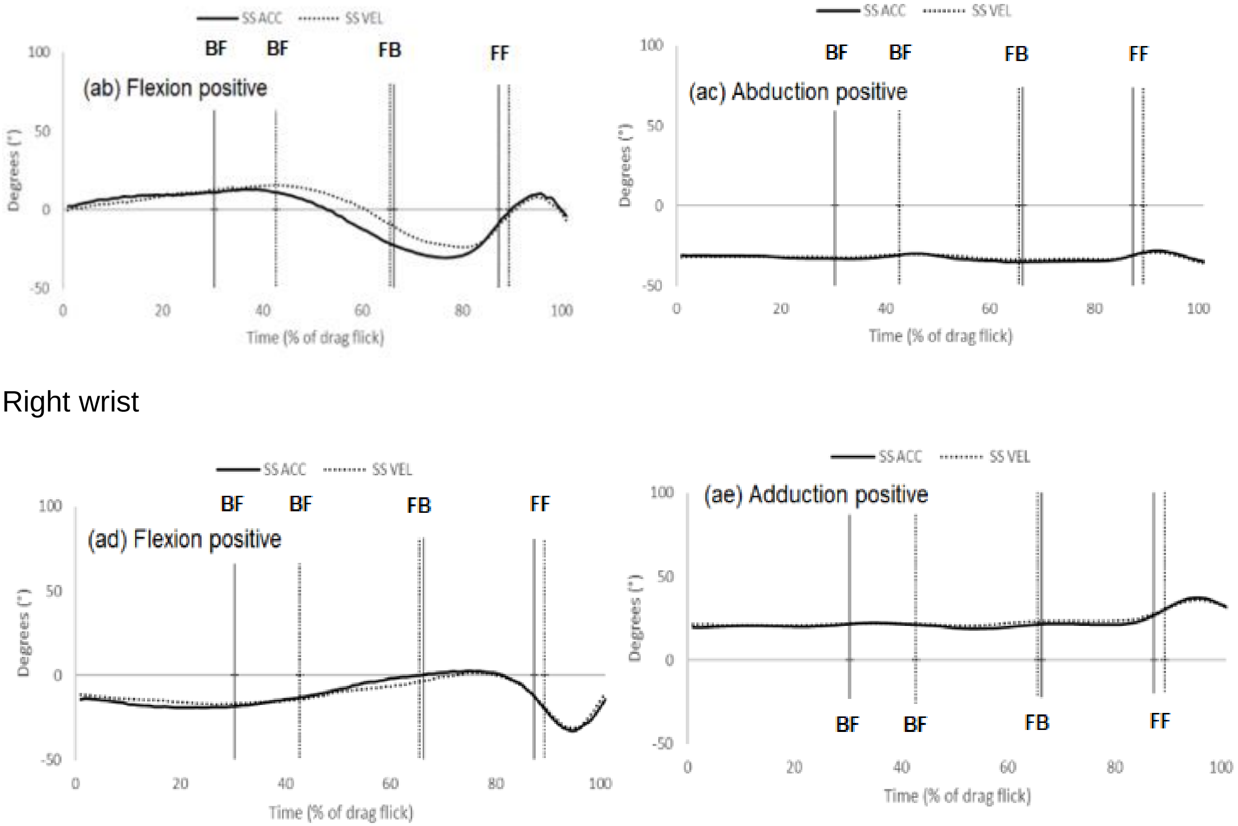


Figure 28: Mean joint angle data for Participant 5: Condition SS ACC and SS VEL. Vertical lines indicate back foot position at ball pick up (BF); foot to ball distance at end of crossover step (FB); and front foot position at stance width (FF). Source: Created by the author.

6.3.4.1 Participant 5: comparison between accuracy and velocity constraints

Participant 5 was selected as there was no change in their kinematic sequencing and only a 2% difference in the mean ball velocity produced in each condition (slower in the velocity condition). As might be expected there is therefore little change within the kinematic data of each joint angle between the two conditions for this participant (Figure 28). There is more abduction at the right ankle following front foot placement in condition SS VEL, and similar to participant 2 there is some change in the kinematic data of both the left and right knee flexion/extension angle prior to ball pick-up and a greater magnitude of left wrist flexion between back foot placement and front foot placement in condition SS VEL. All other joint angles follow the same pattern regardless of the condition being undertaken for this participant, which as explained earlier might be expected given the same kinematic sequencing and similar ball velocities achieved in both conditions.

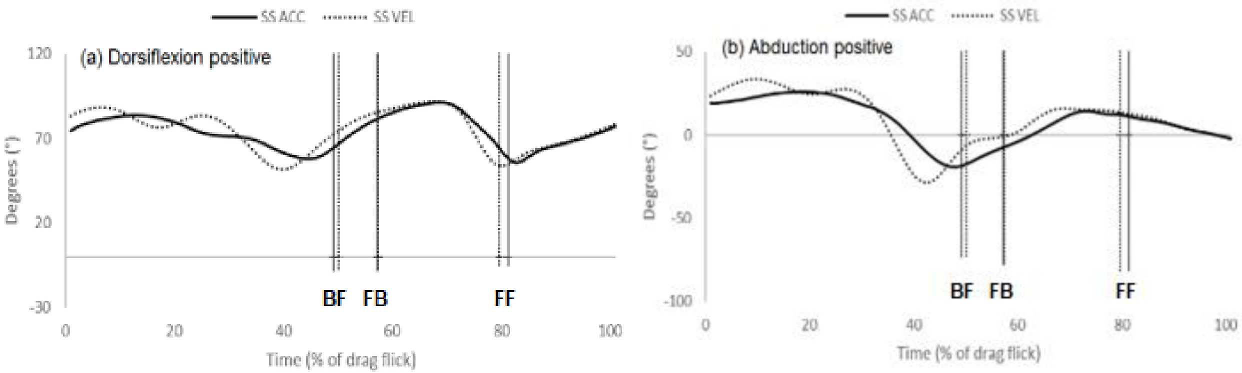
6.3.4.2 Participant 2: comparison between accuracy and velocity constraints

Two trials have been selected and video files containing the visual 3D animation of each trial can be viewed in the link in Appendix N. The trial from each condition has been selected based on two examples of noticeable differences between each condition. The ball velocity was 20.00 $m \cdot s^{-1}$ for condition SS ACC and 24.94 $m \cdot s^{-1}$ for condition SS VEL (25% greater for SS VEL). The absolute time taken to perform the drag flick in each trial is different between the two conditions (SS ACC: 0.87 s / SS VEL: 0.79 s; 10%), and the length of time the ball is dragged is also different (SS ACC: 0.46 s / SS VEL: 0.38 s; 17%). The participant completes the drag flick technique in the velocity condition quicker compared with the accuracy condition. Visually the posture is similar throughout both conditions as well as at previously identified important key events throughout the drag flick technique (back foot placement; foot to ball distance and front foot placement). However, the measures for kinematic sequencing have been calculated on angle velocities, not segment angles and it is difficult to visually identify differences in posture between the two example videos. Nevertheless, there are differences in some performance variables, participant 2 plants the right foot further in front of the ball in condition SS ACC (0.39 m) compared with SS VEL (0.29 m), and the stance width is wider for condition SS VEL (SS ACC: 1.46 m / SS VEL: 1.70).

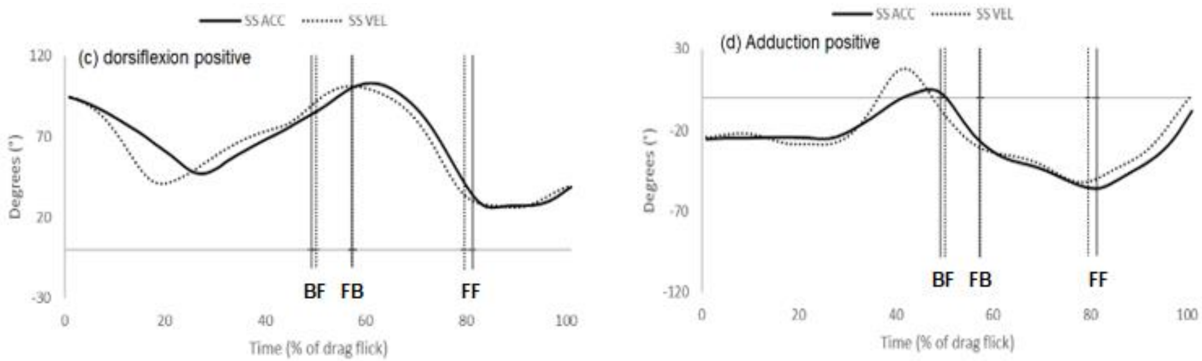
The kinematic data presented in Figure 29 identifies some noteworthy changes between the two conditions. Most of the timing and magnitude differences between conditions occur prior to ball pick up in both the left and right ankles, which may suggest the participant is altering the set-up position in preparation for ball pick-up. The left ankle is plantarflexing earlier in preparation for the wide stance width in the velocity condition which may be linked to the wider stance width observed for this trial. Again, the right ankle is more plantarflexed and adducted in condition SS VEL which is also possibly linked to the wider stance width within this condition for participant 2. The flexion/extension angle for the left and right knee also mostly differ between the two conditions prior to ball pick-up. Following ball pick-up, the kinematics are similar between both conditions. However, there is a magnitude shift between the two conditions for the internal/external rotation angle for both the left and right knee. The left knee is more internally rotated throughout the drag flick technique in the velocity condition whereas the right knee is more externally rotated within the velocity condition. However, if this rotation is being used by the participant to create torque this torque is not being transferred up through the legs into the hips in terms of visual differences in postural variation, though this may be explained by the faster movement pattern for the velocity condition, with the time taken from ball pick-up to ball release being slower in the accuracy condition (SS ACC: 0.46 s / SS VEL: 0.38 s; 17%). Following ball pick-up there is little differentiation between the left and right hips, the thorax pelvis differential and the right shoulder between the two conditions. However, there are some kinematic changes for the left shoulder. Following the setting of foot to ball distance the left shoulder externally rotates more in the velocity condition, and there is greater flexion in the left elbow and greater extension and abduction in the right wrist. This movement suggests the participant is reaching back further for the ball in this trial and therefore creating a longer drag distance (SS ACC: 2.58 m / SS VEL: 2.98 m 13%). It is possible that participant 2 is using the knee internal/external rotation kinematics to generate torque and increase velocity with similar postural variation, which is accompanied by kinematic changes in the left shoulder, left elbow and right wrist.

Flexion/Extension | Abduction/Adduction positive | Internal/External Rotation

Left ankle



Right ankle

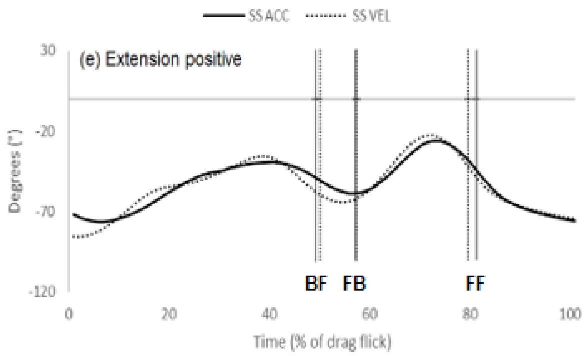


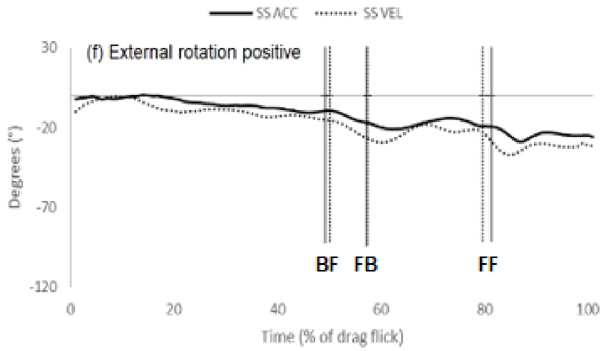
Flexion/Extension

Abduction/Adduction positive

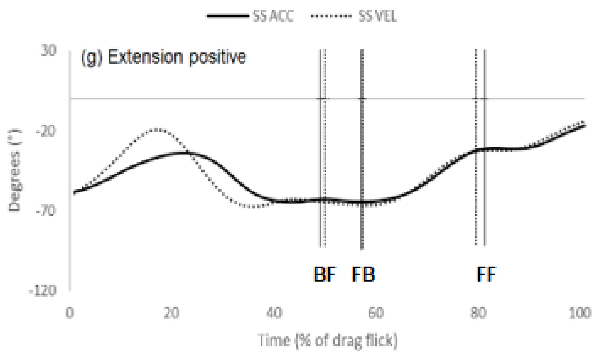
Internal/External Rotation

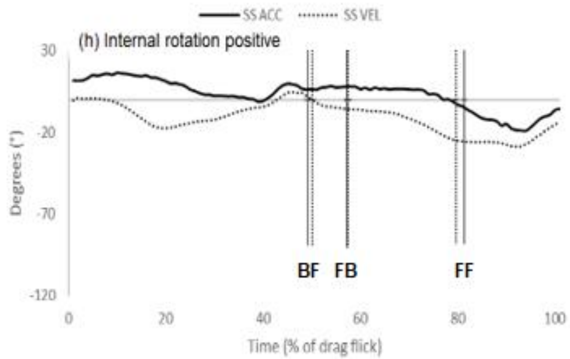
Left knee





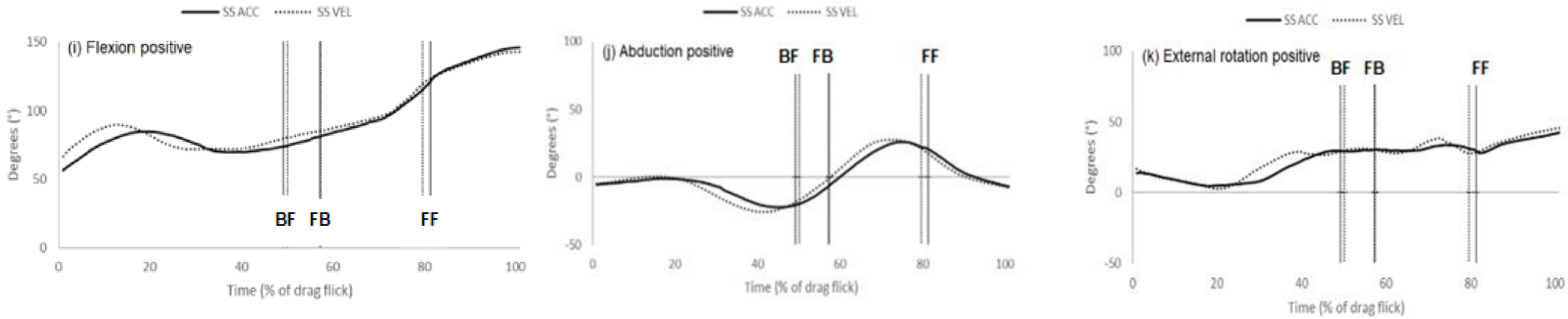
Right knee



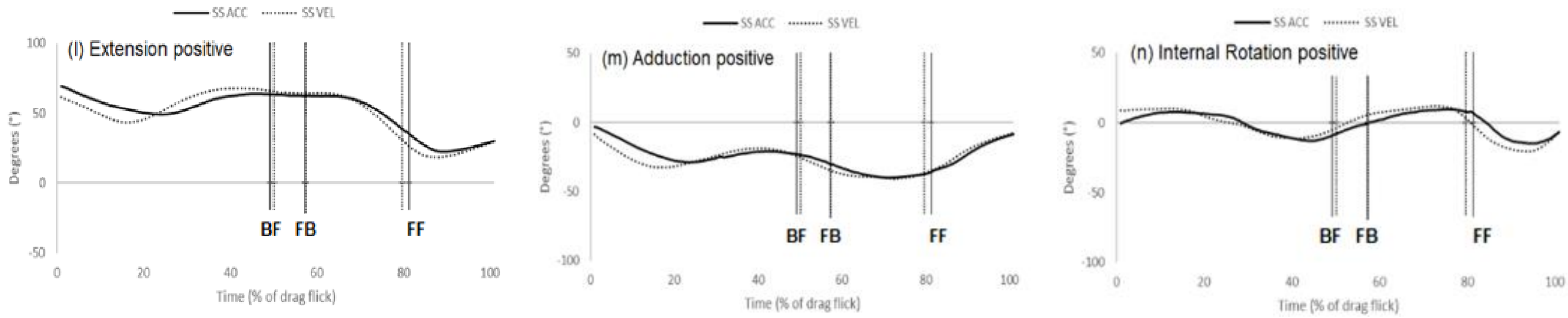


Flexion/Extension | Abduction/Adduction | Internal/External Rotation

Left hip

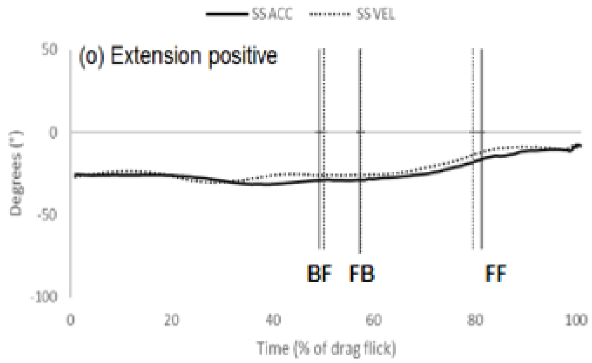


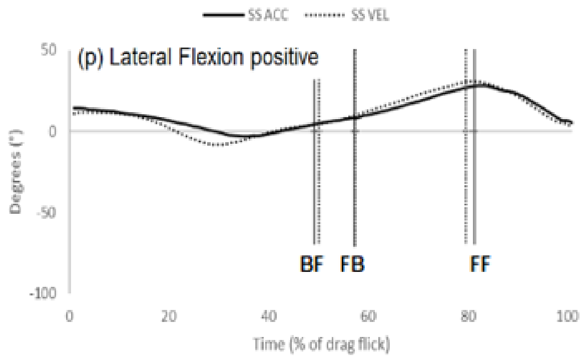
Right hip

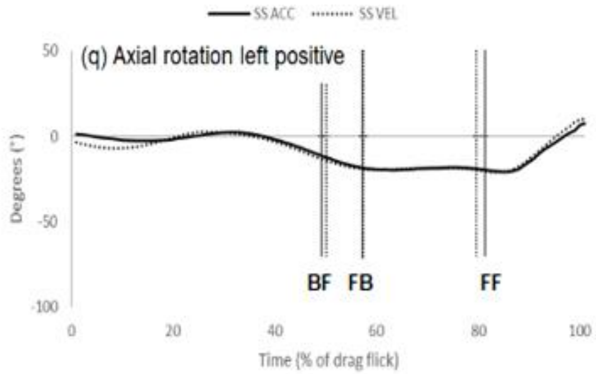


Flexion/Extension Lateral Flexion Axial Rotation

Thorax Pelvis Differential

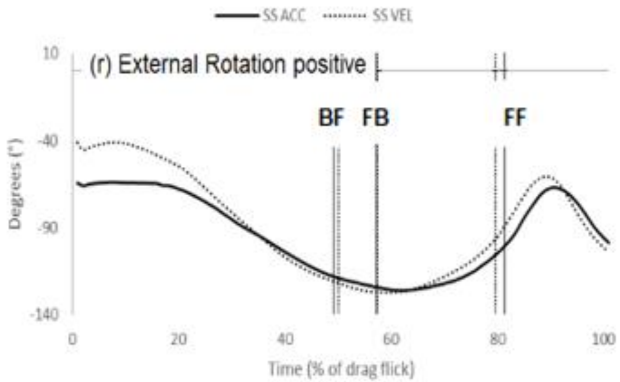


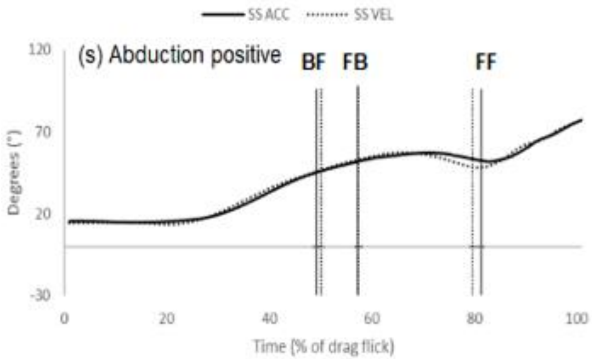


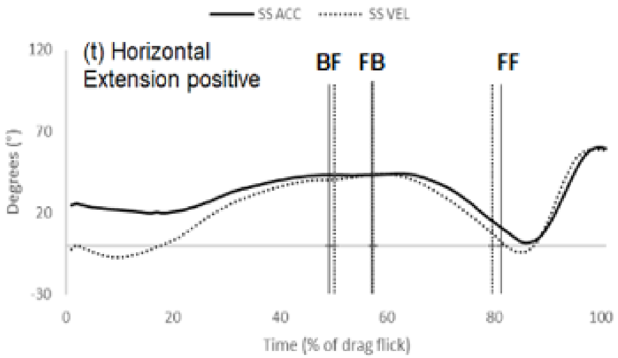


Internal/External Rotation | Abduction/Adduction | Horizontal Flexion/Extension

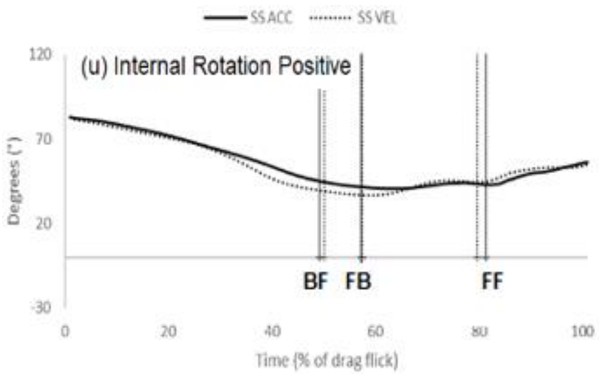
Left Shoulder

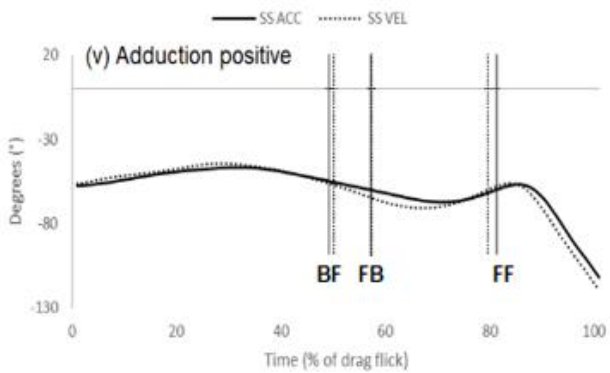


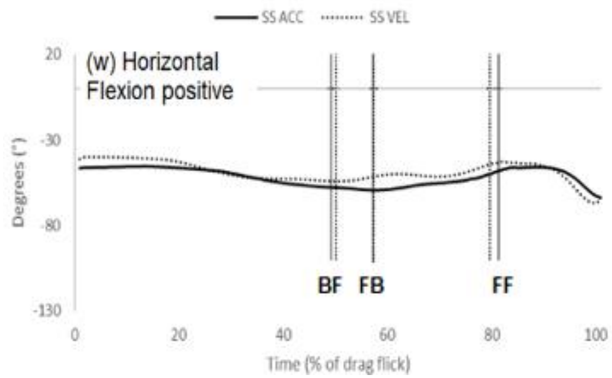




Right Shoulder

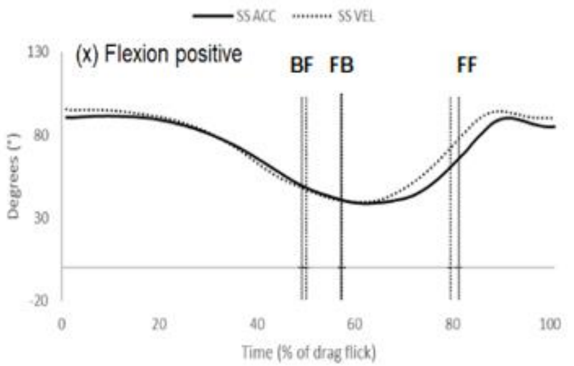


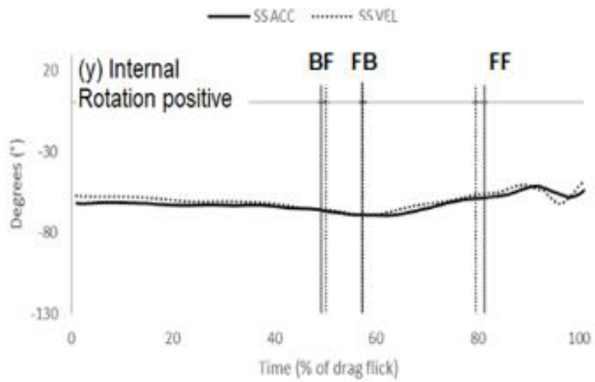




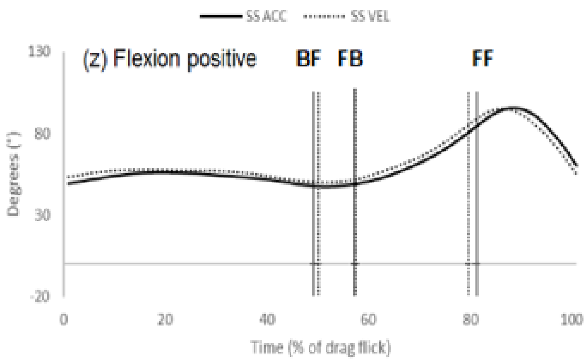
Flexion/Extension | Abduction/Adduction | Internal/External Rotation

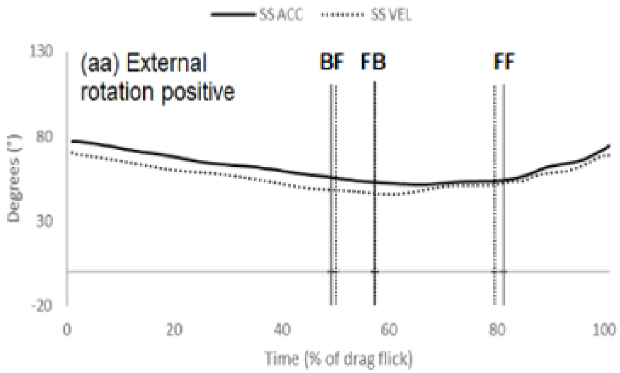
Left elbow





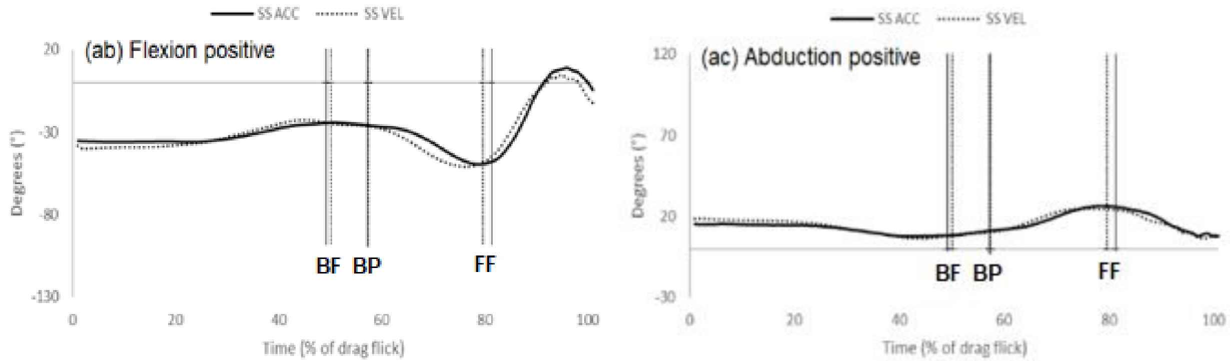
Right elbow





Flexion/Extension | Abduction/Adduction | Internal/External Rotation

Left Wrist



Right wrist

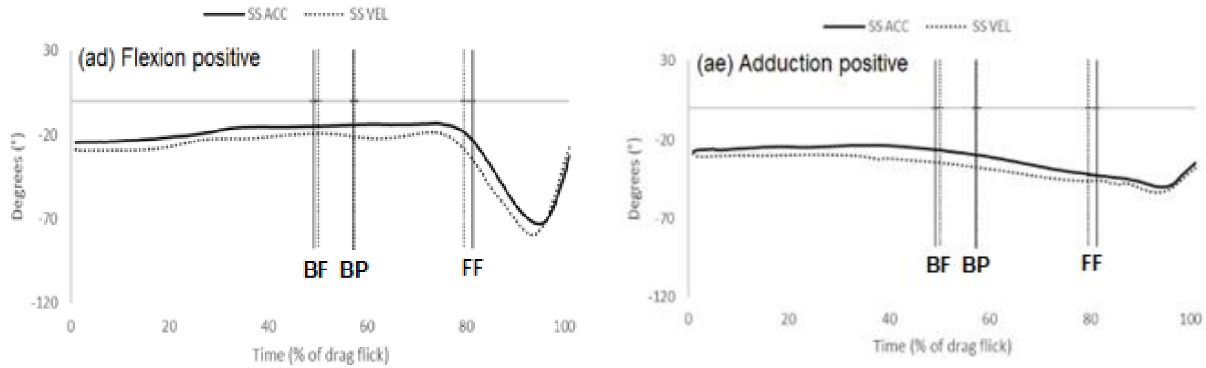


Figure 29: Mean joint angle data for Participant 2: Condition SS ACC and SS VEL Vertical lines indicate back foot position at ball pick up (BF); foot to ball distance at end of crossover step (FB); and front foot position at stance width (FF). Source: Created by the author.

6.3.4.3 Participant 7: comparison between accuracy and velocity constraints

Participant 7 was selected due to the change in kinematic sequencing from KS 2 (T1-T4-T3-T2-T5-T6) to the preferred kinematic sequencing, KS1 according to published literature (T1-T2-T3-T4-T5-T6 ; T1, foot contact; T2, peak negative linear velocity of the stick; T3, peak pelvis angular velocity; T4, peak upper trunk velocity; T5, peak positive linear velocity of the stick; T6 ball release), and little change in ball velocity between the two conditions (SS ACC: 23.37 $m \cdot s^{-1}$ / SS VEL: 23.89 $m \cdot s^{-1}$; 2%). Figure 30 presents the joint angle data for participant 7. Two trials have been selected and video files containing the visual 3D animation of each trial can be viewed in Appendix O. The trials from each condition have been selected based on two examples of noteworthy differences between each condition. The ball velocity was 21.41 $m \cdot s^{-1}$ for condition SS ACC and 21.32 $m \cdot s^{-1}$ for condition SS VEL, a difference of less than 1%. The absolute time to complete each trial is also very similar between the two conditions (SS ACC: 0.87 s / SS VEL: 0.86 s; 1%), producing the same value for the accuracy trial as participant 2. However, the length of time the ball is dragged is different between the two conditions (SS ACC: 0.64 s / SS VEL: 0.48 s). The participant completes the drag flick technique in a similar time overall but spends longer dragging the ball in the accuracy condition. The most notable difference between the two videos of each trial is the cross-over step. In the SS ACC condition, the participant does not cross the legs, a more skip like action is evident, whereas in the velocity condition a more typical cross-over step is completed although the right leg crosses in front of the left leg at ball pick-up and foot to ball distance. This does not impact on the foot to ball distance as the foot is planted further in front of the ball in the SS ACC (1.02 m) condition compared with the SS VEL condition (0.90 m). This could, however, explain some of the kinematic differences between the ankle kinematics presented below. Again, the stance width is greater in the accuracy condition for this participant (SS ACC: 1.55 m / SS VEL: 1.47 m).

The kinematic data presented in Figure 30 supports the observations from the video footage (Appendix N and O) and performance variables (Table 28). Video files of two other participants (P4 and P10) have also been presented in Appendix N and O to provide a visual comparison to P2 and P7. The right ankle is more plantarflexed and adducted following ball pick-up in preparation for foot to ball distance in the velocity condition, two movements that would be needed for the right foot placement following the cross-over step. The left knee is more flexed and the left hip is more extended throughout the drag flick technique until approximately 80% where the two conditions are more aligned, again supporting the lack of cross-over step in SS ACC as explaining differences between conditions and that the left knee would be more extended and left hip more flexed in order to undertake a more skip like action as opposed to a more traditional cross-over step. There is a magnitude shift between the two conditions for the internal rotation of the right knee and the external rotation of the left hip throughout the whole technique. This movement is possibly being used to generate torque in the velocity condition moving through to the left shoulder. The left shoulder has greater external rotation throughout the drag flick technique in the velocity condition. The thorax pelvis differential position is more flexed throughout the technique. Most of the changes in the left and right elbow occur prior to foot to ball distance which may be as a result of the participant adjusting the position of the ball in order to prepare for the drag during the wider stance width.

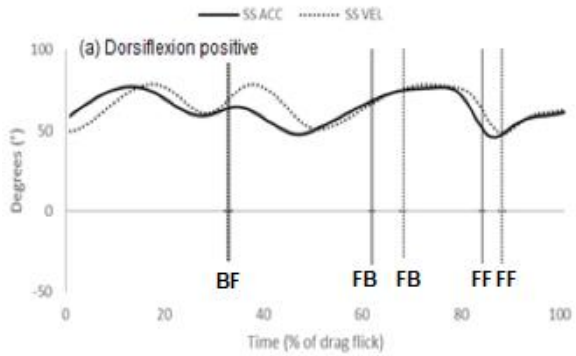
Following analysis of the video footage and the kinematic data, the right ankle flexion and adduction at ball pick-up combined with the change in technique of the cross-over step, the change in internal rotation of the right knee, external rotation of the left hip and the change in external rotation of the left shoulder may explain the change in kinematic sequencing from KS2 to KS1 for participant 7 between the two conditions.

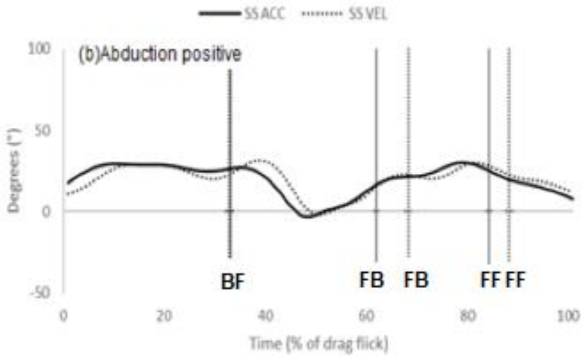
Flexion/Extension

Abduction/Adduction positive

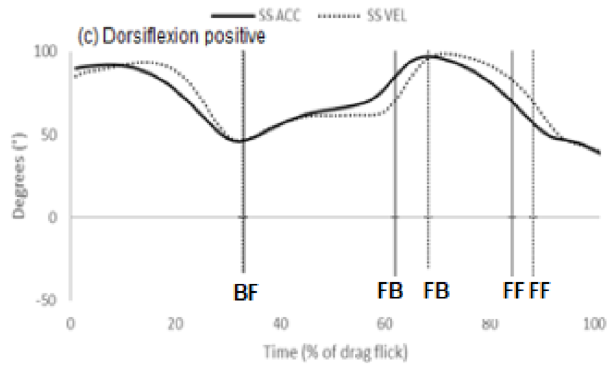
Internal/External Rotation

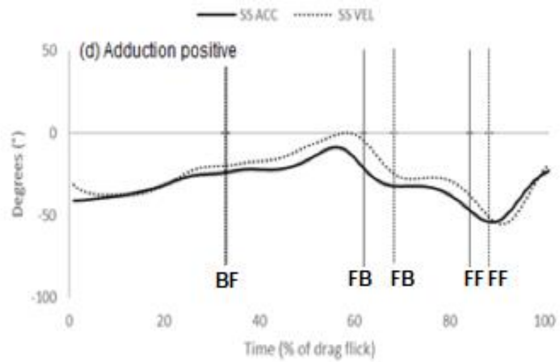
Left ankle





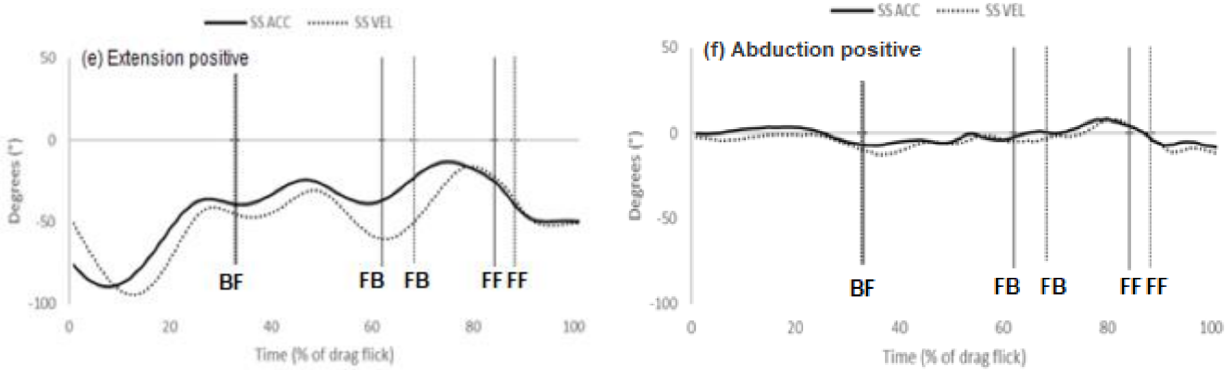
Right ankle



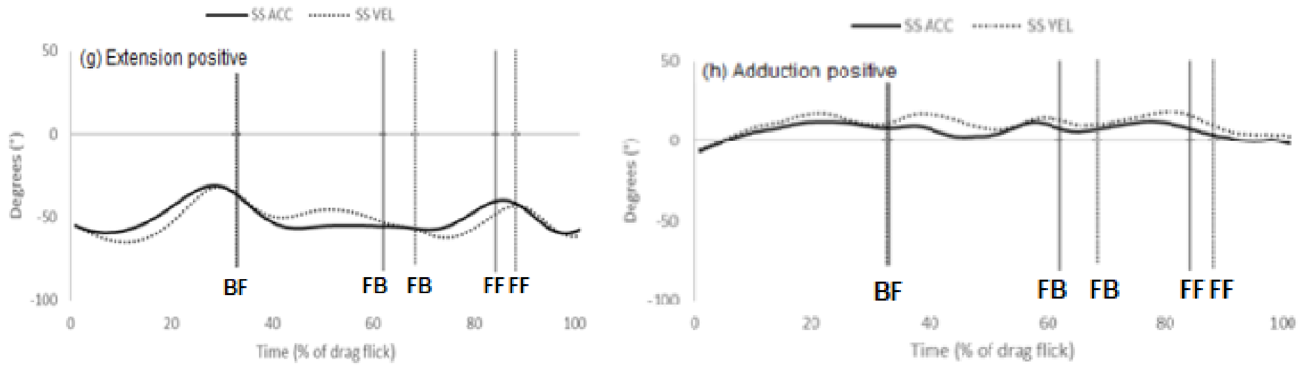


Flexion/Extension | Abduction/Adduction positive | Internal/External Rotation

Left knee

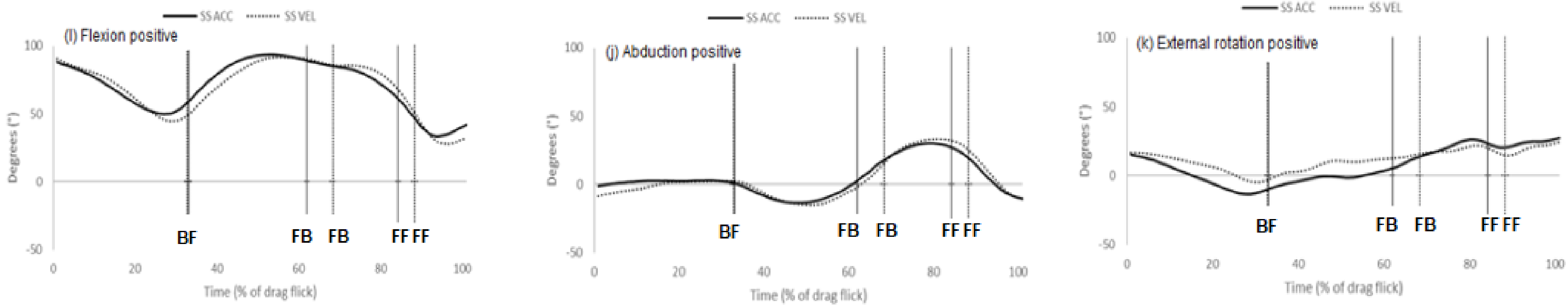


Right knee

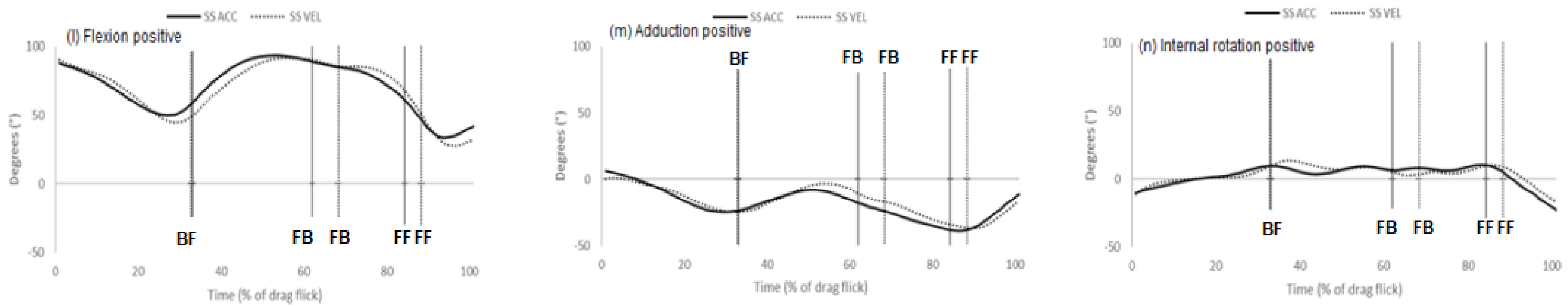


Flexion/Extension | Abduction/Adduction positive | Internal/External Rotation

Left hip

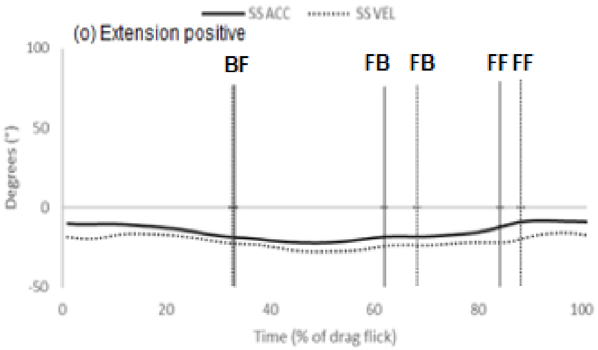


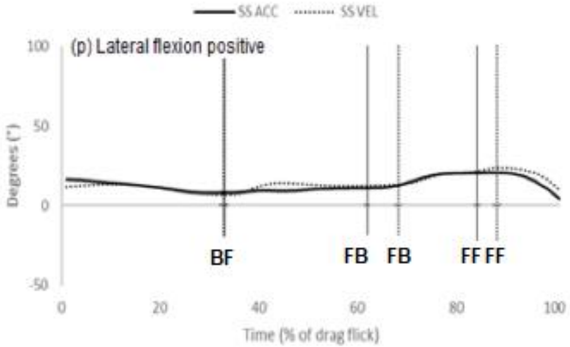
Right hip

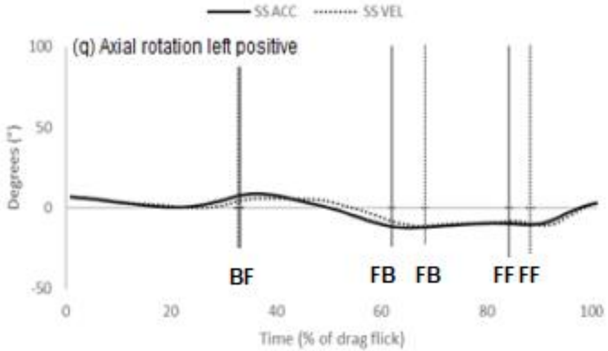


Flexion/Extension | Lateral Flexion | Axial Rotation

Thorax Pelvis Differential

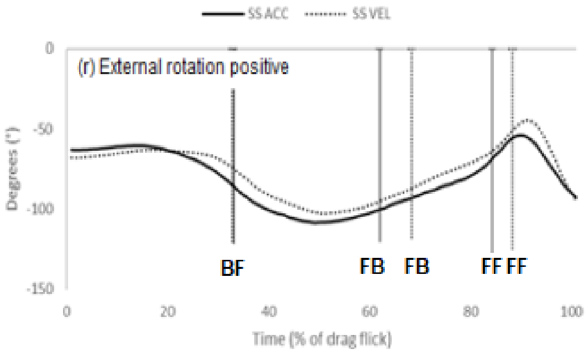


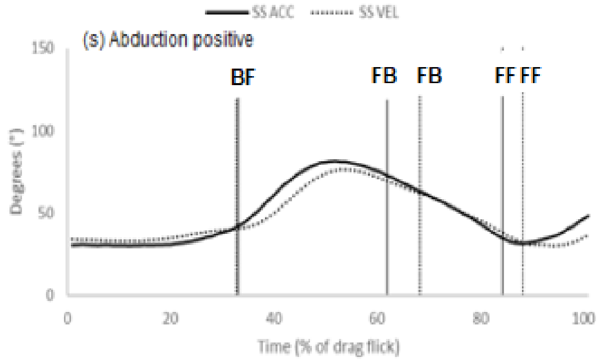


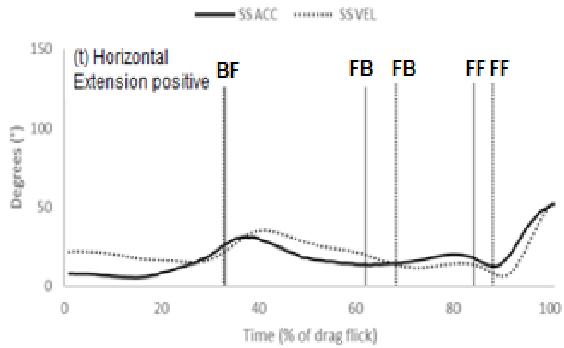


Internal/External Rotation | Abduction/Adduction | Horizontal Flexion/Extension

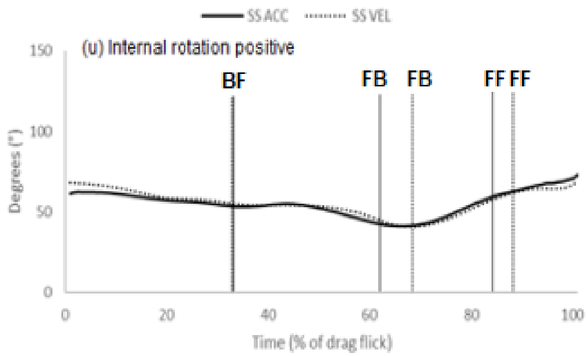
Left Shoulder

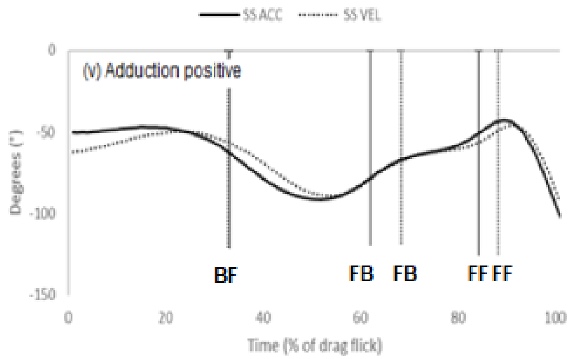


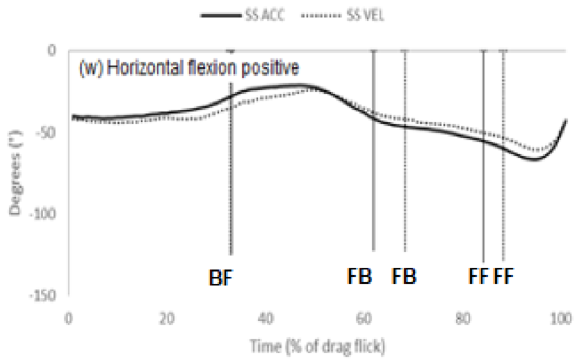




Right Shoulder

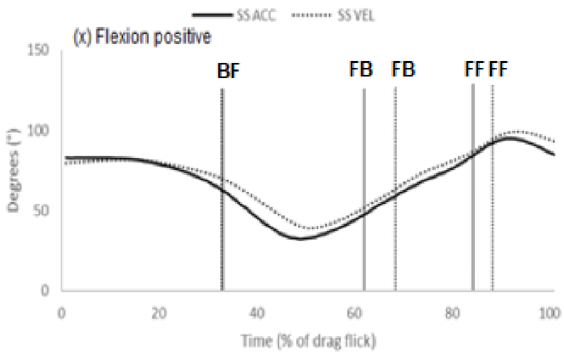


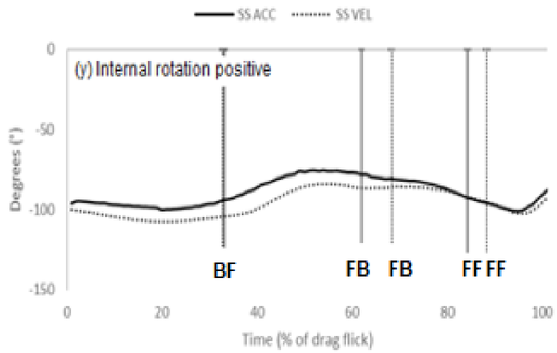




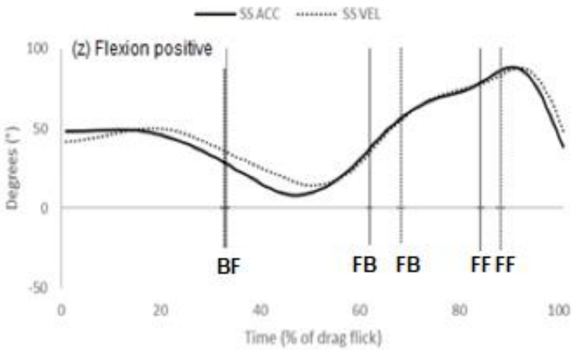
Flexion/Extension | Abduction/Adduction positive | Internal/External Rotation

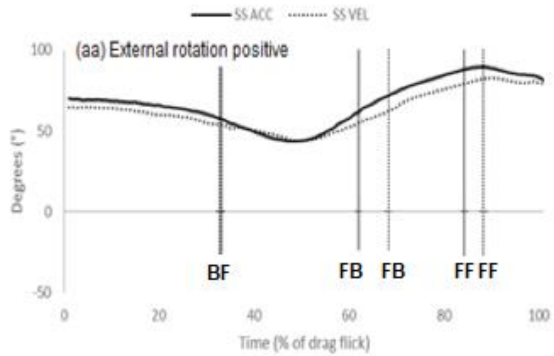
Left elbow





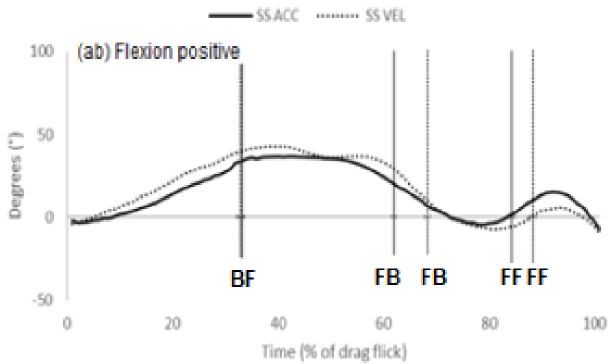
Right elbow

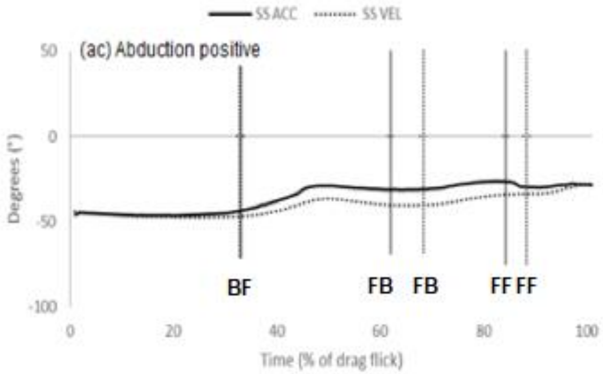




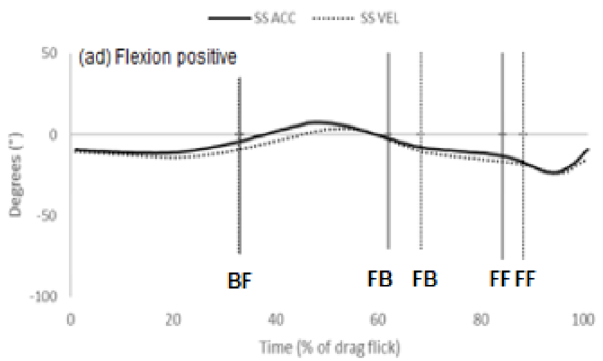
Flexion/Extension   Abduction/Adduction positive   Internal/External Rotation

Left Wrist





Right wrist



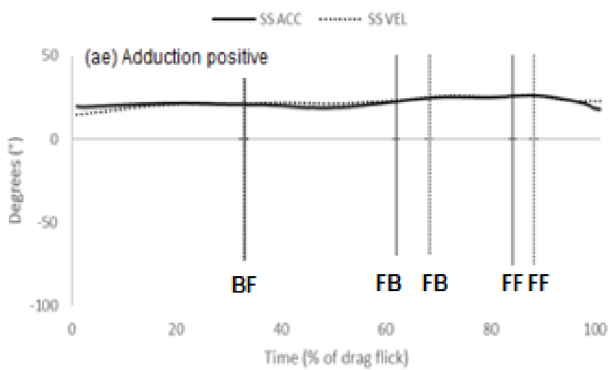


Figure 30: Mean joint angle data for Participant 7: Condition SS ACC and SS VEL Vertical lines indicate back foot position at ball pick up (BF); foot to ball distance at end of crossover step (FB); and front foot position at stance width (FF). Source: Created by the author.

For the performance variables these two participants (P2 and P7) were selected due to the same kinematic sequences but the difference between the change in ball velocities of the two conditions. Participant 2 presented a 25% greater ball velocity in condition SS VEL in contrast to participant 7 who presented only a 2% increase in ball velocity following the SS VEL condition. There are few similarities between participant 2 and 7, even though they both complete KS 2 for SS ACC condition and change to KS 1 for SS VEL condition. Both participants have similar stance widths and similar changes from accuracy to velocity condition (P2: 2% increase from SS ACC to SS VEL / P7: 1% decrease from SS ACC to SS VEL). In addition, both participants have different left and right ankle dorsi/plantarflexion prior to ball pick-up suggesting both players are adjusting their set-up position. In addition, the left shoulder of both participants has greater external rotation following ball pick-up through to ball release. There are notable differences between the two conditions for each participant for the right knee however, they are rotating differently. Participant 2 has greater external rotation of the right knee and participant 7 has greater internal rotation of the right knee both in the velocity condition. There are noticeable differences of both participants for the foot to ball position of the right foot although P2 has a smaller foot to ball distance for both conditions (SS ACC: 0.18 m / SS VEL: 0.14 m) compared with P7 (SS ACC: 0.48 m / SS VEL: 0.52 m). The notable changes between the two conditions for P2 are seen at the left knee internal rotation, left elbow flexion and right wrist extension and abduction. In contrast P7 has notable changes between the two conditions at the left knee flexion, left hip extension and external rotation, and thorax pelvis differential flexion.

6.4 Chapter Discussion

This chapter evaluates the kinematic patterns that are used when performing the drag flick technique. The primary aim of this study was to determine whether or not there was a core movement strategy of the drag flick technique within field hockey and to identify the elements of technique that are modified to produce different outcomes and styles.

6.4.1 Ball Velocity

The ball velocities obtained within this study for hit targets (SS ACC: 20.47 ± 2.73 $m \cdot s^{-1}$; SS VEL: 21.19 ± 3.03 $m \cdot s^{-1}$; P ACC: 20.36 ± 2.98 $m \cdot s^{-1}$;) are comparable to those reported by Lopez et al. (2010), (17.9 to 21.9 $m \cdot s^{-1}$), Yusoff et al. (2008), (19.61 to 27.83 $m \cdot s^{-1}$), Gómez et al. (2012), (22.20 $m \cdot s^{-1}$) and McLaughlin (1997), (19.1 $m \cdot s^{-1}$). However, they were below that reported by Ibrahim et al. (2017), (31.7 $m \cdot s^{-1}$). This is probably explained by Ibrahim et al. (2017) reporting the kinematic pattern of ten male elite field hockey players comprising three Olympic level drag flickers, four national level drag flickers and three Olympic level hockey players (not specialising in drag flick). In the present study, the constraint of ball velocity within condition SS VEL was adhered to by the participants as the mean ball velocity within this condition was greater (4%) than the other two conditions for which accuracy was the primary driver. The increase in ball velocity will allow the interpretation and evaluation of what effects the task constraints (in this case ball velocity) have on the kinematics of the drag flick technique and what kinematics can be considered as part of the core movement strategy.

6.4.2 Performance variables

The stick resultant velocities of hit targets within this study (SS ACC: 18.43 $m \cdot s^{-1}$; SS VEL: 19.40 $m \cdot s^{-1}$; P ACC: 18.32 $m \cdot s^{-1}$) support the ball velocities presented and are greater than those reported by Lopez et al. (2010) (8.6 to 11.6 $m \cdot s^{-1}$), and smaller than those reported by Yusoff et al. (2008), (21.25 to 24.21 $m \cdot s^{-1}$). As with ball velocity and stick resultant velocity, drag flick time of hit targets for the velocity condition was smaller compared to accuracy constraints (SS ACC: 0.49 s; SS VEL: 0.47 s; P ACC: 0.51 s). Yusoff et al. (2008) presented comparable drag flick times (0.3 to 0.56 s), however, McLaughlin (1997) reported much shorter drag flick times with a mean of 0.23 s. Theoretically if players can undertake a quicker drag flick time the ball will be released earlier, and the defenders have less time to react to both the players position to read queues and the ball. Much of the research within the public domain has failed to report normalised data relative to participant's body height and therefore this data has not been compared to these values, due to the effect the height of participants will have had on the results. Ball drag distance, foot to ball distance and stance width have all been normalised. De Subijana et al. (2010), (1.03 to 1.38 BH) and Gómez et al. (2012) (1.36 to 1.63 BH) reported normalised ball drag distances which were comparable to the data presented here for hit targets (SS ACC: 1.45 BH; SS VEL: 1.52 BH; P ACC: 1.48 BH). The longer ball drag distance should theoretically improve the final ball velocity due to the impulse created, given similar forces applied, especially if this is completed in a smaller drag flick time. Players are either spending less time in the approach phase of the drag flick or undertaking the movement pattern more quickly in order to have a smaller drag flick time overall and a greater ball drag distance. Only De Subijana et al. (2010), has reported normalised foot to ball distance at ball pick up (0.67 to 0.79 BH) which is greater than the data presented from this study for hit targets (SS ACC: 0.27 BH; SS VEL: 0.25 BH; P ACC: 0.31 BH). The final performance variable is normalised stance width. The data presented from this study (SS ACC: 0.79 BH; SS VEL: 0.81 BH; P ACC: 0.81 BH) is smaller than that of De Subijana et al. (2010), (0.88 BH). It is interesting to note that the foot to ball distance and stance width reported for this study are smaller than those reported in the literature, yet the ball drag distance is comparable to those values reported in the literature.

For this study drag flick times were smaller for the velocity condition which suggests the participants are undertaking the kinematic movement pattern more quickly for the velocity condition. However, even though the drag flick times are smaller for SS VEL, participants are completing a greater ball drag distance within this condition. This could theoretically be due to the greater impulse imparted to the ball over the longer drag distance, which would in turn account for the increase in ball velocity for the SS VEL condition. Interestingly, foot to ball distance and stance width are two variables presented within the published literature which support an increase in drag distance. The further in front of the ball the foot is positioned with players still able to reach back for the ball the greater the drag distance will be if the ball is still released at front foot. The wide stance width allows for both the lowering of the body and the front foot being positioned closer to the goal. This supports again the ability to drag the ball over a greater distance. The foot to ball distance and stance width data presented within this research are smaller than that presented in the literature. Therefore, this would be expected to impact negatively on the ball drag distance and ball velocity but that is not the case.

6.4.3 Technique Variables

Most performance related variables have been reported in the literature; however, the technique variables are much less evident. There is a consensus within the literature that the pelvis and thorax angles are reported at key events within the drag flick technique. However, no data reported to date within the drag flick literature has considered the thorax pelvis differential angle and how the separation of the two segments behaves throughout the technique. Brown et al. (2011) defined the pelvis-thorax differential as the joint angle created by the thorax relative to the pelvis using the cardan sequence XYZ. Brown et al. (2011) studied the pelvis-thorax differential within the golf swing, they reported the greater the pelvis-thorax differential at the top of the back swing the greater the clubhead speed. This variable was applied within the current study, and results presented a consistent pattern for all three conditions. The greatest separation occurred as participants reached back for the ball during left foot contact at stance width after which it returned to a smaller separation angle as the ball is dragged towards the front foot and released. In Chapter 3 the expert panel of coaches identified a low position as an important attribute of the drag flick technique. The COM height within this study, was very consistent across all conditions and for both hit and missed targets ranging from 0.33 to 0.34 BH. No literature to date has reported the COM height as a variable, identifying one valuable aspect of the Delphi Poll study undertaken within chapter 3.

Based on the thorax pelvis differential it is evident that the rotation of the pelvis and thorax are an important part of the movement pattern within the drag flick technique and support the theory of proximal to distal sequencing for throw like actions, in this case the drag flick. The pelvis and thorax are separated as participants reach behind to drag the ball towards the front foot (both hit and missed targets - SS ACC: -11.72° / SS VEL: -12.73° / P ACC: -12.44°). All individual participants mean data for hit, missed and all trials across all conditions are presented in Table 21 to 23. This supports the peak angular velocity of the pelvis followed by the peak angular velocity of the trunk in order to increase ball velocity and follow the preferred kinematic sequencing of KS1 (Brown et al., 2011).

6.4.4 Kinematic sequencing

The mean data of the kinematic sequencing of the peak angular velocities presented was different to McLaughlin (1997) and De Subijana et al. (2010) with the mean data following a sequencing of T1-T4-T3-T2-T5-T6 (T1, foot contact; T2, peak negative linear velocity of the stick; T3, peak pelvis angular velocity; T4, peak upper trunk velocity; T5, peak positive linear velocity of the stick; T6 ball release). However, following close inspection of the individual data this mean is not representative of the sequencing adopted by individuals in the group. These findings support the need to evaluate individual participant data as in this case the mean data mask important variability in sequencing of movement within the sample. Based on the published literature and theory of throw like actions, proximal to distal sequencing is the preferred movement pattern and was identified as T1-T2-T3-T4-T5-T6 (KS1), which was reported by McLaughlin (1997) and De Subijana et al. (2010). However, no participants in this study had the preferred KS1 for condition SS ACC. Also, only two participants for conditions SS VEL (P2, and P7) and one participant for condition P ACC (P6) used it. On analysis of the difference between the accuracy condition and the velocity condition it is also evident that having the preferred kinematic sequencing of KS1 does not always result in an increase in ball velocity.

Only mean data has been presented in the published domain and therefore it is possible that these means are also not representative of the sequencing of individual participants in each study. Ibrahim et al. (2017) reported a close to proximal to distal sequencing. However, it is worth noting that the study is not conclusive and the left wrist deviates from this proximal to distal sequencing. In addition, the timing of onset of joints' angular velocity had a wide range of variability for the shoulder and elbow rotations meaning that statistically significant findings were not reported by Ibrahim et al. (2017).

This study has identified some important findings regarding intra and inter-participant variability in kinematic sequencing of the drag flick technique. Although theoretically the drag flick should be considered a throw like technique in order to gain high ball velocities, the need to be accurate on a target showed that all participants are changing their kinematic sequencing between the conditions of velocity and accuracy. As seen in Table 28 no participant follows KS1 kinematic patten in condition SS ACC and only two do in condition SS VEL. Most participants follow a different kinematic sequence which may suggest participants are using a more push like kinematic sequencing or a combination of a throw like and push like pattern. It is possible that participants are using a sequential throw like pattern in the first part of the technique and a simultaneous push like pattern in the later part of the technique to ensure a high ball velocity is achieved but also to ensure accuracy is achieved by hitting the selected target placed in the goal. Even though the overall performance objective of velocity was specified to participants in condition SS VEL, they were still instructed to aim at the specified target and therefore accuracy was still a constraint within the velocity condition. This may explain the different findings to the published literature as few studies provided a specified target for participants to aim at.

The findings in the present study clearly show intra and inter-participant variability in sequencing under the different constraints of velocity and accuracy, supporting the explanation that participants compromise their sequencing in a variety of ways when adapting to the constraints of velocity and accuracy. The suggestion that a clean T1-T2-T3-T4-T5-T6 sequence of pelvis and trunk rotation might not be as prevalent as previously thought is an interesting perspective. The drag flick is a complex and multifaceted motion. While existing literature has commonly presented a sequential pattern of segmental rotations, the data presented in this thesis show some nuances that challenge the notion of a strict T1-T2-T3-T4-T5-T6 sequence. Notably, T3 (peak pelvis angular velocity and T4 (peak upper trunk angular velocity) were often closely aligned, indicating a potential interaction or simultaneous motion between the pelvis and the upper trunk during certain phases of the drag flick. Moreover, the wide stance adopted by participants during the drag flick, may indeed restrict the independent pelvis rotation. This wide stance can promote more of a unitary motion where the pelvis and trunk move together. While these findings may deviate from the sequential pattern reported in the literature, they provide valuable insights into the variability and adaptability of the drag flick technique, which can be influenced by the posture and components of the movement itself, individual differences, coaching methods, and the demands of the sport itself. In challenging the conventional T1-T2-T3-T4-T5-T6 sequence, the results of this chapter reveal a participant with an exceptionally early peak negative linear velocity of the stick and two participants with notably late peaks. These nuanced results may be explained by participants endeavouring to adjust their posture in relation to the ball. It is plausible that this adjustment is responsible for the nuanced variations in peak negative linear stick velocity observed. The novel findings, presented in the results and discussion of the kinematic sequencing have not previously been documented in the literature, and have implications for coaching the hockey drag flick.

6.4.5 Joint angles

To date only one study has investigated individual joint angles and their movement pattern throughout the entire drag flick technique. De Subijana et al. (2010) presented the left knee joint angles at front foot contact during the stance width and at stick resultant velocity but did not consider the entire time series of data for the knee. Ladru et al. (2019) investigated the entire time series of data but only for the lead knee joint angle of the front foot (left knee). The results presented in this chapter report the mean joint angles with standard deviations to understand the departure from the mean score across all participants. The mean data reports the left and right hip joints as producing the greatest range of movement throughout the drag flick technique in all three directions before any consideration of the effect of the constraints within the three conditions (left hip - X: 58.32°, Y: 48.29°, Z: 34.59° / right hip – X: 52.63°, Y: 36.90°, Z: 34.21°). The flexion/extension movement of the elbows (left: 48.54°, right: 44.38°) and wrists (left: 40.08°, right: 43.44°) on both sides also produce a wide range of movement throughout this technique. The left shoulder axial rotation and horizontal flex-/extension produces a wide range of movement compared with the right shoulder however, the right shoulder ab-/adduction is greater compared with the left (left - (Z: 56.94°, Y: 41.16°, Z: 37.23°, right - Z: 19.38°, Y: 58.71°, Z: 10.68°). Again, there are differences between the left and right ankles. The right ankle produces a greater range of movement (X: 41.29°, Y: 39.59°) compared with the left (X: 25.55°, Y: 23.07°). It appears, based on the range of movement and the variation around this movement across participants, that the left and right elbows and wrists for flexion/extension can be considered as part of the core movement strategy of the drag flick technique as they make substantial contributions to the technique in terms of range of movement but show relatively modest variation across participants and conditions when variation around the mean is expressed relative to the magnitude of range of motion (all figures for variation are represented by expressing SD as a percentage of the joint angle range – LELB x: 31.6%, RELB x: 33%, LWRI x: 35.6%, RWRI x: 33.3%). The abduction/adduction of the left and right hips and the left and right shoulders, the axial rotation of the right hip and the left shoulder and the ab-/adduction of the right ankle also make a substantial contribution to the technique in terms of range of joint angle but similar to the elbows and wrist they have modest variation around the mean across all participants and conditions (LHIP y: 21.2%, RHIP y: 26%, RHIP z: 36.6%, LSHO y: 34.1%, LSHO x: 36.6%, RSHO y: 26.6%, and RANK y: 28.2%) and therefore could be considered as being part of the core movement strategy of the drag flick technique. The left elbow and thorax pelvis differential axial rotation all have a smaller range of movement but again show little variation about the mean (LELB z: 33.4%, TPD z: 37.6%) compared with other joint angles, and therefore could also be considered as being part of the core movement strategy of the drag flick technique. Other joint angles which make a substantial contribution to the technique in terms of range of movement but also have a wide departure from the mean are right ankle flexion/extension; right and left hip flexion/extension and left hip axial rotation; left shoulder horizontal flexion. Therefore, these are key joint angles to consider which influence the movement but there is a larger range of individual variation (RANK x: 101.4%, LHIP x: 75.5%, RHIP x: 69%, LHIP z: 43.3°, LSHO z: 53.3°)

The techniques used within this chapter to determine the core movement strategy is only useful for analysing variability in a single joint. When techniques such as the drag flick researched within this thesis involve multiple degrees of freedom – as with most sport techniques, this analysis does not consider the coordination and variability of the task as a whole. In addition, just analysing the individual joint angles it is not possible to pull out the core features and how these elements change with task or target. An adaptation of Principal Component Analysis (PCA) proposed by Daffertshofer et al. (2004) and presented in Chapter 2 will be applied to continuous waveforms to assess inter-joint coordination in Chapter 7.

6.5 Summary

This study is unique in a number of ways. The use of target areas, the constraints of accuracy and velocity and analysis of hits and misses have had little consideration in the previous literature. In addition, the entire time series of joint angle kinematics for all major joints has been examined taking into consideration the intra and inter participant variability and considering evidence that supports or refutes the existence of elements of a core movement strategy. However, the discrete performance and technique variables in this study are consistent with values reported in the literature (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010, Gómez et al., 2012).

The kinematic sequencing provided an original contribution to the drag flick research through empirical evidence showing how the constraint of accuracy on the drag flick impacts on the typical throw like pattern of proximal to distal sequencing, demonstrating that all participants revert to either a more push like pattern or a combination of throw and push to ensure accuracy is achieved. From a practical perspective the kinematic sequencing insights gained from the present study should be very useful to coaches and players to help determine the best training methods to ensure players are being accurate but utilising a proximal to distal sequencing to ensure appropriately high ball velocity. The drag flick in field hockey, with its complex motion involving the upper trunk and stick head, is known to have a high number of degrees of freedom. This complexity implies that the movement of the arms and their sequencing may play a crucial role in the execution of this skill. In the current study, the primary focus of the kinematic sequencing looked at the time discrete events of T1-T4-T3-T2-T5-T6 (T1, foot contact; T2, peak negative linear velocity of the stick; T3, peak pelvis angular velocity; T4, peak upper trunk velocity; T5, peak positive linear velocity of the stick; T6 ball release). While this provided valuable insights into the overall movement patterns and variations among participants, it didn't specifically delve into the intricate details of the arm sequencing. In future analyses, it would be beneficial to explore the sequencing and coordination of the arms during the drag flick in more depth. This could involve analysing the timing and synchronization of various segments of the arms, the relative contributions of the upper arm, forearm, and hand, and how these elements interact with the trunk and stick motion. Such an investigation may reveal valuable insights into the kinematic intricacies of the drag flick and how they relate to performance and consistency. The joint angle kinematics also provide an original contribution to the drag flick research literature by identifying which joint angles were major contributors to the drag flick technique with little variation from the mean and therefore could be considered as part of the core movement strategy of the drag flick technique. The abduction/adduction of the left and right hips and shoulders provided the greatest range of motion across all participants and conditions with consistency in the movement pattern leading to limited variation from the mean data across all participants and conditions and therefore can be considered as key joint angles in the drag flick technique. Alongside these are the flexion/extension of the left and right elbows and wrists, the right hip axial rotation, left shoulder flex-/extension and right ankle ab-/adduction which also make significant contributions to the technique with consistency and little variation across participants or constraints. This is a novel finding as few studies have looked at the contribution of the upper body when analysing the drag flick technique. Other joint angles which have limited variation from the mean data are the left elbow and thorax pelvis differential axial rotation although these joint angles have smaller joint angle ranges over the entire drag flick technique.

The following bullet points summarise the key aspects of study 2 presented in this chapter and the novel findings which contribute to the body of knowledge:

- The task constraint of accuracy alters the kinematic sequencing of players from a throw like pattern to more of a push like pattern.
- The following joint angles are considered to be the core movement strategy of the drag flick technique. This has been based initially on: the consistency of the kinematic patterns of movement at these joints across all participants, conditions, and all target areas for both hit and missed targets; the large range of movement of each joint angle; and the relatively small variability in the movement compared with other joint angles.
    - Left hip ab-/adduction
    - Right hip ab-/adduction
    - Left shoulder ab-/adduction
    - Right shoulder ab-/adduction
    - Left elbow flex-/extension
    - Right elbow flex-/extension
    - Left wrist flex-/extension
    - Right wrist flex-/extension
    - Right hip axial rotation
    - Left shoulder axial rotation
    - Right ankle ab-/adduction

- The following joint angles are also considered part of the core movement strategy of the drag flick technique but are less consistent based on the same criterion as presented above:
    - Left elbow axial rotation
    - TPD axial rotation

- Other joint angles which make a contribution, again based on the earlier presented criterion consistency of movement pattern, a substantial range of movement but with a larger range of variation across participants are:
    - Right ankle flex-/extension
    - Left hip flex-/extension
    - Right hip flex-/extension
    - Left hip axial rotation
    - Left shoulder axial rotation

CHAPTER 7:
STUDY 3: TECHNIQUE ANALYSIS IN THE FIELD HOCKEY DRAG FLICK USING PRINCIPAL COMPONENT ANALYSIS

7.1 Introduction

Chapter 6 showed that there is a core movement strategy of the drag flick technique but there were no identifiable elements of the drag flick technique that were modified to produce different outcomes based on the various task constraints implemented. Individual participants displayed trial to trial variations across a range of technique, performance, and task variables. However, this traditional biomechanical approach did not show any consistent clear differences between hit and missed targets or between conditions and target areas across multiple variables. The findings did provide some meaningful information but in a limited way to help determine which aspects of the technique could have influenced drag flick accuracy based on the different target areas and different constraints of the task.

A method, which has gained attention in the last few years to account for the high dimensionality of movement, is analysing kinematic data using Principal Component Analysis (PCA) (Daffertshofer et al., 2004, Federolf et al., 2014, Haid et al., 2018). PCA is a method that is used to analyse large data sets and to identify patterns, which are representative of the most variance in the data. It can be used to identify the most relevant movement dimensions. Following the proposed approach, the *eigenvectors* as one output from the PCA, characterise the resulting variables. The variables are one-dimensional representations of the involved components, which are called principal components (PC_k). PC_1 is the dimension with the greatest variance and further PC_k's contain less variance than the previous PC_k. PCA has been applied for technique analysis in sports (Federolf et al., 2014, Witte et al., 2010), on individual participants. However, anthropometric differences prevented a direct comparison of the techniques between athletes. Gløersen et al. (2018) provided a major methodological advancement of an improved normalisation technique that filters out anthropometric differences and considers the weight distribution between body segments within cross country skiing. This enabled direct comparison of movement between participants. The approach taken by Gløersen and colleagues (2018), was adopted for this study to allow for a technique analysis to determine the standard motion of the drag flick technique across a range of mixed ability participants. This study was conducted to determine principal movement strategies during the drag flick technique with a specific focus on task constraints. The purpose of this study was to investigate variance in movement strategies between different target areas and different overall task objectives using a different approach to analysis applied to the same data as collected and analysed in chapter 6 (see Chapter 5 for the methodological procedures).

In summary, all participants undertook 60 drag flicks in total, 20 in each of the three conditions. All participants completed the conditions in a randomised order within the same testing session:

- ball accuracy as the performance criterion (ACC) using a self-selected target area,
- ball velocity as the performance criterion (VEL) using a self-selected target area,
- ACC was also used as a performance criterion for a prescribed target area.

Participants self-selected one target area which was used for ball accuracy and ball velocity. Participants were randomly prescribed target areas that coaches identified as ideal target areas presented in chapter 3 (i.e., all four corners of the goal). The primary research objectives were:

- To determine the variability of individuals undertaking the drag flick and establish the effects of task constraints on the movement pattern and variability.
- To apply Principal Component Analysis (PCA) to kinematic data of the drag flick technique to establish a biomechanical analysis of the entire time-series of kinematic data.

The objectives of this chapter contributed to the primary research objectives of the thesis:

1. To analyse task constraints in whole-body movement patterns during the field hockey drag flick technique as quantified by a kinematic PCA.
2. To produce a visual representation of the core movement strategy of the drag flick to facilitate communication between scientists, athletes, and coaches.

7.2 Method

These objectives were addressed by a novel data normalisation approach based around analysing the kinematic data using Principal Component Analysis (PCA). The data were collated from all participants, allowing a direct comparison of the postural movement components between participants based on the work of (Gløersen et al., 2018). All calculations were computed using MatLab (Mathworks, Inc., USA) software. Data for each drag flick trial was normalised by subtracting its mean posture and dividing by the trials mean Euclidean distance (Federolf et al., 2013). Finally, the marker coordinates were weighted according to the relative body mass, which they represent (Federolf, 2016).

This normalisation was designed to remove anthropometric differences while conserving the differences in marker movement to ensure that each participant equally affects the

PCA output (Federolf et al., 2013). Following these procedures, a matrix was created for each participant: N [N = 1…12], which was then pooled into a 24,240 x 60 matrix. A PCA was conducted on this matrix resulting in one set of eigenvalues (EV) and one set of eigenvectors (PC), which are common to all participants across all conditions and all trials. From this analysis postural movements were quantitatively compared between participants. Following this the normalised data of each successful trial for each individual condition was projected onto the Principal Component (PC) basis vectors to create a principal postural position (PP) for each time point and establish how much this PP deviates from the mean posture according to the movement pattern defined by the associated PC vector (Daffertshofer et al., 2004, Federolf et al., 2013, Haid et al., 2018). Results of this analysis presented within this chapter were characterised qualitatively as movements of an animated stick figure. This thesis positioned itself as using the PCA analysis to identify the core movement strategy of the drag flick technique and to establish what effect different task constraints have on this core movement strategy. It did not set out to examine all individual participants and their unique style of drag flicking technique. Therefore, when stick figures have been used to present the qualitative movements that occur in each principal movement, participants have been selected which present the greatest range of movement and therefore ensure the best visual representation of the movement (Appendix Q).

Mean line density plots of the time evolution coefficients were generated which allowed a comparison between participants within each condition and between the three conditions. The purpose of this was to identify the core movement strategy of the drag flick and analyse what deviations there were from the core movement strategy for each participant. Therefore, the data of one participant for all their successful trials was analysed in comparison to the data of all participants (all target areas) for all hit and missed targets and all conditions. The purpose was to present the individual participant's data of successful trials and analyse the variability within each individual participant compared to the data of all participants across all trials. Mean line density plots of the time evolution coefficients were generated which allowed a comparison of participants across conditions using a colour coded system of red = SS ACC condition, yellow = SS VEL condition and green = P ACC condition. Differences between conditions, participants and target areas have been presented within the results of this chapter. These coefficient figures were evaluated for differences in amplitude and timing. The timing differences have been analysed using the time discrete points identified within the drag flick by published literature and the Delphi poll study within this thesis (ball pickup; foot to ball distance and wide stance width). However, technique differences identified in the time evolution coefficients are difficult to interpret for athletes and coaches. Therefore, the results in this chapter were used to create a visual impression of the technique differences for each participant. For an athlete or coach, they provide an objective means for assessing intra-individual technique for different targets and inter-individual comparisons that should reveal variations in participant adaptations within the technique execution. Due to the difficulty of interpreting the visual impression of the participants, particularly in the lower principal movements, an angle analysis was undertaken using two vectors to determine the joint angle of each of the joint centres. This enabled objective analysis of which joint angles were contributing to the principal movement.

7.2.1 Principal Positions – Waveform Analysis

To investigate quantitatively whether the time-normalised evolution coefficient waveforms were different between conditions a second PCA analysis was conducted. Other literature has compared waveforms by limiting the analysis to discrete time points such as differences in minima and maxima amplitude, and differences in timing (Gløersen et al., 2018). A second PCA enabled the entire waveform shape and amplitude to be compared between conditions. The time-normalised waveforms of all drag flick trials and all participants for each condition (159 successful hit target drag flicks in total across all participants) were collated into a (159 rows 101 time points) PCA input matrix. The second PCA produced a new set of eigenvectors where the eigenvalue represented the largest variation in shape and/or amplitude of the analysed drag flick trial waveforms. The projection of the principal position input matrix onto the first eigenvector produced a score for each successful drag flick trial and participant, indicting the extent to which the analysed waveform shows the pattern described by the first eigenvector. These waveform scores for each participant were then averaged across successful drag flick trials, producing one average score per participant and principal movement. This created the dependent variables for statistical analysis. This analysis was based on (Mohr et al., 2021), who completed this waveform analysis to determine sex-specific differences in hip movement during running.

7.2.2 Statistical Analysis

Descriptive statistics of participants' age, height, and weight were determined. The primary statistical analysis was to investigate whether waveform scores corresponding to the shapes of principal movements differed between conditions (SS ACC, SS VEL, and P ACC). A set of univariate analysis of variance (repeated measures ANOVA) was performed with the waveform scores for the specific principal movement as the dependent variable and the conditions as the independent variable.

7.3 PCA results

7.3.1 Participant characteristics

Age, height, and mass of all participants are presented in Table 29:

Table 29: Participant mean age, height, and mass. Source: Created by the author.

	Participants (n = 12)
Age (years, mean ± SD)	25.33 ± 4.72
Height (cm, mean ± SD)	175.27 ± 8.79
Mass (kg, mean ± SD)	77.29 ± 17.44

7.3.2 Differences between conditions

Assumptions of the repeated measures ANOVA were confirmed based on Mauchly's test of sphericity, which for principal movement 1 indicated that the assumption of sphericity had been met, $\chi^2(2) = 5.86$, $p = 0.53$. The results show that there was no significant effect between conditions for principal movement 1 (PM_1), $F(2, 22) = 0.76$, $p = 0.48$. PM_2 showed a significant effect between conditions ($F(2, 22) = 5.18$, $p = 0.014$) but no significant effect when looking at the individual means of conditions. All other principal movements showed no significant differences between each of the conditions: PM_3 [$F(2, 22) = 0.48$, $p = 0.63$]; PM_4 [$F(1.13, 12.47) = 0.591$, $p = 0.48$]; PM_5 [$F(1.23, 13.56) = 1.14$, $p = 0.32$]; PM_6 [$F(2, 22) = 2.82$, $p = 0.81$]; PM_7 [$F(1.51, 16.56) = 0.27$, $p = 0.70$]; PM_8 [$F(2, 22) = 2.27$, $p = 0.13$]; and PM_9 [$F(2, 22) = 0.69$, $p = 0.51$].

7.3.3 Description of Principal Movements

The first nine analysed movement components for each condition explained over 95% of the overall movement variance during the drag flick trials (SS ACC = 95.98%; SS VEL = 96.19%; and P ACC = 96.39%). Various studies of Principal Component Analysis have reported principal movements that have covered over 95% of the overall variance (Doná, et al., 2009 (95%); Federolf, et al., 2013 (95%); Federolf, et al., 2014 (95.5%); and Gløerson, et al., (2018). (96%). A video sequence, which can be found using the link in

Appendix Q, contains visualisations of these movement components and what aspects of variation were quantified by the principal movements (PM). The extreme positions of each principal movement along with qualitative descriptions are presented in this chapter. The first seven principal movements ($PM_{k)}$ characterised by their time evolution coefficients and by stick figures representing associated changes in movement are displayed in Figure 31 to 46. The full description of the dominating movement patterns in each PM for each condition and their cumulative, explained variance relative to the total movement is summarised in Table 30 after each of the principal movement findings have been presented. For each PM individual participants have been selected which best represent the movement occurring at each PM. For each individual, their mean time evolution coefficient figures have been presented for the relevant condition presenting intra variability, with the appropriate time discrete events for each participant. Alongside these stick figures of each individual participant have been presented to identify the postures associated with each PM at the peaks of the time evolution coefficient figures which are identified on the respective time evolution coefficient figures.

7.3.4 **PM1**

The principal movements identified for PM_1 were consistent for each of the three conditions. PM_1 (Figure 31) captured the reaching back with the stick and lowering of the thorax, the dragging motion of the stick the abduction/adduction of the left hip, and flexion/extension of the left wrist. For all three conditions, all target areas and all participants PM_1 captured the same movement, identifying the lowering of the thorax in order to drag the ball, and the left hip abduction/adduction and the left wrist flexion/extension being key movements within the drag flick technique.

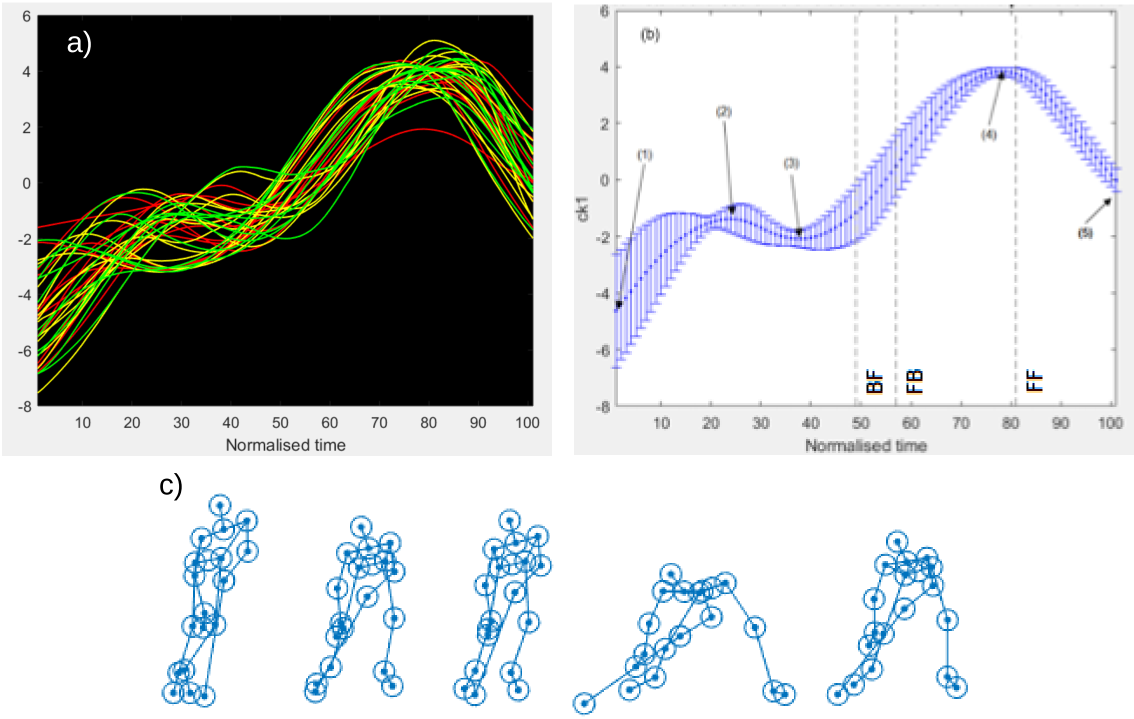


Figure 31: Mean time evolution coefficient of the postural movement PM_1 for all participants across all conditions and all target areas (a); mean and standard deviation of time evolution coefficient of the postural movement PM_1 for participant 2 for hit targets with mean time discrete events for participant 2 (b); and stick figures for participant 2 (c) representing the posture at the indicated time points (1,2,3,4,5). Time evolution coefficients: red line represents SS ACC condition (Self-selected target area and ball accuracy); yellow line represents SS VEL condition (Self-selected target area and ball velocity); green line represents P ACC condition (Prescribed target and ball accuracy). Vertical dashed lines indicate average back foot placement (BF); foot to ball distance at end of crossover step (FB); and front foot placement (FF). Source: Created by the author.

7.3.5 PM2

PM_2 for condition SS ACC was different to the other two conditions which were similar to each other (SS VEL & P ACC) (Figure 32 and 33). PM_2 captured the movement of the stick across the body, and the abduction and extension of the right hip, flexion of the right knee, and flexion of the left hip and left knee. There is a large range of flexion and extension of the left wrist and the left and right elbows. The movement that occurs for PM_2 is similar for all conditions, however, the order and timing of the movement differs between conditions SS ACC and SS VEL/P ACC. In condition SS ACC the stick moves forward and the right leg backwards first, the stick then moves backwards and returns to a forward position whilst the participant finishes in a forward lunging position. Conditions SS VEL and P ACC start with the stick moving backwards initially, then forwards with the participant in the lunging position and then returning to a crossover step position and stick backwards. The main joints contributing to PM_2 are right hip (adduction and extension), right knee (flexion), left hip and knee (flexion), left wrist (flexion/extension) left and right elbows (flexion/extension). PM_2 is the same movement for all conditions but the timing differs for SS VEL and P ACC.

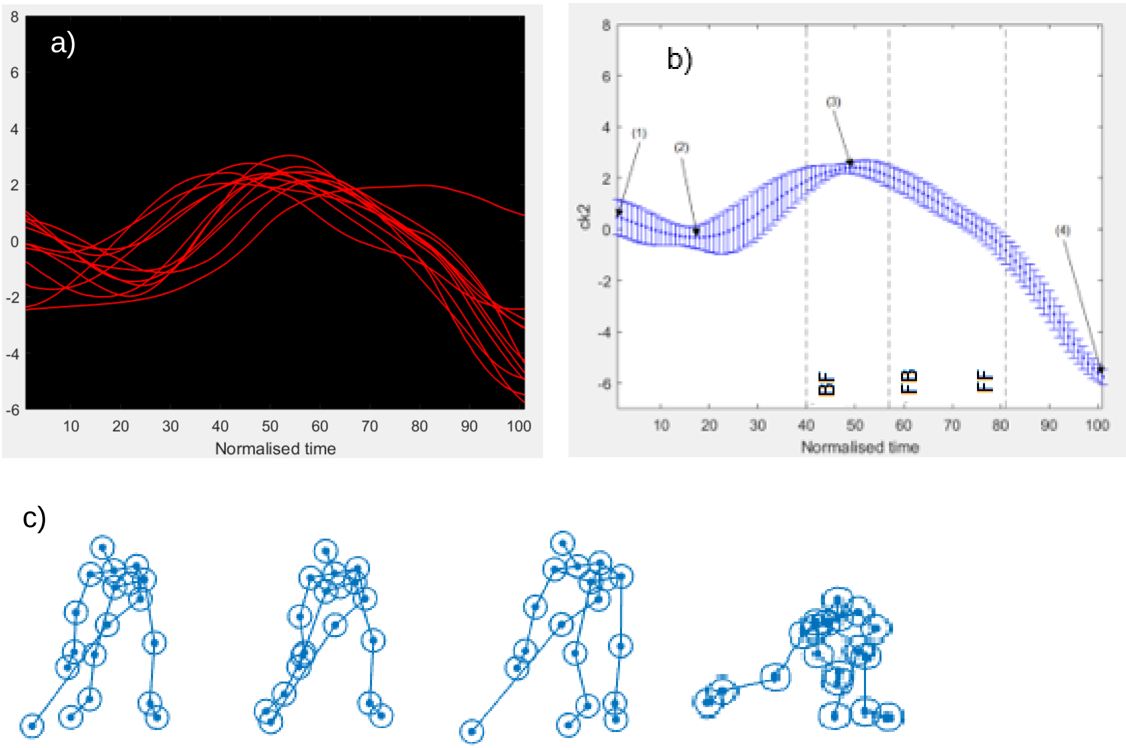


Figure 32: Mean time evolution coefficient of the postural movement PM_2 for all participants across SS ACC condition (self-selected target area; ball accuracy) across all target areas (a); Mean and standard deviation of standardised evolution coefficient of the postural movement for participant 2 for hit targets with mean time discrete events for participant 2 (condition SS ACC target area bottom left) (b) and stick figures (c) representing the posture at the indicated time points (1,2,3,4). Vertical dashed lines indicate average back foot placement (BF); foot to ball distance at end of crossover step (FB); and front foot placement (FF). Source: Created by the author.

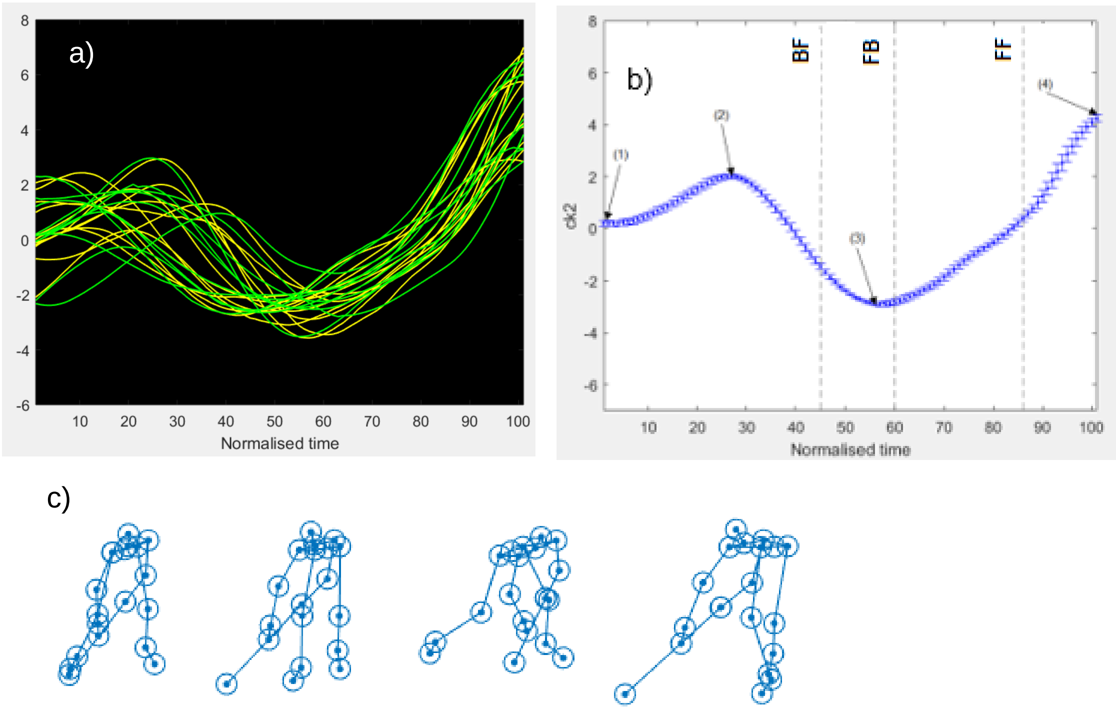


Figure 33: Mean time evolution coefficient of the postural movement PM_2 for all participants; across SS VEL and P ACC conditions across all target areas (a); mean and standard deviation of standardised evolution coefficient for participant 1 for hit targets with mean time discrete events for participant 1 (condition SS VEL; ball velocity (b); and stick figures (c) representing the posture at the indicated time points (1,2,3,4). Time evolution coefficients: yellow line represents SS VEL condition (Self-selected target area and ball velocity); green line represents P ACC condition (Prescribed target area and ball accuracy). Vertical dashed lines indicate average back foot placement (BF); foot to ball distance at end of crossover step (FB); and front foot placement (FF). Source: Created by the author.

7.3.6 PM_3

PM_3 differed between conditions but remained unchanged for each target area within each condition (

Figure 34, 35 and 36). For example, condition SS ACC remained the same movement for all target areas within this condition. Within condition SS ACC a similar movement as PM_2 occurs but with a smaller range of motion at each joint centre. There is again movement of the stick across the body, with ab-/adduction of the right hip, flexion of the right knee and flexion of the left hip and left knee. However, the largest range of movement is flexion and extension for the left and right wrists this is the first time there is significant contribution from the right wrist. Condition P ACC follows the same movement as condition SS VEL but as with PM_2 the timing of this movement is different, with the timing of the leg's abduction/adduction changing between the two conditions. In SS VEL the legs finished in an abducted position at the end of the movement which contrasts with condition P ACC where the legs finished in an adducted position at the end of the movement.

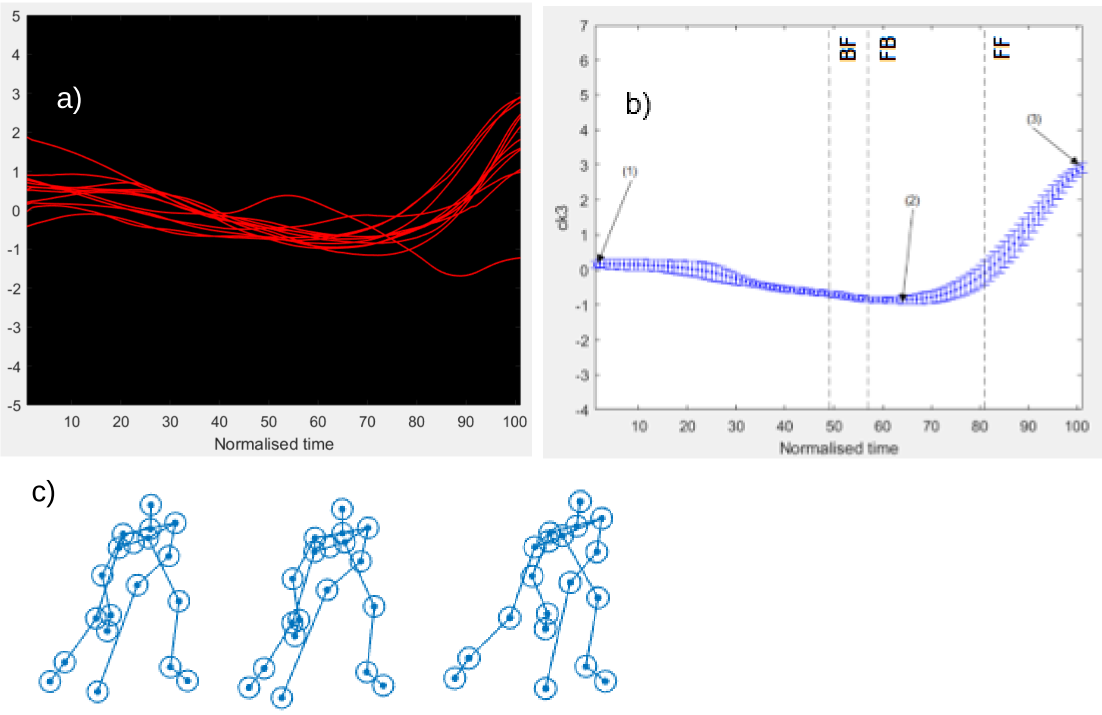


Figure 34: Mean time evolution coefficient of the postural movement PM_3 for all participants across SS ACC condition (self-selected target area; ball accuracy) across all target areas (a); mean and standard deviation of standardised evolution coefficient of participant 2 for

hit targets and with mean time discrete events for participant 2 (target area bottom left) (b); and stick figures (c) representing the posture at the indicated time points (1,2,3). Vertical dashed lines indicate average back foot placement (BF); foot to ball distance at end of crossover step (FB); and front foot placement (FF). Source: Created by the author.

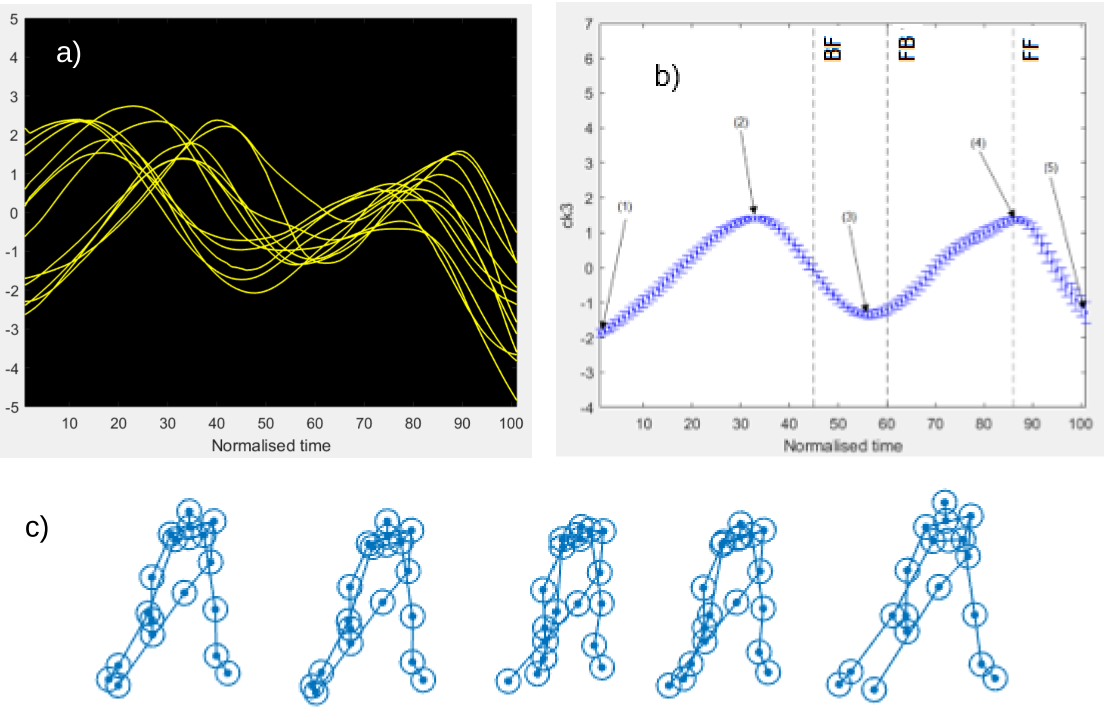


Figure 35: Mean time evolution coefficient of the postural movement PM_3 for all participants across SS VEL condition (self-selected target area; ball velocity) across all target areas (a); mean and standard deviation of standardised evolution coefficient for participant 1 for hit targets with mean time discrete events for participant 1 (target area bottom left) (b); and stick figures (c) representing the posture at the indicated time points (1,2,3,4,5). Vertical dashed lines indicate average back foot placement (BF); foot to ball distance at end of crossover step (FB); and front foot placement (FF). Source: Created by the author.

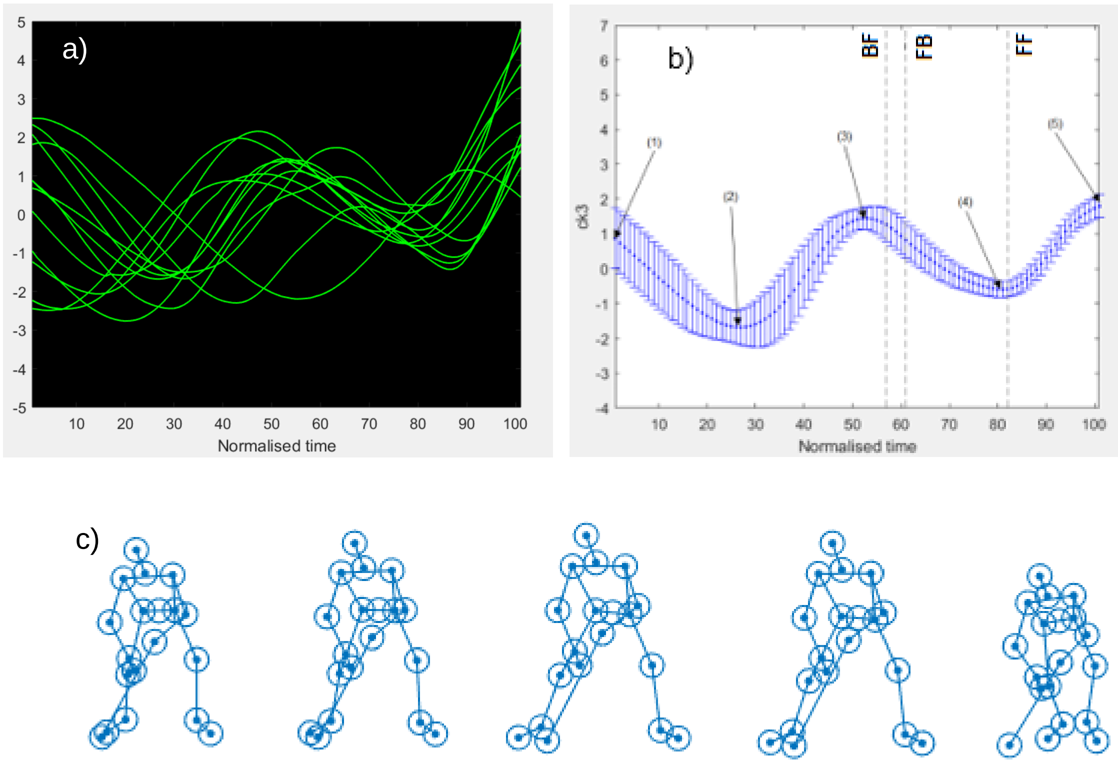


Figure 36: Mean time evolution coefficient of the postural movement PM_3 for all participants across P ACC condition (prescribed target area; ball accuracy) across all target areas (a); mean and standard deviation of standardised evolution coefficient of participant 9 for hit targets with mean time discrete events for participant 9 (P ACC condition; target area Bottom left) (b); and stick figures (c) representing the posture at the indicated time points (1,2,3,4,5). Vertical dashed lines indicate average back foot placement (BF); foot to ball distance at end of crossover step (FB); and front foot placement (FF). Source: Created by the author.

7.3.7 PM_4

It is not until PM_4 that there are changes across conditions and across target areas. SS ACC condition, as with previous principal movements, follows the same movement regardless of the target area (

Figure 37). There are some timing and amplitude differences within individual participants, but all participants follow the same movement across all target areas. This movement is in fact the same movement that is presented for PM_3 for conditions SS VEL and P ACC.

Flexion/extension occurs at the shoulders, elbows, and wrist of both the left and right sides. This movement replicates the leaning forward of the trunk. There is a small amount of flexion/extension at the left and right knees and flexion/extension and abduction/adduction of the left and right hips. As with condition P ACC the legs finish in an adducted position for PM_4 in condition SS ACC.

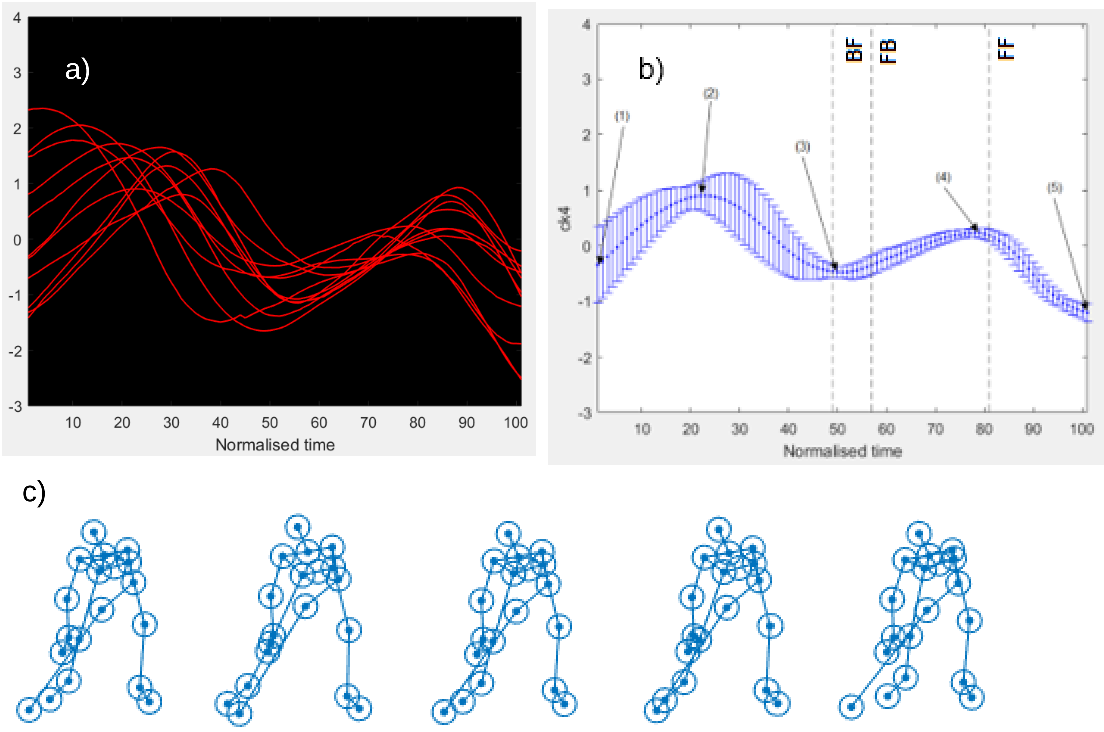


Figure 37: Mean time evolution coefficient of the postural movement PM_4 for all participants across SS ACC condition (self-selected target area; ball accuracy) across all target areas (a); mean and standard deviation of standardised evolution coefficient of participant 2 for hit targets with mean time discrete events for participant 2 (target area bottom left) (b); and stick figures (c) representing the posture at the indicated time points (1,2,3,4,5). Vertical dashed lines indicate average back foot placement (BF); foot to ball distance at end of crossover step (FB); and front foot placement (FF). Source: Created by the author.

Again, condition SS VEL follows the same pattern regardless of the target area, although the amplitude and timing differences are more differentiated within the evolution coefficients (

Figure 38). PM_4, condition SS VEL captured a twisting movement of the thorax and pelvis. Ab-/adduction occurred at the left hip, and flex-/extension of the right hip. In addition, both dorsiflex-/plantarflexion of the left and right ankles. There was again, large movement in both the left and right wrists.

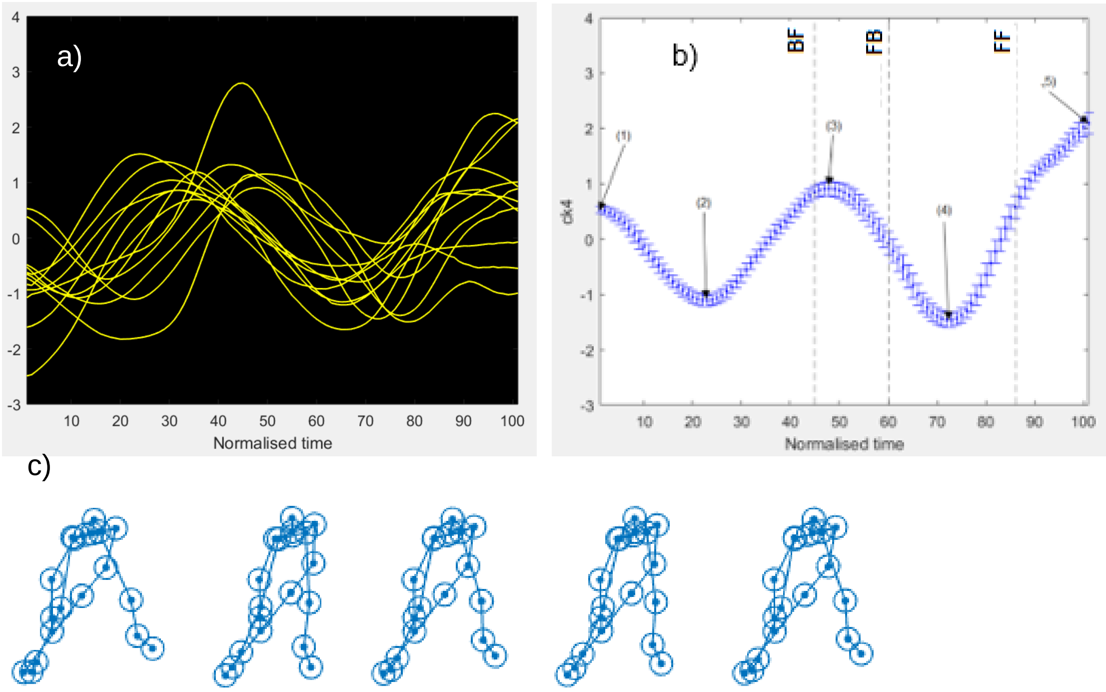
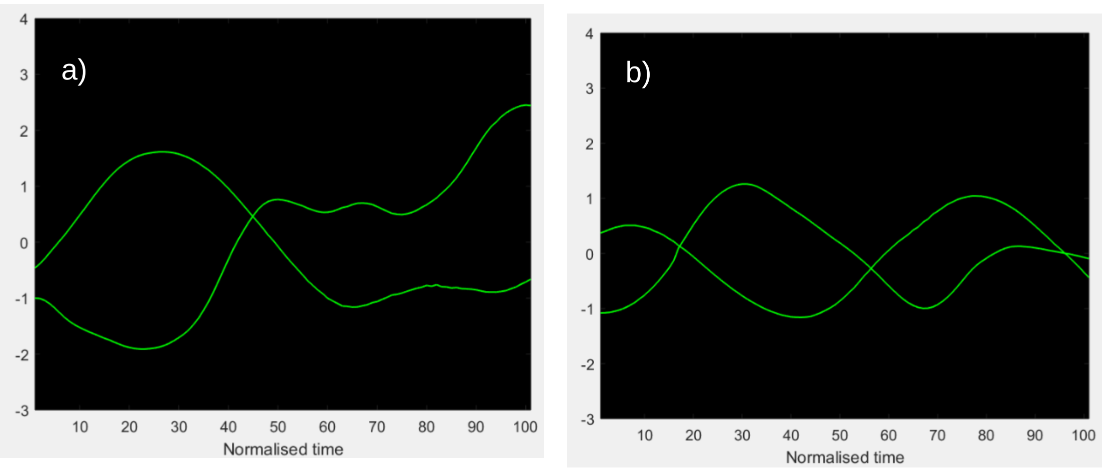


Figure 38: Time evolution coefficient of the postural movement PM_4 for all participants across SS VEL condition across all target areas (a); mean and standard deviation of standardised evolution coefficient of participant 1 for hit targets with mean time discrete events for participant 1 (target area bottom left) (b); and stick figures (c) representing the posture at the indicated time points (1,2,3) . Time evolution coefficients: yellow line represents SS VEL condition (Self-selected target area and ball velocity). Vertical dashed lines indicate average back foot placement (BF); foot to ball distance at end of crossover step (FB); and front foot placement (FF). Source: Created by the author.

PM_4 for condition P ACC seems to again follow the same pattern across the condition for target areas bottom right and bottom left but with significant timing differences. However, top right and top left are more individual to the participant (

Figure 39). The principal movement for PM_4 within condition P ACC presents the splitting of the legs, the left hip abducting and adducting whilst the right hip and knee flexes and extends, and a leaning forward of the trunk. The angle analysis presents movement at the hips and shoulders and again, a large movement of the left wrist. Individual participant evolution coefficients and stick figures to represent the movement taking place in PM_4 for condition P ACC have been presented in

Figure 39, 40 and 41 to identify the differences across the target areas.



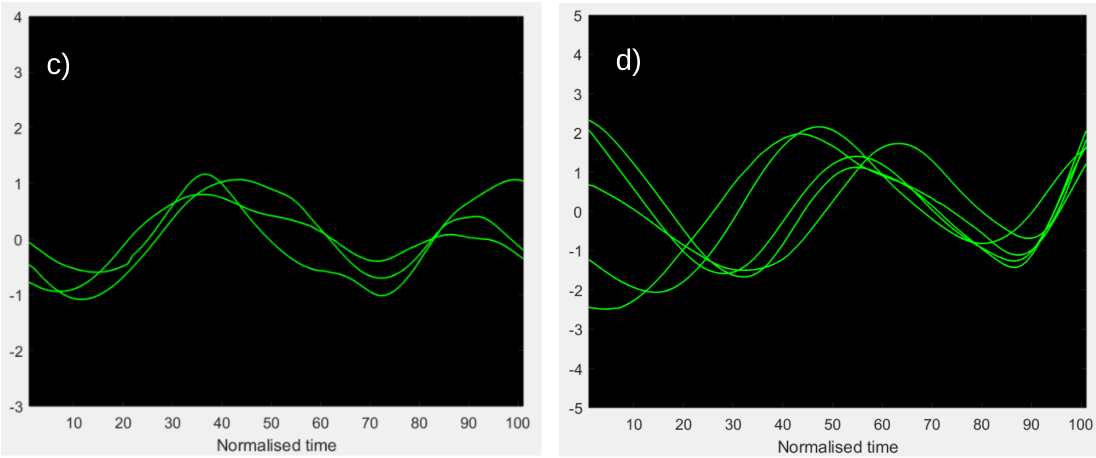
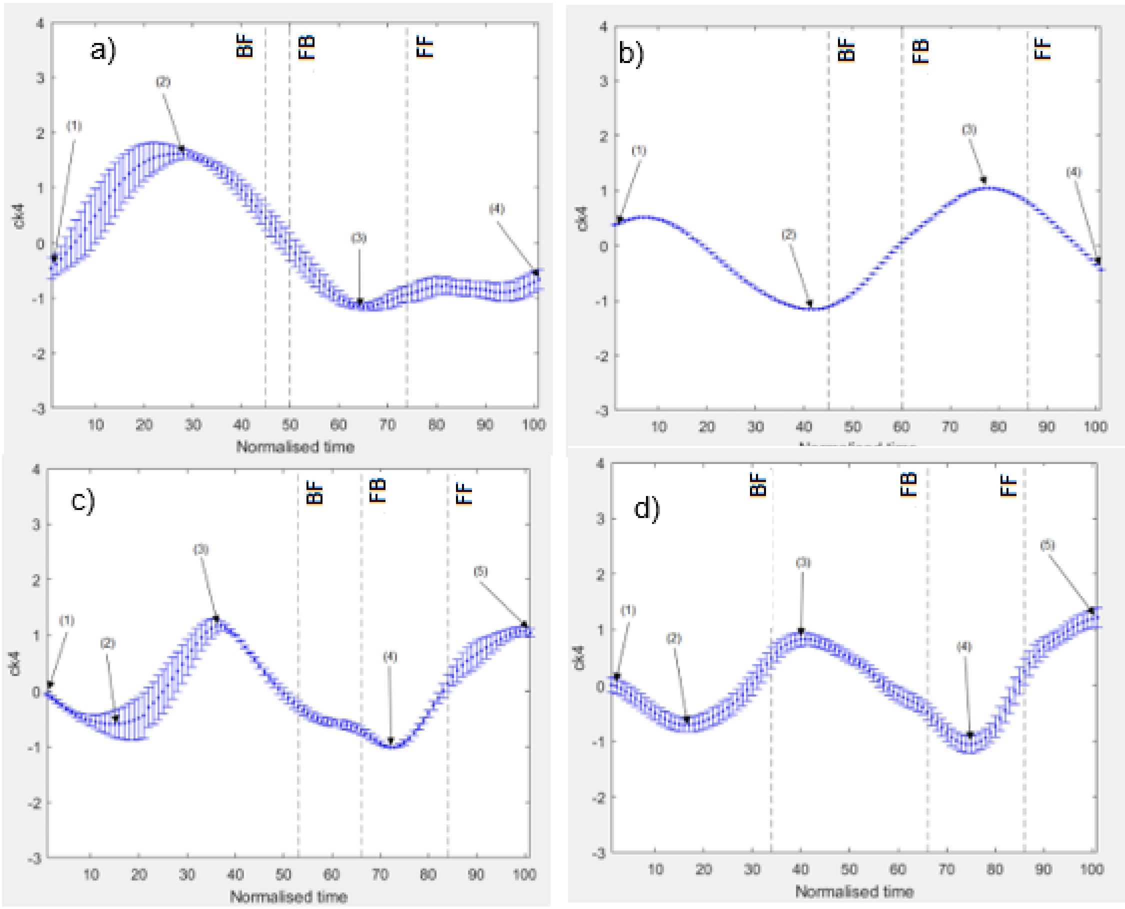
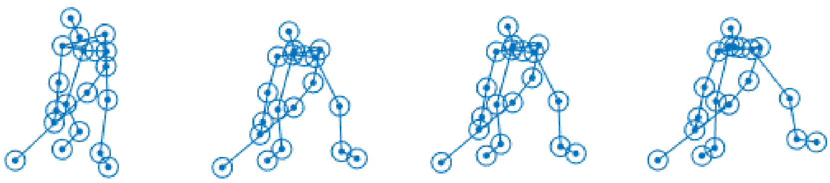


Figure 39: Mean evolution coefficient of the postural movement PM_4 for all participants across P ACC condition (Prescribed target area and ball accuracy) across target area top left (a); target area top right (b); target area bottom left (c); and target area bottom right (d). Source: Created by the author.



a)



b)

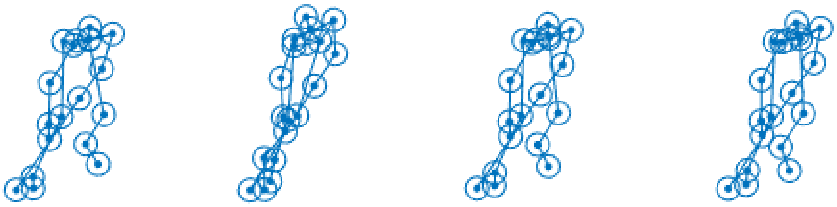
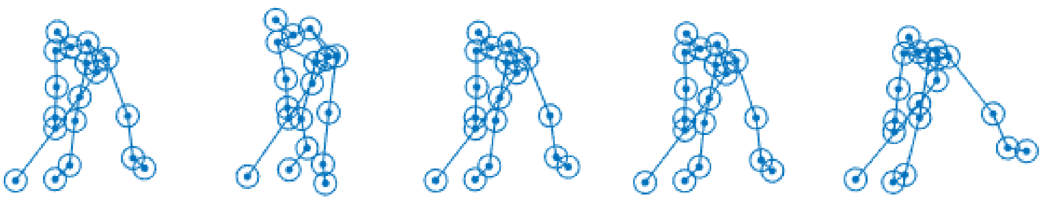


Fig ... ith standard de ... rticipant time dis ... right) (b); P3 (target area bottom left) (c) and, P7 (target area bottom right) (d) for condition P ACC (prescribed target area – ball accuracy). Vertical dashed lines indicate average back foot placement (BF); foot to ball distance at end of crossover step (FB); and front foot placement (FF). Source: Created by the author.

c)



d)

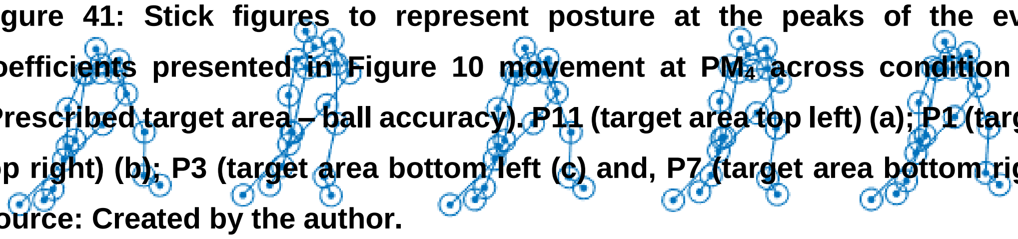


Figure 41: Stick figures to represent posture at the peaks of the evolution coefficients presented in Figure 10 movement at PM_4 across condition P ACC (Prescribed target area – ball accuracy). P11 (target area top left) (a); P1 (target area top right) (b); P3 (target area bottom left (c) and, P7 (target area bottom right) (d). Source: Created by the author.

The two participants used to represent bottom left (P3) and bottom right targets (P7), both start with the left hip adducted and finish with the left hip adducted. However, the top left starts with the left hip in an adducted position and finishes abducted. Top right starts with the left hip abducted but finishes with it adducted.

7.3.8 PM_5

As with other principal movements, for PM_5, participants within condition SS ACC follow the same pattern of movement regardless of the target area (

Figure 42). Again, the movement is representing the leaning forward of the thorax which creates a lowering of the stick, the thorax is lowered towards the ground, abduction/adduction and flexion/extension is taking place for the left leg. As can be seen in

Figure 42 by the stick figures used to present the posture there is minimal variation from the mean posture.

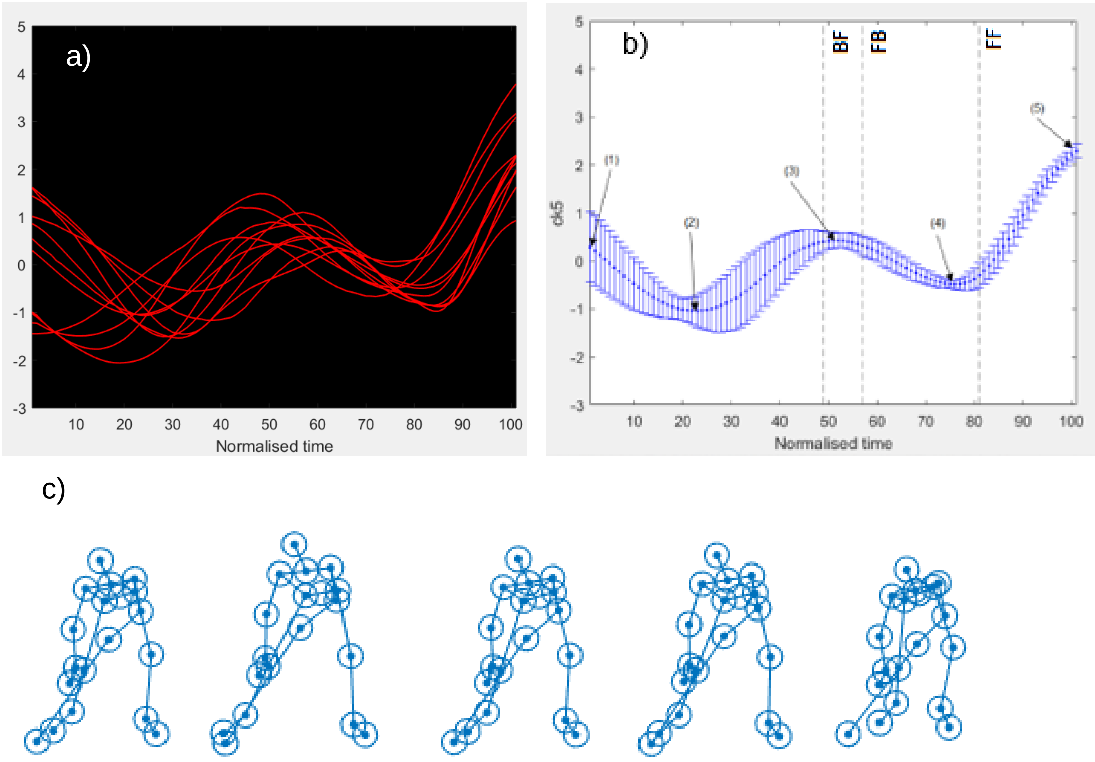
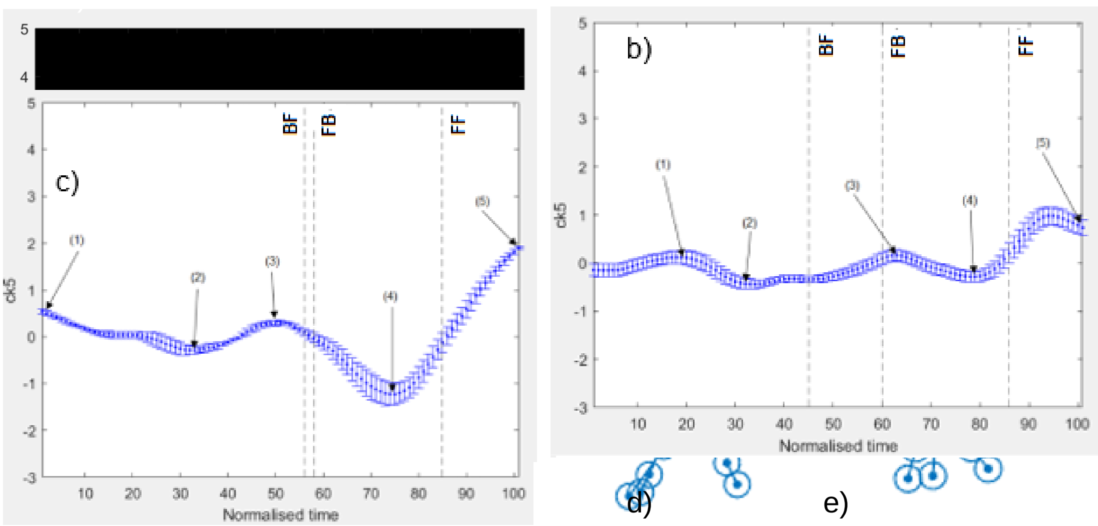
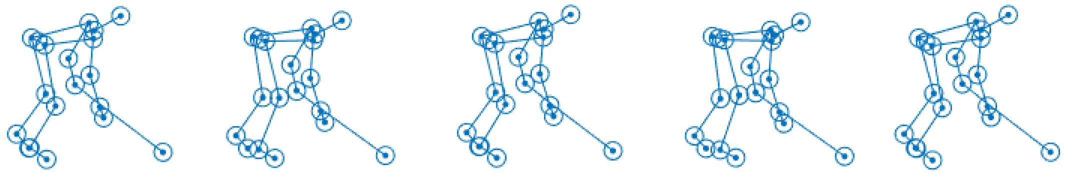


Figure 42: Mean time evolution coefficient of the postural movement PM_5 for all participants across SS ACC condition (self-selected target area; ball accuracy) across all target areas (a); mean and standard deviation standardised evolution coefficient of participant 2 for hit targets with time discrete events for participant 2 (target area bottom left) (b); and stick figures (c) representing the posture at the indicated time points (1,2,3,4). Vertical dashed lines indicate average back foot placement (BF); foot to ball distance at end of crossover step (FB); and front foot placement (FF). Source: Created by the author.



f)



g)

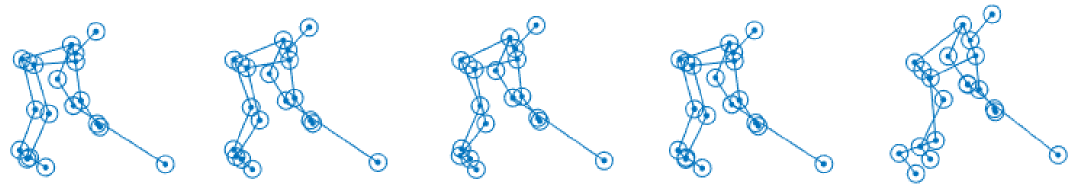


Figure 43: Mean time evolution coefficient of the postural movement PM_5 for all participants across SS VEL condition (self-selected target area; ball velocity) across all target areas (a); mean and standard deviation standardised evolution coefficient of participant 1 (target area bottom left) (b); mean and standard deviation standardised evolution coefficient of participant 10 (target area bottom left) (c); and stick figure for participant 1 front view (d); and participant 10 (e) representing the posture at indicated time point (4); and stick figures for participant 1 side view (f); and participant 10 (g) representing the posture at the indicated time points (1,2,3,4,5). Vertical dashed lines indicate average back foot placement (BF); foot to ball distance at end of crossover step (FB); and front foot placement (FF). Source: Created by the author.

Figure 43 presents the evolution coefficients of PM_5 for condition SS VEL for target area bottom left as this was the largest group for any given target area within this condition. There is no consistent pattern within the evolution coefficients across individual participants and this continues for all target areas within this condition. There appears to be some common features within this principal movement across participants as well as some individual variation. The common features presented in the video sequences and stick figures capture the flexion/extension of the right knee which creates a dipping of the right-hand side of the body and the lowering of the stick. Stick figures are presented in Figure 43 as examples of the individual variation across participants. Participant 1 illustrates the common features across all participants with the right knee flexing and extending and the lowering of the thorax towards the ground (d). Participant 10 also presents this movement (e) however, there is an additional twisting motion of the upper body for this participant which is easily identified with the front view of these participants (d and e).

Following checking of the data and the variation of individual participants there were no patterns within either the condition or target areas for the remaining PM_k's for SS VEL. As the focus of this thesis is to identify the core movement strategy of the drag flick technique condition SS VEL will not be presented within the rest of this chapter. In summary for condition SS VEL the core movements are represented in the first five PM's, it is not until PM_6 onwards that individual variation Is more evident within this condition.

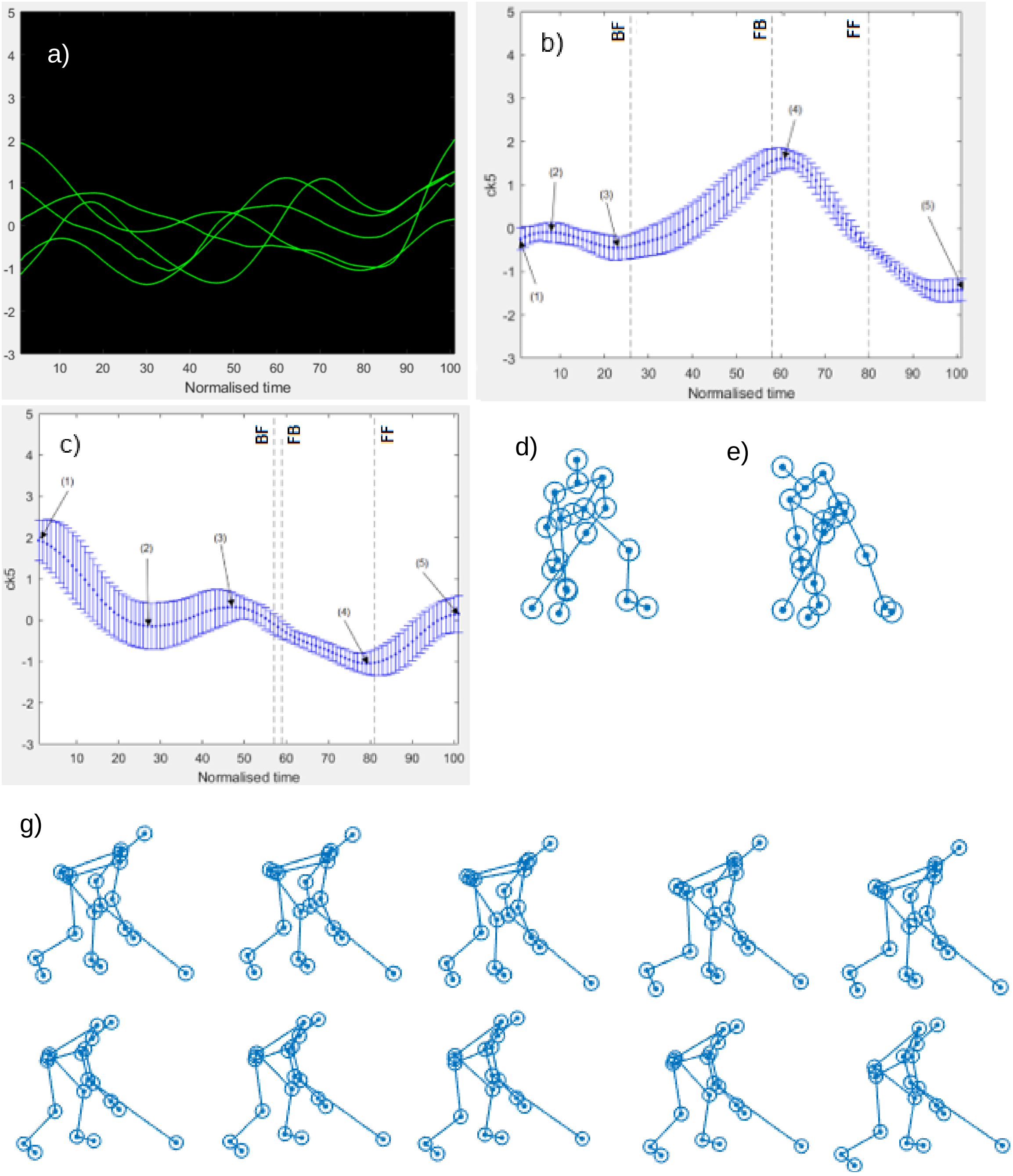


Figure 44: Mean time evolution coefficient of the postural movement PM_5 for all participants across P ACC condition (Prescribed target area and ball accuracy) across target area bottom right (a); mean time evolution coefficient and standard deviation bars of the postural movement for participant 6 (bottom right) (b); mean time evolution coefficient and standard deviation bars of the postural movement for participant 4 (bottom right) (c); stick figures of participant 6 front view (d); participant 4 front view (e) at the time the right knee is most flexed at the end of the movement (time point 5); and stick figures of participant 6 side view (f); stick figures of participant 4 side view (g) representing the posture at the indicated time points (1,2,3,4,5). Vertical dashed lines indicate average back foot placement (BF); foot to ball distance at end of crossover step (FB); and front foot placement (FF). Source: Created by the author.

Figure 44 presents the evolution coefficients of PM_5 for condition P ACC for target area bottom right as this was the largest group for any given target area within this condition. There is no consistent pattern within the evolution coefficients across individual participants and this continues for all target areas within this condition. Similar to PM_5 for condition SS VEL there appears to be some common features within this principal movement across participants and target areas as well as some individual variation. The common features presented in the video sequences and stick figures capture the same movement as PM_5 condition SS VEL which was flexion/extension of the right knee which creates a dipping of the right-hand side of the body and the lowering of the stick. Stick figures are presented in Figure 44 as examples of the individual variation across participants. Participant 6 consists of the common features across all participants with the right knee flexing and extending and the lowering of the thorax towards the ground (Figure 44 (d). Participant 4 also presents this movement (e) however, there is an additional twisting motion of the upper body for this participant the individual is facing a different direction to participant 6 which is easily identified with the front view of these participants (d and e).

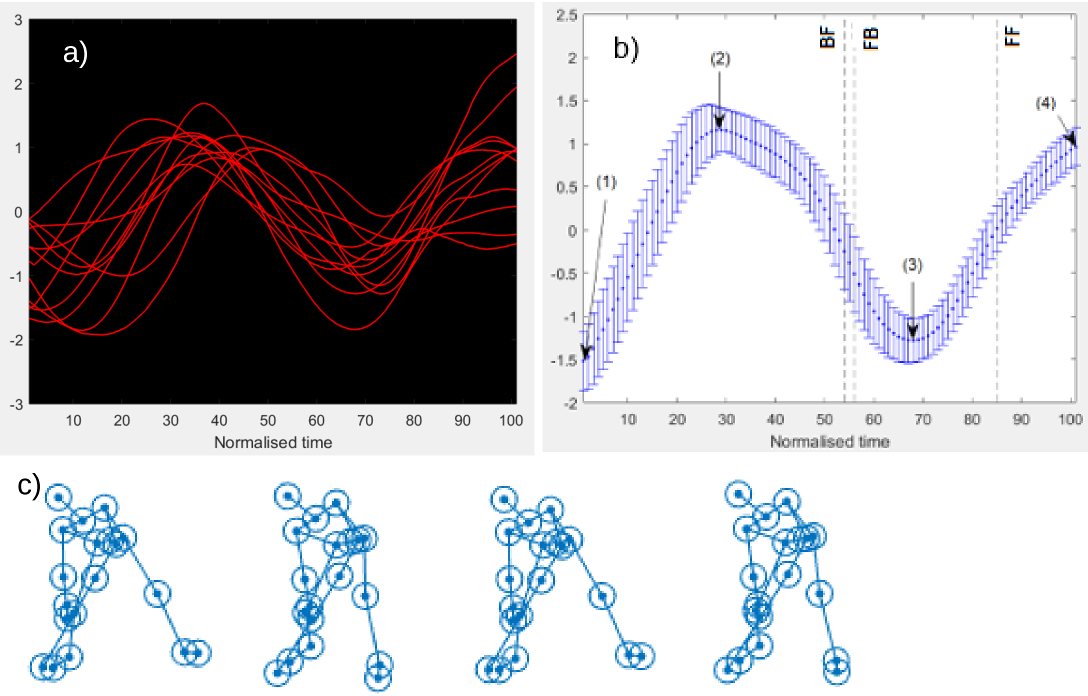


Figure 45: Mean time evolution coefficient of the postural movement PM_6 for all participants across SS ACC condition (Self-selected target area and ball accuracy) across all target areas (a) mean time evolution coefficient and standard deviation error bars of the postural movement for participant 4 and time discrete events for participant 4 (bottom right) (b); and stick figures (c) representing the posture at the indicated time points (1,2,3,4). Vertical dashed lines indicate average back foot placement (BF); foot to ball distance at end of crossover step (FB); and front foot placement (FF). Source: Created by the author.

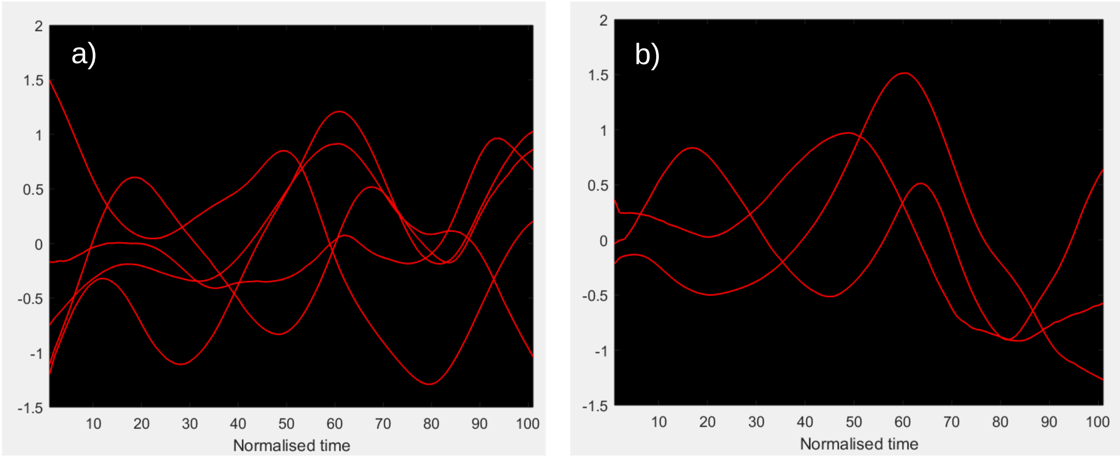


Figure 46: Time evolution coefficient of the postural movement PM_7 for all participants across SS ACC condition (self-selected target area and ball accuracy) target area bottom left (a) and target area bottom right (b). Source: Created by the author.

7.3.9 PM_6

Participants within the SS ACC condition still follow a similar pattern within the evolution coefficients of PM_6 across all target areas (Figure 45), although, there is more variability within the amplitude and timing of peaks compared to other previously presented PMk's within this condition. Within this principal movement the left hip abducts and extends followed by the left hip adducting and flexing. There is also flexion/extension of both the right knee and ankle.

7.3.10 PM_7

It is not until PM_7 in condition SS ACC where more individual differences are apparent within the data (Figure 46). There is no consistent pattern within the evolution coefficients between target areas or participants. Also, upon checking of the data individual participants present individual variability from the mean posture and there are no consistent movements across the participants regardless of the target area. It would seem that there is more PM's which account for the core movement strategy within condition SS ACC compared with other two conditions. It is not until PM_7 that there is individual variation and no patterns across target area or condition.

Table 30: Description of principal movements (PMs) for each condition and the cumulative, explained variance (%) relative to the total movement variance (var.). (Where there are blank principal movement descriptions individual participant variations were found within the data that precluded a summary description). Source: Created by the author.

SS ACC	SS VEL	P ACC	SS ACC	SS VEL	P ACC
	PM_k [Var.]			Principal movement description	
[34.55%]	PM_1 [46.55%]	[46.61%]	Reaching back with the Stick. Lowering of the thorax. Dragging motion of the stick. Abduction/adduction of the left hip, and flexion/extension of the left wrist		
[52.82%]	PM_2 [70.5%]	[70.97%]	Movement of stick across the body Abduction and extension of the right hip, flexion of the right knee, and flexion of the left hip and left knee. Substantial contributions from left and right elbows and left wrist.		
[70.27%]	PM_3 [81.8%]	[81.87%]	Movement of stick across the body, abduction and adduction of the right hip, flexion of the right knee and flexion of the left hip and left knee. Substantial contribution of both left and right wrists	Leaning forward with the thorax especially on the right side Flexion/extension at the shoulders, elbows, and wrists of both the left and right sides. Small amount of flexion/extension at the left and right knees and flexion/extension and abduction/adduction of the left and right hips.	
[79.45%]	PM_4 [87.61%]	[87.35%]	Leaning forward with the trunk especially on the right side Flexion/extension at the shoulders, elbows, and wrists of both the left and right sides. Small amount of flexion/extension at the left and right knees and flex-/extension and ab-/adduction of the left and right hips.	The left hip ab-/adducting whilst the right hip and knee flexes and extends, a leaning forward of the trunk, and flex-/extension of the left and right shoulders. There was again, large movement in the left wrist.	Splitting of the legs, the left hip ab-/adducting whilst the right hip flexes and extends, a twisting movement of the thorax and pelvis. The angle analysis presents movement at the right ankle, left and right hips, and again, a large movement of the left wrist.
[87.32%]	PM_5 [90.83%]	[91.17%]	Leaning forward of the trunk lowering the thorax towards the ground, ab-/adduction and flex-/extension is taking place for the left leg.	Flexion/extension of the right knee which creates a dipping of the right-hand side of the body and the lowering of the stick.	

[91.42%]	PM_6 [92.9%]	[93.14%]	Left hip abducts and extends followed by the left hip adducting and flexing. There is also flex-extension of both the right knee and right ankle.
[93.52]	PM_7 [94.37]	[94.69]	
[94.86%]	PM_8 [95.41%]	[95.65%]	
[95.98%]	PM_9 [96.19%]	[96.39%]	

Table 30 presents the distinctive characteristic movements of each PM_k for all three conditions. This table is presented to give the reader an overview of each principal movement across each condition so the reader can easily identify how each PM_k is consistent or differs for each condition and how much each PM_k accounts for the variability within the data.

7.4 Discussion

This aim of this chapter was to analyse the whole-body movement patterns during the field hockey drag flick as quantified by a kinematic PCA, and to identify what is the core movement strategy of the drag flick technique and what effect different task constraints have on the core strategy (overall performance objectives of accuracy and maximum velocity and different target areas). A secondary aim was to visualise any differences using animated stick figures, offering a visualisation of how different groups of participants (a group being the successful trials of individual participants within each individual condition) might alter their technique based on results from the technique analysis of the whole sample across multiple conditions (the whole sample considered all participants for both hit and missed trials across all three conditions and targets).

The analysis produced principal movements and positions of whole-body posture changes associated with each condition as set out in the methods. The holistic approach of the kinematic principal movements and waveform analysis is more likely to detect condition and target differences compared to a more traditional biomechanical analysis such as that presented in Chapter 6. This is because it takes into account all measured joint angles and the coordination between joint angles as a function of time instead of focussing on discrete variables.

7.4.1 PM_1

The first two principal movements explained the main features of the drag flick technique according to study 1, (crossover-step, the wide stance width, lowering of the body, and dragging motion) and there was no difference between conditions for these consistent features. PM_1 presented no difference between any condition or target area which was supported by the waveform analysis. It captured the reaching back with the stick during the side stance width, the dragging motion of the ball towards ball release, ab-/adduction of the left hip at its peak during the stance width phase, and flex-/extension of the left wrist. These motions are consistent with the existing published literature on drag flicking which examines which variables contribute to the performance of the drag flick (De Subijana et al., 2010, Ibrahim et al., 2017). However, the mention of wrist movement is limited within the current body of literature, but it is clearly evident in the PM_k analysis presented here and regularly features within the principal movements identified which supports its importance within the drag flick technique.

7.4.2 PM_2

The results for PM_2 showed distinct and significant differences between the three conditions with respect to the shape and/or amplitude of the principal positions and waveform analysis, which captured the movement of the stick across the body towards ball release, and a combination of abduction and extension of the right hip during the crossover-step and ball pick up, flexion of the right knee, and flexion of the left hip and left knee at ball release. There was also a large range of flexion and extension of both the left and right wrists throughout the whole drag flick. Condition SS ACC differed from conditions SS VEL and P ACC, in terms of the timing of the movement. The peaks of the amplitude for all conditions are occurring at the end of the crossover step; in condition SS ACC the peak occurs with the right hip adducted, and the left hip extended, which then at ball release moves to a lunging position with the right hip extended and abducted and the left hip flexed and adducted. However, in conditions SS VEL and P ACC the right hip is abducted and extended, and the left hip flexed and adducted at the end of the crossover step and at ball release the legs are crossed. There is no literature which looks at the difference between ball accuracy and ball velocity to determine if this is replicated within the published literature, although Gómez et al. (2012) does analyse the differences between drag flicks aimed at the left side of the goal compared to the right side of the goal. Gómez et al. (2012) concluded that the stick position in relation to the ball determines the direction of the flick. Although the results from this thesis are not directly comparable with these outcomes, it is interesting to note that both pieces of research agree that the early phases of the drag flick are key to the overall outcome of the flick.

7.4.3 PM_3

PM_3 captured different positions for each condition but no change across target areas. In condition SS ACC there is again movement of the stick across the body, with ab-/adduction of the right hip, flexion of the right knee and flexion of the left hip and left knee. These movements and findings support much of the drag flick literature in terms of the abduction of the right hip and flexion of the left hip, right and left knees being integral to creating a wide stance width in order to drag the ball (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010, Gómez et al., 2012). Again, the largest range of movement is flexion and extension for the left and right wrists, which as previously stated is rarely mentioned within the literature. In SS VEL and P ACC, leaning forward with the trunk was captured, especially on the right-hand side. Flex-/extension at the shoulder, elbows and wrists occurred on both sides, and a small amount of flex-/extension and ab-/adduction of the hips on both sides. However, the timing in these two conditions differed. In condition SS VEL the legs finished in an adducted position but, in contrast, were abducted in condition P ACC. This PM supports the findings of Yusoff et al. (2008) which identified a low style drag flick in contrast to an upright style. The finding of different timings between conditions is novel and possibly links to the different kinematic sequencing and push like kinematic pattern that was presented in Chapter 6.

7.4.4 PM_4

In PM_4 condition SS ACC captures a similar movement which occurred in PM_3 for conditions SS VEL and P ACC, however, individual differences within the timing and amplitude were visible. In the SS VEL condition greater individual variability was presented in the timing and amplitude of the evolution coefficients which captured the leaning forward of the trunk and a twisting movement of the thorax and pelvis. Ab-/adduction occurred at the left hip and flex-/extension of the right hip. There was also relatively large movement in the left wrist. PM_4 for condition P ACC is where changes were visible between different target areas. Target areas bottom left, and bottom right produced the same shape of time evolution coefficient but with significant timing differences. However, patterns of coefficients for top right and top left were more individual to the participant. It is not until this Principal Movement that differences within movement pattern occurs in relation to the target area participants aimed at. This principal movement captured the splitting of the legs and the leaning forward with the trunk. There was also twisting of the thorax and pelvis evident. The rotation of the thorax and pelvis is a consistent finding in the kinematics of the drag flick (Ibrahim et al., 2017, De Subijana et al., 2010, McLaughlin, 1997), with studies presenting a proximal to distal pattern of movement, likening it to a throwing action.

7.4.5 PM_5

In PM_5, condition SS ACC, again, the participants presented the same movement regardless of the target area each participant was aiming at. The movement captured was the leaning forward and the lowering of the thorax to the ground, together with ab-/adduction and flex-/extension of the left hip and knee. This only accounted for 7.9% of the variance and therefore the movement presented is a relatively small contribution. PM_5 for condition SS VEL presented no within group patterns and the shape, timing and amplitude differed across the individual participants regardless of target area each participant aimed at. In addition to the variability between participants there was a large range of variability within participants. However, some common features of variability from the mean posture were presented which involved the flex-/extension of the right knee which creates a lowering of the body on the right side and a lowering of the stick to a more parallel position with the ground. For PM_5 within condition P ACC, again there is no pattern within target areas, as participants varied in the shape, timing, and amplitude. However, again similar to condition SS VEL, this condition and principal movement appear to have some features of variability in common with the mean posture. The common features presented in the video sequences and stick figures capture the same movement as PM_5 condition SS VEL, which was flex-/extension of the right knee which creates a dipping of the right-hand side of the body and the lowering of the stick. As with condition SS VEL there was again intra variability across participants.

7.4.6 PM_6 and PM_7

Participants within the SS ACC condition follow a similar pattern within the evolution coefficients of PM_6 across all target areas, although, there is more variability within the amplitude and timing of peaks compared to other previously presented principal movements within this condition. The left hip abducts and extends during the crossover-step and again at ball release. The left hip adducts and flexes just after ball pickup midway through the wide stance width. There is also flex-/extension of both the right knee and ankle. It is not until PM_7 in condition SS ACC where more individual differences are apparent within the data, and as a result there is no consistent pattern within or between target areas or participants.

Following analysis of each principal movement, PM_1 and PM_2 form the core strategy of the drag flick technique as these PMs do not differ across conditions or target areas. The cross-over step, wide stance width, lowering of the body, dragging motion of the ball, movement of the stick across the body, abduction and extension of the right hip during the cross-over step and ball-pick up, flexion of the right knee, flexion of the left hip and knee at ball release and flex-/extension of the left and right wrists throughout the drag flick are all the foci of the drag flick that coaches and players should consider as elements of the core strategy of this technique based on the methodology adopted within this chapter. The target area, condition constraint or individual style of a player do not affect these principal movements.

It might be anticipated that the self-selected accuracy condition (SS ACC) and the self-selected velocity condition (SS VEL) would exhibit the most similarities across the conditions, given that they share the same target areas for each participant. However, the data presented in this study demonstrated a notable contrast. SS ACC consistently displayed more uniform movement patterns across all participants, while SS VEL and the pre-defined accuracy condition (P ACC) showed greater variations earlier in the Principal Movements within and between participant groups. This may be attributed to the degree of task familiarity which can significantly influence movement patterns. In this context, SS ACC, being the most familiar condition to participants, is more likely to elicit automated, consistent movement patterns. Participants may have developed a well-established and stable technique for aiming at this specific target over time.

Conversely, SS VEL and P ACC, being less familiar due to the novelty of the task objective of Velocity or target location of prescribed target, may result in participants to adapting their movement patterns more dynamically. The unfamiliarity of these conditions could lead to exploration and experimentation, resulting in greater inter-individual and intra-individual variability. When the performance criterion is changed to velocity, or an alternative target area, players appear to lean forward with the thorax especially on the right-hand side, there is greater flex-/extension of the shoulders, elbows and wrists and smaller movements of the legs (left and right knee flex-/extension and left and right ab-/adduction of the hips). It is possible these are the movements the players are undertaking in order to adjust the ball position in preparation for ball release.

It is not until PM_4 where differences become evident between players aiming for higher ball velocity and players aiming for an alternative target area. For players aiming to increase ball velocity the left hip is ab-/adducting whilst the right hip and knee flexes and extends, there is a leaning forward of the thorax, and flex-/extension of the left and right shoulders, and again large flex-/extension movement in the left wrist. Whereas when aiming at alternative target areas players are splitting the legs, the left hip is ab-/adducting whilst the right hip flexes and extends, a twisting movement of the thorax and pelvis occurs. Again, there is a large movement of the left wrist. Players are replicating movements in the velocity constraint which indicate they are getting into a lower position, whereas players aiming for an alternative target area are using the rotation of the pelvis and thorax.

It is worth noting that although clear patterns of variability from the mean posture have been identified across conditions and target areas, the data has presented challenges in interpretation. As the analysis has been undertaken with joint centres as per Gløersen et al., (2018), it has not been possible to analyse the in-/external rotation of the shanks, thighs, hands, lower arms and upper arms, within the drag flick technique. Based on the results presented in Chapter 6, and the previous academic literature (Gómez et al., 2012, Yusoff et al., 2008, McLaughlin, 1997), which has presented a proximal to distal kinematic sequencing, it is likely in-/external rotation of the thorax and pelvis has had a significant effect on the variability within the data, which is supported within the results section of this chapter. Recommendations for how the present methodology could be developed to account for other in-/external rotation in the body will be discussed in the general discussion.

In addition, due to the complexity of the technique it is difficult to explain how the same movements presented within different principal movements contribute to the drag flick technique itself. For example, PM_1 captured the reaching back of the stick and the dragging motion of the ball with the stick and the ab-/adduction of the left hip and flex-/extension of the left wrist. This presents the wide stance width in order to drag the ball and increase the length of the drag, and the left wrist movement, which are all contributors to the core movement strategy of the drag flick technique, which again is consistent with research presented on the kinematics of the drag flick (McLaughlin, 1997, De Subijana et al., 2010, Ibrahim et al., 2017). However, the ab-/adduction of the left hip is also a key part of PM_4 in condition P ACC (splitting of the legs, the left hip ab-/adducting whilst the right hip flexes and extends). Given this methodology is enabling analysis to consider the coordination of joint angles it is likely that the left hip in combination with the other joint angles is what differentiates PM_1 and PM_4. PM1 is explaining the drag motion of the drag flick which the ab-/adduction is a key movement to facilitate this to allow the wide stance width, and PM4 is explaining the rotation of the thorax and pelvis, and which again occurs preparing for the wide stance width and throughout the wide stance width which again the left hip ab-/adduction is key to enable this part of the technique.

The findings of the current study achieve the objectives of analysing the impact of task constraints in whole-body movement patterns during the drag flick. Both conditions and target area differences were identified, and a core movement strategy was presented for the drag flick technique. In addition, a methodology which provides visual representations were presented of this core movement strategy of the drag flick, which will facilitate communication between scientist, athletes, and coaches.

7.4.7 Limitations

It is important to acknowledge that the differences in target locations between the conditions may have played a significant role in shaping the observed movement variations. Specifically, in the self-selected conditions, six out of twelve participants aimed at their "easiest" target, Bottom Left, while three chose bottom right, two middle right and one participant chose middle left, no "Top targets" were featured. To disentangle the origins of movement differences stemming from variations in task objectives and target locations, in future studies it may be beneficial to systematically manipulate both the task objectives (e.g., accuracy, velocity) and target locations. By creating conditions with varying levels of difficulty, and ensuring that participants aim at different targets, researchers can better isolate the impact of these factors on movement patterns. This approach can help clarify whether the observed differences are primarily attributed to task constraints or variations in target areas.

The approach used within this study is strengthened by analysis of PM waveform scores and the range of motion with respect to the joint angular movements that were evident from the corresponding principal movement animations. However, the lower principal movements did not present a significant finding for the waveform analysis, as they account for only small percentages of variance in the data. This suggests that the elements of the core movement are consistent regardless of the hit or missed target, target area or condition constraints, as represented by the higher principal movements 1 and 2. It is only small deviations from the mean posture that differentiates the movement pattern at lower principal movements when comparing target areas or constraints, but these could be significant for intra and inter-participant variations is terms of variability in response to different targets and constraints and in some cases define individual participant's style.

The PMk's are whole-body movement components, however, the qualitative descriptions of the principal movements in the results and the discussion of specific technique features focus on the largest visual representations within the presented movement which could present a selection bias. Angle analysis was undertaken to try and minimise the impact of this limitation. However, the angle analysis also presented a limitation as it was calculated based on the angle of two vectors. Therefore, visual representation had to be relied upon to determine the type of movements occurring such as flexion vs abduction. With such a complex movement there were challenges determining the movement that was occurring is PM_k's particularly as the amount of variance within each PM_k reduced.

The pooling procedure used in this study enabled a direct comparison of multi-segment movements between participants. An individual-specific PCA could have revealed larger individual differences in technique, by defining individual specific principal movements, or pooling of only successful trials as opposed to all trials of both hit and missed trials. However, the focus of the study was to determine the core movement strategy across a group of participants and to determine what effect task constraints had on this core movement of the drag flick technique. For that reason, the pooling procedure was deemed best suited for this study.

7.5 Summary

The first objective of this chapter was to identify the core movement strategy of the field hockey drag flick. This was achieved within the analysis, based on the first two principal movements which were consistent across all conditions and target areas. Some of the findings within PM_1 and PM_2 support the current literature, including the importance of the cross-over step, wide stance width, and the dragging motion of the ball with the stick moving across the body, which are all key features of the drag flick technique (McLaughlin 1997, Yusoff et al., 2008, De Subijana et al., 2010). The PCA analysis presents the left and right hip and the left and right knees in particular being integral to enabling some of these features of the drag flick technique to enable the players to complete a cross-over step, and to position the hips and knees to allow the wide stance width.

However, there are a number of findings which are new contributions to the body of knowledge. The importance of flex-/extension of the left and right wrists, which is evident in a number of PMs for all conditions. This study also presents the lowering of the thorax and the reaching behind for the ball as a core part of the movement strategy of the drag flick technique. The movement of the joints in the lower body appear to explain a greater contribution to the core strategy, however, the shoulders and elbows also form part of the core movement strategy across all conditions. What is interesting is that it is not until PM_4 that there is any evidence of rotation of the pelvis and/or thorax, emphasising the importance of the movements identified above that occur as part of the core of the drag flick technique.

The effects of constraints produced some interesting and novel findings throughout this study. PM_1 was a consistent movement across all conditions and all target areas suggesting this is part of the core movement strategy of the drag flick technique (reaching back with the stick; lowering of the thorax; dragging motion of the stick; abduction/adduction of the left hip, and flexion/extension of the left wrist). PM_2 was also a consistent movement across all conditions and all target areas (movement of stick across the body; abduction and extension of the right hip; flexion of the right knee; and flexion of the left hip and left knee), however, there were differences in timing between conditions SS ACC and SS VEL/P ACC.

The second objective of this chapter was to identify the elements of technique that are modified to produce different outcomes. The first evidence of this was at PM_3. This was the first principal movement where different movements were presented between the conditions. SS ACC was again consistent across all target areas with little inter variability, whereas the other two conditions presented the same movement in each condition but there were again timing differences between the two conditions. PM_4 is the first principal movement where a different movement occurs in all three conditions, it is also the first principal movement where there is evidence of between participant variability within conditions, as there is individual variation evident in all three conditions. In addition, PM_4 also introduces greater intra variability within participants. Within condition P ACC there is evidence of the target area affecting the variability between participants, with all participants following the same movement for target areas bottom left and right but adopting a more individual movement for target areas situated at the top of the goal. PM_5 is the final PM presented for conditions SS VEL and P ACC, as although there are some common movements presented between participants (Flex-/extension of the right knee which creates a dipping of the right-hand side of the body and the lowering of the stick.) the movements are much more individual throughout these conditions and therefore are not deemed to form part of the core movement strategy. PM_6 and PM_7 are presented for condition SS ACC but as with earlier PMs for the other conditions there is greater variability between participants. PM_6 presents the same movements but with timing differences between participants and PM_7 provides evidence of individual variability, even within the same target area.

The following bullet points summarise study 3 presented in this chapter and how the Principal Movement Analysis makes original contributions to the body of knowledge:

- The left and right flex-/extension of the wrists are key to drag flick technique as they are involved with the first five PMs across all conditions. It seems logical that the wrists are key to aiming at a specified target area given the consistency across all conditions and would explain why they feature in the first five PMs.
- The lowering of the thorax is also key to the drag flick technique presented in PM1. The lowering of the thorax is enabling the lengthy dragging motion of the ball.
- The lower body kinematics explain greater variance compared with the shoulder and elbow joints, as they dominate the early principal components accounting for most of the variance.
- There is more between participant variability within the constraint of ball velocity as a performance outcome and prescribed target area compared with ball accuracy in a self-selected target area.
- Ball velocity has a greater impact on variability than different target areas.

CHAPTER 8:

GENERAL DISCUSSION

8.1 Introduction

This chapter synthesises the findings of the three separate studies, identifying the key learnings from the overall evaluation of the body of work presented in this thesis setting it in the context of the extant research. This includes an evaluation of the approaches used in this thesis for technique analysis which could be applied across other sporting techniques and the practical implications of the findings for coaches and players. The limitations and recommendations for future research have been presented and finally the original contributions to literature and an overall conclusion.

8.2 Summary of the research area

Several aspects of the field hockey drag flick have been shown to be important for contributing to overall ball velocity (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010, Gómez et al., 2012). In particular, quantitative approaches to establish which factors contribute to the performance of the drag flick technique have identified that ball velocity is dependent on the position of the right foot from the ball at right foot placement, a wide stance width, the length of the drag distance, stick velocity and a proximal to distal kinematic sequencing (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010, Gómez et al., 2012, Ibrahim et al., 2017, Palaniappan and Viswanath, 2018, Ladru et al., 2019). Drag flicking research has focussed on the overall performance of ball velocity without considering firstly if ball velocity is the most appropriate performance outcome and secondly gaining a further understanding of what is the core movement strategy of the drag flick to gain a better understanding of how this technique is performed. Technique analysis is the term given to an analytical method that is used to understand how skills/movements/or techniques are performed and through this understanding, provide the basis for improved performance (Lees, 2002).

Movement variability (MV) has traditionally been considered as unwanted noise and the focus in early research has been on reducing this noise, but more recently studies have re-evaluated the role of MV and tried to understand the importance of MV in the analysis of sports techniques. Variability can provide a measure of coordination to produce the desired outcome (Preatoni et al., 2013). The literature review of this thesis provided an overview of a variety of methods that exist to quantify variability. To date there has been no consideration of MV within the drag flick literature. With respect to kinematic data, traditionally, discrete values are reported for single variables or combinations of several variables, these discrete values are often key events within a technique. The analysis of discrete values has been criticised as these fail to capture the dynamic nature of a technique (Mullineaux and Wheat, 2018). The analysis of variability and patterns of coordination over multiple trials should enable researchers to distinguish between patterns of coordination that tend to lead to successful performances and outcomes from those that do not, or that tend to be a more individualistic style of a technique (Glazier, 2021).

The aim of this project, therefore, was to undertake a technique analysis on the drag flick technique and investigate the extent of similarity and differences in the MV of the drag flick technique.

This research, therefore, provides original contributions to both drag flick specific research and sports biomechanics research in the areas of technique analysis and the role of MV in sport techniques. This research will also have practical implications for coaches and hockey players, by providing a better understanding of the technique of the drag flick and the relationship between MV within drag flicking.

8.3 Biomechanical Differences in the core movement strategy of the field hockey drag flick.

8.3.1 Delphi Poll Method – Study 1

The findings from the Delphi Poll Method established 28 attributes by consensus that were deemed important for the drag flick technique. As this research is based around the biomechanics of the drag flick the attributes established in the technical category were used to inform the research questions and subsequent studies. This technical category was broken down into distinct phases of the drag flick technique (approach to the ball; gathering of the ball; the drag; and ball release). These phases were consistent with the phases identified in Palaniappan and Viswanath (2018). The attributes identified within the technique category were carried forward as dependent variables to be analysed in the biomechanical analysis in chapter 6. Positions of foot to ball at pickup; length of the drag; time of the length of the drag; stance width; centre of mass height; the kinematic sequencing and the thorax/pelvis differential were all dependent variables that were identified through the Delphi poll which were used to inform the methodological procedures for the biomechanical analysis presented within this thesis. Similar findings have also been noted in studies that have used dependent variables for the drag flick technique (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010, Gómez et al., 2012, Palaniappan and Viswanath, 2018). However, the centre of mass height and thorax pelvis differential were novel findings from the Delphi Poll Method which have not been presented in the drag flick literature to date. However, the thorax pelvis differential has been presented in Brown et al. (2011) who analyse the characteristics of a golf drive on low handicap female golfers to gain an understanding of swing kinematics in relation to performance.

In addition to the attributes identified through the Delphi poll to inform the methodological procedures in chapter 5, the expert panel of coaches were asked to provide their preferred target areas from their perspective. Top left and right were identified as the two preferred target areas in terms of success as the defence has the lowest chance of saving the ball in these target areas. However, these two target areas were also identified as the most challenging in terms of the drag flick technique for the attackers. Therefore, the two bottom corners (left and right) were identified as easier for the drag flickers to achieve success and still challenging areas for the defenders to save the ball. Bottom left and right were also identified as likely target areas to receive deflections from running attackers, to increase the likelihood of a goal being scored. Surprisingly, to date little research has incorporated specific, identifiable target areas into the body of research on the drag flick. Gómez et al. (2012) analysed the difference in performance of the drag flick between the right and left side of the goal and Rosalie et al. (2017) examined individual differences in ball velocity and accuracy between specialist and non-specialist drag flickers. Rosalie et al. (2017) also identified the four corners of a standard goal as the preferred target areas for the drag flick technique.

Level of agreement for consensus was not reached for the overall performance criteria of the drag flick technique, however, through the qualitative analysis, accuracy, was identified as the key performance criteria for this research. Due to the lack of agreement between coaches' ball velocity was also factored into the research as a constraint within one of the conditions.

8.3.2 Biomechanical Analysis – Study 2

The findings from the traditional biomechanical analysis of the drag flick technique showed key performance and technique variables that were consistent with values reported in the literature (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010, Gómez et al., 2012). A wide range of values have been reported for the drag flick technique performance and technique variables because of factors such as the standard of participant measured (e.g., novice vs elite), and different sex of participants (e.g. male vs female). This is highlighted by ball velocities values ranging from 9.97 $m \cdot s^{-1}$ (Eskiyecek et al., 2018) to 31.7 $m \cdot s^{-1}$ (Ibrahim et al., 2017). Based on this range, the values for peak ball velocities for hit targets were typically high for all three conditions for this project (SS ACC: 20.47 ± 2.73 $m \cdot s^{-1}$; SS VEL: 21.19 ± 3.03 $m \cdot s^{-1}$; P ACC: 20.36 ± 2.98 $m \cdot s^{-1}$).

The findings from individual analysis revealed that participants produced unique kinematic sequencing differences to the group data. These differences varied across constraints, for example participants 2 and 7 were the only participants who followed a typical proximal to distal sequencing which has been identified within the drag flick literature (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010, Gómez et al., 2012) but this was only evident in the velocity constraint (SS VEL). Both participants followed a different kinematic sequencing for the two accuracy conditions (SS ACC and P ACC), all participants followed a more push like pattern for these conditions. Only considering the hit trials there were six different kinematic patterns evident between participants, with only one participant consistent with the sequencing across all three conditions, participant 11, with a part sequential part simultaneous sequencing (T1-T2-T3 & T4-T5-T6).

Based on study 2 there is empirical evidence to suggest when an accuracy constraint is placed on a participant it alters their kinematic sequencing to a more push like pattern. Although this is a novel finding for the drag flick literature this is reported within the biomechanics literature by Kreighbaum and Barthels (1996) for different techniques where the overall performance objective is ball velocity but where accuracy is also a factor, such as golf swing, tennis forehand and backhand.

The findings from the group analysis revealed that ab-/adduction of the left and right hips and shoulders, flex-/extension of the left and right elbows and wrists, right hip and left shoulder axial rotation, and right ankle ab-/adduction are all key joint angles which form part of the core movement strategy of the drag flick technique.

To a lesser extent the flex-/extension of the left knee and the lateral flexion and axial rotation of the TPD all contribute as part of the core movement strategy. Other joint angles were identified as making substantial contributions to the core strategy but with more individual variability. Entire time-series of multiple joints data has not been presented in the literature before the present study with only Ladru et al. (2019) presenting the entire time series focussing on the left knee contribution. However, Ladru et al. (2019) only found statistical significance with the left knee velocity in terms of contribution to ball velocity (R^b .127 / p<.001), no significance was found with knee angle contributing to either accuracy (R^b .000 / p=.931) or ball velocity (R^b .082 / p= *.274*).

8.3.3 Principal Movement Analysis – Study 3

Principal Movement Analysis was used for this research as it has been shown to be a powerful tool to analyse patterns of coordination and control to quantify movement technique in sport (Federolf et al., 2013). PMA has also been shown to be a novel data normalisation approach to allow data from all participants to be combined, thus facilitating a direct comparison of the postural movement components between players and establishing a core movement strategy of the drag flick technique (Gløersen et al., 2018). This analytical method, therefore, provides a method for technique analysis which has been defined as:

"An analytical method that is used to understand the way in which sports skills are performed, providing the basis for improved performance."

(Lees and Nolan, 2002)

Based on this definition, PMA can be used as a methodology to quantify and scientifically assess "technique" in sports and bridge the gap between researchers and practitioners in sport.

The findings from the group analysis support the current drag flick literature in identifying the importance of the cross-over step, wide stance width, dragging motion off the ball, and stick moving across the body are all identified within literature (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010). The movement at the left hip is integral to enable these features, the flex-/extension of the left and right wrists and lowering of the thorax were also key contributors to the core movement strategy following the PMA analysis. The higher order PMs (PM_1; 42.57% and PM_2; 22.19%, percentage of variance accounted for) all display a consistent movement pattern regardless of the condition or participant, however there were some timing differences between SS ACC and SS VEL/P ACC. These PMs accounted for reaching back with the stick, lowering of the thorax, the dragging motion of the ball, ab-/adduction of the left hp and flex-/extension of the left wrist (PM_1); movement of the stick across the body, abduction and extension of the right hip, flexion of the right knee, and flexion of the left hip and left knee (PM_2). PM_3 remained consistent for all target areas but there were some notable differences based on the condition constraints. Condition SS ACC followed a similar movement to PM_2 for the respective condition however, there was substantial contribution of the right wrist for PM_3. A different movement occurred in PM_3 for the other two conditions (leaning forward of the thorax in particular the right-hand side, flex-/extension at the shoulders, elbows and wrists for both left and right). PM_4 is the first instance where a twisting motion is visible between the pelvis and the thorax (SS VEL and P ACC) and in addition PM_4 is the first PM where there is both target and individual variation within the conditions (P ACC). PM_5 was the first PM for conditions SS VEL and P ACC where individual variation was evident as there were no group patterns within this condition for any target areas. It is not until PM_7 that individual variation is seen within condition SS ACC, as no group patterns are evident within this PM.

Chapter 7 highlighted that for condition SS ACC over 91% of the variance is explained by the core movement strategy of the drag flick regardless of target area (PM_1 to PM_6). More individual variation occurs earlier for conditions with the constraint of ball velocity (87%) and a less familiar target area (81%).

8.4 Contribution to the theoretical understanding of the field hockey drag flick.

There are consistent findings regarding the technique of the drag flick which are evidenced across all three studies. The cross-over step is a key event to ensure participants are positioning the body relative to the ball appropriately to enable a lengthy dragging motion of the ball. As a result, participants are planting the right foot in front of the ball and separating the TPD angle which enables participants to reach back for the ball and consequently increasing the distance that the ball can be dragged. All three studies present the need for a wide stance width, again in order to increase the drag distance of the ball. The cross-over step, wide stance width and long dragging motion of the ball all mean the left and right hips make key joint contributions to the core strategy of the drag flick technique. These findings have been regularly reported in the drag flick literature. McLaughlin (1997) reported the importance of the right foot placement as it effects the drag length which influenced the ball velocity and the need for a wide double base of support to set the body to ensure the correct timing of the hips, shoulders and arm movements, which should all lead to high ball velocities. Du Subijana et al. (2010) concluded that a wide stance width, a whipping action (rapid back lift) of the stick followed by a typical proximal to distal sequencing of the pelvis, thorax and stick all contribute to high ball velocities.

This thesis also presents evidence to support the thorax position as a key contributor to the drag flick technique as identified by the expert panel of coaches in study 1. Study 3 supports the findings in the Delphi Poll Method with flexion at the thorax created by the TPD angle and the hips. However, study 2 presented the lateral flexion and axial rotation of TPD as part of the core movement strategy. The axial rotation of the TPD may not be evident as a high order PM in study 3 due to the kinematic sequencing pattern participants are undertaking in study 2 which suggests participants are undertaking a more push like pattern rather than a typical proximal to distal pattern for throwing actions which has been presented in the drag flick literature (McLaughlin, 1997, Yusoff et al., 2008, De Subijana et al., 2010, Gómez et al., 2012). McLaughlin (1997) identified two different kinematic patterns that occurred within the study. A group which achieved ball velocities over 20.89 $m \cdot s^{-1}$ which followed a typical proximal to distal pattern of maximum rotation of the hips, maximum rotation of the shoulders, the push of the right hand and the summation of velocities to the toe of the stick. However, the group which achieved ball velocities under 20.89 $m \cdot s^{-1}$ followed a different kinematic sequencing of maximum rotation of the hips, push of the right hand, maximum rotation of the shoulders then the tow of the stick achieved maximum velocity after ball release. It is thought the change in kinematic sequencing for this thesis is due to the change in performance criteria from ball velocity to accuracy.

There is strong evidence of timing differences of the selected movement pattern between the three constraints. This can be seen in the kinematic sequencing of study 2 but also in the PMs in study 3. However, there is greater consistency of inter variability for the self-selected accuracy conditions particularly in study 3.

The findings from this research present empirical evidence that the left and right wrists are key joint angles in the drag flick. This is evidenced in study three in the core movement strategy and the large contribution of the wrists and again in the high order PMs in study 3 which continue to be present in the lower order PMs as well. However, the importance of the wrist contribution was not identified in the Delphi poll study. No coaches identified the importance of the wrist contribution to the drag flick technique. This is also generally the case for the shoulder contributions but to a lesser extent.

Notable differences in the findings across this research are the influence of the left and right knees. The traditional biomechanical analysis places an emphasis on the left knee in particular but this is in contrast to the Principal Movement Analysis in study 3 where an emphasis is placed on both knees. The contribution of the left knee has been established in the literature, by both De Subijana et al. (2010) and Ladru et al. (2019). Du Subijana et al. (2010) presented the left knee angle at foot contact and at peak angular velocity of the stick which occurred near ball velocity. There were significant differences between the model drag flicker (foot contact (°): 165.0 ± 1.7 / peak positive AV of the stick (°): 131.2 ± 2.2) and the female group of participants (foot contact (°): 157.7 ± 6.6 / peak positive AV of the stick: 109.6 ± 17.9) (p<0.05), with the model drag flicker presenting a significantly smaller knee flexion angle and also showing a smaller angle change than the female group. However, there was no evidence to suggest the knee angle contributed to ball velocity which was the performance outcome for this particular study. Ladru et al. (2019) examined the entire time series of data for the left knee angle and left knee angular velocity relative to accuracy and ball velocity. Although the entire time series was presented only the maximum knee angle and maximum extension velocity were considered in any quantitative analysis. Multiple regression analysis between maximum knee flexion angle was not found to significantly contribute to ball speed (R^b .082 / *p*= .274) or accuracy (R^b <0.001 / *p*= .931*).* Maximum left knee extension velocity did not contribute to accuracy (*R*b .001 / *p*= .880) but did significantly contribute to ball speed (*R*b .127 / *p*=<0.001). Ladru et al. (2019) concluded that maximal angular velocity of the lead knee extension is associated with ball velocity. This thesis, however, considers the left knee across the entire time series of data as opposed to a time discrete event.

8.4.1 Approaches used for technique analysis.

As previously identified, definitions of technique appear well established in the literature, but the concept of technique analysis is less well developed. Researchers are often concerned with variables that influence performance rather than technique and their influence on performance (Lees, 2002). Lees (2002) identified the methods of technique analysis as being qualitative, quantitative and predictive. The approach used within this thesis has adopted both qualitative and quantitative methods of analysis to undertake a technique analysis on the Field Hockey drag flick. Initially expert coaches were approached to determine what their knowledge and understanding of this technique was. This was achieved in a structured way to ensure there was a consensus reached across the coaching panel. This was to establish expert coaches' subjective interpretation of the drag flick. Given the dearth of literature of the drag flick, consulting coaches was a sensible approach to gain a better understanding of the technique but also to inform the biomechanical data collection.

Following study 1 a quantitative analysis was undertaken which for this research relied on kinematic data collection methods. The literature and results from study 1 were used to identify key technique variables. Traditionally quantitative analysis has been criticised for not establishing the characteristics of the whole skill by reducing data down to time discrete points, which may cause research to miss important information (Lees, 2002). The approach used in this thesis has attempted to overcome this limitation by analysing the entire time series of individual joint angle data and use a pattern recognition method to extract features from a large data set to determine objective comparison between the technique of players and to determine what change in technique may be beneficial for players (Federolf et al., 2014, Gløersen et al., 2018). This research used a PCA-based approach by (Federolf et al., 2014, Gløersen et al., 2018) to combine data from all participants, thus facilitating a direct comparison of the postural movement components between participants to establish the characteristics of the whole technique. The combination of these three approaches to undertake a technique analysis on any sporting technique is rarely evident in the published literature and should be considered to ensure a thorough technique analysis is undertaken to improve the understanding of different sporting movements. In particular, the PCA performed offers an objective and quantitative criterion for both an assessment of an athlete's individual technique and to compare across athlete's during complex human movements and could provide coaches and practitioners with valuable information regarding technique in their sport and their athletes.

8.4.2 Practical Implications for Coaches and Players

The development of greater understanding of what is the core movement strategy of the drag flick technique has several practical implications for coaches and practitioners. The knowledge of what is core movement and what is individual style confirms that MV can be useful in allowing players to utilise a wider range of solutions to adapt their coordination patterns to stabilise performance variables and produce an accurate, high velocity shot at goal. There is strong evidence in the literature to suggest a drag flick should follow a proximal to distal sequencing in order to obtain high ball velocities. However, following the research in this thesis there is empirical evidence to suggest that ball velocity is not the only performance outcome that needs to be addressed by coaches and players. Both accuracy and ball velocity need to be considered and the results of this research present new knowledge to coaches that players' adapt their movement pattern when given an accuracy constraint. Therefore, this needs consideration in the training of players to develop their drag flick technique and be able to perform high ball velocities that have accuracy.

The methodologies used within this thesis, in particular the PCA analysis in study 3, allow coaches and players to visualise the individual components of a drag flick technique and will help develop a better understanding of how complex movements such as the drag flick are executed. Following the PMA analysis, the first two PMs present the core movement strategy. These are elements of the drag flick which are invariant. The first two PMs allow coaches to focus their attention on the essential elements of a drag flick technique: reaching back with the stick, lowering of the thorax, dragging motion of the stick, ab-/adduction of the left hip, and flexion/extension of the left wrist (PM_1), movement of stick across the body, abduction and extension of the right hip, flexion of the right knee, and flexion of the left hip and left knee. Substantial contributions from left and right elbows and left wrist (PM_2).

The methodology takes into account the whole movement pattern which is not possible with a more traditional biomechanical analysis. In addition, the PMA methodology allows analysis of a large data set, which makes the analysis more manageable, but in addition focussing on few key variables may represent a risk of bias (Lees, 2002). The stick figure animations created allow the visualisation of the core movement strategy. For an athlete or coach, they provide an objective tool for technique assessments, where individual athletes can be compared to whole groups objectively, though not with a view to expecting or coaching conformity to one specific way of performing the drag flick technique. In addition to this, the application of a coordinate system that moves with the COM, can be used to avoid body displacements being represented as PMs which may come about due to the adjustment of body positioning due to the accuracy of the player dragging the ball out from the baseline and any miss traps by the stopper at the top of the circle.

This research also has wider implications for the coaches and athletes as this approach to technique analysis is not limited to the drag flick technique and can be applied across multiple sports to enhance the understanding and body of knowledge. At the time of writing this approach has not widely been adopted for technique analysis. One research group has produced three studies (Federolf et al., 2012, Gløersen et al., 2018, Werner et al., 2021) adopting this approach within technique analysis. The research in this thesis is a step forward in expanding the use of this analysis. It is an approach which has value for helping coaches to simplify their thinking about a technique, which more studies should adopt to explore technique analysis.

As previously stated, the PCA analysis allows analysis of the entire movement pattern which a more traditional biomechanical analysis cannot do. It has been proven to be a successful methodological approach to deal with a large data set. The results in this thesis in particular allow coaches to understand what is core for the drag flick technique (PM_1 and PM_2) and what elements coaches can allow players to explore in order to adapt to achieve higher ball velocities or successfully aim for alternative target areas.

8.5 Limitations

A number of limitations were noted for this research that were based on general methodology and the PCA method**.**

The Delphi Poll Method is a method based on expert opinion where a consensus is gained of this expert opinion. It is not necessarily a method where right or wrong answers are provided on what makes a good drag flick technique, what are the optimal target areas and what is the overall performance criterion. While this is true of all Delphi Poll studies it is notable in this study that there is for the most part good agreement between the consensus in the Delphi Poll study and the extant research, with some additional insight offered by the expert coaching panel.

In study 3, as the PMs were extracted based on joint centre locations this does not allow for the representation of axial rotation within the animated stick figures. Each PM must be carefully interpreted. The PMs are defined by one linear movement of each marker. Since the drag flick technique is not just linear, individual PMs can at best only approximate real movements in the drag flick. This limitation is discussed further in future recommendations to potentially include axial rotation in future analysis.

The PMs are whole-body movement components, however, the qualitative description of each PM of specific technique features are interpretations and therefore it is likely that observers focus on the largest movement in the visual representation as this is the most obvious characteristic. This may constitute a selection bias. However, the PMs themselves, including their representations as animations, are objective and purely data driven outcomes (Mohr et al., 2021). The impact of this limitation was reduced based on the angle analysis undertaken in Chapter 7 to interpret the results and determine what movements were taking place. Particularly in the lower order PMs.

Finally, this research is limited as a piece of work regarding the performance aspects of the drag flick. This was outside the scope of this thesis, as performance is not an indicator of good technique (Bartlett, 1999) given that factors other than technique can affect performance. Although it is generally accepted that a better technique will lead to improved performance (Lees, 2002).

8.6 Future research

This section will provide an overview of directions for future research based on the findings from this research.

As identified earlier in the thesis and in the limitations, the PCA methodology is a relatively new approach in sport literature and is not at the time of writing widely adopted for technique analysis. Future research should firstly attempt to overcome the lack of axial rotation in the analysis. One suggestion would be to explore using the marker coordinate data for each selected segment in place of the joint centre data. This may allow axial rotation to be considered in the output for analysis. Secondly, possibilities of reimporting the output data of the PMA analysis into software such as Visual 3D to enhance the visualisation of animations and improve the usability for coaches and practitioners, would be a worthy investigation to enhance the practical implications of technique analysis.

In addition to the proposed future research around the PCA analysis it is recommended that further technique analysis of the drag flick or any other sporting movement could correlate the principal movements with functional variables such as ground reaction forces or performance variables which should offer a deeper understanding of the functional consequences of players' actions and therefore may help the improvement of a players technique.

To continue further analysis of the drag flick technique other quantitative biomechanical data could be collected and analysed. Force data would confirm where torque is being created and an inverse dynamics analysis would lead to a better understanding of the contributions of the different joints to the generation of stick velocity.

Whilst not within the scope of this research a post-doctoral piece of work will allow the time to take the results of this research back to the expert coaches in the Delphi Poll Method to gain their thoughts on the outcomes and ensure the feedback loop is closed. It would also be interesting to work with coaches and governing bodies to assist them in designing training practices to enhance the technique of the drag flick in players and therefore potentially improve performance levels within this technique taking into consideration both the accuracy and velocity of the drag flick.

8.7 Original contributions to knowledge

This thesis makes a number of contributions to the knowledge and understanding of the technique of the drag flick in Field Hockey.

1. The four corners of the goal (TL, TR, BL, and BR) are the preferred target areas for the drag flick technique in competition. TL and TR are preferred but expert opinion agreed that these are more challenging than BL and BR and therefore player ability should determine the preferred target area.
2. The performance outcome criterion of the drag flick should include both accuracy and ball velocity.
3. Task constraint of accuracy alters the kinematic sequencing of players from a throw like pattern to a more push like pattern or combined throw-push pattern.
4. Between participant variability is greater within the constraints of ball velocity as a performance outcome and prescribed target area compared with ball accuracy in a self-selected target area.
5. Ball velocity has a greater impact on inter participant variability than different target areas.

6. Target areas and performance outcome constraints affect the timing of the drag flick sequence.
7. The lowering of the thorax is part of the core movement strategy.
8. The following joints angles are key as part of the core movement strategy of the drag flick technique:
    a. Flex-/extension of the left and right wrists are key movements to achieve the movement of the ball for the dragging motion and the accuracy of ball release.
    b. Ab-/adduction / flex-/extension of the left hip
    c. Ab-/adduction / flex-/extension of the right hip
    d. Flex-/extension of the left and right shoulders
    e. Flex-/extension of the left and right elbows

The joint angles of the legs are all key to allow the earlier identified characteristics of the drag flick technique (cross-over step, and wide stance width) in addition to enabling the players to get a low body position and create a long drag length.

Finally, the constraints of velocity and accuracy cause greater adaptations to technique than different target areas. This was not considered or evident from the Delphi Poll Method; coaches assumed that the same technique is used regardless of the constraint of accuracy or the target area a player is aiming at in the goal. In addition to these, coaches placed emphasis on rotation of the hips, however, it was evident following the PMA analysis that the rotation of the pelvis and thorax is an adaption to the core strategy of the drag flick to hit an alternative target area.

8.8 Conclusions

The purpose of this research was to undertake a thorough biomechanical technique analysis of the Field Hockey drag flick, and to determine the extent of similarity and difference in the movement variability of the drag flick technique. The following research questions were posed to facilitate completion of the overall aims of the research.

1. What physical and technical attributes do hockey coaches feel determine the success of the drag flick technique?

Research question 1 was fulfilled through an adaptation of the Delphi Poll Method of obtaining consensus across a panel of 10 expert field hockey coaches. 28 attributes were identified across three broad categories (technical; physiological; and psychological). The technical attributes were used to inform the methodological procedures of further studies in the thesis (foot to ball distance at ball pick-up; length of drag; stance width; height of

COM; kinematic sequencing; and thorax pelvis differential). In addition, the expert coaching panel suggested using top left; top right; bottom left; and bottom right as target areas for the research in the thesis. Although a consensus wasn't reached by the criteria set for the quantitative analysis of the Delphi Poll Method, analysis of qualitative discourse was used to determine that accuracy would be the performance criterion used for the research with ball velocity as a constraint on one condition in the biomechanics methodology.

2. What are the biomechanical characteristics and variability of the hockey drag flick?

A rigorous methodology was established using a series of recommended procedures to ensure the validity of the drag flick variables measured. For example, calibration tests were used in the motion capture data; a 15-segment model was created using recommended definitions from the ISB and C-motion; data processing was conducted using a residual analysis method recommended by Winter (2005); and key technique and performance variables were selected from a comprehensive review of the literature and the results of study 1, the Delphi Poll Method. Variables were analysed through a detailed investigation of hit, missed and overall performance of trials across three different conditions undertaken by each participant. Mean values of time discrete variables were consistent with those reported in the literature. Kinematic joint angle data was analysed in terms of its contribution to the drag flick and its departure from the mean of all participants across all trials in each condition.

Following the more traditional biomechanical analysis a PCA analysis was undertaken with the same data set to determine principal movements of the drag flick technique. The PMA analysis provided a novel insight into the drag flick technique. The principal movements were determined by investigating the successful trials of each individual participant and analysing their departure from a mean posture created by all participants across all trials of both hit and missed trials. Nine PMs accounted for over 95% of the variance.

Across both biomechanical studies the following characteristics of the drag flick technique were determined:

- The cross-over step is a key event to ensure a mechanically advantageous position of the body in relation to the ball.
- A lengthy drag motion is desirable and required to achieve high ball velocities.
- The separation of the thorax pelvis differential angle is key to increase the drag length of the ball.

- A wide stance width is required to achieve a long drag distance.
- The lowering of the thorax is part of the core movement strategy.
- The following joint angles are key as part of the core movement strategy of the drag flick technique:
    - Flex-/extension of the left and right wrists are key movements to achieve the movement of the ball for the dragging motion and the accuracy of ball release.
    - Ab-/adduction / flex-/extension of the left hip
    - Ab-/adduction / flex-/extension of the right hip
    - Flex-/extension of the left and right shoulders
    - Flex-/extension of the left and right elbows

The joint angles of the legs are all key to allow the earlier identified characteristics of the drag flick technique (cross-over step, and wide stance width) in addition to enabling the players to get a low body position and create a long drag length.

The drag flick technique is defined by the cross-over step, a long dragging motion of the ball, a wide stance width, the lowering of the thorax and the movement at the wrists to aid accuracy and ball velocity. These findings may allow coaches to simplify a conceptual model of the drag flick as opposed to considering all 28 attributes which were agreed upon by consensus in the Delphi Poll Method. Once the core strategy has been adopted by players, coaches would be able to work with players to develop individual style to achieve higher ball velocities and success at hitting a range of different targets.

CHAPTER 9:

REFERENCES

ACKLEY, B., SWAN, B., LADWIG, G. & TUCKER, S. (2008). Evidence-Based Nursing Care Guidelines: Medical-Surgical Interventions; Mosby Elsevier: St. *Louis, MO, USA*, 7.

ADLER, M. & ZIGLIO, E. (1996). *Gazing into the oracle: The Delphi method and its application to social policy and public health*, Jessica Kingsley Publishers.

ADRIAN, M. & COOPER, J. (1995). *Biomechanics of Human Movement,* Madison, WI, Brown & Benchmark.

AE, M. (2020). The next steps for expanding and developing sport biomechanics. *Sports Biomechanics,* 19, 701-722.

ALEXANDER, V. D., THOMAS, H., CRONIN, A., FIELDING, J. & MORAN-ELLIS, J. (2008). Mixed methods. *Researching social life,* 3, 125-144.

ANSARI, N. W., BARI, M. A., HUSSAIN, I. & AHMAD, F. (2014). Three Dimensional Biomechanical Analysis of the Drag in Penalty Corner Drag Flick Performance. *Journal of Education and Practice,* 5, 91-96.

ANSON, G. & ELLIOTT, D. (2005). Information processing and constraints-based views of skill acquisition: divergent or complementary? *Motor control,* 9, 217-241.

ASTORINO, T. A., TAM, P. A., RIETSCHEL, J. C., JOHNSON, S. M. & FREEDMAN, T. P. (2004). Changes in physical fitness parameters during a competitive field hockey season. *Journal of Strength and Conditioning Research,* 18, 850-854.

BARBOZA, S. D., JOSEPH, C., NAUTA, J., VAN MECHELEN, W. & VERHAGEN, E. (2018). Injuries in field hockey players: a systematic review. *Sports Medicine,* 48, 849-866.

BARI, M. A., ANSARI, N. W., HUSSAIN, I., AHMAD, F. & KHAN, M. A. (2014). Three dimensional analysis of variation between successful and unsuccessful drag flick techniques in field hockey. *International Journal of Research Studies in Science, Engineering and Technology,* 1**,** 74-78.

BARTLETT, R. (1999). *Sports Biomechanics: Reducing Injury and Improving Performance,* London, E & FN Spon.

BARTLETT, R. (2014). *Introduction to sports biomechanics : analysing human movement patterns.,* Oxon, Routledge.

BARTLETT, R., WHEAT, J. & ROBINS, M. (2007). Is movement variability important for sports biomechanists? *Sports Biomechanics,* 6**,** 224-243.

BAUER, H.-U. & SCHÖLLHORN, W. (1997). Self-organizing maps for the analysis of complex movement patterns. *Neural Processing Letters,* 5**,** 193-199.

BEECH, B. F. (1991). Changes: the Delphi technique adapted for classroom evaluation of clinical placements. *Nurse Education Today,* 11**,** 207-212.

BELL, A. L., BRAND, R. A. & PEDERSEN, D. R. (1989). Prediction of hip joint centre location from external landmarks. *Human movement science,* 8**,** 3-16.

BELL, A. L., PEDERSEN, D. R. & BRAND, R. A. (1990). A comparison of the accuracy of several hip center location prediction methods. *Journal of biomechanics,* 23**,** 617-621.

BERNSTEIN, N. (1966). The co-ordination and regulation of movements. *The co-ordination and regulation of movements*.

BLOOMFIELD, J., POLMAN, R., O'DONOGHUE, P. & MCNAUGHTON, L. (2007). Effective speed and agility conditioning methodology for random intermittent dynamic type sports. *The Journal of Strength & Conditioning Research,* 21**,** 1093-1100.

BRADSHAW, E. J., MAULDER, P. S. & KEOGH, J. W. (2007). Biological movement variability during the sprint start: Performance enhancement or hindrance? *Sports Biomechanics,* 6**,** 246-260.

BRAUN, V. & CLARKE, V. (2006). Using thematic analysis in psychology. *Qualitative research in psychology,* 3**,** 77-101.

BRÉTIGNY, P., SEIFERT, L., LEORY, D. & CHOLLET, D. (2008). Upper-limb kinematics and coordination of short grip and Classic drives in field hockey. *Journal of Applied Biomechanics,* 24**,** 215-223.

BRONNER, S. & SHIPPEN, J. (2015). Biomechanical metrics of aesthetic perception in dance. *Experimental brain research,* 233**,** 3565-3581.

BROWN, S. J., NEVILL, A. M., MONK, S. A., OTTO, S. R., SELBIE, W. S. & WALLACE, E. S. (2011). Determination of the swing technique characteristics and performance outcome relationship in golf driving for low handicap female golfers. *Journal of Sports Sciences,* 29**,** 1483-1491.

BUNN, J. W. (1972). *Scientific Principles of Coaching*, Prentice-Hall.

BUTTON, C., MACLEOD, M., SANDERS, R. & COLEMAN, S. 2003. Examining movement variability in the basketball free-throw action at different skill levels. *Research quarterly for exercise and sport,* 74**,** 257-269.

CAMPBELL, A. C., LLOYD, D. G., ALDERSON, J. A. & ELLIOTT, B. C. (2009). MRI development and validation of two new predictive methods of glenohumeral joint centre location identification and comparison with established techniques. *Journal of Biomechanics,* 42**,** 1527-1532.

CAPPOZZO, A., CATANI, F., DELLA CROCE, U. & LEARDINI, A. (1995). Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clinical biomechanics,* 10**,** 171-178.

CARR, G. (1997). *Mechanics of Sport,* Champaign, IL, Human Kinetics.

CHANG, D. H. & TROJE, N. F. (2009). Acceleration carries the local inversion effect in biological motion perception. *Journal of Vision,* 9**,** 19-19.

CHAPMAN, D. W., NEWTON, M. J. & MCGUIGAN, M. R. (2009). Efficacy of interval-based training on conditioning of amateur field hockey players. *The Journal of Strength & Conditioning Research,* 23**,** 712-717.

CHIVERS, L. & ELLIOTT, B. (1987). The penalty corner in field hockey. *Excel,* 4**,** 5-8.

CHOW, J. W. & KNUDSON, D. V. (2011). Use of deterministic models in sports and exercise biomechanics research. *Sports biomechanics,* 10**,** 219-233.

CLAYTON, M. J. (1997). Delphi: a technique to harness expert opinion for critical decision-making tasks in education. *Educational psychology,* 17**,** 373-386.

CLIBBENS, N., WALTERS, S. & BAIRD, W. (2012). Delphi research: issues raised by a pilot study. *Nurse researcher,* 19.

COCHRANE, D. & STANNARD, S. (2005). Acute whole body vibration training increases vertical jump and flexibility performance in elite female field hockey players. *British journal of sports medicine,* 39**,** 860-865.

COOMBE, A., MILLAR, S.-K., BUTTON, C. & OLDHAM, T. (2020). Defining tactical competency during turnovers in Netball: Using the Delphi method to capture expert coach knowledge. *Sport and Exercise Science New Zealand (SESNZ),* 18.

DAFFERTSHOFER, A., LAMOTH, C. J., MEIJER, O. G. & BEEK, P. J. (2004). PCA in studying coordination and variability: a tutorial. *Clinical biomechanics,* 19**,** 415-428.

DAVIDS, K., BENNETT, S. & NEWELL, K. M. (2006). *Movement system variability*, Human kinetics.

DAVIDS, K., LEES, A. & BURWITZ, L. (2000). Understanding and measuring co-ordination and control in kicking skills in soccer: Implications for talent identification and skill acquisition. *Journal of Sports Sciences,* 18**,** 703-714.

DE SUBIJANA, C. L., DE ANTONIO, R., JUAREZ, D. & NAVARRO, E. (2009). The effectiveness of the bullwhip effect in the Drag-flick in field hockey. *European Journal of Human Movement,* 23**,** 41-48.

DE SUBIJANA, C. L., GÓMEZ, M., MARTIN-CASADO, L. & NAVARRO, E. (2012). Training-induced changes in drag-flick technique in female field hockey players. *Biology of sport,* 29**,** 263-268.

DE SUBIJANA, C. L., JUÁREZ, D., MALLO, J. & NAVARRO, E. (2011). The application of biomechanics to penalty corner drag-flick training: a case study. *Journal of sports science & medicine,* 10**,** 590.

DE SUBIJANA, C., JUÁREZ, D., MALLO, J. & NAVARRO, E. (2010). Biomechanical analysis of the penalty-corner drag-flick of elite male and female hockey players. *Sports biomechanics / International Society of Biomechanics in Sports,* 9**,** 72-78.

DE WITT, J. K. & HINRICHS, R. N. (2012). Mechanical factors associated with the development of high ball velocity during an instep soccer kick. *Sports Biomechanics,* 11**,** 382-390.

DEMPSTER, W. T. (1955). Space requirements of the seated operator, geometrical, kinematic, and mechanical aspects of the body with special reference to the limbs. Michigan State Univ East Lansing.

DIAZ, G. J., FAJEN, B. R. & PHILLIPS, F. (2012). Anticipation from biological motion: the goalkeeper problem. *Journal of experimental psychology: human perception and performance,* 38**,** 848.

DICTIONARY OF SPORTS SCIENCE (1992). *Dictionary of Sports Science,* Malaga, Unisport.

DONA, G., PREATONI, E., COBELLI, C., RODANO, R. & HARRISON, A. J. (2009). Application of functional Principal Component Analysis in race walking: an emerging methodology. *Sports Biomechanics,* 8**,** 284-301.

DONOGHUE, O. A., HARRISON, A. J., COFFEY, N. & HAYES, K. (2008). Functional data analysis of running kinematics in chronic Achilles tendon injury. *Medicine and science in sports and exercise,* 40**,** 1323.

ELLIOTT, B. (1999). *Training in Sport,* Chichester, Wiley.

ELLIOTT, B. C., MARSHALL, R. N. & NOFFAL, G. J. (1995). Contributions of upper limb segment rotations during the power serve in tennis. *Journal of applied Biomechanics,* 11**,** 433-442.

ELLIOTT, B., MARSH, T. & BLANKSBY, B. (1986). A three-dimensional cinematographic analysis of the tennis serve. *Journal of Applied Biomechanics,* 2**,** 260-271.

ELLIOTT, B., MARSH, T. & OVERHEU, P. (1989). A biomechanical comparison of the multisegment and single unit topspin forehand drives in tennis. *Journal of Applied Biomechanics,* 5**,** 350-364.

ELLIOTT, B., MARSHALL, R. & NOFFAL, G. (1996). The role of upper limb segment rotations in the development of racket-head speed in the squash forehand. *Journal of sports sciences,* 14**,** 159-165.

ESKIYECEK, C., BINGÜL, B., BULGAN, Ç. & AYDIN, M. (2018). 3D biomechanical analysis of targeted and non-targeted drag flick shooting technique in field hockey. *Acta Kinesiologica,* 2**,** 13-19.

FEDEROLF, P. A. (2013). A novel approach to solve the "missing marker problem" in marker-based motion analysis that exploits the segment coordination patterns in multi-limb motion data. *PloS one,* 8**,** e78689.

FEDEROLF, P. A. (2016). A novel approach to study human posture control:"Principal movements" obtained from a Principal Component Analysis of kinematic marker data. *Journal of biomechanics,* 49**,** 364-370.

FEDEROLF, P., BOYER, K. & ANDRIACCHI, T. (2013). Application of Principal Component Analysis in clinical gait research: identification of systematic differences between healthy and medial knee-osteoarthritic gait. *Journal of biomechanics,* 46**,** 2173-2178.

FEDEROLF, P., REID, R., GILGIEN, M., HAUGEN, P. & SMITH, G. (2014). The application of Principal Component Analysis to quantify technique in sports. *Scandinavian Journal of Medicine & Science in Sports,* 24**,** 491-499.

FEDEROLF, P., REID, R., GILGIEN, M., HAUGEN, P. & SMITH, G. (2012). Quantitative assessment of skiing technique using Principal Component Analysis. *Science and Skiing V,(152-159)*.

FELTNER, M. & DAPENA, J. (1986). Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch. *Journal of Applied Biomechanics,* 2**,** 235-259.

FETISOVA, Y., ZOIS, J., SPITTLE, M. & DAWSON, A. (2021). Coaches' internal model of the tennis serve technique: Knowing or understanding? *International Journal of Sports Science & Coaching,* 16**,** 568-584.

FLEISIG, G., CHU, Y., WEBER, A. & ANDREWS, J. (2009). Variability in baseball pitching biomechanics among various levels of competition. *Sports Biomechanics,* 8**,** 10-21.

FRISTON, K., HOLMES, A., POLINE, J., GRASBY, P., WILLIAMS, S., FRACKOWIAK, R., & TURNER, R. (1995). Analysis of fMRI time-series revisited. *Neuroimage,* 2, 45-53.

GLAZIER, P. S. & ROBINS, M. T. (2012). Comment on "Use of deterministic models in sports and exercise biomechanics research" by Chow and Knudson. *Sports Biomechanics,* 11**,** 120-122.

GLAZIER, P. S. (2021). Beyond animated skeletons: How can biomechanical feedback be used to enhance sports performance? *Journal of Biomechanics,* 129**,** 110686.

GLAZIER, P. S., WHEAT, J. S., PEASE, D. L., BARTLETT, R. M., DAVIDS, K., BENNETT, S. & NEWELL, K. (eds.) (2006). *The interface of biomechanics and motor control*.

GLØERSEN, Ø., MYKLEBUST, H., HALLÉN, J. & FEDEROLF, P. (2018). Technique analysis in elite athletes using Principal Component Analysis. *Journal of sports sciences,* 36**,** 229-237.

GOLLHOFER, A., TAUBE, W. & NIELSEN, J. (2012). *Routledge handbook of motor control and motor learning* Abingdon, Routledge.

GÓMEZ, M., DE SUBIJANA, C., ANTONIO, R. & NAVARRO, E. (2012). Kinematic pattern of the drag-flick: a case study. *Journal of human kinetics,* 35**,** 27-33.

GOULD, D., DIEFFENBACH, K. & MOFFETT, A. (2002). Psychological characteristics and their development in Olympic champions. *Journal of applied sport psychology,* 14**,** 172-204.

GREEN, H., HUNTER, C. & MOORE, B. (1990). Assessing the environmental impact of tourism development: use of the Delphi technique. *Tourism Management,* 11**,** 111-120.

GUBA, E. G. & LINCOLN, Y. S. (1994). Competing paradigms in qualitative research. *Handbook of qualitative research,* 2**,** 105.

HAID, T. H., DOIX, A.-C. M., NIGG, B. M. & FEDEROLF, P. A. (2018). Age effects in postural control analyzed via a Principal Component Analysis of kinematic data and interpreted in relation to predictions of the optimal feedback control theory. *Frontiers in aging neuroscience,* 10**,** 22.

HAMILL, J., VAN EMMERIK, R. E., HEIDERSCHEIT, B. C. & LI, L. (1999). A dynamical systems approach to lower extremity running injuries. *Clinical biomechanics,* 14**,** 297-308.

HARRISON, A. J., RYAN, W. & HAYES, K. (2007). Functional data analysis of joint coordination in the development of vertical jump performance. *Sports Biomechanics,* 6**,** 199-214.

HAY, J. & REID, G. (1982). *Anatomy, Mechanics and Human Motion,* Englewood Cliffs, NJ, Prentice-Hall.

HEIDERSCHEIT, B. C., HAMILL, J. & VAN EMMERIK, R. E. (2002). Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain. *Journal of applied biomechanics,* 18**,** 110-121.

HOWELL, D. C. 2012. *Statistical methods for psychology*, Cengage Learning.

HUBLEY-KOZEY, C., DELUZIO, K., LANDRY, S., MCNUTT, J. & STANISH, W. (2006). Neuromuscular alterations during walking in persons with moderate knee osteoarthritis. *Journal of Electromyography and Kinesiology,* 16**,** 365-378.

HUCKLEKEMKES, J. (1992). Model technique for the women's 100-meter hurdles. *Track Technique,* 118**,** 3759-3766.

HUDSON, J. L. (1997). The biomechanics body of knowledge. Proceedings of the fourth national symposium on teaching biomechanics. Denton: Texas Woman's University, Citeseer, 21-43.

HUGHES, M. D. & BARTLETT, R. M. (2002). The use of performance indicators in performance analysis. *Journal of sports sciences,* 20**,** 739-754.

HUGHES, M., FRANKS, I. M. & DANCS, H. (2019). *Essentials of performance analysis in sport*, Routledge.

HUSSAIN, I., AHMED, S. & KHAN, S. (2012). Biomechanical study on drag flick in field hockey. *International Journal Behavioral Social Mvt Sciences,* 1**,** 186-193.

HUSSAIN, I., MOHAMMAD, A., KHAN, A., BARI, A., AHMAD, A. & AHMAD, S. (2010). Penalty Stroke in Field Hockey: A Biomechanical Study. *International Journal of Sports Science and Engineering,* 5**,** 53-57.

HUYS, R., SMEETON, N. J., HODGES, N. J., BEEK, P. J. & WILIAMS, A. M. (2008). On the dynamic information underlying visual anticipation skill. *Perception & Psychophysics,* 70**,** 1217-1234.

IBRAHIM, R., FABER, G., KINGMA, I. & VAN DIEËN, J. (2017). Kinematic analysis of the drag flick in field hockey. *Sports Biomechanics,* 16**,** 45-57.

ISHII, K., SUZUKI, M., SAITO, Y., MUIRA, K. & FUKINAGA, H. (1984). Contribution factors to increase velocity of a distal end in human body: Ball throwing. Biomechanics: The Olympic Scientific Congress Proceedings. Eugene, OR: Microform Publications, 1986. 87-93.

JÖRIS, H., VAN MUYEN, A. E., VAN INGEN SCHENAU, G. & KEMPER, H. (1985). Force, velocity and energy flow during the overarm throw in female handball players. *Journal of biomechanics,* 18**,** 409-414.

KENT, M. (2006). *Oxford dictionary of sports science and medicine*, OUP Oxford.

KEOGH, J. W., WEBER, C. L. & DALTON, C. T. (2003). Evaluation of anthropometric, physiological, and skill-related tests for talent identification in female field hockey. *Canadian Journal of Applied Physiology,* 28**,** 397-409.

KERR, R. & NESS, K. (2006). Kinematics of the field hockey penalty corner push-in. *Journal of Sports Biomechanics,* 5**,** 47-61.

KNUDSON, D. & MORRISON, C. (1996). An integrated qualitative analysis of overarm throwing. *Journal of Physical Education, Recreation & Dance,* 67**,** 31-36.

KNUDSON, D. (2007). Qualitative biomechanical principles for application in coaching. *Sports biomechanics / International Society of Biomechanics in Sports,* 6**,** 109-18.

KNUDSON, V. & MORRISON, S. (2002). *Qualitative analysis of human movement,* Champaign, IL, Human Kinetics.

KOHONEN, T. (2012). *Self-organizing maps*, Springer Science & Business Media.

KREIGHBAUM, E. & BARTHELS, K. (1996). Biomehanics: A qualitative approach for studying human movement. Allyn and Bacon.

KUHN, T. (1970). *The structure of scientific revolutions,* Chicago, London, University of Chicago Press Ltd.

LADRU, B.-J., LANGHOUT, R., VEEGER, D.-J., GIJSSEL, M. & TAK, I. (2019). Lead knee extension contributes to drag-flick performance in field hockey. *International Journal of Performance Analysis in Sport,* 19**,** 556-566.

LAIRD, P. & SUTHERLAND, P. (2003). Penalty corners in field hockey: A guide to success. *International Journal of Performance Analysis in Sport,* 3**,** 19-26.

LAMB, P. & BARTLETT, R. (2013). Neural networks for analysing sports techniques. *Routledge handbook of sports performance analysis.* Routledge.

LAMB, P. F. & BARTLETT, R. M. (2017). Assessing movement coordination. *In:* PAYTON, C. (ed.) *Biomechanical Evaluation of Movement in Sport and Exercise.* Routledge.

LAMB, P. F., BARTLETT, R. M. & ROBINS, A. (2011). Artificial neural networks for analyzing inter-limb coordination: The golf chip shot. *Human Movement Science,* 30**,** 1129-1143.

LANDRY, S. C., MCKEAN, K. A., HUBLEY-KOZEY, C. L., STANISH, W. D. & DELUZIO, K. J. (2007). Knee biomechanics of moderate OA patients measured during gait at a self-selected and fast walking speed. *Journal of biomechanics,* 40**,** 1754-1761.

LANGDOWN, B. L., BRIDGE, M. & LI, F.-X. (2012). Movement variability in the golf swing. *Sports Biomechanics,* 11**,** 273-287.

LATASH, M. L. (2008). *Synergy*, Oxford University Press.

LATASH, M. L. (2012). The bliss (not the problem) of motor abundance (not redundancy). *Experimental brain research,* 217**,** 1-5.

LATASH, M. L., SCHOLZ, J. P. & SCHÖNER, G. (2002). Motor control strategies revealed in the structure of motor variability. *Exercise and sport sciences reviews,* 30**,** 26-31.

LATASH, M. L., SCHOLZ, J. P. & SCHÖNER, G. (2007). Toward a New Theory of Motor Synergies. *Motor Control,* 11**,** 276-308.

LAVRAKAS, P. J. (2008). *Encyclopedia of survey research methods*, Sage publications.

LEES, A. & NOLAN, L. (2002). Three-dimensional kinematic analysis of the instep kick under speed and accuracy conditions. *In:* SPINKS, W., REILLY, T. & MURPHY, A. (eds.) *Science and football IV.* London: Routledge.

LEES, A. (1999). Biomechanical assessment of individual sports for improved performance. *Sports medicine,* 28**,** 299-305.

LEES, A. (2002). Technique analysis in sports: a critical review. *Journal of sports sciences,* 20**,** 813-828.

LEES, A. (2008). Qualitative biomechanical analysis of technique. *In:* HUGHES, M. & FRANKS, I. M. (eds.) *The essentials of performance analysis: an introduction.* London: Routledge.

LEES, A. (2017). Qualitative biomechanical analysis of technique. *In:* PAXTON & BURGEN, A. (eds.) *Biomechanical Evaluation of Movement in Sport and Excercise.* London: Routledge.

LEWIS-BECK, M., BRYMAN, A. E. & LIAO, T. F. (2003). *The Sage encyclopedia of social science research methods*, Sage Publications.

LI, X., SANTAGO, A., VIDT, M., & SAUL, K. Analysis of effects of loading and postural demands on upper limb reaching in older adults using statistical parametric mapping. *J. Biomech*. 49, 2806–2816.

LIAMPUTTONG, P. (2008). *Doing cross-cultural research: Ethical and methodological perspectives*, Springer.

LU, T.-W. & O'CONNOR, J. (1999). Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. *Journal of biomechanics,* 32**,** 129-134.

LUTTGENS, K. & HAMILTON, N. (1997). *Kinesiology,* Madison, WI, Brown & Benchmark.

MANAL, K., MCCLAY, I., STANHOPE, S., RICHARDS, J. & GALINAT, B. (2000). Comparison of surface mounted markers and attachment methods in estimating tibial rotations during walking: an in vivo study. *Gait & posture,* 11**,** 38-45.

MANNA, I., KHANNA, G. & DHARA, P. (2009). Training induced changes on physiological and biochemical variables of young Indian field hockey players. *Biology of Sport,* 26**,** 33.

MCKENNA, H. P. (1994). The Delphi technique: a worthwhile research approach for nursing? *Journal of advanced nursing,* 19**,** 1221-1225.

MCLAUGHLIN, P. (1997). *Three-dimensional biomechanical analysis of the hockey drag flick: full report*, Australian Sports Commission.

MCPHERSON, M. (1990). A systematic approach to skill analysis. *Sports Science Periodical on Research Technology in Sport,* 11**,** 1-10.

MCPHERSON, M. N. (1996). Qualitative and quantitative analysis in sports. *The american journal of sports medicine,* 24**,** S85-S88.

MITCHELL-TAVERNER, C. (2005). *Field Hockey Techniques & Tactics*, Human Kinetics.

MOHR, M., PIEPER, R., LÖFFLER, S., SCHMIDT, A. R. & FEDEROLF, P. A. (2021). Sex-specific hip movement is correlated with pelvis and upper body rotation during running. *Frontiers in bioengineering and biotechnology,* 9**,** 521.

MORRISON, A., MCGRATH, D. & WALLACE, E. (2016). Motor abundance and control structure in the golf swing. *Human movement science,* 46**,** 129-147.

MOSQUERA, R. P., MOLINUEVO, J. S. & ROMÁN, I. R. (2007). Differences between international men's and women's teams in the strategic action of the penalty corner in field hockey. *International Journal of Performance Analysis in Sport,* 7**,** 67-83.

MULLINEAUX, D. & WHEAT, J. (2018). Research Methods: Sample size and variability effects on statistical power. *In:* PAYTON, C. & BURDEN, A. (eds.) *Biomechanical evaluation of movement in sport and exercise : the British Association of Sport and Exercise Sciences guide.* Second edition. ed. London: Routledge.

MUNIZ, A. & NADAL, J. (2009). Application of Principal Component Analysis in vertical ground reaction force to discriminate normal and abnormal gait. *Gait & posture,* 29**,** 31-35.

MURRY JR, J. W. & HAMMONS, J. O. (1995). Delphi: A versatile methodology for conducting qualitative research. *The review of higher education,* 18**,** 423-436.

NEWELL, K. M. & CORCOS, D. M. (1993). Issues in variability and motor control. *In:* NEWELL, K. M. & CORCOS, D. M. (eds.) *Variability and motor control.* Champaign, Illinois: Human Kinetics.

ORMONEIT, D., BLACK, M. J., HASTIE, T. & KJELLSTRÖM, H. (2005). Representing cyclic human motion using functional analysis. *Image and Vision Computing,* 23**,** 1264-1276.

PALANIAPPAN, R. & VISWANATH, S. (2018). Biomechanical analysis of penalty corner drag flick in field hockey. *ISBS Proceedings Archive,* 36**,** 690.

PATAKY, T., ROBINSON, M., & VANRENTERGHEM, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *J. Biomech.* 46, 2394–2401.

PATAKY, T., VANRENTERGHEM, J., ROBINSON, M., & LIEBL, D. (2019). On the validity of statistical parametric mapping for nonuniformly and heterogeneously smooth one-dimensional biomechanical data. *Journal of Biomechanics*. 91, 114-123.

PATTON, M. Q. (2002). *Qualitative research & evaluation methods*, sage.

PAYTON, C. & BARTLETT, R. (2008). Biomechanical Evaluation of Movement. *Sports Biomechanics*.

PAYTON, C. J. & BURDEN, A. (2017). *Biomechanical evaluation of movement in sport and exercise: the British Association of Sport and Exercise Sciences guide*, Routledge.

PEREZ, M. A. & NUSSBAUM, M. A. (2003). Principal components analysis as an evaluation and classification tool for lower torso sEMG data. *Journal of biomechanics,* 36**,** 1225-1229.

PIÑEIRO, R., SAMPEDRO, J. & REFOYO, I. (2007). Differences between international men's and women's teams in the strategic action of the penalty corner in field hockey. . *International Journal of Performance Analysis in Sport,* 7**,** 67-83.

PINTER, I. J., VAN SWIGCHEM, R., VAN SOEST, A. K. & ROZENDAAL, L. A. (2008). The dynamics of postural sway cannot be captured using a one-segment inverted pendulum model: a PCA on segment rotations during unperturbed stance. *Journal of neurophysiology,* 100**,** 3197-3208.

PLAGENHOEF, S. (1971). *Patterns of Human Motion: A Cinematographic Analysis. Artists, Don Curtis [and Others] Photographer (tracing Reductions) Louis Musante*, Prentice-Hall.

PREATONI, E., HAMILL, J., HARRISON, A. J., HAYES, K., VAN EMMERIK, R. E., WILSON, C. & RODANO, R. (2013). Movement variability and skills monitoring in sports. *Sports biomechanics,* 12**,** 69-92.

PROVOST, M. P., QUINSEY, V. L. & TROJE, N. F. (2008). Differences in gait across the menstrual cycle and their attractiveness to men. *Archives of Sexual Behavior,* 37**,** 598-604.

PUTNAM, C. A. (1993). Sequential motions of body segments in striking and throwing skills: descriptions and explanations. *Journal of biomechanics,* 26**,** 125-135.

RAMSAY, J. O. & SILVERMAN, B. W. (2002). *Applied Functional Data Analysis: Methods and Case Studies*, Springer New York.

ROBERTSON, D. G. E., CALDWELL, G. E., HAMILL, J., KAMEN, G. & WHITTLESEY, S. (2013). *Research methods in biomechanics*, Human kinetics.

ROBINS, R., WHEAT, J., IRWIN, G. & BARTLETT, R. (2006). The effect of shooting distance on movement variability in basketball. *Journal of Human Movement Studies,* 50**,** 217-238.

ROSALIE, S. M., MCINTYRE, A. S., STOCKMAN, S., KING, C., WATKINS, C., WILD, C. Y. & NG, L. (2017). Does skill specialisation influence individual differences in drag flicking speed and accuracy? *Journal of Sports Sciences,* 35**,** 602-609.

ROSENBLATT, N. J., HURT, C. P., LATASH, M. L. & GRABINER, M. D. (2014). An apparent contradiction: increasing variability to achieve greater precision? *Experimental brain research,* 232**,** 403-413.

RYAN, W., HARRISON, A. & HAYES, K. (2006). Functional data analysis of knee joint kinematics in the vertical jump. *Sports Biomechanics,* 5**,** 121-138.

SACKMAN, H. (1974). Delphi assessment: Expert opinion, forecasting, and group process. Rand Corp Santa Monica CA.

SADLER, G. R., LEE, H. C., LIM, R. S. H. & FULLERTON, J. (2010). Recruitment of hard-to-reach population subgroups via adaptations of the snowball sampling strategy. *Nursing & health sciences,* 12**,** 369-374.

SAHAKIAN, C. E. (1997). *The Delphi Method*, Corporate Partnering Institute.

SANDREY, M. A. & BULGER, S. M. (2008). The Delphi method: an approach for facilitating evidence based practice in athletic training. *Athletic Training Education Journal,* 3**,** 135-142.

SCHMIDT, R. A. & WRISBERG, C. A. (2008). *Motor learning and performance: A situation-based learning approach*, Human kinetics.

SCHÖLLHORN, W. I. & BAUER, H. U. (1998). Identifying individual movement styles in high performance sports by means of self-organizing Kohonen maps. ISBS-conference proceedings archive.

SCHOLZ, J. P. & SCHONER, G. (1999). The uncontrolled manifold concept: identifying control variables for a functional task. *EXPERIMENTAL BRAIN RESEARCH,* 126**,** 289-306.

SCHOLZ, J. P., SCHÖNER, G. & LATASH, M. L. (2000). Identifying the control structure of multijoint coordination during pistol shooting. *Experimental brain research,* 135**,** 382-404.

SCHOUTEN, B., TROJE, N. F., BROOKS, A., VAN DER ZWAN, R. & VERFAILLIE, K. (2010). The facing bias in biological motion perception: Effects of stimulus gender and observer sex. *Attention, Perception, & Psychophysics,* 72**,** 1256-1260.

SEIFERT, L., BUTTON, C. & DAVIDS, K. (2013). Key properties of expert movement systems in sport. *Sports medicine,* 43**,** 167-178.

SIDAWAY, B., HEISE, G. & SCHOENFELDER-ZOHDI, B. (1995). Quantifying the variability of angle-angle plots. *Journal of Human Movement Studies,* 29**,** 181-197.

SKULMOSKI, G. J., HARTMAN, F. T. & KRAHN, J. (2007). The Delphi Method for Graduate Research. *Journal of Information Technology Education,* 6**,** 1-21.

SMEETON, N. & HUYS, R. (2011). Anticipation of tennis-shot direction from whole-body movement: The role of movement amplitude and dynamics. *Human Movement Science,* 30**,** 957-965.

SMITH, B., SPARKES, A. C. & CADDICK, N. (2014). Judging qualitative research. *Research methods in sports coaching.* Routledge.

SPENCER, M., LAWRENCE, S., RECHICHI, C., BISHOP, D., DAWSON, B. & GOODMAN, C. (2004). Time–motion analysis of elite field hockey, with special reference to repeated-sprint activity. *Journal of sports sciences,* 22**,** 843-850.

STERGIOU, N., SCHOLTEN, S. D., JENSEN, J. L. & BLANKE, D. (2001). Intralimb coordination following obstacle clearance during running: the effect of obstacle height. *Gait & Posture,* 13**,** 210-220.

TEFERI, G. & ENDALEW, D. (2020). Methods of Biomechanical Performance Analyses in Sport: Systematic Review. *American Journal of Sports Science and Medicine,* 8**,** 47-52.

TIDOW, G. (1990). Models for teaching techniques and assessing movements in athletics: the long jump. *Track Technique,* 113**,** 3607-3615.

TROJE, N. F. & WESTHOFF, C. (2006). The inversion effect in biological motion perception: Evidence for a “life detector”? *Current biology,* 16**,** 821-824.

TROJE, N. F. (2002). Decomposing biological motion: A framework for analysis and synthesis of human gait patterns. *Journal of Vision,* 2**,** 371-387.

VAN GHELUWE, B., DE RUYSSCHER, I. & CRAENHALS, J. (1987). Pronation and endorotation of the racket arm in a tennis serve. *Biomechanics XB***,** 667-672.

VAUGHN, R. (1985). An algorithm for determining arm action during overarm baseball pitches. *Biomechanics IX-B***,** 510-515.

VROMEN, A. (2010). *Debating methods: Rediscovering qualitative approaches*, na.

WARMENHOVEN, J., BARGARY, N., LIEBL, L., HARRISON, A., ROBINSON, M., GUNNING, E., & HOOKER, G. (2021). PCA of waveforms and functional PCA: A primer for biomechanics. *Journal of Biomechanics*. 116, 110106.

WELLS, R. P. (1980). Assessment of signal and noise in the kinematics of normal, pathological and sporting gaits. *Proc. Special Conf. Can. Soc. Biomech.* 92-93.

WERNER, I., SZELENCZY, N., WACHHOLZ, F. & FEDEROLF, P. (2021). How Do Movement Patterns in Weightlifting (Clean) Change When Using Lighter or Heavier Barbell Loads?—A Comparison of Two Principal Component Analysis-Based Approaches to Studying Technique. *Frontiers in psychology,* 11**,** 606070.

WILLIAMS, S. J. & KENDALL, L. (2007). Perceptions of elite coaches and sports scientists of the research needs for elite coaching practice. *Journal of sports sciences,* 25**,** 1577-1586.

WINTER, D. A. (2009). *Biomechanics and motor control of human movement*, John Wiley & Sons.

WITTE, K., GANTER, N., BAUMGART, C. & PEHAM, C. (2010). Applying a Principal Component Analysis to movement coordination in sport. *Mathematical and Computer Modelling of Dynamical Systems,* 16**,** 477-488.

WOO, H. & CHAPMAN, A. E. (1992). A 3D kinematic analysis of the squash forehand stroke. *Journal of Biomechanics,* 25**,** 720.

WRIGLEY, A. T., ALBERT, W. J., DELUZIO, K. J. & STEVENSON, J. M. (2006). Principal Component Analysis of lifting waveforms. *Clinical Biomechanics,* 21**,** 567-578.

WU, G., VAN DER HELM, F. C., VEEGER, H., MAKHSOUS, M., VAN ROY, P., ANGLIN, C., NAGELS, J., KARDUNA, A. R., MCQUADE, K. & WANG, X. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. *Journal of biomechanics,* 38**,** 981-992.

YOUNG, C. & REINKENSMEYER, D. J. (2014). Judging complex movement performances for excellence: a principal components analysis-based technique applied to competitive diving. *Human Movement Science,* 36**,** 107-122.

YUSOFF, S., HASAN, N. & WILSON, B. (2008). Three-dimensional biomechanical analysis of the hockey drag flick performed in competition. *ISN Bulletin.* Malaysia: National Sport Institute of Malaysia.

CHAPTER 10:
APPENDICES

10.1 Appendix A INFORMED CONSENT EXAMPLE & PARTICIPANT INFORMATION SHEET. Source: Created by the author.

LEEDS BECKETT UNIVERSITY

Faculty of Carnegie
School of Sport

INFORMED CONSENT FORM
TITLE OF PROJECT: Physical and technical attributes that determine the success of a field hockey drag flick: A coach's perspective
RESEARCHER'S NAME: **COURSE TITLE:** **STUDENT NUMBER:** **SUPERVISORS NAME:**
The participant should complete the whole of this sheet himself/herself
Delphi Poll Method This form allows you to record your consent (or not) for the research outlined in the Information Sheet (a copy of which you received with your consent form in your joining instructions). If you choose to participate in the conversations, you will be asked to complete this form at the beginning of your interview and provided with the opportunity to ask any questions that would help you understand the research and/or the completion of this form. Please tick (✓) all boxes where you give consent and date and sign where indicated below:
A. The nature aims and risks of the research have been explained to me. I have read and understood the Information for Participants and understand what is expected of me. All my questions have been answered fully to my satisfaction. ☐ B. I understand that I can refuse to take part at any time in the research. I can notify the researchers involved and be withdrawn from it immediately without having to give a reason. I also understand that I may be withdrawn from it at any time. ☐ C. I consent to the processing of personal information for the purposes of this research study. I understand that such information will be treated as strictly confidential and handled in accordance with the provisions of the Data Protection Act 1998. ☐

D. I agree to volunteer as a participant for the study described in the information sheet and give full consent. ☐

E. This consent is specific to the particular study described in the Information for participants attached and shall not be taken to imply my consent to participate in any subsequent study or deviation from that detailed here. ☐

F. I agree that any resulting data I provide can be published without my name or identification

G. I agree to be contacted in the future by the researchers who would like to invite me to participate in follow up studies to this project, or in future studies of a similar nature. My email address is: Click here to enter text. ☐

Consent to scientific illustration

Participant's Statement:

I Click here to enter text.

agree that the research project named above has been explained to me to my satisfaction and I agree to take part in the study. I have read both the notes written above and the Information for Participants about the project and understand what the research study involves.

Signed: (Print Name) Click here to enter text. Date: Click here to enter a date.

Researcher's Statement:

I Click here to enter text.

confirm that I have carefully explained the nature, demands and any foreseeable risks (where applicable) of the proposed research to the Participant.

Signed: Click here to enter text. Date: Click here to enter a date.

10.2 Appendix B: ETHICS APPROVAL

Research Ethics - Message (HTML)

Research Ethics

researchethics@leedsmet.ac.uk

Tue 10/06/2014 17:24

Application Ref: 3914
Applicant Name: KIRSTIE GRACE
Project Title: Physical and technical attributes that determine the success of a field hockey drag flick: A coach's perspective

Dear can confirm that the above research project has been given ethical approval and can commence. Please see your online application for any comments or recommendations.

Please note that if you wish to make substantial changes to the project, new ethical approval would be required.

Click Here to View

This email has been sent to your supervisor.

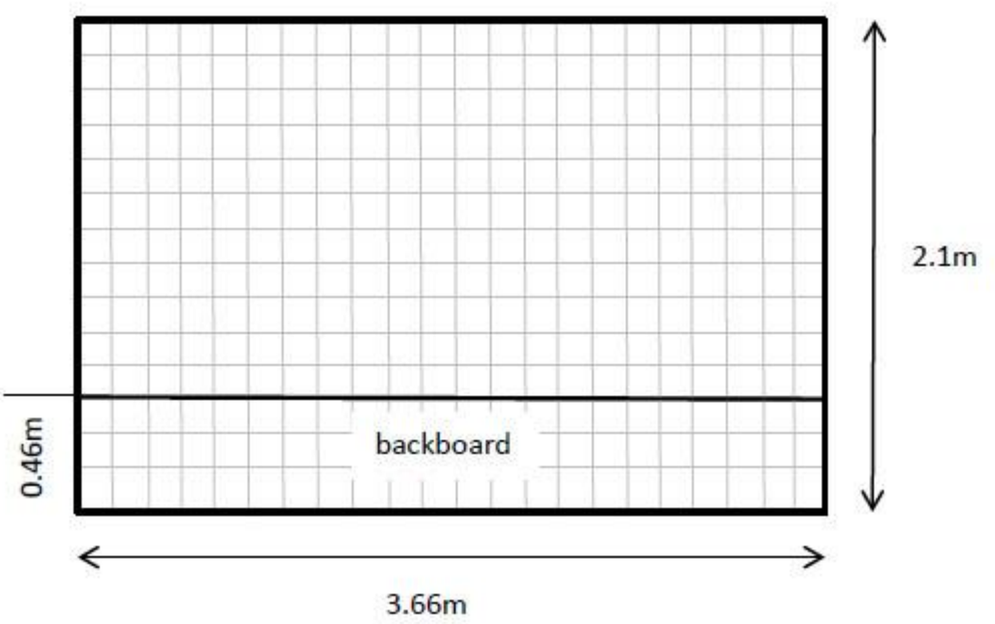
10.3 Appendix C: INTERVIEW QUESTIONS

Physical and technical attributes that determine the success of a field hockey drag flick:

A coach's perspective.

Interview Questions: First round of the Delphi Poll Method.

1. What target areas of the goal below do you feel are most successful for the drag flick?



2. What attributes do you feel contribute to a successful drag flick?

Prompts - Core skills for England Hockey

a. Timing (speed of pick up)
b. Basic grip (left hand rotated to the left)
c. Four step approach (right foot leads off, then left, right foot crosses behind left, then left)
d. Ball picked up on the shaft of the stick (hands low to the ground)
e. Placement of right foot (As far past the ball as comfortable)
f. Upper body parallel to the ground (rotates to the left during execution)
g. Stride length (Pointing forwards, as long as comfortable)
h. Ball contact (Remains in contact as long as possible)
i. Movement of ball along the shaft of the stick

Other prompts

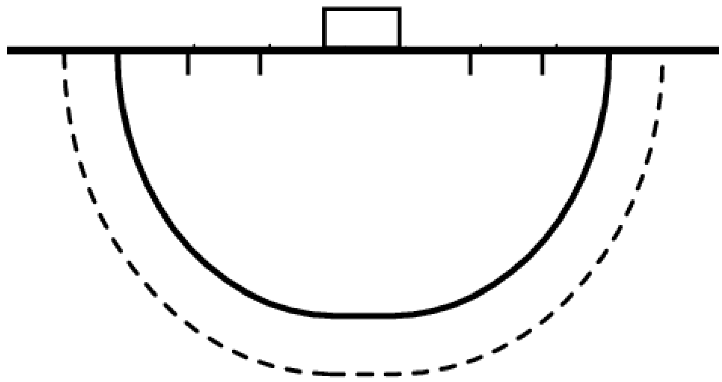
i. Core Strength (Hip rotator muscles, legs)
ii. Upper body strength
iii. Dynamic Balance
iv. Control
v. Ability to disguise
vi. Confidence
vii. Composure
viii. Bend of the knee for low position
ix. Anthropological Data

3. What performance criteria do you use for determining a successful drag flick technique?

   Prompts

   a. Accuracy
   b. Speed
   c. Trade off
   d. Disguise

4. What positions on the circle below do you coach players to perform the drag flick from at the top of the circle?



5. Does any change in position on the circle affect how they undertake the drag flick and/or how you coach it?

   Prompts

   a. Change in technique
   b. Psychological

6. Do you feel there are any differences between groups of individuals in their ability to undertake the drag flick, and if so, what are these differences? For example, novice vs. experienced, male vs. female.

   Prompts

   a. Speed females can impart on the ball (hitting faster)
   b. Experience of individuals
   c. Nurture v's nature
   d. Defenders/Attackers/midfielders
   e. Equipment such as different sticks.

7. Do your coaching/training methods change between different groups of individuals?

   Prompts

   a. Alter technique if successful
   b. Change for males or females
   c. Novice or experience both in terms of flick experience but also in general playing experience.

10.4 Appendix D: TRANSCRIPT EXAMPLE

Physical and technical attributes that determine the success of a field hockey drag flick:

Interviewee: A	Researcher: Kirstie Grace
	Supervisor:
Email: xxx	
Date of interview: 9th December 2015	
Location of interview: Remote	
K = interviewer (Kirstie) P = participant (A)	

A coach's perspective.

K: What are the attributes which contribute to a successful drag flick?

P: The challenge ill think you'll, there is a core generic method which the majority of people adopt and then you've got all sorts of variations. Ashley Jackson is always quoted as being different to everybody else. He has fast hands, fast drive, yes he has got a reasonably open body and he depends a hell of a lot on his wrist. Creating a variance into the direction. Then you will go to someone like Richard Mantell who for years when he dragged flicked for England always took the ball from the top of the circle, and he based everything on strong wrists and on small strides and was shear upper body strength. He worked on the concept of getting the ball moving from his stick at the earliest opportunity once I've got it, if you then look at the general, if you look at (Therelo) from Australia, he was working off a long slow drag, and I think this is increasingly happening, why is the case so what do I need to do first. The ball is being pulled from behind the right foot with a very long left stride, and what they're doing now is they start with a slow pull through. Then accelerate the pull through in the final phase. The other thing is watching Stoop with what Matthew did, he is saying once you've got to the final point then using the push off the back foot, and to get the extra acceleration. One of the fundamentals behind that is clearly huge amount of body strength, huge amount of core strength, huge amount of quad strength, and clearly upper arm strength in the wrist, in the forearm and in the shoulder. You cannot do a drag flick these days without that. Mink van der Weerden from

Holland, he's built incredibly strongly. The interesting one is Sardara Singh from Indian and the emerging youngster that's being played out in India are quite tall, and don't have the same European physical strength, the body appearance the muscular definition. But they are still working a long stride and fast hands, movement. They guy that was years the number one drag flicker for Hale in Pakistan he virtually created the long stride and the fast pull through. The other thing you will see is that the drag flicker once he's got the ball and he's beginning to get to the point of release, they switch feet. They transfer the weight to the right foot as the body comes through. A lot of this replicates what happens in athletics with trajectory throwing. So whenever I coach it and the same with slap hitting, foot to the ball first, foot, head, and then the ball comes through. You've got that A, B, C kind of principle. If you look at shot putting, not of course we have spinning in the circle and they change feet on the final sling. It all comes through strong core strength, and of course the upper body is incredibly strong. Even then with the shot put the final action of the push is the last think that happens and now hockey, the drag flick is exactly the same. The final things that happens is the body is in position the feet are in position and then ball through and then the fling. Same with throwing the discus, which is a more obvious one where the discus is trailing the body all the way through, the same with throwing the hammer and they're trying to generate speed on the twist and the turn, that is what is happening when the drag flickers changes foot, when he gets through onto his left foot the ball is coming through, and they change feet very quickly and they are just trying to get that final acceleration. What's the speed? They reckon these days around about 80 mph. It's a danger element, the interesting thing is that a lot of guys now are getting down the running line, and I've felt over the last 4 to 5 years it was almost banned from the game. But you will see players now running out carrying the stick well in front of the body and they're just getting hit. They'd rather do that than risk the direct shot at goal. Directional change this is interesting because now the emergence of double castle, that you've got a whole variety of ways of moving the ball to the goal and away from the goal and then back into the goal. There's not much at the moment of the player running in front of the keeper and getting the lift, it's either a direct or its wide of the right-hand post for the man running in. So how does the man do it? Well they will change the angle, either by the way the ball is carried off the wrist or the forearm or by changing position at the top of the circle. So if you look at the Dutch at the moment when they set up their double castle microseconds before injector injects, they step one to the left. If you look at Holland vs India, Mink van der Weerden, two goals, two short corner goals he got, two out of two, he steps one to the left and he just changes the angle going across the goalkeeper to the top right-hand corner and that's how he gets his angle changed, going to that side.

K: Where do they initially set up? Is it in line with the left post or?

P: Double castle in line then you step to the left. So you go outside the line of the post outside the drag. This means he's creating an angle, across the keeper so when the keepers looking at it, it's a bit like the bowler that's bowling across the body of the batsman, so he gets the picture of it going across him and it's going high as opposed to up and down which allows him to go for drive. This makes it more difficult for the goalkeeper and the runner out because the runner out at this point hasn't got the comfort of the straight line. How do they then change it to go to the other side of the goalkeeper? Well this is principally we will stick at top of the circle or we'll go at second castle to the right and then as the stick is brought through, the stick is closed over, very, very late to get the change of direction to the left of the taker, and to where the injector has gone onto the far post with a flat stick. What's happened over the last 4 to 5 years, double castles players interchanging a castle, so you might get a second castle man, if the stick receiver doesn't receive but he might run somewhere else, all your doing is looking to cause the defender eyes to be looking at something different. Psychology point of view, it's distraction stuff. The intent there is to disrupt the standard running out whether its 3 on 1, 2 on 1 high or low boxes etc. So you're always, the takers of the penalty corners always looking to outwit clearly the plans of the defending side. Who will have watched bucket loads of videos, where they will have seen where it is received? How often it is moved this way, so everybody's gambling, risk taking or predicting. How would a person develop all of this, erm, and I think this is where Matthew's work in getting Teen Stoops over from Holland to work with young players is so valuable. Clearly this guy knows exactly what he wants technically, what he doesn't do is inhibit the individual. I'll come onto Taeke Taekema. I think it's worth going back to him. Looking at his video's and he is saying I will let do this, I'll let you'll do that and then I'll give you feedback and explain how you might change one thing. He was there he was working with Josh Pavis from Beeston and Trent. He's playing under 16's a year early, and will be a top flicker, he's just getting him to have a slower drag and more push of the back foot. As he pushes through, he transfers his feet.

K: He also seemed to be, getting him to be closer to the ball on pick up which I would assume is forcing him to be a bit more in an upright position?

P: Actually Mantell might start low down, but I slightly disagree, that he's an upright man like Jackson. Erm, the Dutch, Australian, those guys all go low. They all start up but in order to get the long stride the body has to drop, with the ball being carried from back if the right foot, all the way through the body has to be low. Otherwise you would be like Jackson; there is a short step there and a lot on deception with his shoulders and his hands. How do you train somebody, A you must know what you're looking for as a coach, not to inhibit the individualism that's within that but have the principles in your own mind? Where your foot is in relation, left foot, right foot, relation to the ball, pace of the ball through. Taeke Taekema he played before he went to Klein, Switzerland, no it wasn't Klein and erm Chris the Scottish, erm…. Anyway it doesn't matter he was out there playing and coaching and when this young man was 16 he had already identified that he had got the basic techniques. He then got him into upper body strength building. He defined that what you're going to need is more powerful arms, more powerful thighs in order to generate, to allow your body to be lower and to be able to push off and get the flick. Taeke Taekema was number one in the world for some years, he's now retired from international hockey, or he got retired.

K: Performance criteria for successful drag flick?

P: Speed one because you're getting the thing moving towards goal quicker. Accuracy 2, then deception 3. What Simon Mason would say and what a goalkeeper would say, what they dislike most and I would think the ball coming at them fast, and quick whilst they potentially still moving. But these days' international goal keepers they will only go one pace off the line because they've got to react. The way you drag it's going off 14 yards. So it's not a big distance before this thing is going up into their face.

K: Target areas at the goal?

P: If I was working with younger players, then they will always think the first development themselves is top corners. I would say it isn't, I would say pace on the ball into the bottom corners. Now why do I say that? Number 1 is depends obviously you might get a players like Josh Davies who's an exception and you do get some very good flickers at the age of 15.16 with the boys now. I say them more than the girls because obviously strength, but it is happening. The other thing is the goal keepers they are playing against aren't good enough so if they go off from corners the chances are they are going to score. As strength improves then that through the growth curve and their strength development it should mean that they develop greater pace when getting the ball off the ground. And their accuracy should follow thereafter. For me you've got the body mechanics have to be right first, the positioning of the ball, before they have absolute comfort sorry to get the pace before that have absolute comfort to start getting accuracy. It's the same with chucking the aerial. I could be totally wrong because the more old fashion way is chuckling the aerial, is the ball off the back foot, left foot, and knee down, and yet you will see a lot of things. Nationals will stand up and chuck an aerial 40 yards, which is all strength. I think this is one of the things which has hugely changed over the last years, the arms strength and upper body strength of hockey players has gone up incredible. So they can chuck aerials virtually standing still. Sorry in standing position.

K: Any other target areas?

P: To go top right corner, facing the goal, right corner, bottom left. If you're going to go bottom right corner then the chances are you are going to for a deflection. And that's the other thing is that how do train that person to become able to change direction, not just to close the stick off and the body off, because if you're going to try and pull the ball to the left the chances are their body stays in a closed position. They say closed position i.e. left shoulder towards the goal and down so as to keep the runner out thinking it's going straight or right and then it's the stick and arm which does the final change. Also as they bring the ball through, then the ball starts to move on the stick as well. Sorry if they're going to the left, the ball moves left on the stick. When they are wanting to sling the ball to the right, the shoulders start open more and the ball is accelerating down the stick end. It's back to the whole concept of slinging.

K: Different groups of individuals, or any differences between groups?

P: I think at the junior end its practice, and practice. The more the elite the more likely it is you are looking for micro change. You're looking to do more video feedback, tablet feedback. You are looking for the detail of the hand position the ball position etc. The generics are still the same; they will always be the same. The same with a golfer. The ball's here, my feet are here, by body position is here, my swing is this, but how can a micro change make a difference. Moving the ball another inch backwards, having another 1 inch, 2 inch longer stride, you are in small details and that will come by experimentation and then feedback. Either the result of feedback is the ball on the goal, or in the place where you want it. Or the feedback is by looking at your own videos. I don't know of many people who do speed, measurements of the ball leaving the stick. It's extremely difficult, but I guess there is somebody who has slow mo equipment that could give feedback on the pace which people get better technique, stronger, more stronger; it goes quicker from the point of release. Jackson interestingly enough, I would suspect he's not the fastest. He gets where he gets with, I mean A he's got quite different technique; he's got a huge ability to deceive on his final movement. He is a regular right or top left, he will tend to let the ball go slightly more upright stick and off the stick end off the hook, whereas the majority of the guys are letting the ball go from say 6 inches in to the bottom of the stick and then their stick is at a 45 degree angle because that is where the body position is to the ball.

K: Participant A rang back with some additional information. He wanted to add that a lot of the examples that he had given in his previous interview were tall individuals, and therefore it is imperative that they take that long stride with their left step, to enable them to get low enough with the ball. To be able to create the speed into the ball, he also wanted to add about the footwork of the individuals and that it's important that they get that cross-over step, which then allows them to create that large step with the left leg, and then allows them to create that slinging action. He named a few girls that are successful in drag flicking; Anna Flanagan, Crista Cullen, and again they have quite a male like action in terms of the left large step and the slinging action. He mentioned something about hip and upper body.

Interview ends

10.5 Appendix E: ETHICS APPROVAL FOR BIOMECHANICAL ANALYSIS

Research Ethics - Message (HTML)

Research Ethics

researchethics@leedsbeckett.ac.uk

To [redacted]

Fri 11/12/2015 21:14

Application Ref: 20338
Applicant Name: KIRSTIE GRACE
Project Title: Biomechanical analysis of the field hockey drag flick

Dear KIRSTIE GRACE, the Local Research Ethics Co-ordinator, can confirm that the above research project has been given ethical approval and may commence. Please see your online application for any comments or recommendations.

This project has received research ethical approval in line with the Research Ethics Policy and Procedures of Leeds Beckett University.

Please note that if you wish to make substantial changes to the project, new ethical approval would be required.

Sent on behalf of the Local Research Ethics Co-ordinator.

Click Here to View

This email has been sent to your supervisor for information.

10.6 Appendix F: INFORMED CONSENT EXAMPLE & PARTICIPANT INFORMATION SHEET SOURCE: CREATED BY THE AUTHOR.

LEEDS BECKETT UNIVERSITY

Faculty of Carnegie
School of Sport

INFORMED CONSENT FORM

TITLE OF PROJECT: Biomechanical analysis of the field hockey drag flick

RESEARCHER'S NAME:
COURSE TITLE: Doctor of Philosophy
STUDENT NUMBER:

SUPERVISORS NAME:

The participant should complete the whole of this sheet himself/herself

Biomechanical analysis

This form allows you to record your consent (or not) for the research outlined in the Information Sheet (a copy of which you received with your consent form in your joining instructions). If you choose to participate in the study, you will be asked to complete this form prior to any data collection and provided with the opportunity to ask any questions that would help you understand the research and/or the completion of this form.

Please tick (✓) all boxes where you give consent and date and sign where indicated below:

	YES	NO
A. The nature, aims and risks of the research have been explained to me. I have read and understood the Information for Participants and understand what is expected of me. All my questions have been answered fully to my satisfaction.	☐	☐
B. I understand that the study will involve a small amount of super glue being in contact with my skin and there is a risk of a skin/allergy reaction to the glue. *A test of one marker will be used (on and off) prior to placing further markers on.	☐	☐
C. I understand that I can refuse to take part at any time in the research. I can notify the researchers involved and be withdrawn from it immediately without having to give a reason.	☐	☐
D. I consent to the processing of personal information for the purposes of this research study. I understand that such information will be treated as strictly confidential and handled in accordance with the provisions of the Data Protection Act 1998.	☐	☐

	YES	NO
E. I agree to volunteer as a participant for the study described in the information sheet and give full consent.	☐	☐
F. I agree to the video footage being shown to a panel of expert field hockey coaches, and understand my anonymity will be compromised with these coaches.	☐	☐
G. This consent is specific to the particular study described in the Information for participants attached and shall not be taken to imply my consent to participate in any subsequent study or deviation from that detailed here.	☐	☐
H. I agree that any resulting data I provide can be published without my name or identification	☐	☐
I. I agree to be contacted in the future by the researchers who would like to invite me to participate in follow up studies to this project, or in future studies of a similar nature. My email address is: ______________________________	☐	☐

Consent to scientific illustration

Participant's Statement:

I ______________________________

agree that the research study named above has been explained to me to my satisfaction and I agree to take part in the study. I have read both the notes written above and the Information for Participants about the study, and understand what the research study involves.

Signed: ______________________________ Date:

Researcher's Statement:

I Kirstie Grace confirm that I have carefully explained the nature, demands and any foreseeable risks (where applicable) of the proposed research to the Participant.

Signed: ______________________________ Date:

LEEDS BECKETT UNIVERSITY

Carnegie Faculty
School of Sport

Participant Information Sheet

Postgraduate Research Project

Project Title	Biomechanical analysis of the field hockey drag flick
Supervisor/Director of Studies	
Principal Investigator	
Principal Investigator telephone/mobile number	
Independent contact	

Purpose of Study and Brief Description of Procedures
(Not a legal explanation but a simple statement)

1. **What is the evaluation for?**

This research is a study in part fulfilment of a doctoral research degree. The purpose of this research is to establish a biomechanical analysis of the field hockey drag flick. The penalty corner drag flick is a relatively new skill therefore there is little published research on the skill. Given the paucity of research around the drag flick within field hockey it is the intention to collect movement analysis data on participants performing the drag flick skill under three different conditions.

- A target of 0.5^2 m will be placed in the corner of your preferred target area and you will be asked to hit the specified target with the instruction that accuracy is the primary driver.
- A target of 0.5^2 m will be placed in the corner of your preferred target area and you will be asked to hit the specified target with the instruction that velocity of the ball is the primary driver.
- Place the specified target in a different corner of the goal with the instruction of accuracy as the primary driver.

2. **Do I have to take part?**

No you do not have to take part it is your choice to do so; I am asking for a selection of participants to volunteer to take part in order to collect data to undertake a biomechanical analysis. I am hoping to analyse 20 participants who have the necessary inclusion criteria of being able to perform the drag flick skill.

3. **Can I decide what I do?**

If you choose to volunteer, you can change your mind at any time and withdraw from the research without needing to tell me why. You are also entitled to, without reason, to ask for all or part of your data to be destroyed. However, this will only be possible up to the point of analysing your data. Once it is included in the evaluation of the research, I will not be able to extract it from the study, but it will not be identifiable as your contribution.

4. **What would you like me to do?**

   You will be required to complete a par-q questionnaire initially to ensure you are fit and free from injury. If you can continue you will be marked up with 44 reflective markers in various locations on the body which will be attached to your skin with a small amount of superglue. There is a risk of skin/allergy reaction to the glue, therefore this will be tested with one marker positioned and removed before commencing placement of all other markers. You will then be given an opportunity to warm-up and familiarise yourself with the laboratory setting before testing will commence. The data collection will involve you undertaking 60 trials of the drag flick skill under three different conditions (specific in section 1 of this sheet) relating to accuracy and speed of the ball. The 60 trials will be completed in three blocks of 20 trials. You will be given a set of instructions relating to the accuracy or speed of the ball at the start of each block of twenty trials. You will be able to take breaks in between trials as necessary. Data collection will only commence when you are ready. The laboratory has been specifically set up with the dimensions of a field hockey goal and the distance to the ball is representative of the top of the circle on a field hockey pitch. In addition to the cameras which will identify the reflective markers you will also be videoed throughout your trials. This footage will be shown to a panel of expert field hockey coaches who will review your technique and offer feedback to the researcher.

5. **What are risks of taking part in this study?**

   There is a risk of fatigue within this study as you will be required to undertake 60 trials of the drag flick skill. This should be fairly standard to your training requirements, so it is recommended you do not undertake additional drag flicks outside of this study during the same training week, to minimise the effect of fatigue and possible occurrence of injury.

   There is also the risk of skin/allergy reaction to the superglue. One test marker will be used (on and off) in a small skin area prior to placing further markers. The markers will be removed by twisting and as superglue has no torsional strength; the markers will be removed with none to very mild discomfort.

   Finally there is a risk of your anonymity being compromised as your drag flicks may be viewed by a panel of expert coaches which may be known to you. You have the option of opting out of this part of the study and your confidentially will not be compromised.

6. **What are the possible benefits of taking part in this study?**

   The study is being undertaken for research purposes and to improve the current body of coaching knowledge not to critique your individual technique. You may benefit from participating in the study if you are interested in the drag flick skill. From the results I may be able to suggest qualitative feedback on your technique based on a quantitative methodology.

7. **What happens if something goes wrong?**

   All of the experimental procedures within this study are actions typical of movements undertaken regularly on a hockey pitch undertaking a drag flick skill in competition or training. Therefore, you will be familiar with the experimental protocol. Risk assessments have also been devised for use of the equipment and facilities and for the specific protocol of testing. Please inform Kirstie Grace if you would like to see these.

In the event of an accident the University code of practice on first aid will be implemented. This involves location of a first aid qualified staff and nearest first aid kit. As testing will only commence in opening hours of the fitness centre there will always be a first aider who is contactable. In rare circumstances first aid assistance is available via security via the emergency number of 4444(internal). All accidents will also be recorded using a HS1 accident report form.

In the unlikely event of you experiencing any problems that may be caused by this study you must inform Kirstie Grace immediately (contact details are at the top of this sheet) and we will do our utmost to address these.

8. What will happen to the information I provide?

All data will be saved onto a computer. This information will be password protected and not be associated with your name. Any paper files will be kept secure and not be identified by your name. Only the consent forms, which will be stored separately, will identify you by name. The information will also be used in conference presentations and for research papers, as well as for completion of a doctoral thesis.

The video footage of your drag flicks will be shown to a panel of expert field hockey coaches. Therefore, your anonymity will be compromised with these coaches. It is also possible that some coaches will recognise you and may be coaches from either your own or opposition teams to which you currently play. There is the option for you to request that your video footage is not shared with the coaching panel.

In all other cases your identity will not be discernable, except in your consent form, so all other data remains confidential.

9. Who can I talk to who knows about the research but is not involved?

If you wish to talk to someone who knows about the evaluation but is independent of the project, you can contact the independent contact for independent advice highlighted at the start of this information sheet. Alternatively, if you wish to make a complaint about the process you can contact the supervisory team also highlighted at the start of this information sheet.

10. Giving your consent

Thank for taking the time to read through this information sheet. Please ask any questions about any aspect of the research.

If you are happy to volunteer to take part you will have a copy of this information sheet to keep and I will ask you to complete a consent form recording you are happy to participate in the research as a volunteer.

This study has received ethical approval from the Local Research Ethics Co-ordinator of the Carnegie Faculty, in line with Leeds Beckett University's Research Ethics Policy.

10.7 Appendix G: MEAN INDIVIDUAL PARTICIPANT BALL VELOCITY DATA FOR EACH CONDITION.

Table 31: Mean ball velocities, Standard Deviation, and range ($m \cdot s^{-1}$); of all participants for SS ACC condition (self-selected target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	21.89	2.02	5.45	22.48	1.28	4.47	22.27	1.53	6.29
2	23.07	1.86	4.60	22.88	2.39	6.38	22.98	2.05	6.38
3	20.46	1.53	4.79	20.82	1.35	4.60	20.73	1.45	5.46
4	17.81	0.46	1.18	17.82	0.79	2.20	17.81	0.66	2.20
5	17.18	0.22	0.52	16.81	1.01	4.14	16.89	0.90	4.14
6	21.38	1.76	5.02	20.77	1.79	5.67	21.11	1.75	6.41
7	23.05	1.43	2.61	23.43	1.16	4.65	23.37	1.17	4.65
8	16.27	1.13	2.50	16.54	1.24	4.58	16.47	1.18	4.58
9	21.22	0.07	0.10	21.26	2.30	11.07	21.26	2.16	11.07
10	17.28	0.47	0.86	17.58	1.25	4.04	17.52	1.13	4.04
11	22.58	1.49	4.53	21.89	0.65	1.90	22.26	1.19	4.53
Overall	20.47	2.73	10.24	20.06	2.87	12.62	20.19	2.82	12.62

Table 32: Mean ball velocities, Standard Deviation, and range ($m \cdot s^{-1}$); of all participants for SS VEL condition (self-selected target area – ball velocity). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	24.12	1.44	4.00	23.47	2.12	4.08	23.93	1.57	4.96
2	26.13	2.02	2.85	25.18	1.98	6.63	25.32	1.93	6.63
3	21.80	1.61	3.19	21.57	0.97	3.65	21.61	1.04	3.69
4	17.78	1.53	4.50	17.92	1.37	5.10	17.88	1.38	5.10
5	17.98	0.39	0.72	16.35	1.63	6.34	16.61	1.62	6.43
6	22.52	1.58	4.04	21.95	1.37	5.13	22.12	1.41	6.42
7	21.27	0.00	0.00	24.04	1.63	6.57	23.89	1.71	7.37
8	17.62	0.14	0.19	17.29	0.97	3.44	17.33	0.93	3.44
9	21.32	0.00	0.00	20.90	3.02	15.08	20.93	2.94	15.08
10	19.11	3.03	5.98	18.07	1.26	3.81	18.33	1.74	6.04
11	22.25	1.41	3.02	24.20	1.45	4.41	23.55	1.67	6.26
Overall	21.19	3.03	12.43	20.59	3.40	18.05	20.72	3.33	18.05

Table 33: Mean ball velocities, Standard Deviation, and range ($m \cdot s^{-1}$); of all participants for P ACC condition (prescribed target area – ball velocity). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	21.84	0.00	0.00	22.96	1.49	5.64	22.87	1.46	5.64
2	23.56	1.09	2.73	23.33	1.55	4.99	23.39	1.42	4.99
3	19.58	0.98	1.39	20.34	1.61	7.21	20.27	1.55	7.21
4	16.49	1.34	4.09	16.29	1.05	3.65	16.36	1.13	4.31
5	17.93	0.68	1.82	17.61	0.88	2.84	17.72	0.81	2.84
6	20.33	1.97	5.03	20.98	1.33	4.95	20.82	1.48	6.11
7	22.90	2.69	10.08	24.12	1.54	4.37	23.57	2.16	10.08
8	16.65	1.18	2.29	16.48	0.86	2.65	16.51	0.89	2.65
9	21.39	0.96	3.09	20.82	3.84	15.08	21.08	2.88	15.08
10	17.58	0.00	0.00	17.79	1.07	3.65	17.77	1.04	3.65
11	23.18	0.67	1.55	22.16	1.20	3.49	22.50	1.14	3.49
Overall	20.36	2.98	13.70	20.36	3.08	15.08	20.19	3.04	15.68

10.8 Appendix H: MEAN INDIVIDUAL PARTICIPANT STICK RESULTANT VELOCITY DATA FOR EACH CONDITION.

Table 34: Mean stick resultant linear velocity, standard deviation, and range (m/s); of all participants for SS ACC condition (self-selected target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	20.97	1.38	3.52	21.70	1.88	6.11	21.44	1.70	6.52
2	20.43	1.07	3.20	19.23	0.91	2.61	19.87	1.14	4.54
3	19.12	2.00	5.13	19.36	1.12	3.23	19.30	1.35	5.23
4	15.76	0.52	1.38	15.90	0.62	1.93	15.85	0.57	1.93
5	15.54	0.60	1.43	14.94	0.98	3.29	15.06	0.94	3.29
6	20.15	0.95	2.91	19.25	1.61	5.14	19.75	1.33	5.69
7	20.60	0.65	1.17	20.67	1.25	4.45	20.66	1.17	4.45
8	11.89	2.49	5.17	13.95	2.45	7.25	13.40	2.55	9.95
9	18.56	0.42	0.59	19.03	0.99	2.97	18.97	0.95	2.97
10	15.90	0.46	0.92	15.71	1.11	3.87	15.75	1.00	3.87
11	20.48	1.85	4.31	21.90	1.78	4.28	21.26	1.87	5.51
Overall	18.43	2.95	14.59	18.09	2.91	14.48	18.19	2.92	17.18

Table 35: Mean stick resultant linear velocity, standard deviation, and range (m/s); of all participants for SS VEL condition (self-selected target area – ball velocity). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	22.91	2.27	5.83	24.37	4.02	6.98	23.35	2.74	6.98
2	21.11	0.21	0.29	21.47	0.90	2.48	21.42	0.84	2.48
3	19.61	0.49	0.95	19.88	0.91	3.16	19.84	0.85	3.16
4	16.24	1.25	3.26	15.75	1.64	5.83	15.90	1.52	5.83
5	15.23	1.05	1.97	15.29	1.07	3.67	15.28	1.04	3.67
6	22.05	1.03	2.62	21.41	1.94	5.62	21.60	1.72	5.62
7	20.24	0.00	0.00	21.65	0.91	2.87	21.58	0.94	2.87
8	18.19	1.34	1.90	16.84	2.20	9.16	16.98	2.14	9.16
9	16.23	0.00	0.00	19.38	0.89	3.17	19.20	1.14	4.24
10	17.24	1.32	2.58	18.73	1.21	3.48	18.38	1.34	3.84
11	19.61	2.59	6.03	20.03	3.62	10.22	19.87	3.15	10.34
Overall	19.40	3.07	11.66	19.02	2.89	14.71	19.10	2.92	14.71

Table 36: Mean stick resultant linear velocity, standard deviation, and range (m/s); of all participants for P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	23.85	0.00	0.00	23.26	2.85	8.75	23.31	2.71	8.75
2	21.87	1.03	2.66	21.26	1.10	3.87	21.42	1.09	4.49
3	18.76	0.61	0.86	18.42	1.08	4.26	18.46	1.04	4.26
4	13.87	1.63	3.97	13.51	2.05	5.75	13.64	1.88	5.75
5	15.98	0.84	2.18	15.92	0.85	3.01	15.94	0.82	3.02
6	18.69	0.58	1.36	19.56	1.16	4.37	19.34	1.10	4.37
7	21.53	1.33	3.84	21.28	1.39	4.20	21.40	1.33	4.34
8	11.24	1.78	3.21	15.21	4.47	17.80	14.47	4.35	18.16
9	19.26	0.98	2.91	19.15	1.31	4.24	19.20	1.14	4.24
10	15.18	0.00	0.00	15.20	1.48	5.82	15.20	1.43	5.82
11	20.63	0.35	0.83	21.01	1.53	4.72	20.88	1.25	4.72
Overall	18.32	3.45	13.76	18.29	3.50	17.80	18.30	3.48	18.16

10.9 Appendix I: MEAN INDIVIDUAL PARTICIPANT LENGTH OF TIME OF DRAG DATA FOR EACH CONDITION.

Table 37: Mean length of time of drag, Standard Deviation, and range (s); of all participants for SS ACC condition (self-selected target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.53	0.12	0.30	0.47	0.06	0.19	0.49	0.09	0.32
2	0.42	0.02	0.08	0.40	0.03	0.09	0.41	0.03	0.10
3	0.41	0.03	0.06	0.45	0.04	0.16	0.44	0.04	0.16
4	0.37	0.05	0.18	0.36	0.05	0.18	0.36	0.05	0.19
5	0.56	0.04	0.10	0.55	0.04	0.13	0.55	0.04	0.13
6	0.50	0.02	0.05	0.51	0.02	0.06	0.50	0.02	0.07
7	0.60	0.06	0.10	0.56	0.05	0.20	0.56	0.05	0.20
8	0.74	0.11	0.25	0.79	0.07	0.25	0.78	0.09	0.30
9	0.48	0.03	0.04	0.46	0.12	0.52	0.46	0.11	0.52
10	0.38	0.03	0.05	0.41	0.05	0.19	0.40	0.05	0.19
11	0.43	0.03	0.10	0.41	0.03	0.08	0.42	0.03	0.12
Overall	0.49	0.05	0.12	0.49	0.05	0.19	0.49	0.05	0.21

Table 38: Mean length of time of drag, Standard Deviation, and range (s); of all participants for SS VEL condition (self-selected target area – ball velocity). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.46	0.04	0.10	0.51	0.11	0.19	0.48	0.06	0.21
2	0.35	0.01	0.02	0.38	0.03	0.09	0.37	0.03	0.09
3	0.46	0.06	0.10	0.47	0.04	0.17	0.47	0.04	0.17
4	0.34	0.03	0.07	0.34	0.03	0.10	0.34	0.03	0.10
5	0.58	0.05	0.10	0.58	0.02	0.09	0.58	0.03	0.10
6	0.48	0.01	0.03	0.48	0.03	0.10	0.48	0.03	0.10
7	0.48	0.00	0.00	0.57	0.04	0.13	0.56	0.04	0.16
8	0.77	0.06	0.08	0.76	0.09	0.30	0.76	0.08	0.30
9	0.41	0.00	0.00	0.47	0.08	0.28	0.46	0.08	0.28
10	0.41	0.02	0.04	0.44	0.04	0.15	0.44	0.04	0.15
11	0.44	0.05	0.10	0.43	0.04	0.12	0.43	0.04	0.13
Overall	0.47	0.03	0.06	0.49	0.05	0.16	0.49	0.05	0.16

Table 39: Mean length of time of drag, standard deviation, and range (s); of all participants for P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.54	0.00	0.00	0.49	0.06	0.17	0.50	0.05	0.17
2	0.40	0.04	0.10	0.40	0.04	0.11	0.40	0.04	0.12
3	0.52	0.05	0.07	0.50	0.04	0.16	0.50	0.04	0.16
4	0.33	0.04	0.10	0.33	0.06	0.24	0.33	0.05	0.24
5	0.56	0.04	0.12	0.58	0.04	0.12	0.57	0.04	0.14
6	0.51	0.03	0.07	0.52	0.02	0.06	0.52	0.02	0.08
7	0.63	0.05	0.15	0.62	0.05	0.18	0.62	0.05	0.18
8	0.89	0.05	0.08	0.86	0.06	0.24	0.87	0.06	0.24
9	0.46	0.09	0.24	0.45	0.06	0.20	0.45	0.07	0.25
10	0.37	0.00	0.00	0.39	0.05	0.17	0.39	0.05	0.17
11	0.45	0.02	0.06	0.43	0.03	0.09	0.43	0.03	0.09
Overall	0.51	0.04	0.09	0.51	0.05	0.16	0.51	0.05	0.17

10.10 Appendix J: MEAN INDIVIDUAL PARTICIPANT NORMALISED DRAG DISTANCE DATA FOR EACH CONDITION.

Table 40: Mean normalised drag distance, Standard Deviation, and range (BH); of all participants for SS ACC condition (self-selected target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	1.38	0.04	0.09	1.40	0.10	0.29	1.39	0.08	0.29
2	1.51	0.18	0.57	1.51	0.26	0.67	1.51	0.21	0.67
3	1.69	0.19	0.47	1.75	0.12	0.38	1.74	0.14	0.49
4	1.07	0.12	0.38	1.08	0.08	0.27	1.08	0.09	0.38
5	1.34	0.09	0.21	1.30	0.09	0.34	1.31	0.09	0.37
6	1.64	0.13	0.48	1.64	0.10	0.34	1.64	0.11	0.48
7	1.79	0.15	0.29	1.84	0.17	0.68	1.83	0.16	0.68
8	1.33	0.31	0.72	1.58	0.20	0.60	1.51	0.25	0.92
9	1.40	0.03	0.05	1.36	0.04	0.13	1.37	0.03	0.14
10	0.97	0.15	0.28	0.98	0.16	0.48	0.98	0.15	0.48
11	1.60	0.12	0.34	1.71	0.15	0.36	1.66	0.14	0.43
Overall	1.45	0.27	1.09	1.46	0.31	1.47	1.46	0.29	1.47

Table 41: Mean normalised drag distance, Standard Deviation, and range (BH); of all participants for SS VEL condition (self-selected target area – ball velocity). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	1.56	0.05	0.15	1.52	0.10	0.19	1.55	0.07	0.19
2	1.47	0.05	0.07	1.53	0.15	0.45	1.52	0.14	0.45
3	1.76	0.22	0.42	1.73	0.12	0.47	1.73	0.13	0.47
4	1.23	0.14	0.38	1.07	0.12	0.43	1.12	0.14	0.60
5	1.17	0.14	0.28	1.19	0.11	0.39	1.19	0.11	0.39
6	1.73	0.11	0.21	1.71	0.13	0.47	1.71	0.12	0.47
7	1.53	0.00	0.00	1.79	0.15	0.50	1.78	0.16	0.50
8	1.70	0.14	0.20	1.54	0.20	0.67	1.55	0.20	0.67
9	1.56	0.00	0.00	1.36	0.14	0.55	1.37	0.14	0.55
10	1.22	0.11	0.20	1.11	0.13	0.44	1.14	0.13	0.44
11	1.88	0.24	0.52	1.74	0.15	0.46	1.79	0.19	0.64
Overall	1.52	0.27	1.15	1.48	0.29	1.23	1.49	0.29	1.38

Table 42: Mean normalised drag distance, Standard Deviation, and range (BH); of all participants for P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	1.62	0.00	0.00	1.61	0.09	0.29	1.61	0.08	0.29
2	1.43	0.06	0.14	1.48	0.16	0.59	1.47	0.14	0.59
3	1.70	0.13	0.19	1.76	0.19	0.77	1.75	0.19	0.77
4	1.09	0.10	0.31	1.13	0.19	0.62	1.12	0.16	0.62
5	1.33	0.04	0.15	1.29	0.06	0.19	1.30	0.05	0.22
6	1.69	0.12	0.34	1.77	0.08	0.30	1.75	0.09	0.40
7	1.84	0.16	0.51	1.93	0.15	0.49	1.89	0.16	0.72
8	1.78	0.16	0.28	1.65	0.13	0.49	1.67	0.14	0.57
9	1.33	0.13	0.41	1.41	0.14	0.44	1.37	0.14	0.55
10	0.81	0.00	0.00	0.99	0.18	0.76	0.98	0.18	0.76
11	1.69	0.06	0.14	1.65	0.07	0.19	1.67	0.07	0.22
Overall	1.52	0.27	1.15	1.48	0.29	1.23	1.49	0.29	1.38

10.11 Appendix K: MEAN INDIVIDUAL PARTICIPANT NORMALISED FOOT TO BALL DISTANCE DATA FOR EACH CONDITION.

Table 43: Mean normalised foot to ball distance, Standard Deviation, and range (BH); of all participants for SS ACC condition (self-selected target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.26	0.02	0.04	0.25	0.03	0.10	0.26	0.03	0.10
2	0.19	0.03	0.10	0.16	0.03	0.09	0.18	0.03	0.11
3	0.51	0.03	0.06	0.52	0.04	0.13	0.52	0.03	0.13
4	0.00	0.07	0.23	-0.03	0.08	0.30	-0.02	0.08	0.30
5	0.21	0.02	0.05	0.19	0.04	0.15	0.19	0.04	0.15
6	0.43	0.03	0.09	0.45	0.05	0.16	0.44	0.04	0.16
7	0.49	0.07	0.12	0.48	0.06	0.20	0.48	0.06	0.20
8	0.38	0.16	0.34	0.45	0.10	0.30	0.43	0.11	0.46
9	0.02	0.25	0.35	0.04	0.15	0.50	0.02	0.17	0.59
10	-0.13	0.04	0.09	-0.23	0.07	0.25	-0.21	0.08	0.30
11	0.36	0.07	0.18	0.32	0.04	0.13	0.34	0.06	0.18
Overall	0.27	0.20	0.74	0.23	0.25	1.01	0.24	0.24	1.01

Table 44: Mean normalised foot to ball distance, Standard Deviation, and range (BH); of all participants for SS VEL condition (self-selected target area – ball velocity). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.34	0.02	0.07	0.34	0.03	0.05	0.34	0.02	0.08
2	0.10	0.09	0.13	0.15	0.03	0.12	0.14	0.05	0.18
3	0.47	0.04	0.06	0.46	0.05	0.20	0.46	0.05	0.20
4	0.01	0.14	0.39	-0.07	0.07	0.24	-0.05	0.10	0.46
5	0.12	0.09	0.17	0.07	0.07	0.27	0.08	0.07	0.27
6	0.50	0.04	0.11	0.53	0.04	0.13	0.52	0.04	0.13
7	0.50	0.00	0.00	0.52	0.05	0.17	0.52	0.04	0.17
8	0.49	0.04	0.06	0.50	0.08	0.26	0.50	0.08	0.26
9	0.16	0.00	0.00	0.16	0.13	0.54	0.16	0.12	0.54
10	-0.13	0.03	0.05	-0.10	0.07	0.22	-0.11	0.06	0.22
11	0.39	0.06	0.12	0.37	0.05	0.15	0.37	0.05	0.15
Overall	0.25	0.23	0.72	0.27	0.25	0.84	0.27	0.24	0.84

Table 45: Mean normalised foot to ball distance, Standard Deviation, and range (BH); of all participants for P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.47	0.00	0.00	0.42	0.04	0.11	0.42	0.04	0.11
2	0.18	0.03	0.08	0.17	0.04	0.16	0.17	0.03	0.16
3	0.53	0.03	0.04	0.50	0.03	0.11	0.50	0.03	0.11
4	-0.02	0.10	0.22	0.00	0.09	0.29	-0.01	0.09	0.31
5	0.28	0.05	0.15	0.24	0.06	0.17	0.25	0.06	0.18
6	0.41	0.06	0.13	0.43	0.05	0.15	0.43	0.05	0.18
7	0.63	0.06	0.18	0.63	0.04	0.17	0.63	0.05	0.20
8	0.60	0.05	0.09	0.50	0.09	0.33	0.52	0.09	0.37
9	0.18	0.16	0.54	0.15	0.09	0.28	0.16	0.12	0.54
10	-0.07	0.00	0.00	-0.06	0.07	0.25	-0.06	0.07	0.25
11	0.24	0.05	0.12	0.26	0.04	0.12	0.25	0.04	0.13
Overall	0.31	0.24	0.89	0.30	0.22	0.93	0.30	0.23	0.95

10.12 Appendix L: MEAN INDIVIDUAL PARTICIPANT NORMALISED STANCE WIDTH DATA FOR EACH CONDITION.

Table 46:Mean normalised stance width, standard deviation, and range (BH); of all participants for SS ACC condition (self-selected target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.76	0.01	0.03	0.77	0.01	0.04	0.77	0.01	0.05
2	0.83	0.03	0.10	0.85	0.02	0.07	0.84	0.03	0.12
3	0.73	0.04	0.10	0.70	0.05	0.17	0.71	0.05	0.17
4	0.77	0.01	0.04	0.77	0.02	0.06	0.77	0.02	0.06
5	0.82	0.01	0.02	0.81	0.02	0.05	0.81	0.02	0.06
6	0.79	0.03	0.10	0.81	0.04	0.11	0.80	0.03	0.13
7	0.86	0.01	0.02	0.84	0.02	0.07	0.84	0.02	0.07
8	0.68	0.03	0.06	0.68	0.03	0.10	0.68	0.03	0.10
9	0.82	0.02	0.03	0.82	0.02	0.05	0.82	0.02	0.06
10	0.71	0.02	0.04	0.74	0.02	0.07	0.74	0.03	0.09
11	0.90	0.02	0.07	0.90	0.02	0.04	0.90	0.02	0.07
Overall	0.79	0.07	0.30	0.78	0.06	0.29	0.79	0.06	0.31

Table 47: Mean normalised stance width, standard deviation, and range (BH); of all participants for SS VEL condition (self-selected target area – ball velocity). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.81	0.02	0.06	0.82	0.01	0.02	0.81	0.02	0.06
2	0.86	0.01	0.01	0.86	0.01	0.03	0.86	0.01	0.03
3	0.79	0.03	0.05	0.76	0.02	0.07	0.77	0.03	0.08
4	0.77	0.02	0.05	0.78	0.02	0.09	0.77	0.02	0.09
5	0.82	0.02	0.05	0.80	0.02	0.09	0.80	0.02	0.09
6	0.82	0.02	0.06	0.82	0.03	0.10	0.82	0.03	0.10
7	0.82	0.00	0.00	0.83	0.01	0.05	0.83	0.01	0.05
8	0.65	0.01	0.02	0.69	0.04	0.17	0.69	0.04	0.17
9	0.81	0.00	0.00	0.82	0.02	0.05	0.82	0.02	0.05
10	0.75	0.01	0.02	0.75	0.02	0.06	0.75	0.02	0.06
11	0.93	0.01	0.02	0.91	0.02	0.06	0.92	0.02	0.08
Overall	0.81	0.07	0.30	0.80	0.06	0.34	0.80	0.06	0.35

Table 48: Mean normalised stance width, standard deviation, and range (BH); of all participants for P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.84	0.00	0.00	0.83	0.01	0.02	0.83	0.01	0.02
2	0.86	0.01	0.02	0.87	0.02	0.06	0.87	0.01	0.06
3	0.76	0.01	0.02	0.75	0.02	0.07	0.75	0.02	0.07
4	0.77	0.03	0.08	0.77	0.02	0.08	0.77	0.02	0.09
5	0.82	0.02	0.07	0.82	0.02	0.08	0.82	0.02	0.09
6	0.82	0.03	0.08	0.82	0.02	0.08	0.82	0.02	0.10
7	0.83	0.01	0.03	0.82	0.01	0.04	0.83	0.01	0.05
8	0.62	0.06	0.12	0.62	0.04	0.11	0.62	0.04	0.14
9	0.82	0.02	0.05	0.82	0.01	0.05	0.82	0.02	0.05
10	0.77	0.00	0.00	0.76	0.02	0.06	0.76	0.02	0.06
11	0.92	0.02	0.05	0.92	0.02	0.05	0.92	0.02	0.05
Overall	0.81	0.07	0.38	0.79	0.07	0.36	0.79	0.07	0.37

10.13 Appendix M: MEAN INDIVIDUAL PARTICIPANT CENTRE OF MASS DATA FOR EACH CONDITION AT BOTH STANCE WIDTH AND BALL RELEASE.

Table 49: Mean normalised centre of mass (COM) height at stance width, standard deviation, and range (BH); of all participants for SS ACC condition (self-selected target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.34	0.01	0.02	0.34	0.00	0.01	0.34	0.01	0.02
2	0.31	0.00	0.01	0.31	0.01	0.03	0.31	0.01	0.03
3	0.32	0.01	0.03	0.32	0.01	0.05	0.32	0.01	0.06
4	0.32	0.01	0.02	0.31	0.01	0.02	0.32	0.01	0.03
5	0.37	0.00	0.01	0.37	0.01	0.03	0.37	0.01	0.03
6	0.30	0.01	0.03	0.31	0.01	0.02	0.30	0.01	0.03
7	0.35	0.00	0.00	0.36	0.00	0.02	0.36	0.01	0.02
8	0.37	0.01	0.02	0.36	0.01	0.02	0.36	0.01	0.03
9	0.37	0.00	0.00	0.38	0.01	0.03	0.38	0.01	0.03
10	0.35	0.02	0.03	0.34	0.01	0.03	0.34	0.01	0.03
11	0.32	0.01	0.02	0.32	0.00	0.01	0.32	0.01	0.02
Overall	0.33	0.02	0.09	0.34	0.03	0.10	0.34	0.03	0.10

Table 50: Mean normalised centre of mass (COM) height at ball release, standard deviation, and range (BH); of all participants for SS ACC condition (self-selected target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.33	0.01	0.02	0.34	0.01	0.02	0.34	0.01	0.02
2	0.31	0.01	0.03	0.30	0.00	0.01	0.30	0.01	0.03
3	0.34	0.01	0.03	0.34	0.01	0.06	0.34	0.01	0.06
4	0.33	0.01	0.03	0.32	0.01	0.04	0.33	0.01	0.04
5	0.37	0.01	0.02	0.37	0.01	0.03	0.37	0.01	0.03
6	0.31	0.01	0.03	0.31	0.01	0.03	0.31	0.01	0.03
7	0.35	0.00	0.01	0.36	0.01	0.02	0.36	0.01	0.03
8	0.36	0.01	0.02	0.35	0.01	0.03	0.36	0.01	0.03
9	0.36	0.01	0.02	0.36	0.01	0.02	0.36	0.01	0.02
10	0.35	0.01	0.02	0.34	0.01	0.04	0.34	0.01	0.04
11	0.33	0.02	0.05	0.34	0.01	0.02	0.33	0.01	0.05
Overall	0.33	0.02	0.08	0.34	0.02	0.09	0.34	0.02	0.09

Table 51: Mean normalised centre of mass (COM) height at stance width, standard deviation, and range (BH); of all participants for SS VEL condition (self-selected target area – ball velocity). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.33	0.01	0.01	0.33	0.01	0.02	0.33	0.01	0.02
2	0.31	0.01	0.01	0.31	0.01	0.02	0.31	0.01	0.02
3	0.32	0.01	0.01	0.33	0.01	0.03	0.33	0.01	0.03
4	0.33	0.00	0.02	0.32	0.01	0.02	0.32	0.01	0.02
5	0.36	0.01	0.02	0.36	0.01	0.03	0.36	0.01	0.03
6	0.30	0.01	0.02	0.30	0.01	0.02	0.30	0.01	0.02
7	0.36	0.00	0.00	0.36	0.01	0.02	0.36	0.01	0.02
8	0.36	0.01	0.01	0.36	0.01	0.02	0.36	0.01	0.02
9	0.37	0.00	0.00	0.37	0.01	0.02	0.37	0.01	0.02
10	0.34	0.01	0.03	0.34	0.01	0.02	0.34	0.01	0.03
11	0.32	0.01	0.01	0.32	0.01	0.02	0.32	0.01	0.02
Overall	0.33	0.02	0.08	0.34	0.03	0.10	0.34	0.02	0.10

Table 52: Mean normalised centre of mass (COM) height at ball release, standard deviation, and range (BH); of all participants for SS VEL condition (self-selected target area – ball velocity). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.33	0.01	0.04	0.33	0.01	0.02	0.33	0.01	0.04
2	0.30	0.00	0.00	0.30	0.01	0.03	0.30	0.01	0.03
3	0.33	0.00	0.01	0.34	0.01	0.04	0.34	0.01	0.04
4	0.34	0.01	0.02	0.33	0.01	0.03	0.33	0.01	0.03
5	0.35	0.00	0.01	0.36	0.01	0.03	0.35	0.01	0.03
6	0.30	0.01	0.03	0.30	0.01	0.03	0.30	0.01	0.03
7	0.35	0.00	0.00	0.36	0.01	0.03	0.36	0.01	0.03
8	0.37	0.01	0.01	0.35	0.01	0.03	0.35	0.01	0.04
9	0.35	0.00	0.00	0.36	0.01	0.02	0.36	0.01	0.02
10	0.34	0.02	0.04	0.34	0.01	0.03	0.34	0.01	0.04
11	0.33	0.01	0.02	0.32	0.01	0.02	0.32	0.01	0.03
Overall	0.33	0.02	0.08	0.34	0.02	0.09	0.34	0.02	0.09

Table 53: Mean normalised centre of mass (COM) height at stance width, standard deviation, and range (BH); of all participants for P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.34	0.00	0.00	0.33	0.01	0.02	0.33	0.01	0.02
2	0.31	0.01	0.02	0.31	0.01	0.02	0.31	0.01	0.02
3	0.34	0.00	0.00	0.34	0.01	0.03	0.34	0.01	0.03
4	0.32	0.01	0.02	0.31	0.01	0.02	0.32	0.01	0.02
5	0.37	0.00	0.01	0.37	0.01	0.03	0.37	0.01	0.03
6	0.32	0.01	0.02	0.32	0.01	0.03	0.32	0.01	0.03
7	0.35	0.01	0.02	0.35	0.01	0.02	0.35	0.01	0.02
8	0.37	0.00	0.01	0.36	0.01	0.03	0.36	0.01	0.03
9	0.36	0.01	0.03	0.36	0.01	0.02	0.36	0.01	0.03
10	0.34	0.00	0.00	0.35	0.01	0.02	0.35	0.01	0.02
11	0.32	0.01	0.01	0.32	0.01	0.02	0.32	0.01	0.02
Overall	0.34	0.02	0.07	0.34	0.02	0.09	0.34	0.02	0.09

Table 54: Mean normalised centre of mass (COM) height at ball release, standard deviation, and range (BH); of all participants for P ACC condition (prescribed target area – ball accuracy). Source: Created by the author.

	Hit Targets			Missed Targets			Overall		
Participant	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
1	0.33	0.00	0.00	0.34	0.01	0.02	0.34	0.01	0.02
2	0.29	0.01	0.01	0.30	0.01	0.04	0.30	0.01	0.04
3	0.34	0.03	0.04	0.36	0.01	0.05	0.35	0.01	0.07
4	0.33	0.01	0.02	0.32	0.01	0.03	0.32	0.01	0.03
5	0.37	0.01	0.02	0.37	0.01	0.03	0.37	0.01	0.03
6	0.32	0.01	0.03	0.31	0.01	0.02	0.31	0.01	0.03
7	0.35	0.00	0.01	0.36	0.01	0.02	0.35	0.01	0.02
8	0.36	0.00	0.01	0.36	0.01	0.02	0.36	0.01	0.02
9	0.36	0.00	0.01	0.35	0.01	0.02	0.35	0.01	0.02
10	0.34	0.00	0.00	0.35	0.01	0.03	0.35	0.01	0.03
11	0.32	0.00	0.00	0.32	0.01	0.04	0.32	0.01	0.04
Overall	0.34	0.02	0.08	0.34	0.02	0.11	0.34	0.02	0.11

10.14 Appendix N: VIDEO LINKS TO TRIALS OF PARTICIPANT 2 FOR SS ACC CONDITION AND SS VEL CONDITION.

Link to all videos below

P2 SS ACC example trial

P2 SS VEL example trial

P4 SS ACC example trial

P4 SS VEL example trial

P10 SS ACC example trial

P10 SS VEL example trial

10.15 Appendix O: VIDEO LINKS TO TRIALS OF PARTICIPANT 7 FOR SS ACC CONDITION AND SS VEL CONDITION.

Link to all videos below

P7 SS ACC example trial

P7 SS VEL example trial

P4 SS ACC example trial

P4 SS VEL example trial

P10 SS ACC example trial

P10 SS VEL example trial

10.16 Appendix P: PMA MATLAB CODE

```
% Script to create a dimensional weight vector for male
participants
Dimweightvector =
[1.3700,1.3700,1.3700,3.535,3.5350,3.5350,9.2450,9.2450,9.2450,14
.3233,14.3233,14.3233,1.3700,1.3700,1.3700,3.5350,3.5350,3.5350,9
.2450,9.2450,9.2450,14.3233,14.3233,14.3233,7.2433,7.2433,7.2433,
7.2433,7.2433,7.2433,6.9400,6.9400,6.9400,8.5983,8.5983,8.5983,2.
1650,2.1650,2.1650,1.1150,1.1150,1.1150,0.6100,0.6100,0.6100,8.59
83,8.5983,8.5983,2.1650,2.1650,2.1650,1.1150,1.1150,1.1150,0.6100
,0.6100,0.6100,1,1,1];


% Script to create a dimensional weight vector for female
participants
Dimweightvector =
[1.29,1.29,1.29,3.695,3.695,3.695,9.795,9.795,9.795,14.4683333333
333,14.4683333333333,14.4683333333333,1.29,1.29,1.29,3.695,3.695,
3.695,9.795,9.795,9.795,14.4683333333333,14.4683333333333,14.4683
333333333,7.095,7.095,7.095,7.095,7.095,7.095,6.68,6.68,6.68,8.37
,8.37,8.37,1.965,1.965,1.965,0.97,0.97,0.97,0.56,0.56,0.56,8.37,8
.37,8.37,1.965,1.965,1.965,0.97,0.97,0.97,0.56,0.56,0.56,1,1,1];



function [P1normdata] = Matrix(Data, Dimweightvector)
%Matrix - Matlab function to centre a participant's raw marker data
and normalise marker
%data to account for anthropometric differences so that data can
be
%subsequently pooled

% Written by Kirstie Grace/Chris Low Oct 2018
% Input - 3D marker data with n markers over m trials x 101(t)
% as a tx[nx3] matrix
%
% Output - Normalised 3D marker data as a tx[nx3] matrix


%% Variable Definitions
columns = size(Data,2);
frames  = size(Data,1);

%% Step 1 Create mean free data (center the data)
Meandata = mean(Data,1); % Calculate the mean marker co-ordinate
across the whole movement to produce a mean posture
Meanfreedata = Data-repmat(Meandata,size(Data,1),1); % Centre each
marker movement around the mean posture

%% Step 2 Normalise to account for anthropetric difference
(Federolf, Roos and Nigg,2013)
% Vectornormdata = vecnorm(Meanfreedata);
% VNdata = mean(Vectornormdata);
% Vectornormfreedata = Meanfreedata/VNdata;

% CL interpretation
```

```
% Need to calculate the vector norm for each centred posture, i.e.
each row
% then take the mean of all the vector norms.
Vectornormdata = vecnorm(Meanfreedata,2,2);
VNdata = mean(Vectornormdata);
Vectornormfreedata = Meanfreedata/VNdata;

%% Step 3 Normalise to account for anthropemetric difference Weight
factor(Federolf, 2016)
% segmentdatarepmat = repmat(DimensionalweightvectorMale,909,1);
segmentdatarepmat = repmat(Dimweightvector,frames,1);
P1normdata = Vectornormfreedata.*segmentdatarepmat;

end


function [PC_vectors, PC_values] = PMA_AD(Data)
%PMA - Matlab function to calculate the Principal Components of
the pooled marker data

% Written by Kirstie Grace/Chris Low Oct 2018
% Input - Pooled normalised participant marker data
%
% Output
% - PC_vectors: A matrix of Principal Component vectors (each
column
% is a PC vector) (Eigenvectors)
% - PC_values: A vector comprising of value of each PC (Eigenvalues)



%% Calculate Eigenvectors and Eigenvalues
function PCA_result = pca( Data )
% (c) Peter Federolf, 2013, version 2.0, all rights reserved.
% If you use this code for research - in the current or in a
modified
% version - then please cite the corresponding paper:
% Federolf P.: A novel approach to solve the "missing marker
problem"
% in marker-based motion analysis that exploits the segment
coordination
% patterns in multi-limb motion data. Plos One. (submitted 2013)

% Calculate number of eigenvectors to return
n_eig = min(40,size(Data,2)-3);
opts.v0 = ones(size(Data,2),1); %Options structure starting vector

% compute covariance matrix on time series
% c = cov(Data,1);
c = Data'*Data / size(Data,1);

%Eigenvalue decomposition
[v,EV] = eigs(c,n_eig,'lm',opts);

% build the output structure
PCA_result.Eigenvectors = v;
PCA_result.Eigenvalues = diag(EV);
end
```

```
PC = pca(Data);
PC_vectors = PC.Eigenvectors;
PC_values = PC.Eigenvalues;
figure
bar(PC_values)

%% Calculate % variance explained by PC's? POSS DELETE
totalvariance = sum(PC_values);
PC1percent = (PC_values(1)/totalvariance)*100
PC2percent = (PC_values(2)/totalvariance)*100
PC3percent = (PC_values(3)/totalvariance)*100
PC4percent = (PC_values(4)/totalvariance)*100
PC5percent = (PC_values(5)/totalvariance)*100
PC6percent = (PC_values(6)/totalvariance)*100
PC7percent = (PC_values(7)/totalvariance)*100
PC8percent = (PC_values(8)/totalvariance)*100
PC9percent = (PC_values(9)/totalvariance)*100

end


function [ck,ck1] = ckind(Data, PC_vectors,N)
% function to take each normalised posture vector of a participant
and
% project it onto the pooled principal components by multiplying
each row
% in turn by a PC vector to create a matrix with each column a
vector of
% the time evolution of the coefficient for each PC - see Federolf
(2016. A
% novel approach to study human posture control. Journal of
Biomechanics
%
% Input
% Data is the individual participants normalised data
% PC_vectors is the Princiupal Component vectors
% N is the number of trials in participant data set
% This code is actually the same as simply PXnormdata x PC_vectors

frames = size (Data,1);
PC = size(PC_vectors,2);
% preallocate
ck = zeros(frames,1);

    for n =1:frames
        for j=1:PC
        ck(n,j) = Data(n,:)*PC_vectors(:,j);
        end
    end
```

```
    ck = Data*PC_vectors;

% Plot the time evolution coefficients
% figure
% plot(ck(:,1))
% title( ['Time evolution coefficient Principle Movement 1'] )
% ylabel('ck1')
% xlabel('Normalised time')
% figure
% plot(ck(:,2))
% title( ['Time evolution coefficient Principle Movement 2'] )
% ylabel('ck2')
% xlabel('Normalised time')
% figure
% plot(ck(:,3))
% title( ['Time evolution coefficient Principle Movement 3'] )
% ylabel('ck3')
% xlabel('Normalised time')
% figure
% plot(ck(:,4))
% title( ['Time evolution coefficient Principle Movement 4'] )
% ylabel('ck4')
% xlabel('Normalised time')
% figure
% plot(ck(:,5))
% title( ['Time evolution coefficient Principle Movement 5'] )
% ylabel('ck5')
% xlabel('Normalised time')
% figure
% plot(ck(:,6))
% title( ['Time evolution coefficient Principle Movement 6'] )
% ylabel('ck6')
% xlabel('Normalised time')
% figure
% plot(ck(:,7))
% title( ['Time evolution coefficient Principle Movement 7'] )
% ylabel('ck7')
% xlabel('Normalised time')
% figure
% plot(ck(:,8))
% title( ['Time evolution coefficient Principle Movement 8'] )
% ylabel('ck8')
% xlabel('Normalised time')
% figure
% plot(ck(:,9))
% title( ['Time evolution coefficient Principle Movement 9'] )
% ylabel('ck9')
% xlabel('Normalised time')
```

```
%
% % Plot mean and sd Principle Movement coefficients
% % Reshape command adjusted depending on number of trials
ck1 = reshape(ck(:,1),101,N); % 101 frames, N trials
ck2 = reshape(ck(:,2),101,N);
ck3 = reshape(ck(:,3),101,N);
ck4 = reshape(ck(:,4),101,N);
ck5 = reshape(ck(:,5),101,N);
ck6 = reshape(ck(:,6),101,N);
ck7 = reshape(ck(:,7),101,N);
ck8 = reshape(ck(:,8),101,N);
ck9 = reshape(ck(:,9),101,N);

ckm.ck1 = mean(ck1,2);
ckm.ck2 = mean(ck2,2);

ckm.ck3 = mean(ck3,2);
ckm.ck4 = mean(ck4,2);
ckm.ck5 = mean(ck5,2);
ckm.ck6 = mean(ck6,2);
ckm.ck7 = mean(ck7,2);
ckm.ck8 = mean(ck8,2);
ckm.ck9 = mean(ck9,2);

cksd.ck1 = std(ck1,1,2);
cksd.ck2 = std(ck2,1,2);
cksd.ck3 = std(ck3,1,2);
cksd.ck4 = std(ck4,1,2);
cksd.ck5 = std(ck5,1,2);
cksd.ck6 = std(ck6,1,2);
cksd.ck7 = std(ck7,1,2);
cksd.ck8 = std(ck8,1,2);
cksd.ck9 = std(ck9,1,2);

% figure
% errorbar (ckm.ck1,cksd.ck1,'b.')
% title('Mean time evolution coefficient Principle Movement 1')
% ylabel('ck1')
% xlabel('Normalised time')

% figure
% errorbar (ckm.ck2,cksd.ck2,'b.')
% title('Mean time evolution coefficient Principle Movement 2')
% ylabel('ck2')
% xlabel('Normalised time')

% figure
% errorbar (ckm.ck3,cksd.ck3,'b.')
% title('Mean time evolution coefficient Principle Movement 3')
% ylabel('ck3')
% xlabel('Normalised time')
%
% figure
% errorbar (ckm.ck4,cksd.ck4,'b.')
% title('Mean time evolution coefficient Principle Movement 4')
% ylabel('ck4')
% xlabel('Normalised time')
```

```
%
% figure
% errorbar (ckm.ck5,cksd.ck5,'b.')
% title('Mean time evolution coefficient Principle Movement 5')
% ylabel('ck5')
% xlabel('Normalised time')
%
% figure
% errorbar (ckm.ck6,cksd.ck6,'b.')
% title('Mean time evolution coefficient Principle Movement 6')
% ylabel('ck6')
% xlabel('Normalised time')
%
% figure
% errorbar (ckm.ck7,cksd.ck7,'b.')
% title('Mean time evolution coefficient Principle Movement 7')
% ylabel('ck7')
% xlabel('Normalised time')
%
% figure
% errorbar (ckm.ck8,cksd.ck8,'b.')
% title('Mean time evolution coefficient Principle Movement 8')
% ylabel('ck8')
% xlabel('Normalised time')
%
% figure
% errorbar (ckm.ck9,cksd.ck9,'b.')
% title('Mean time evolution coefficient Principle Movement 9')
% ylabel('ck9')
% xlabel('Normalised time')
%
% Plot mean and sd Principle Movement coefficients (Standardised)
% Reshape command adjusted depending on number of trials
% Axis adjusted depending on min and max of each PM Mean
coeffecients

ck1 = reshape(ck(:,1),101,N); % 101 frames, N trials
ck2 = reshape(ck(:,2),101,N);
ck3 = reshape(ck(:,3),101,N);
ck4 = reshape(ck(:,4),101,N);
ck5 = reshape(ck(:,5),101,N);
ck6 = reshape(ck(:,6),101,N);
ck7 = reshape(ck(:,7),101,N);
ck8 = reshape(ck(:,8),101,N);
ck9 = reshape(ck(:,9),101,N);

ckm.ck1 = mean(ck1,2);
ckm.ck2 = mean(ck2,2);
ckm.ck3 = mean(ck3,2);
ckm.ck4 = mean(ck4,2);
ckm.ck5 = mean(ck5,2);
ckm.ck6 = mean(ck6,2);
ckm.ck7 = mean(ck7,2);
ckm.ck8 = mean(ck8,2);
ckm.ck9 = mean(ck9,2);
```

```
cksd.ck1 = std(ck1,1,2);
cksd.ck2 = std(ck2,1,2);
cksd.ck3 = std(ck3,1,2);
cksd.ck4 = std(ck4,1,2);
cksd.ck5 = std(ck5,1,2);
cksd.ck6 = std(ck6,1,2);
cksd.ck7 = std(ck7,1,2);
cksd.ck8 = std(ck8,1,2);
cksd.ck9 = std(ck9,1,2);
%
% figure
% errorbar (ckm.ck1,cksd.ck1,'b.')
% xline(49,'--',{'BP'});
% xline(57,'--',{'FB'});
% xline(81,'--',{'SW'});
% axis([1 101 -8 6])
% % title('Mean standardised time evolution coefficient Principle
Movement 1')
% ylabel('ck1')
% xlabel('Normalised time')
%
% figure
% errorbar (ckm.ck2,cksd.ck2,'b.')
% xline(45,'--',{'BP'});
% xline(60,'--',{'FB'});
% xline(86,'--',{'SW'});
% axis([1 101 -7 8])
% % title('Mean standardised time evolution coefficient Principle
Movement 2')
% ylabel('ck2')
% xlabel('Normalised time')
%
% figure
% errorbar (ckm.ck3,cksd.ck3,'b.')
% xline(57,'--',{'BP'});
% xline(61,'--',{'FB'});
% xline(82,'--',{'SW'});
% axis([1 101 -4 7])
% % title('Mean standardised time evolution coefficient Principle
Movement 3')
% ylabel('ck3')
% xlabel('Normalised time')

% figure
% errorbar (ckm.ck4,cksd.ck4,'b.')
% xline(45,'--',{'BP'});
% xline(50,'--',{'FB'});
% xline(74,'--',{'SW'});
% axis([1 101 -3 4])
% % title('Mean standardised time evolution coefficient Principle
Movement 4')
% ylabel('ck4')
% xlabel('Normalised time')

figure
errorbar (ckm.ck5,cksd.ck5,'b.')
```

```
xline(26,'--',{'BP'});
xline(58,'--',{'FB'});
xline(80,'--',{'SW'});
axis([1 101 -3 5])
% title('Mean standardised time evolution coefficient Principle
Movement 5')
ylabel('ck5')
xlabel('Normalised time')

% figure
% errorbar (ckm.ck6,cksd.ck6,'b.')
% xline(54,'--',{'BP'});
% xline(56,'--',{'FB'});
% xline(85,'--',{'SW'});
% axis([1 101 -2 2.5])
% % title('Mean standardised time evolution coefficient Principle
Movement 6')
% % ylabel('ck6')
% xlabel('Normalised time')
%
% figure
% errorbar (ckm.ck7,cksd.ck7,'b.')
% axis([1 101 -2 2])
% title('Mean standardised time evolution coefficient Principle
Movement 7')
% ylabel('ck7')
% xlabel('Normalised time')
%
% figure
% errorbar (ckm.ck8,cksd.ck8,'b.')
% axis([1 101 -2.5 1.5])
% title('Mean standardised time evolution coefficient Principle
Movement 8')
% ylabel('ck8')
% xlabel('Normalised time')
% %
% figure
% errorbar (ckm.ck9,cksd.ck9,'b.')
% axis([1 101 -1.5 2.5])
% title('Mean standardised time evolution coefficient Principle
Movement 9')
% ylabel('ck9')
% xlabel('Normalised time')


function [PM_result] = PMind(Data,DimensionalweightvectorMale, ck,
PC_vectors)
% Function to calculate the individual participants's principal
movements
% (PM)
% Input:
% Data - the original participant movement data
% ck - time evolution coefficient (projection of normalised posture
vectors
% onto the principal component vectors
```

```
% PC_vectors - principal component vectors

%% Calculate the Scaling matrix

%% Variable Definitions
columns = size(Data,2);
frames  = size(Data,1);

%% Step 1 Create mean free data (center the data)
Meandata = mean(Data,1);
Meanfreedata = Data-repmat(Meandata,size(Data,1),1);

%%  Step  2  Normalise  to  account  for  anthropetric  difference
(Federolf, Roos and Nigg,2013)
% Vectornormdata = vecnorm(Meanfreedata);
% VNdata = mean(Vectornormdata);
% Vectornormfreedata = Meanfreedata/VNdata;

% CL interpretation
%  Need  to  calculate  the  Eucleidian  norm  (vector  norm)  for  each
centred posture, i.e. each row
% then take the mean of all the vector norms.
Vectornormdata = vecnorm(Meanfreedata,2,2);
VNdata = mean(Vectornormdata);
Vectornormfreedata = Meanfreedata/VNdata;

%% Step 3 Normalise to account for anthropemetric difference Weight
factor(Federolf, 2016)
% segmentdatarepmat = repmat(DimensionalweightvectorMale,909,1);
segmentdatarepmat = repmat(DimensionalweightvectorMale,frames,1);
DWVectordata = Vectornormfreedata.*segmentdatarepmat;

%% Scaling factor
s = diag(1/VNdata.*DimensionalweightvectorMale);
S = s^-1;
sf = diag(S);
%%  Calculate  principal  movements  as  the  sum  of  the  mean  posture
and principal component movements
% request number of PM's
M = repmat(Meandata,size(Data,1),1);
n_PM = 9;
X =['number of Principal Movements created = ',num2str(n_PM)];
disp(X)

PM_result.PM1 = M+(S*(ck(:,1)*PC_vectors(:,1)')')';
PM_result.PM2 = M+(S*(ck(:,2)*PC_vectors(:,2)')')';
PM_result.PM3 = M+(S*(ck(:,3)*PC_vectors(:,3)')')';
PM_result.PM4 = M+(S*(ck(:,4)*PC_vectors(:,4)')')';
PM_result.PM5 = M+(S*(ck(:,5)*PC_vectors(:,5)')')';
PM_result.PM6 = M+(S*(ck(:,6)*PC_vectors(:,6)')')';
PM_result.PM7 = M+(S*(ck(:,7)*PC_vectors(:,7)')')';
PM_result.PM8 = M+(S*(ck(:,8)*PC_vectors(:,8)')')';
PM_result.PM9 = M+(S*(ck(:,9)*PC_vectors(:,9)')')';
```

```
function M = PManimateHockey20_AD(PM,N)
% Function to animate the Principle movement
% Output: Structure array with animation data
% Input: PM in format PM.PMx for principle movement to animate%
PManimateGrace
% N is number of trials
% Script to animate the Principle movement
%% Create mean PMA data
a = PM; %Principle movement to plot postures from
% Frame = 1; %Frame to create posture for
n = size(a,2); % number of columns
p = zeros(1,101);
for s = 1:n
    m = posturedataprepHockey(a,s,N);
    p = [p;m'];
end
p = p(2:n+1,:);
p = p';

%% Reshape for 20 markers
Frame = 1; %Frame to create posture for
% d = PM.PM1; %Principle movement to plot postures from
P = reshape(p(Frame,:),3,20)';
x = P(:,1);
y = P(:,2);
z = P(:,3);
figure
scatter3(P(:,1),P(:,2),P(:,3))
hold on
line([x(11)              x(10)],[y(11)              y(10)],[z(11)
z(10)],'Marker','.','LineStyle','-')%Head to mid shoulder
line([x(16)              x(12)],[y(16)              y(12)],[z(16)
z(12)],'Marker','.','LineStyle','-')%left   shoulder   to   right
shoulder
line([x(16)               x(4)],[y(16)               y(4)],[z(16)
z(4)],'Marker','.','LineStyle','-')%LeftShoulder to Left Hip
line([x(12)               x(8)],[y(12)               y(8)],[z(12)
z(8)],'Marker','.','LineStyle','-')%Right Shoulder to Right Hip
line([x(16)              x(17)],[y(16)              y(17)],[z(16)
z(17)],'Marker','.','LineStyle','-')%Left Shoulder to Left Elbow
line([x(17)              x(18)],[y(17)              y(18)],[z(17)
z(18)],'Marker','.','LineStyle','-')%Left Elbow to Left Wrist
line([x(18)              x(19)],[y(18)              y(19)],[z(18)
z(19)],'Marker','.','LineStyle','-')%Left Wrist to Left Hand
line([x(12)              x(13)],[y(12)              y(13)],[z(12)
z(13)],'Marker','.','LineStyle','-')%Right Shoulder to Right Elbow
line([x(13)              x(14)],[y(13)              y(14)],[z(13)
z(14)],'Marker','.','LineStyle','-')%Right Elbow to Right Wrist
line([x(14)              x(15)],[y(14)              y(15)],[z(14)
z(15)],'Marker','.','LineStyle','-')%Right Wrist to Right Hand
line([x(19)              x(20)],[y(19)              y(20)],[z(19)
z(20)],'Marker','.','LineStyle','-')%LHand to Stick
line([x(4)                x(3)],[y(4)                y(3)],[z(4)
z(3)],'Marker','.','LineStyle','-')%Left Hip to Left Knee
line([x(3)                x(2)],[y(3)                y(2)],[z(3)
z(2)],'Marker','.','LineStyle','-')%Left Knee to Left Ankle
```

```
line([x(2)                          x(1)],[y(2)                          y(1)],[z(2)
z(1)],'Marker','.','LineStyle','-')%Left Ankle to Left Foot
line([x(8)                          x(7)],[y(8)                          y(7)],[z(8)
z(7)],'Marker','.','LineStyle','-')%Right Hip to Right Knee
line([x(7)                          x(6)],[y(7)                          y(6)],[z(7)
z(6)],'Marker','.','LineStyle','-')%Right Knee to Right Ankle
line([x(6)                          x(5)],[y(6)                          y(5)],[z(6)
z(5)],'Marker','.','LineStyle','-')%Right Ankle to Right Foot
line([x(4)                          x(8)],[y(4)                          y(8)],[z(4)
z(8)],'Marker','.','LineStyle','-')%Left Hip to Right Hip
hold off
% xlim([-0.01 0.01])
% ylim([-0.01 0.01])
% zlim([-0.01 0.01])
xlim([-2 2])
ylim([-2 2])
zlim([-2 2])
axis square
az = 120;
el = 5;
% az = -180;%-180 162
% el = 90;%90 10
view(az,el);
grid off
box off
camtarget([0,0,0])% Adjust camera position
zoom(2.0)
% h=gca;
% hold(h)
M(1)=getframe;
NoFrames = size(p,1);
for j = 2:NoFrames
    P = reshape(p(j,:),3,20)';
    x = P(:,1);
    y = P(:,2);
    z = P(:,3);
    scatter3(P(:,1),P(:,2),P(:,3))
    hold on
line([x(11)                      x(10)],[y(11)                      y(10)],[z(11)
z(10)],'Marker','.','LineStyle','-')%Head to mid shoulder
line([x(16)                      x(12)],[y(16)                      y(12)],[z(16)
z(12)],'Marker','.','LineStyle','-')%left   shoulder   to   right
shoulder
line([x(16)                        x(4)],[y(16)                        y(4)],[z(16)
z(4)],'Marker','.','LineStyle','-')%LeftShoulder to Left Hip
line([x(12)                        x(8)],[y(12)                        y(8)],[z(12)
z(8)],'Marker','.','LineStyle','-')%Right Shoulder to Right Hip
line([x(16)                      x(17)],[y(16)                      y(17)],[z(16)
z(17)],'Marker','.','LineStyle','-')%Left Shoulder to Left Elbow
line([x(17)                      x(18)],[y(17)                      y(18)],[z(17)
z(18)],'Marker','.','LineStyle','-')%Left Elbow to Left Wrist
line([x(18)                      x(19)],[y(18)                      y(19)],[z(18)
z(19)],'Marker','.','LineStyle','-')%Left Wrist to Left Hand
line([x(12)                      x(13)],[y(12)                      y(13)],[z(12)
z(13)],'Marker','.','LineStyle','-')%Right Shoulder to Right Elbow
```

```
line([x(13)                    x(14)],[y(13)                    y(14)],[z(13)
z(14)],'Marker','.','LineStyle','-')%Right Elbow to Right Wrist
line([x(14)                    x(15)],[y(14)                    y(15)],[z(14)
z(15)],'Marker','.','LineStyle','-')%Right Wrist to Right Hand
line([x(19)                    x(20)],[y(19)                    y(20)],[z(19)
z(20)],'Marker','.','LineStyle','-')%LHand to Stick
line([x(4)                      x(3)],[y(4)                      y(3)],[z(4)
z(3)],'Marker','.','LineStyle','-')%Left Hip to Left Knee
line([x(3)                      x(2)],[y(3)                      y(2)],[z(3)
z(2)],'Marker','.','LineStyle','-')%Left Knee to Left Ankle
line([x(2)                      x(1)],[y(2)                      y(1)],[z(2)
z(1)],'Marker','.','LineStyle','-')%Left Ankle to Left Foot
line([x(8)                      x(7)],[y(8)                      y(7)],[z(8)
z(7)],'Marker','.','LineStyle','-')%Right Hip to Right Knee
line([x(7)                      x(6)],[y(7)                      y(6)],[z(7)
z(6)],'Marker','.','LineStyle','-')%Right Knee to Right Ankle
line([x(6)                      x(5)],[y(6)                      y(5)],[z(6)
z(5)],'Marker','.','LineStyle','-')%Right Ankle to Right Foot
line([x(4)                      x(8)],[y(4)                      y(8)],[z(4)
z(8)],'Marker','.','LineStyle','-')%Left Hip to Right Hip
hold off
xlim([-2 2])
ylim([-2 2])
zlim([-2 2])
axis square
az = 120;
el = 5;
% az = -180;
% el = 90;
view(az,el);
grid off
box off
camtarget([0,0,0])% Adjust camera position
zoom(2.0)
%     h=gca;
%     hold(h)
    M(j)=getframe;
end
% pause
% movie(M1,1)


function
PMpostureHockey20(PM,N,Frame1,Frame2,Frame3,Frame4,Frame5)
% Function to capture particular posture in a Principle movement
% Input:    PM in format PM.PMx for principle movement to animate
%           Frame as a number
% Marker arrangement set up for Hockey data
%% Calculate mean posture matrix
% Uncomment for multiple trials
a = PM;
n = size(a,2); % number of columns
p = zeros(1,101);
for s = 1:n
    m = posturedataprepHockey(a,s,N);
    p = [p;m'];
```

```
end
p = p(2:n+1,:);
p = p';

%% Frame 1 plot
% reshape for 19 marker co-ords (Hockey data set)
figure
set(gcf,'color','w'); % set figure background to white
subplot(1,5,1)

P = reshape(PM(Frame1,:),3,20)';
x = P(:,1);
y = P(:,2);
z = P(:,3);
scatter3(P(:,1),P(:,2),P(:,3))
title( ['Frame ' num2str( Frame1 )] )
hold on
line([x(11) x(10)],[y(11) y(10)],[z(11)
z(10)],'Marker','.','LineStyle','-')%Head to mid shoulder
line([x(16) x(12)],[y(16) y(12)],[z(16)
z(12)],'Marker','.','LineStyle','-')%left shoulder to right
shoulder
line([x(16) x(4)],[y(16) y(4)],[z(16)
z(4)],'Marker','.','LineStyle','-')%LeftShoulder to Left Hip
line([x(12) x(8)],[y(12) y(8)],[z(12)
z(8)],'Marker','.','LineStyle','-')%Right Shoulder to Right Hip
line([x(16) x(17)],[y(16) y(17)],[z(16)
z(17)],'Marker','.','LineStyle','-')%Left Shoulder to Left Elbow
line([x(17) x(18)],[y(17) y(18)],[z(17)
z(18)],'Marker','.','LineStyle','-')%Left Elbow to Left Wrist
line([x(18) x(19)],[y(18) y(19)],[z(18)
z(19)],'Marker','.','LineStyle','-')%Left Wrist to Left Hand
line([x(12) x(13)],[y(12) y(13)],[z(12)
z(13)],'Marker','.','LineStyle','-')%Right Shoulder to Right Elbow
line([x(13) x(14)],[y(13) y(14)],[z(13)
z(14)],'Marker','.','LineStyle','-')%Right Elbow to Right Wrist
line([x(14) x(15)],[y(14) y(15)],[z(14)
z(15)],'Marker','.','LineStyle','-')%Right Wrist to Right Hand
line([x(19) x(20)],[y(19) y(20)],[z(19)
z(20)],'Marker','.','LineStyle','-')%LHand to Stick
line([x(4) x(3)],[y(4) y(3)],[z(4)
z(3)],'Marker','.','LineStyle','-')%Left Hip to Left Knee
line([x(3) x(2)],[y(3) y(2)],[z(3)
z(2)],'Marker','.','LineStyle','-')%Left Knee to Left Ankle
line([x(2) x(1)],[y(2) y(1)],[z(2)
z(1)],'Marker','.','LineStyle','-')%Left Ankle to Left Foot
line([x(8) x(7)],[y(8) y(7)],[z(8)
z(7)],'Marker','.','LineStyle','-')%Right Hip to Right Knee
line([x(7) x(6)],[y(7) y(6)],[z(7)
z(6)],'Marker','.','LineStyle','-')%Right Knee to Right Ankle
line([x(6) x(5)],[y(6) y(5)],[z(6)
z(5)],'Marker','.','LineStyle','-')%Right Ankle to Right Foot
line([x(4) x(8)],[y(4) y(8)],[z(4)
z(8)],'Marker','.','LineStyle','-')%Left Hip to Right Hip
hold off
xlim([-2 2])
```

```
ylim([-2 2])
zlim([-2 2])
axis square
az = 120;
el = 5;
% az = -180;%-180 162
% el = 90;%90 10
view(az,el);
grid off
axis off
zoom(2.0)
%% Frame 2 plot
subplot(1,5,2)
P = reshape(PM(Frame2,:),3,20)';
x = P(:,1);
y = P(:,2);
z = P(:,3);
scatter3(P(:,1),P(:,2),P(:,3))
title( ['Frame ' num2str( Frame2 )] )
hold on
line([x(11) x(10)],[y(11) y(10)],[z(11) z(10)],'Marker','.','LineStyle','-')%Head to mid shoulder
line([x(16) x(12)],[y(16) y(12)],[z(16) z(12)],'Marker','.','LineStyle','-')%left shoulder to right shoulder
line([x(16) x(4)],[y(16) y(4)],[z(16) z(4)],'Marker','.','LineStyle','-')%LeftShoulder to Left Hip
line([x(12) x(8)],[y(12) y(8)],[z(12) z(8)],'Marker','.','LineStyle','-')%Right Shoulder to Right Hip
line([x(16) x(17)],[y(16) y(17)],[z(16) z(17)],'Marker','.','LineStyle','-')%Left Shoulder to Left Elbow
line([x(17) x(18)],[y(17) y(18)],[z(17) z(18)],'Marker','.','LineStyle','-')%Left Elbow to Left Wrist
line([x(18) x(19)],[y(18) y(19)],[z(18) z(19)],'Marker','.','LineStyle','-')%Left Wrist to Left Hand
line([x(12) x(13)],[y(12) y(13)],[z(12) z(13)],'Marker','.','LineStyle','-')%Right Shoulder to Right Elbow
line([x(13) x(14)],[y(13) y(14)],[z(13) z(14)],'Marker','.','LineStyle','-')%Right Elbow to Right Wrist
line([x(14) x(15)],[y(14) y(15)],[z(14) z(15)],'Marker','.','LineStyle','-')%Right Wrist to Right Hand
line([x(19) x(20)],[y(19) y(20)],[z(19) z(20)],'Marker','.','LineStyle','-')%LHand to Stick
line([x(4) x(3)],[y(4) y(3)],[z(4) z(3)],'Marker','.','LineStyle','-')%Left Hip to Left Knee
line([x(3) x(2)],[y(3) y(2)],[z(3) z(2)],'Marker','.','LineStyle','-')%Left Knee to Left Ankle
line([x(2) x(1)],[y(2) y(1)],[z(2) z(1)],'Marker','.','LineStyle','-')%Left Ankle to Left Foot
line([x(8) x(7)],[y(8) y(7)],[z(8) z(7)],'Marker','.','LineStyle','-')%Right Hip to Right Knee
line([x(7) x(6)],[y(7) y(6)],[z(7) z(6)],'Marker','.','LineStyle','-')%Right Knee to Right Ankle
line([x(6) x(5)],[y(6) y(5)],[z(6) z(5)],'Marker','.','LineStyle','-')%Right Ankle to Right Foot
```

```
line([x(4) x(8)],[y(4) y(8)],[z(4) z(8)],'Marker','.','LineStyle','-')%Left Hip to Right Hip
hold off
xlim([-2 2])
ylim([-2 2])
zlim([-2 2])
axis square
az = 120;
el = 5;
% az = -180;%-180 162
% el = 90;%90 10
view(az,el);
grid off
axis off
zoom(2.0)
%% Frame 3 plot
subplot(1,5,3)
P = reshape(PM(Frame3,:),3,20)';
x = P(:,1);
y = P(:,2);
z = P(:,3);
scatter3(P(:,1),P(:,2),P(:,3))
title( ['Frame ' num2str( Frame3 )] )
hold on
line([x(11) x(10)],[y(11) y(10)],[z(11) z(10)],'Marker','.','LineStyle','-')%Head to mid shoulder
line([x(16) x(12)],[y(16) y(12)],[z(16) z(12)],'Marker','.','LineStyle','-')%left shoulder to right shoulder
line([x(16) x(4)],[y(16) y(4)],[z(16) z(4)],'Marker','.','LineStyle','-')%LeftShoulder to Left Hip
line([x(12) x(8)],[y(12) y(8)],[z(12) z(8)],'Marker','.','LineStyle','-')%Right Shoulder to Right Hip
line([x(16) x(17)],[y(16) y(17)],[z(16) z(17)],'Marker','.','LineStyle','-')%Left Shoulder to Left Elbow
line([x(17) x(18)],[y(17) y(18)],[z(17) z(18)],'Marker','.','LineStyle','-')%Left Elbow to Left Wrist
line([x(18) x(19)],[y(18) y(19)],[z(18) z(19)],'Marker','.','LineStyle','-')%Left Wrist to Left Hand
line([x(12) x(13)],[y(12) y(13)],[z(12) z(13)],'Marker','.','LineStyle','-')%Right Shoulder to Right Elbow
line([x(13) x(14)],[y(13) y(14)],[z(13) z(14)],'Marker','.','LineStyle','-')%Right Elbow to Right Wrist
line([x(14) x(15)],[y(14) y(15)],[z(14) z(15)],'Marker','.','LineStyle','-')%Right Wrist to Right Hand
line([x(19) x(20)],[y(19) y(20)],[z(19) z(20)],'Marker','.','LineStyle','-')%LHand to Stick
line([x(4) x(3)],[y(4) y(3)],[z(4) z(3)],'Marker','.','LineStyle','-')%Left Hip to Left Knee
line([x(3) x(2)],[y(3) y(2)],[z(3) z(2)],'Marker','.','LineStyle','-')%Left Knee to Left Ankle
line([x(2) x(1)],[y(2) y(1)],[z(2) z(1)],'Marker','.','LineStyle','-')%Left Ankle to Left Foot
line([x(8) x(7)],[y(8) y(7)],[z(8) z(7)],'Marker','.','LineStyle','-')%Right Hip to Right Knee
```

```
line([x(7)                          x(6)],[y(7)                          y(6)],[z(7)
z(6)],'Marker','.','LineStyle','-')%Right Knee to Right Ankle
line([x(6)                          x(5)],[y(6)                          y(5)],[z(6)
z(5)],'Marker','.','LineStyle','-')%Right Ankle to Right Foot
line([x(4)                          x(8)],[y(4)                          y(8)],[z(4)
z(8)],'Marker','.','LineStyle','-')%Left Hip to Right Hip
hold off
xlim([-2 2])
ylim([-2 2])
zlim([-2 2])
axis square
az = 120;
el = 5;
% az = -180;%-180 162
% el = 90;%90 10
view(az,el);
grid off
axis off
zoom(2.0)
%% Frame 4 plot
subplot(1,5,4)
P = reshape(PM(Frame4,:),3,20)';
x = P(:,1);
y = P(:,2);
z = P(:,3);
scatter3(P(:,1),P(:,2),P(:,3))
title( ['Frame ' num2str( Frame4 )] )
hold on
line([x(11)                      x(10)],[y(11)                      y(10)],[z(11)
z(10)],'Marker','.','LineStyle','-')%Head to mid shoulder
line([x(16)                      x(12)],[y(16)                      y(12)],[z(16)
z(12)],'Marker','.','LineStyle','-')%left   shoulder   to   right
shoulder
line([x(16)                       x(4)],[y(16)                       y(4)],[z(16)
z(4)],'Marker','.','LineStyle','-')%LeftShoulder to Left Hip
line([x(12)                       x(8)],[y(12)                       y(8)],[z(12)
z(8)],'Marker','.','LineStyle','-')%Right Shoulder to Right Hip
line([x(16)                      x(17)],[y(16)                      y(17)],[z(16)
z(17)],'Marker','.','LineStyle','-')%Left Shoulder to Left Elbow
line([x(17)                      x(18)],[y(17)                      y(18)],[z(17)
z(18)],'Marker','.','LineStyle','-')%Left Elbow to Left Wrist
line([x(18)                      x(19)],[y(18)                      y(19)],[z(18)
z(19)],'Marker','.','LineStyle','-')%Left Wrist to Left Hand
line([x(12)                      x(13)],[y(12)                      y(13)],[z(12)
z(13)],'Marker','.','LineStyle','-')%Right Shoulder to Right Elbow
line([x(13)                      x(14)],[y(13)                      y(14)],[z(13)
z(14)],'Marker','.','LineStyle','-')%Right Elbow to Right Wrist
line([x(14)                      x(15)],[y(14)                      y(15)],[z(14)
z(15)],'Marker','.','LineStyle','-')%Right Wrist to Right Hand
line([x(19)                      x(20)],[y(19)                      y(20)],[z(19)
z(20)],'Marker','.','LineStyle','-')%LHand to Stick
line([x(4)                          x(3)],[y(4)                          y(3)],[z(4)
z(3)],'Marker','.','LineStyle','-')%Left Hip to Left Knee
line([x(3)                          x(2)],[y(3)                          y(2)],[z(3)
z(2)],'Marker','.','LineStyle','-')%Left Knee to Left Ankle
```

```
line([x(2)                    x(1)],[y(2)                    y(1)],[z(2)
z(1)],'Marker','.','LineStyle','-')%Left Ankle to Left Foot
line([x(8)                    x(7)],[y(8)                    y(7)],[z(8)
z(7)],'Marker','.','LineStyle','-')%Right Hip to Right Knee
line([x(7)                    x(6)],[y(7)                    y(6)],[z(7)
z(6)],'Marker','.','LineStyle','-')%Right Knee to Right Ankle
line([x(6)                    x(5)],[y(6)                    y(5)],[z(6)
z(5)],'Marker','.','LineStyle','-')%Right Ankle to Right Foot
line([x(4)                    x(8)],[y(4)                    y(8)],[z(4)
z(8)],'Marker','.','LineStyle','-')%Left Hip to Right Hip
hold off
xlim([-2 2])
ylim([-2 2])
zlim([-2 2])
axis square
az = 120;
el = 5;
% az = -180;%-180 162
% el = 90;%90 10
view(az,el);
grid off
axis off
zoom(2.0)
%% Frame 5 plot
subplot(1,5,5)
P = reshape(PM(Frame5,:),3,20)';
x = P(:,1);
y = P(:,2);
z = P(:,3);
scatter3(P(:,1),P(:,2),P(:,3))
title( ['Frame ' num2str( Frame5 )] )
hold on
line([x(11)                 x(10)],[y(11)                 y(10)],[z(11)
z(10)],'Marker','.','LineStyle','-')%Head to mid shoulder
line([x(16)                 x(12)],[y(16)                 y(12)],[z(16)
z(12)],'Marker','.','LineStyle','-')%left   shoulder   to   right
shoulder
line([x(16)                  x(4)],[y(16)                  y(4)],[z(16)
z(4)],'Marker','.','LineStyle','-')%LeftShoulder to Left Hip
line([x(12)                  x(8)],[y(12)                  y(8)],[z(12)
z(8)],'Marker','.','LineStyle','-')%Right Shoulder to Right Hip
line([x(16)                 x(17)],[y(16)                 y(17)],[z(16)
z(17)],'Marker','.','LineStyle','-')%Left Shoulder to Left Elbow
line([x(17)                 x(18)],[y(17)                 y(18)],[z(17)
z(18)],'Marker','.','LineStyle','-')%Left Elbow to Left Wrist
line([x(18)                 x(19)],[y(18)                 y(19)],[z(18)
z(19)],'Marker','.','LineStyle','-')%Left Wrist to Left Hand
line([x(12)                 x(13)],[y(12)                 y(13)],[z(12)
z(13)],'Marker','.','LineStyle','-')%Right Shoulder to Right Elbow
line([x(13)                 x(14)],[y(13)                 y(14)],[z(13)
z(14)],'Marker','.','LineStyle','-')%Right Elbow to Right Wrist
line([x(14)                 x(15)],[y(14)                 y(15)],[z(14)
z(15)],'Marker','.','LineStyle','-')%Right Wrist to Right Hand
line([x(19)                 x(20)],[y(19)                 y(20)],[z(19)
z(20)],'Marker','.','LineStyle','-')%LHand to Stick
```

```
line([x(4)                          x(3)],[y(4)                          y(3)],[z(4)
z(3)],'Marker','.','LineStyle','-')%Left Hip to Left Knee
line([x(3)                          x(2)],[y(3)                          y(2)],[z(3)
z(2)],'Marker','.','LineStyle','-')%Left Knee to Left Ankle
line([x(2)                          x(1)],[y(2)                          y(1)],[z(2)
z(1)],'Marker','.','LineStyle','-')%Left Ankle to Left Foot
line([x(8)                          x(7)],[y(8)                          y(7)],[z(8)
z(7)],'Marker','.','LineStyle','-')%Right Hip to Right Knee
line([x(7)                          x(6)],[y(7)                          y(6)],[z(7)
z(6)],'Marker','.','LineStyle','-')%Right Knee to Right Ankle
line([x(6)                          x(5)],[y(6)                          y(5)],[z(6)
z(5)],'Marker','.','LineStyle','-')%Right Ankle to Right Foot
line([x(4)                          x(8)],[y(4)                          y(8)],[z(4)
z(8)],'Marker','.','LineStyle','-')%Left Hip to Right Hip
hold off
xlim([-2 2])
ylim([-2 2])
zlim([-2 2])
axis square
az = 120;
el = 5;
% az = -180;%-180 162
% el = 90;%90 10
view(az,el);
grid off
axis off
zoom(2.0)
end

function playmovie(M1)
% playmovie script
% use 1st frame to get dimensions
[h, w, p] = size(M1(1).cdata);
hf = figure;
% resize figure based on frame's w x h, and place at (150, 150)
set(hf,'Position', [150 150 w h]);
axis off
% Place frames at bottom left
movie(hf,M1,4,30,[0 0 0 0]);
end
```

10.17 Appendix Q: VIDEO LINKS TO PRINCIPAL MOVEMENTS

Link to all videos below

Figure 31 P2 PM1 All Conditions

Figure 32 P2 PM2 SS ACC

Figure 33 P1 PM2 SS VEL and P ACC

Figure 34 P2 PM3 SS ACC

Figure 35 P1 PM3 SS VEL

Figure 36 P9 PM3 P ACC

Figure 37 P2 PM4 SS ACC

Figure 38 P1 PM4 SS VEL

Figure 40a P11 PM4 P ACC

Figure 40b P1 PM4 P ACC

Figure 40c P3 PM3 P ACC

Figure 40d P7 PM4 P ACC

Figure 42 P2 PM5 SS ACC

Figure 43d P1 PM5 SS VEL

Figure 43e P10 PM5 SS VEL

Figure 44f P6 PM5 P ACC

Figure 44g P4 PM5 P ACC