THE LONGITUDINAL APPLICATION OF BIOMECHANICAL BIOFEEDBACK TOWARD WHOLE LIMB COMPLEX MOTOR SKILL DEVELOPMENT

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ABSTRACT

The Longitudinal Application of Biomechanical Biofeedback on Whole Limb Complex Motor Skill Development

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The provision of augmented feedback using biomechanical measures, termed biofeedback (BFb), both guides and reinforces skill development. Previous BFb research has; mostly used simple skills that do not transfer to complex skills, focused on single joints thus missing BFb influence on other variables within the kinematic chain, and omitted long-term retention testing so learning is not assessed. Therefore, using 3 themes, the aim of this thesis was to identify the effectiveness of knowledge of performance (KP) BFb on influencing a whole limb complex motor skill, and assess longitudinal retention.

Theme 1 identified biomechanically relevant task dynamics, using the fencing attacking lunge as a vehicle for analysis. Differences between skilled (n=7) and novice (n=8) fencers in the rear leg kinematic chain identified skilled displayed greater proximal-to-distal extension angular velocity (skilled, 1.9±0.7, 6.0±2.4, 9.1±2.1 for hip, knee and ankle; novice, 2.4±0.9, 4.6±1.3, 5.4±2.9 rad·s^{-1}; $p<0.05$) and greater normalised horizontal impulse (skilled 2.51±0.25; novice 1.92±0.36 Ns·kg^{-1}); $p<0.05$), and that ankle plantarflexion correlated with peak horizontal force ($r=0.81$; $p<0.05$).

Findings from Theme 1 informed a visual, KP intervention for Theme 2 to assess the effectiveness of an intervention applied to a whole limb technique. Novice participants randomized to BFb (n=16) and Control groups (n=16) visited the laboratory on three occasions over one week, and returned for retention testing at 4-6weeks. Findings indicated that KP on whole limb kinematic extension angular velocities, and sequential patterning of joints, was effective in manipulating the whole limb kinematic chain in a novel lunge task. Angular velocities significantly increased at post testing by 34±38%, 25±24% and 33±47% for the hip, knee and ankle in the BFb group versus no significant change of 9±29%, 6±20% and 8±28% in

Controls. There were no changes in any external kinetics, and no correlation between ankle plantarflexion and any external kinetic measures for the 4416 lunges.

Theme 3 examined learning through a dynamical systems framework, exploring coordination during a longitudinal, 26-week KP intervention using a fading schedule (i.e. increasing time between visits). Kinematic changes occurred within just two visits, and were retained throughout the intervention for the BFb group. Coordination coupling of both the hip-knee and knee-ankle angular-velocities, quantified using a modified vector coding (VC) method, did not change in both groups ($p>0.05$). Given known limitations of VC, a new coupling-area based method was developed ($CI2_{Area}$) to quantify longitudinal coordination-variability. BFb participants demonstrated a continual increase in coordination-variability, shown by the positive gradient of $CI2_{Area}$ over the 26-weeks for the BFb versus negative gradient for Controls (hip-knee BFb 0.7, Control -0.9; knee-ankle BFb 3.14, Control -0.24). In addition to the group effect, 9 individuals who had a $CI2_{Area}$ greater than the upper 95%CI of the Control group's gradient were considered to have responded to the BFb.

In conclusion, this thesis contributes to the body of knowledge, using the developed $CI2_{Area}$ as a new method to explore learning in whole-limb complex tasks. This research demonstrated that a fading BFb KP intervention is effective for long-term learning and changes are achieved quickly in targeted variables.

PUBLICATIONS

Journal Articles:

Mulloy, F., Mullineaux, D. R., Graham-Smith, P. and Irwin, G. (2018). An applied paradigm for simple analysis of the lower limb kinematic chain in explosive movements: an example using the fencing foil attacking lunge. *International Biomechanics*, 5 (1), 9-16.

Mulloy, F., Irwin, G., Williams, G.R., and Mullineaux, D. R. (2019). Quantifying bi-variate coordination variability during longitudinal motor learning of a complex skill. *Journal of Biomechanics,* 95.

International Conference Articles:

Mulloy, F., Mullineaux, D.R., and Irwin, G. (2015). Use of the kinematic chain in the fencing attacking. *Proceedings of the 33rd International Conference of Biomechanics in Sport*, Poittiers, France.

Mulloy, F., Mullineaux, D.R., and Irwin, G. (2016). Manipulation of the kinematic chain using visual biofeedback. *Proceedings of the 34th International Conference of Biomechanics in Sport*, Tsukuba, Japan.

Mulloy, F., Mullineaux, D.R., and Irwin, G. (2017). Longitudinal manipulation of the kinematic chain using a reducing biofeedback schedule. *Proceedings of the 35th International Conference of Biomechanics in Sport*, Cologne, Germany.

Mulloy, F., Mullineaux, D.R., Williams, G. R., and Irwin, G. (2018). Coordination variability associated with attendence to a longitudinal reducing biofeedback schedule. *Proceedings of the 36th International Conference of Biomechanics in Sport* Auckland, New Zealand.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE AND DEFINITIONS

Abbreviations used for terminology

BFb	biofeedback
KP	knowledge of performance
KR	knowledge of results
RQ	research question
EMG	electromyography
GRF	ground reaction force
IDA	Inverse dynamics analysis
VC	Vector Coding
CRP	Continuous relative phase
CoM	centre of mass

Symbols used to represent variables in equations and figures

F	force
m	mass
a	acceleration
t	time
v	velocity
g	acceleration due to gravity (-9.81 m·s^{-2})
θ	angular displacement
ω	angular velocity
α	angular acceleration
I	moment of inertia
HK	segment defined from hip to knee
KA	segment defined from knee to ankle
HA	translational separation between hip and ankle
V_{HA}	velocity of separation of hip and ankle
$\hat{Y}$	Mean coupling angle calculated from VC
Ø	Phase angle used in CRP
Θ	Normalised spatial angle used in CRP
Ω	Normalised angular velocity used in CRP
F_{Opt}	Optimal force derived from force-velocity curve
V_{Opt}	Optimal velocity derived from force-velocity curve
P_{Max}	Maximal power derived from force-velocity curve.

CHAPTER 1: INTRODUCTION

1.1. Research Overview

Feedback is critical for motor learning, allowing for the detection and correction of movement errors alongside practice (Salmoni et al., 1984). The provision of external, or augmented, feedback has been shown to accelerate skill development relative to practice alone (Nunes et al., 2014; Ericksen et al., 2015). Further, the majority of information has emerged from the provision of information on task success (knowledge of results), and not information related to the technical requirements (knowledge of performance; KP). The latter is important when specific technique is desired. While feedback has a range of applications in clinical (Cirstea et al., 2006; Secoli et al., 2011; Tsaih et a., 2018), sport (Mononen et al., 2003; Kontinnen et al., 2004; Winchester et al., 2009; Mullineaux et al., 2012; Schaffert and Mattes, 2014; 2015; Hwangbro, 2015), and exercise domains (Crowell et al., 2010; Creaby et al., 2016; Bowser et al., 2018; Zhang et al., 2019), applications to complex, multi-joint skill performed in everyday life skills are not clear. Historically, guiding principles for the application of biofeedback have emerged from research with simple skills (Adams, 1971; Newell et al., 1983; Swinnen et al., 1990; Smith and Loschner, 2002; Snodgrass et al., 2010) with the assumption that findings apply to more complex, ecologically valid skills. However, principles derived from simple tasks do not always apply to complex skills (Wulf and Shea, 2002).

Human movement in complex motor skills involves the interaction of multiple joint rotations (van Ingen Schenau, 1989a). Biofeedback interventions that have focused on complex skills have predominantly targeted changes of individual joints (e.g.

Jackson et al., 2017). Problematically, changes in one joint can have negative implications on other joints within the linked kinematic chain (Ford et al., 2015; Richards et al., 2018a). The neuromuscular design of the kinematic chain is an effective proximal-to-distal power transfer mechanism which utilises bi-articular muscles (Gregoire et al., 1984; Jacobs et al., 1996; Bobbert and van Soest, 2001; Cleather et al., 2015; Wong et al., 2016). It is important, therefore, that biofeedback designs to modify complex skills incorporate the whole limb contribution and do not detrimentally disrupt this power transfer mechanism. This research builds on previous research in technique-based biofeedback (Kernodle and Carlton, 1992; Eriksson et al., 2011; Mullineaux et al., 2012; Thow et al., 2012; Ericksen et al., 2015; Jackson et al., 2017; Richards et al., 2018a; 2018b) and the whole limb kinematic chain (Gregoire et al., 1984; Jacobs et al., 1996; Cleather et al., 2011) to provide a more holistic approach toward enhancing the influence of biofeedback in complex motor skill development.

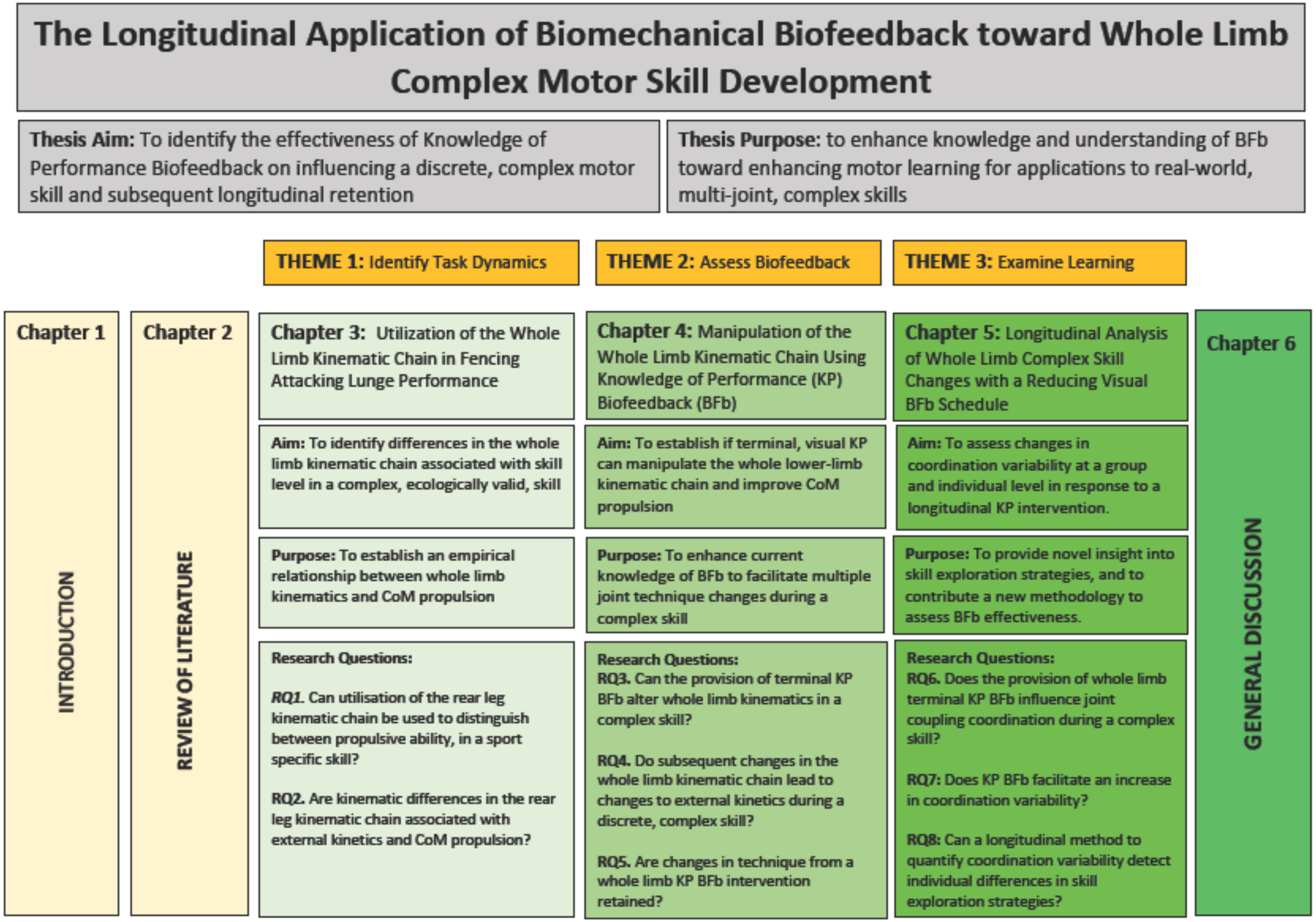
Biofeedback is considered to provide direction (Lauber et al., 2013) and aid in the search for emergent movement patterns, refining muscle synergies and creating a faster and more efficient learning process (Araújo et al., 2004). The dynamical systems perspective to motor learning frames the emergence of coordination through skill exploration (Bernstein, 1967; Newell, 1986; Turvey, 1990; Newell and Vaillencourt, 2001). Biofeedback, in the context of learning, has been assessed from a linear biomechanical perspective where the assessment of permanent learning is obtained using simple retention tests, within relatively short timeframes (Broker et al., 1993; Mononen et al., 2003; Kontinnen et al., 2004; Mullineaux et al., 2012;

Ericksen et al., 2015). Long term retention is important to assess the permanency of learning (Newell, 2003; Williams and Hodges, 2005). This research will combine traditional biomechanical measures with theoretical approaches underpinning the more contemporary dynamic systems perspective. By combining biomechanics and motor learning, this research aims to provide information to inform and guide effective skill development for practitioners using technique-based biofeedback.

1.2. Statement of Aim and Purpose

To date, there is limited evidence documenting knowledge to underpin biofeedback (BFb) applications related to technique of complex, gross motor skills. Although there are a variety of applications of BFb within the literature, there is limited evidence addressing multi-joint interaction and guiding direction. The overall aim of this thesis, therefore, was **to identify the effectiveness of KP BFb on influencing a whole limb complex motor skill, and the subsequent longitudinal retention.** This thesis combines traditional biomechanical approaches to whole limb contributions with a dynamic systems framework to motor learning. Through these complimentary approaches, the purpose of this research was **to enhance knowledge and understanding of BFb toward enhancing motor learning for applications to real-world, multi-joint, complex skills.** This research will provide applied practitioners in clinical and sports settings with guidelines to enhance motor learning interventions.

In order to address the aims and purpose of this thesis, a discrete, complex motor task is required as a vehicle to explore skill development. Throughout this thesis, the the fencing attacking lunge is used as the skill selected required a whole limb to contribute to task success, in this case generating centre of mass velocity, however with the velocity-accuracy trade off requiring a refinement of motor skill. The overall aim was addressed through three themes, explored within the empirical chapters (chapters 3-5) of this body of work. The themes were 1) to **identify** biomechanically relevant **task dynamics** for biofeedback, 2) **assess** the effectiveness of **biofeedback** applied to whole limb technique, and 3) **examine learning** through the perspective of Dynamic Systems Theory. The overview, themes, and general layout of the thesis are displayed in figure 1.1.



The Longitudinal Application of Biomechanical Biofeedback toward Whole Limb Complex Motor Skill Development

Thesis Aim: To identify the effectiveness of Knowledge of Performance Biofeedback on influencing a discrete, complex motor skill and subsequent longitudinal retention

Thesis Purpose: to enhance knowledge and understanding of BFb toward enhancing motor learning for applications to real-world, multi-joint, complex skills

THEME 1: Identify Task Dynamics

THEME 2: Assess Biofeedback

THEME 3: Examine Learning

Chapter 1

INTRODUCTION

Chapter 2

REVIEW OF LITERATURE

Chapter 3: Utilization of the Whole Limb Kinematic Chain in Fencing Attacking Lunge Performance

Aim: To identify differences in the whole limb kinematic chain associated with skill level in a complex, ecologically valid, skill

Purpose: To establish an empirical relationship between whole limb kinematics and CoM propulsion

Research Questions:

RQ1. Can utilisation of the rear leg kinematic chain be used to distinguish between propulsive ability, in a sport specific skill?

RQ2. Are kinematic differences in the rear leg kinematic chain associated with external kinetics and CoM propulsion?

Chapter 4: Manipulation of the Whole Limb Kinematic Chain Using Knowledge of Performance (KP) Biofeedback (BFb)

Aim: To establish if terminal, visual KP can manipulate the whole lower-limb kinematic chain and improve CoM propulsion

Purpose: To enhance current knowledge of BFb to facilitate multiple joint technique changes during a complex skill

Research Questions:

RQ3. Can the provision of terminal KP BFb alter whole limb kinematics in a complex skill?

RQ4. Do subsequent changes in the whole limb kinematic chain lead to changes to external kinetics during a discrete, complex skill?

RQ5. Are changes in technique from a whole limb KP BFb intervention retained?

Chapter 5: Longitudinal Analysis of Whole Limb Complex Skill Changes with a Reducing Visual BFb Schedule

Aim: To assess changes in coordination variability at a group and individual level in response to a longitudinal KP intervention.

Purpose: To provide novel insight into skill exploration strategies, and to contribute a new methodology to assess BFb effectiveness.

Research Questions:

RQ6. Does the provision of whole limb terminal KP BFb influence joint coupling coordination during a complex skill?

RQ7: Does KP BFb facilitate an increase in coordination variability?

RQ8: Can a longitudinal method to quantify coordination variability detect individual differences in skill exploration strategies?

Chapter 6

GENERAL DISCUSSION

Figure 1.1. Schematic displaying the organisational structure of the thesis.

1.3. Development of Research Questions

A limitation which permeates throughout motor learning literature is that research relating to skill development often does not assess biomechanically relevant variables linked to the sought performance outcome (e.g. Wulf et al., 2010) or complex skills with multiple DoF. Therefore, the first theme of this thesis, and subsequent research questions, were developed to ensure that the content of biofeedback was empirically linked to the task selected as a vehicle of research throughout.

Theme 1: Identification of Relevant Task Dynamics as Content for Biofeedback

The bi-articularity of the kinematic chain as a power transfer mechanism has been offered as an explanation of stereotypical proximal-to-distal sequenced kinematics leading to large propulsive capabilities (Gregoire et al., 1984; van Ingen Schenau, 1989a; Putnam, 1991; 1993; Jacobs et al., 1996; Bobbert, 2001; Bobbert and van Soest, 2001; Cleather et al., 2011; Cleather et al., 2015; Wong et al., 2016). The fencing attacking lunge requires the rear leg to generate CoM propulsion, with greater velocity achieved in higher level athletes (Yiou and Do, 2000; Bottoms et al., 2013). The kinematic chain allows for the whole limb to be assessed, however limited research has applied analysis of the kinematic chain to single leg propulsion outside of sprinting tasks (Jacobs et al., 1996). To address the limitations of existing research related to whole limb contribution, the following research question was established:

RQ1. Can utilisation of the rear leg kinematic chain be used to distinguish between propulsive ability, in a sport specific skill?

It is important to link kinematic contributions to performance. Therefore, considering that the whole limb kinematic chain is reportedly a mechanism to generate greater propulsive forces (van Ingen Schenau, 1986; Hof, 2001; Jacobs et al., 1996), which would lead to greater sword velocity (Yio and Do, 2000) the following research question was developed:

RQ2. Are kinematic differences in the rear leg kinematic chain associated with external kinetics and CoM propulsion?

Research questions 1-2 formulated chapter 3 which sought to better understand differences in the kinematic chain which may relate to greater propulsive capabilities within the constraints of the fencing attacking lunge skill.

Theme 2: The Effectiveness of Biofeedback Applied to Whole Limb Technique

Considering that biofeedback relating to a single joint can have adverse effects on related joints within the kinematic chain (Richards et al., 2018a), information that encompasses the whole limb would be an effective tool to facilitate successful complex skill modifications. Limited research applies biofeedback to multiple joints simultaneously, therefore if it can be it was established that magnitude and timing of hip, knee and ankle joint extension within the rear leg kinematic chain were linked to propulsive force capabilities, the following research question emerged:

RQ3. Can the provision of terminal KP BFb alter whole limb kinematics in a complex skill?

Chapter 3 identifies correlations between performer kinematics and external kinetics in a cross-sectional design. Additionally, biofeedback research has shown the provision of kinematics can result in secondary effects if the theoretical relationship is strong (Ford et al., 2015; van der Noort et al., 2015; Baggaley et al., 2017). Therefore, to confirm the relationship between rear leg kinematics and kinetics in chapter 3, and to investigate the secondary effects of altering the rear leg kinematic chain, the next research question was formulated:

RQ4. Do subsequent changes in the whole limb kinematic chain lead to changes to external kinetics during a discrete, complex skill?

Alterations in skill can be temporary modifications to performance, or more permanent changes deemed as learning. Within biofeedback, retention testing is essential to assess the permanence of learning (Schmidt and Lee, 2005). Surprisingly, within the biofeedback literature, retention testing is often omitted, or is limited to short time periods (e.g. 24 hours). Therefore, the final research question within this theme was:

RQ5. Are changes in technique from a whole limb KP BFb intervention retained?

Research questions 3-5 formed the framework for chapter 4, the second empirical chapter, to assess the effectiveness of biofeedback applied to whole limb kinematics in an explosive complex skill.

Theme 3: Examine Learning through the Perspective of Dynamical Systems Theory

Research has highlighted the usefulness of biofeedback toward enhancing motor skill development. However, limited research offers an explanation on the emergence of skills during these interventions. Dynamic systems theory explains the emergence of coordinative structures (Bernstein, 1967; Newell, 1985; Turvey 1990) through constraints to action (Newell, 1986). With the provision of whole limb technical information to provide direction to learning in chapter 4, understanding the emergence of skill through the lens of DST approach provides invaluable information into the influence of biofeedback on motor learning. Therefore, the following research question was developed:

RQ6. Does the provision of whole limb terminal KP BFb influence joint coupling coordination during a complex skill?

Given that the kinematic chain is seen as a stereotypical movement pattern, inherently emerging in whole limb propulsive movements due to the neuromuscular design (Gregoire et al., 1984; van Ingen Schenau et al., 1989a; Bobbert and van Soest, 2001) it seems reasonable that coordination structures may not change drastically. Biofeedback is thought to direct skill exploration (Lauber et al., 2013). Coordination variability is a central component to the emergence of new skills from a DST perspective (Newell, 1985). Subsequently, the next research question emerged:

RQ7. Does KP BFb facilitate an increase in joint coordination variability?

Coordination variability provides valuable insight into the emergence of skill. Understanding the emergence of skill longitudinally enhances understanding of complex motor learning, with immediate application to applied practitioners (Newell, 2003; Bowser et al., 2018). Existing methodologies to quantify coordination variability do not provide a simple global assessment of coordination and skill exploration and are difficult to apply longitudinally. Further, applicability of findings from group research may not allow for individual application in the applied world. Therefore, a new method to quantify coordination variability on a group and individual level, over time, was developed. The following research question was addressed to direct this theoretical underpinning:

RQ8: Can a longitudinal method to quantify coordination variability detect individual differences in skill exploration strategies?

Research questions 5-8 provided the theoretical framework to address the final theme of this thesis which formulated chapter 5. The aim this chapter was to examine how the provision of whole limb KP biofeedback longitudinally influenced motor learning.

1.4. Organisation of Thesis Chapters

1.4.1. Chapter 2 - Review of Literature

Chapter 2 provides an overview and discussion of the literature from biofeedback, motor learning, and applications of these principles to complex skill development. The first part of this chapter introduces biomechanical biofeedback and provides historical context and concurrent applications. The second component of this chapter introduces and discusses contemporary knowledge underpinning motor learning, both from a neurological and theoretical basis. Motor learning is critically viewed to provide understanding of the mechanisms support biofeedback. Considerations for an effective biofeedback intervention are then critically appraised, before the final component introduces the principle of the kinematic chain and how this may be integrated into the fencing attacking lunge skill identified as a vehicle for analysis during the body of this thesis.

1.4.2. Chapter 3 – Determinants of fencing attacking lunge performance and use of the kinematic chain

Chapter 3 approaches the first theme of this thesis by identifying content which may underpin whole limb contribution in an ecologically valid skill. The chapter uses a traditional biomechanical approach to identify differences between the rear leg kinematic chain toward CoM propulsion, and thus greater sword velocity, associated with skill in task execution. Using a cross sectional design, novice fencers were compared to elite fencers. The rear leg kinematics and external kinetics were investigated, with the findings from Chapter 3 providing content for a whole limb KP intervention designed for Chapter 4.

1.4.3. Chapter 4 – Manipulation of the kinematic chain using knowledge of performance biofeedback to develop a gross complex motor skill

This chapter addresses the second theme of the thesis by assessing the effectiveness of a KP intervention to alter multiple joint kinematics within the kinematic chain. A range of athletes from various sports were presented with visual KP containing joint extension magnitude and timing for the rear leg in a simplified lunge-touch task. Changes in rear leg kinematics, external kinetics, and performance variables were assessed following the intervention. Retention testing at four to six weeks was investigated to confirm the retention of changes induced. Finally, the relationship between the rear leg kinematic chain and propulsion was examined in more detail.

1.4.4. Chapter 5 - Longitudinal Analysis of Whole Limb Complex Skill Changes Using A Reducing Visual Knowledge of Performance Biofeedback Schedule

The final empirical chapter of this thesis, chapter 5 combines the linear traditional biomechanical approaches with a DST perspective to examine longitudinal changes within the complex biological system which emerged with attendance to the biofeedback design. This addresses the final theme within this thesis, by examining how biofeedback influences motor learning. Linear regressions and breakpoint analysis were used to assess where changes occurred with learning, along with vector coding to determine any changes in coordination. A new approach was then developed and applied to quantify coordination variability of joint coupling, using bi-variate continuous data analysis techniques and longitudinal analysis. This method was then used to identify individual skill exploration strategies in accordance with DST approaches to learning,

1.4.5. Chapter 6 – General Discussion

Chapter 6 discusses the findings and theoretical contributions of chapters 3-5. Using the eight research questions identified in section 1.3. as a framework, this chapter addresses key theories underpinning the applications of biofeedback and motor learning within the context of DST. The research questions, within each of the three themes, are reviewed and answered in turn. Following this, the methodological approaches employed within this body of work are critically appraised, prior to the novel contributions and practical applications of this thesis being summarised. Finally, future directions for research are offered.

Chapter 2. REVIEW OF LITERATURE

2.1. Contextualising Biomechanical Biofeedback

2.1.1. Definitions

Feedback is critical for motor learning, supporting and directing practice (Salmoni et al., 1984). Prior to discussing historical developments of feedback, and considerations for feedback design, it is important to define key concepts and terminology. The importance of these definitions will become more relevant throughout this thesis with apparent contradictions within and between motor control paradigms, clinical settings, and the sports science literature. Feedback is considered, in this context, as any information related to action, and can either be intrinsic or extrinsic to the biological system (Sigrist et al., 2013). Intrinsic feedback is information from the inherent sensory perceptual system, and can either be exteroceptive (outside of the body; e.g. visual, auditory, or smell) or proprioceptive (e.g. awareness of the body) (Lauber et al., 2012). Extrinsic, or augmented feedback, is considered to be any information additional to that already available to the performer (Newell, 1991).

Augmented feedback is used to reinforce and complement existing feedback processes (Newell, 1985a). When this augmented information pertains to biological processes (e.g. heart rate, muscle activation or movement) then it is termed biofeedback. Biomechanical biofeedback, specifically information related to movement and the causes of movement, fits within this definition. For the context of this thesis, biomechanical biofeedback shall hereafter be referred to simply as biofeedback (BFb) unless otherwise stated. BFb can either be in the form of knowledge of results (KR) or knowledge of performance (KP). KR is information about the outcome of a task in relation to the goal of the activity (Newell et al., 1983), often presented as a performance score or error relative to the task requirements (Newell, 1976). KP is information on technique, and relates to the movement parameters of how a motor task was achieved (Baudry et al., 2006; Mullineaux et al., 2012; Ford et al., 2015; Richards et al., 2018b). The term, KP was first coined by Gentile (1972), however a lack of clear distinction between the different types of KP content (e.g. joint kinematics, equipment kinematics, external kinetics muscular activation) has led to incoherent guidelines which prevail within the literature. **Section 2.3.1** seeks to address this further and to provide clarity to better inform the development of a BFb intervention design.

Two concepts, arising from the motor learning literature, require clarification. The first is the distinction between instruction and BFb. Instruction informs a performer of a required movement, while feedback specifically guides an individual on how to achieve this movement in relation to their performance (e.g. Wulf et al., 2010). The lack of distinction between the two within BFb research has led to findings from the focus of attention literature being incorrectly applied to BFb interventions. The second concept is the distinction between transient and permanent changes in performance. Learning is a relatively permanent change in skill execution, often brought about by practice, feedback, or a combination of the two (e.g. Bowser et al., 2018). In contrast, changes in performance are the temporary alterations to skill execution (e.g. Noehren et al., 2011). Differentiating between changes in transient performance or more permanent learning are evaluated using retention testing following a defined period of time (e.g. Mononen et al., 2003) or transfer tests using a related skill (e.g. Magill, 1994). If a skill is truly learnt then performance scores will be retained during subsequent tests. The longer the retention period, the more permanent the change can be said to be. Conversely, if there is no retention test then the influence of BFb on true skill learning cannot be assessed.

2.1.2. Applications of Biofeedback

Biofeedback has a vast multitude of applications which highlight the importance of research to underpin various uses. Clinical research using BFb has supported rehabilitation of healthy arm function (Cirstea et al., 2006; Secoli et al., 2011) and lower limb muscle activation following stroke (Tsaih et al., 2018). BFb has a significant place in the treatment of neuromuscular disorders, such as children with cerebral palsy (Thorpe and Valvano, 2002), and has even been applied to patients with incomplete spinal cord injuries to alleviate gait abnormalities (Petrofsky, 2001). BFb has also been used to enhance wheelchair propulsive capabilities (Kotajarvi et al., 2006; Rice et al., 2010; Richter et al., 2011). While these specialist populations may have slightly different response capabilities to BFb, the principles surrounding successful application of BFb and how to make this most effective for the individual remain the same. BFb in support of sport has immediate applications for enhancing motor learning contexts (Helmer et al., 2010), altering exercise movement patterns (Bowser et al., 2018), and high-performance sport (Thow et al., 2012). More broadly, by understanding the role of augmented information to facilitate motor learning in general, accelerating skill development is enhanced for a multitude of applications.

Perhaps problematically, much of the research underpinning BFb and motor learning to date focuses on simple skills and individual joints, therefore research targeting more complex skills is of vital importance.

2.1.3. Simple versus Complex Skills

Early research investigating the provision of augmented information to enhance motor learning primarily focused on the influence of KR on simple skills. The simplicity and experimental control likely led to the paradigm dominance of these research designs. KR research first emerged with Thorndike (1927) assessing the influence of reinforcement on a simple line drawing task. By providing information on the error between the target length and the length drawn, Thorndike found that KR reinforced learning. Since then, a wealth of research has investigated and advanced understanding around the influence of KR on skill execution (Adams, 1971; Newell et al., 1983; Swinnen et al., 1990; Smith and Loschner, 2002; Snodgrass et al., 2010; Schaffert and Mattes, 2014). However, the majority of KR research has continued to focus on simple skills such as line drawing (Simon and Bock, 2016), moving screen pointers (Wong et al., 2016), and typing tasks (Albuquerque et al., 2014). The majority of our understanding of feedback relating to skill development stems from these simple movements. Problematically, findings from simple skills are not always transferable to complex, multi-joint skills (Wulf and Shea, 2002), with KR being effective in line drawing and unidimensional pointing tasks because the information provides all of the necessary detail for what essentially becomes a single degree of freedom task (Newell et al., 1983).

More recently, KR has been applied to complex skills, facilitating improvements in tennis serve speed (Moran et al., 2012) and swim pacing strategies (Pérez et al., 2009), both with national level athletes. However, highly skilled athletes have excellent motor control by definition, and therefore may require moderate information to correct technique. To progress complex skills using BFb, the provision of specific technical considerations is required. Therefore, BFb needs to focus on the provision of information on segment interaction and coordination (Newell et al., 1983; Fujii et al., 2016). KP has greater strength than KR in this regard, allowing for more specific detail that can be tailored toward variables linked with successful skill execution.

Hatze (1976) pioneered the first applications of kinematics toward a model of optimal performance. The author attached a weight to the foot during a leg raising task, which forced a participant to bend their knee, constraining action to create a skill which requires hip-knee coordination. Initially, KR on movement time for the first 120 trials was successful, however the rate of improvement decreased over time. KP based on a movement time optimization model was then provided, prescribing a specific lower and upper lower limb segment trajectory. Learning accelerated with an immediate reduction in error, which was greater than that achieved with KR (figure 2.1). These findings were confirmed by Newell et al., (1983) in a rapid arm movement task, advocating the vital role which KP could play with applications to complex skills.

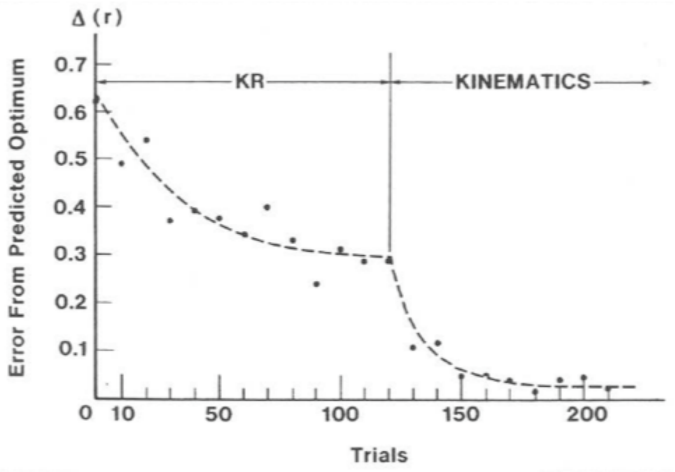


Figure 2.1. Timing error relative to the predicted optimum for a leg with KR and KP feedback (kinematics) over number of trials. Adapted from Hatze (1976).

Since then, the benefit of KP using segment or joint kinematics to improve mechanical characteristics has been demonstrated in a range of complex skills. These range from walking (Shull et al., 2013; Jackson et al., 2017; Richards et al., 2018b), running (Eriksson et al., 2011), and jump landing (Ericksen et al., 2015), through to throwing (Kernodle and Carlton, 1992), basketball and netball shooting (Helmer et al., 2010; Nunes et al., 2014), and gymnastics (Baudry et al., 2006). With more recent advances in technology the content of KP has diversified, with accelerometers used in running (Crowell et al., 2010; Wood and Kipp, 2014; Creaby et al., 2016; Bowser et al., 2018; Zhang et al., 2019) and rowing (Anderson et al., 2005; Schaffert and Mattes, 2015), EMG to present muscle activation patterns (Ekblom and Eiksson, 2012; Gentil et al., 2017; Luc et al., 2016; Tsaih et al., 2018) and real-time inverse dynamics to provide internal joint torques in real time (Beaulieu and Palmieri-Smith, 2014; Richards et al., 2018b). Paradoxically, however, this apparent boom in KP research in complex skills has still predominantly focused on the provision of single variables or individual joints. Newell et al. (1983) advocated that the most beneficial information for complex skills is that which incorporates system organisation. This was shown in Hatze's (1976) work, yet to date limited knowledge on simultaneous whole limb joint interactions exists. Attempts have been made to manipulate coordination (Fujii et al., 2016), but limited work has yet to prescribe target movement patterns of a whole limb in a complex skill.

2.1.4. Knowledge of Results or Knowledge of Performance

Historically, KR has been the primary focus of feedback research within the motor control domain. As discussed in the previous section, these paradigms evolved using the simple, single degree of freedom tasks. KR research designs either provide KR as direct information on task success (e.g. Viera et al., 2012) or error relative to the task (e.g. Alburquerque et al., 2014). Both approaches allow a participant to assess their efforts in relation to a pre-defined goal, and subsequently correct them, but in different ways (Smith and Loschner, 2002). KR is powerful for skills where successful movement can be wholly encapsulated by the KR information, such as in single degree of freedom tasks.

With the emergence of KP research, Newell et al. (1983) anticipated that kinematic information would be the most beneficial in tasks requiring the coordination of multiple degrees of freedom. For complex skills, with a larger number of degrees of freedom to control, more detailed information is needed (Anderson et al., 2005). KP is more beneficial than KR for complex skills due to the increasing skill complexity and multiple joint interactions (Kernodle and Carlton, 1992; Viitasalo et al., 2001; Kontinnen et al., 2004). This is particularly important when specific technique characteristics are required. Kernodle and Carlton (1992) identified that two additional details are required to ensure KP effectiveness with a complex task. These are, 1) cues to direct an athlete's attention to variables to be changed and, 2) transitional information relating to how to correct these variables (figure 2.2). Inherently, complex skills contain complex movement information so if this is not simplified with cues and transitional information, then individuals may not find solutions to achieve the requested movements (Fortier et al., 2005; Richards et al., 2018a). Therefore, in more complex skills KP is more effective than KR as it provides more specific technical information on how to achieve success.

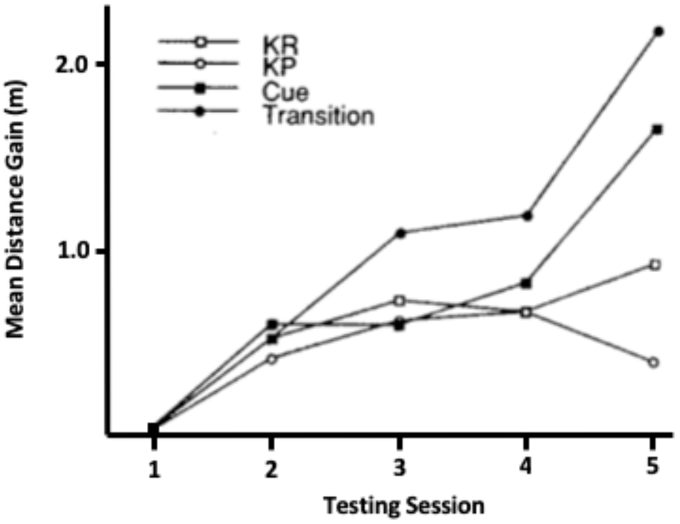


Figure 2.2. Increase in mean throwing distance with KR, KP and KP with the addition of either a cue or transitional information targeting specific kinematic parameters linked with successful throwing performance. Adapted from Kernodle and Carlton, 1992.

2.2. The Influence of Biofeedback on Motor Learning

The process of motor learning can be separated into two theoretical components for consideration. The first element concerns change to the central nervous system, specifically the neuroplasticity of the brain. The second, the emergence of new movement patterns or the development of existing complex skills. This section will discuss both of these areas and establish links between motor learning and BFb.

2.2.1. Neurological Changes with Motor Learning

The development of complex skills invokes specific changes in the brain. Functional MRI (fMRI) scans have been used to show an increase in primary motor cortex (M1) activation, part of the brain responsible for the planning and execution of movement, with sequenced finger tapping (Karni et al., 1995; Karni et al., 1998). Although the M1 is a small component of the neuronal motor system, adaptations in skill execution physically manifest in the brain with practice (Puttemans et al., 2005). Bezzola et al. (2011) sought to identify whether these neural changes were independent of strict laboratory-based protocols by tasking golfers with acquiring 40 hours of regular golf practice in their routines, which was a mean of 149.82 days (range of 92-235 days). The fMRIs before and after showed significant increases in grey matter, which is tissue composed of the brain's neuronal cell bodies. Reduced hip adduction during landing in a VR environment following a BFb intervention has been associated with increased proprioceptive, visual-spatial and motor planning brain activity during a leg extension task (Grooms et al., 2011). Considering that BFb is intrinsically linked with practice for advancing motor learning, neuronal adaptations should also be enhanced with appropriately focused BFb. For example, visual and auditory feedback has been shown to stimulate the cerebellum with limb coordination during bimanual tasks (Ronsse et al., 2011). The cerebellum forms part of a network required to learn and execute skills (Butcher et al., 2017). It receives information from the sensory system and regulates motor movements. Degenerative disorders leading to dysfunction of the cerebellum exhibit an inability to make corrections to movement during execution (Tseng et al., 2007), highlighting the cerebellum's role in encoding live corrections using intrinsic and extrinsically available information to compare movement to an internal model of performance. In addition, the cerebellum plays a critical role in long term motor memory formation and memory-driven performance involving feedforward control (Wolpert et al., 1998).

The motor cortex has also been shown to respond differently to types of KP, with an increase in activity when individuals receive feedback about joint position (Lauber et al., 2013). It is also apparent that neural activity increases in sensory specific areas (Ronsse et al., 2011) so it is important that BFb provides information to compliment sensory channels linked with the skill being practised. In Ronsse et al. (2011) auditory BFb was shown to be more effective than visual BFb in a repetitive bimanual coordination task, however as timing was important to task execution the rhythmic tone of the auditory feedback would likely be more effective. Interestingly, the interpretation of feedback influences motor behaviour and also alters motor cortical activity (Lauber et al., 2013) therefore selection of the BFb content and modality requires careful consideration. These considerations, related to the development of effective BFb designs, will be covered in more detail in the following sections.

2.2.2. From Performance to Learning

From a theoretical perspective, the guidance hypothesis dictates that while BFb is beneficial to direct motor learning, too much BFb can lead to dependency and prevent autonomous exploration processes (Salmoni et al., 1984; Sadowski et al., 2013). It is believed that this dependency may encourage learners to bypass other important sources of feedback information that they may need to develop intrinsic error detection and correction mechanisms (Park et al., 2000). Dependency effects have been linked to neurological adaptations to neural structures within the brain, showing the physical influence of guidance (Ronsse et al., 2011).

Attempts to negate the guidance hypothesis with complex skills tend to focus on a reduction of BFb frequency over time (e.g. Richards et al., 2018b) but could also increase time between visits. Withdrawing BFb over time can allow the body to learn to interpret and utilize its own proprioceptive information that is readily available (Magill, 1994). BFb dependency is typically evidenced with a drop-off in retention once BFb is removed (Maslovat et al., 2009), therefore additional time could be useful. Further, the effects of the guidance hypothesis are considered to be skill specific (Sigrist et al., 2013; Wulf and Shea, 2002), therefore dependency can be problematic to pre-empt. Research designs usually attempt to manipulate elements of a BFb design to avoid these dependent properties while still accelerating the skill development process, but must rely on either previous empirical work or logic. Learning is fundamentally about the relative persistent and permanent changes of behaviour (Newell, 2003). Therefore, within motor learning studies, retention tests are used, typically from 24 hours onwards, to assess if a true learning effect is present (Schmidt and Lee, 2005). Without a retention test within motor learning designs it cannot be determined if a true learning effect took place, or whether changes were transient modifications to performance. To truly understand the development of skill over time research designs need to include multiple time points (Newell, 2003; Bowser et al., 2018). Problematically, few motor learning studies have included multiple time points or longitudinal designs, and limited longitudinal retention testing to assess changes that occur with BFb. Changes in motor learning, from a cognitive perspective, can be considered as fast-learning, within one day and typically one session, or slow-learning which occurs with repetitive practice over multiple sessions (Karni et al., 1998). BFb protocols demonstrating fast learning highlight how successfully changes in technique can be modified in a short timeframe within a range of different complex skills (Broker et al., 1993; Crowell et al., 2010; Eriksson et al., 2011; Richter et al., 2011; Wood and Kipp, 2014; Ericksen et al., 2015; Ford et al., 2015; Hwangbro et al., 2015; Baggeley et al., 2017; Jackson et al., 2017). Very few of these studies, however, include retention testing meaning that the longer lasting effects of these changes cannot be determined.

2.2.3. A Dynamical Systems Theory Perspective to Motor Learning

Theories of motor learning have undergone substantial and progressive paradigm shifts since the introduction of Adam's (1971) closed loop theory of motor learning. Adam's (1971) theory held that a motor programme serves as the executive function to produce a specific skill. This was problematic, and proposed difficult questions surrounding the sheer quantity of storage of individual motor programmes to represent the range of skills learnt over a lifetime (Clark, 1995). Further, this offered a lack of flexibility to adapt to new skills (Newell, 2003). Schmidt (1975) advanced existing motor learning paradigms with schema theory, which proposed the idea of pre-existing generalizable motor programmes, or schemas, which were recalled from memory following sensory observations. These schemas represent the temporal and spatial properties of muscle activation to produce a class of movements, and were scalable to the environment. While this remains as one of the prevalent theoretical camps within motor learning, it has received considerable critique (Newell, 2003), which stimulated an update from the author (Schmidt, 2003). These traditional motor programme approaches still do not provide an answer for how the intrinsic dynamics of the structure and function of biological components find a solution to produce motor outputs (Kugler and Turvey, 1987) and give rise to new skills. Therefore, in the applied domain there have been limited applications of schema theory to complex motor skills, and a need arose to explain dynamic learning.

Bernstein’s (1967) degrees of freedom problem stimulated an alternative paradigm to schema theory. This saw the emergence of theoretical frameworks proposing that motor skills emerged through the development of dynamic coordinated structures (Kugler et al., 1980; 1982; Turvey, 1990). These collectively became what is known as the dynamical systems perspective (Newell, 2003). With an estimated 792 muscles in the human body, spanning a conservative count of 100 joints, there are an infinite number of degrees of freedom to control which became known as ‘Bernstein’s problem’. Dynamical systems theory (DST) was proposed as the solution to such a problem, with the emergence of control arising from the complex interaction of a multiple set of sub-systems, such as muscle synergies (Turvey, 1990; Newell and

Vaillancourt, 2001; Newell, 2003). Coordination is the mastery of the many redundant degrees of freedom (DoF) (Bernstein, 1967; Turvey, 1990), and is seen as an effective approach to reduce the complexity of the DoF (Turvey, 1990; Latash, 2012).

Coordination is a principle at the core of DST. Turvey (1990) outlined a set of overarching principles that arose as a ‘first round’ of research inspired by Bernstein’s (1967) work. Perhaps the most revolutionary component was the notion that the kinematics of any coordinated state are not predetermined by one biological sub-system (i.e. motor units), but are gradually built by multiple subsystems (e.g. motor units, muscle synergies, intra-limb coordination), collaboratively (Turvey, 1990). In the context of motor learning, the emergence of dynamic organisation is guided by constraints to action which channel and guide the emergence of skills, directing self-organisation (Newell, 1986; Newell et al., 1989; Clark, 1995; Chow et al., 2006). These constraints are categorised as individual, environment, or task specific (Newell, 1986; figure 2.3). Specifically, individual constraints are those defined as components of the organism. These can be defined at all levels of the biological system from the macroscopic (i.e. muscles synergies, relation of limbs to the external environment) or microscopic (e.g. tissue behaviour, tensile properties). The environmental constraints relate to physical properties external to the individual, and can be global (e.g. gravity, altitude), or local (e.g. equipment). Finally, task constraints relate to those guiding successful task completion (Newell and Jordan, 2007) and arguably marshal the system into the behaviour we observe (Clark, 1995). Crucially, the emergence of coordination, through self-organisation, is as a response to the interaction of these three constraints to action (Newell, 1986), and occur dynamically via self-organisation (Kelso, 2009). Therefore, order arises dynamically, and in compliance with constraints.

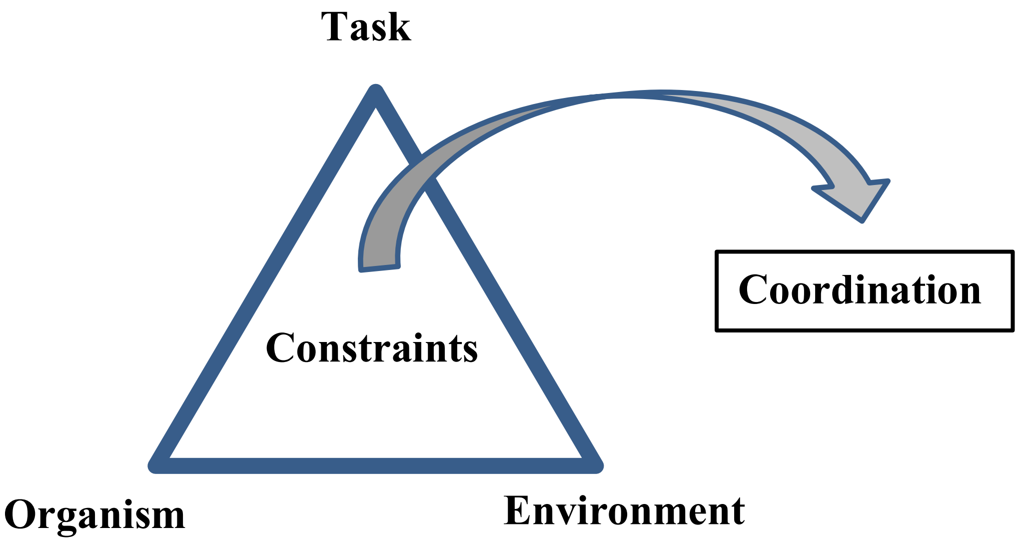


Figure 2.3. Schematic overview of the interaction between the constraints to action, and the emergence of a new coordination mode (Adapted from Newell, 1986).

There are two prevalent theories under the DST umbrella that provide distinct, yet complementary, approaches hypothetically framing the physical emergence of new skills. Bernstein (1967) proposed his three stages of motor learning, which focused around the freezing and freeing of the many degrees of freedom during skill development (Newell and Valliancourt, 2001). Specifically, Bernstein's (1967) stages of learning relate to the control and regulation of system redundancy by:

1) **Freezing** – simplifying the task by reduction the DoF for action.
2) **Freeing** – releasing of the DoF and exploring the redundant availability.
3) **Efficiency** – exploiting the full array of DoF and the environment.

The initial stage identified that an individual would freeze, or reduce, the available degrees of freedom to simplify the task for learning (Williams et al., 2016). Following this stage, individuals can be seen to explore the skill by opening up the DoF, allowing for a greater array of motor options, or affordances (Wilson et al., 2008). Finally, at an advanced level of skill exploration, Bernstein (1967) argues that an individual can exploit the environment to be more effective and efficient in executing the task (e.g. using gravity to assist in the movement). Since then, research has investigated individual stages of learning according to Bernstein's (1967) framework (Irwin and Kerwin, 2007; Chow et al., 2008; Wilson et al., 2008; Cazzola et al., 2016), however the majority of research in this area are snapshots in time rather than transitions through, and across, multiple stages. In order to better understand learning, research covering the longitudinal skill acquisition journey is greatly needed (Newell, 2003).

Newell (1985) proposed an alternative learning framework which he believed was more closely affiliated with the concepts of DST by focusing on the emergence of coordinated structures and variability, both of which are fundamental components to the paradigm. These three stages of included:

1) **Coordination** – the individual is searching for a relationship between the various joints and segments to identify coordinated structures.
2) **Control** - the refinement of the new coordination patterns, and the new parameters being assigned a place, and into a controllable system.
3) **Skill** – the ability to select and organise optimal parameters to achieve successful task execution, either with efficiency or consistency.

2.2.4. Quantifying Coordination

The use of techniques to quantify coordination is essential to directly underpin the emergence of skill and motor development from the perspective of DST (Newell, 1985). However, methods to quantify coordination require careful consideration. There are two core approaches which pervade within the literature for time-series data; continuous relative phase (CRP) and Vector Coding (VC).

CRP calculates the relationship between two segments or joint angles. Individual phase-plane portraits, or joint angle plotted against the angular velocity, are then normalised prior to the angle of each individual phase portrait being determined from the axis origin (figure 2.4.). The relative phase angle is then simply one phase angle subtracted from the other, combining phase relationships (figure 2.5.). A

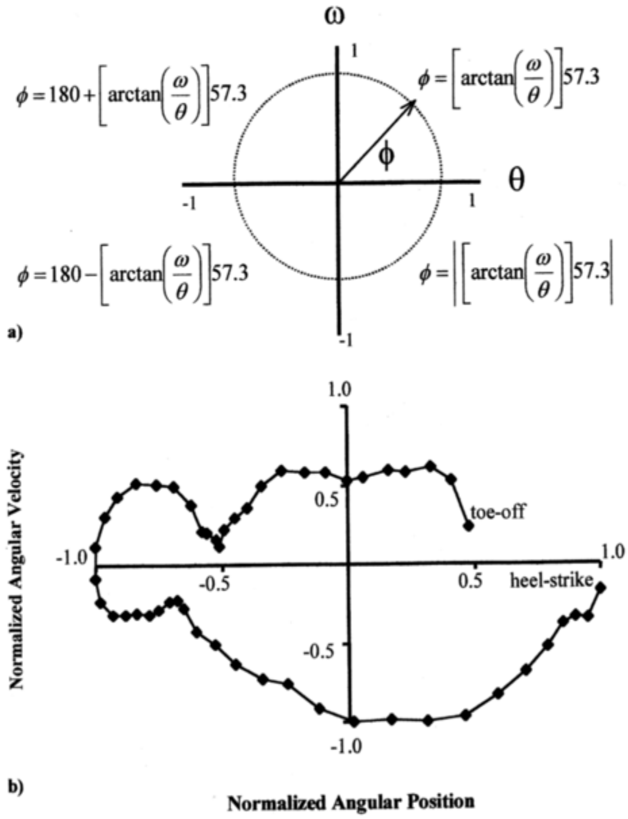


Figure 2.4. a) Phase angle (ø) determination based on the angle of the normalised spatial angle (θ) and normalised angular velocity (ω) phase plot of an individual joint. b) A typical normalized phase angle of lower extremity coupling during gait. Adapted from Hamill et al. (1999).

relative angle of 0° represents segments moving in phase, whereas 180° represents segments are out of phase (Hamill et al., 2012).

Historically, CRP has mostly been applied to running (Hamill et al., 1999; Seay et al., 2011; Bailey et al., 2018; Floría et al., 2018). Although, it has proven effective as a profiling tool for the emergence of skill in novice athletes relative to elite gymnasts (Williams et al., 2016). The incorporation of both spatial and temporal information can provide higher dimensional information of segment relationships (Hamill et al., 1999). However, this increase in complexity becomes problematic for applied practitioners to interpret. Further limitations of CRP are held with normalisation

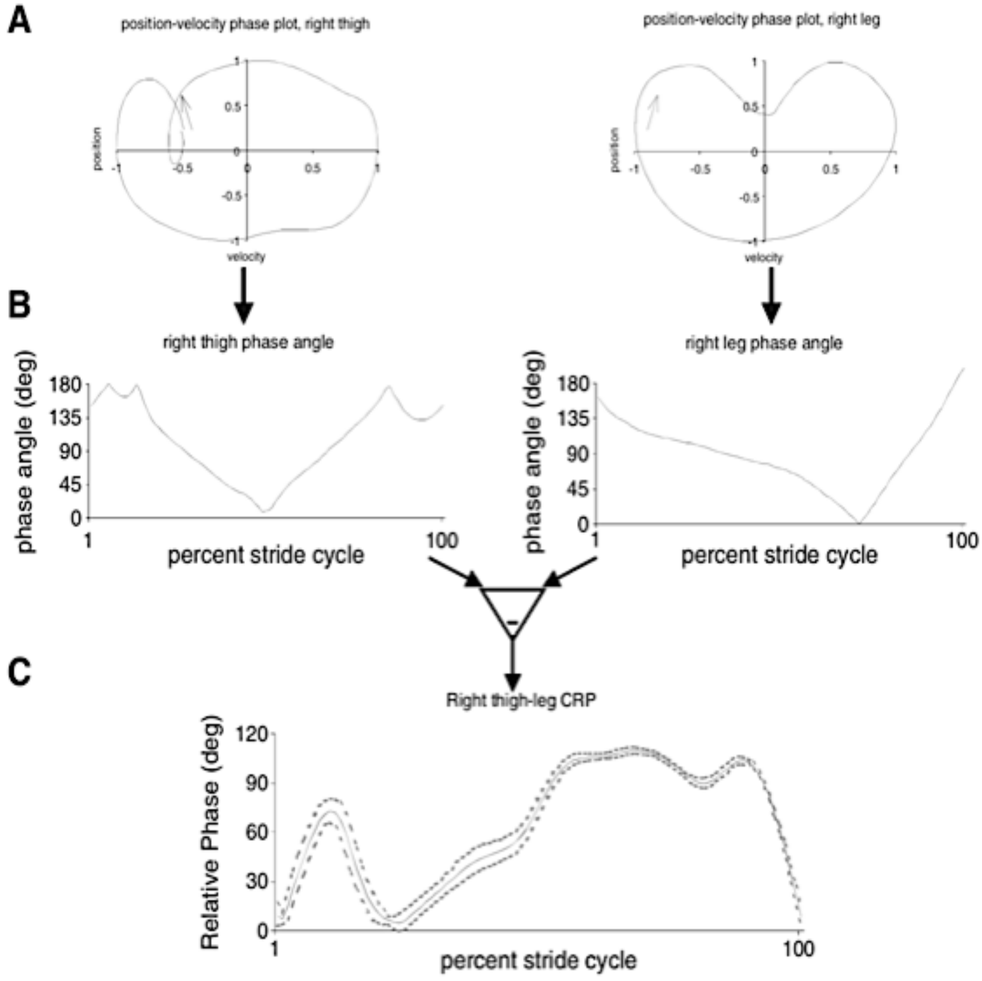


Figure 2.5. Calculation of a continuous relative phase angle; a) Creation of two separate segment normalised phase-plane plots, b) the determination of resultant phase angles, and c) a continuous relative phase angle calculated by subtracting the two-phase angles at each instant in time. Adapted from Hamill et al. (2012).

procedures which must be incorporated to account for frequency differences between segments to be coupled (Peters et al., 2003). While this normalisation should have little effect on coordination measures, scaling could affect the coupling angle for signals with very different amplitudes such as knee flexion relative to rearfoot motion (Miller et al., 2010). Further, CRP is recommended for cyclical oscillators, therefore inappropriate for discrete skills (Peters et al., 2003).

Vector coding (VC) is an alternative, and widely used measure of coordination between two joints or segments (e.g. Hamill et al., 1999; Needham et al., 2014; 2015). This technique evolved as a tool to quantify joint or segment interaction by encoding coupling vectors throughout a time series (Sparrow et al., 1987). In short, the vector angle (Heiderscheit et al., 2002), or vector angle and length (Tepavac and Field-Fote, 2002) relative to the horizontal is determined for each point to point vector (figure 2.6). The mean vector angle is then calculated using circular statistics. Modifications to the vector coding technique have since made this approach more accessible to applied practitioners (Chang et al., 2008; Needham et al., 2014; 2015).

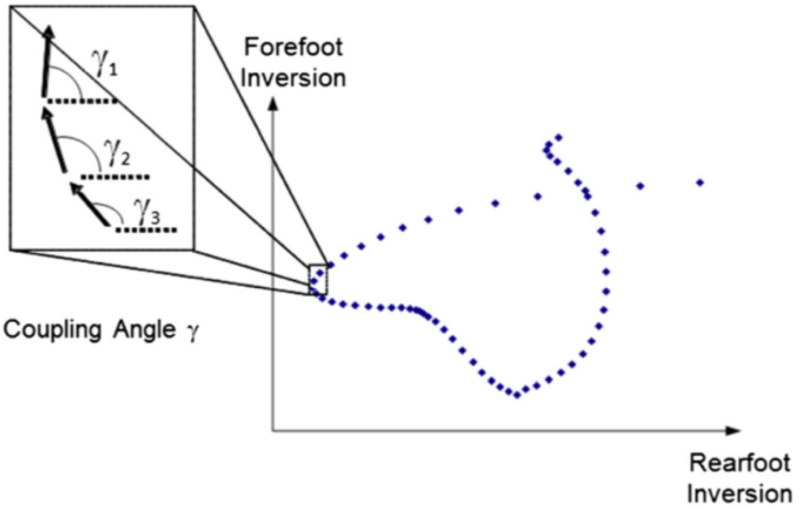


Figure 2.6. Calculation of phase angles using a modified vector coding technique where γ is the coupling angle for each iterative vector throughout the time angle-angle series. Adapted from Hamill et al. (2012).

The creation of coordination pattern frequency bins allows for a simplified interpretation to identify whether joints are moving in or out of phase, or one of the joints is moving alone (figure 2.7.). The orientation of the vector angle at any point provides useful information on joint movement in relation to each other, and can be classified into frequency bins to quantify joint dominancy during movement (e.g. Vidal et al., 2018).

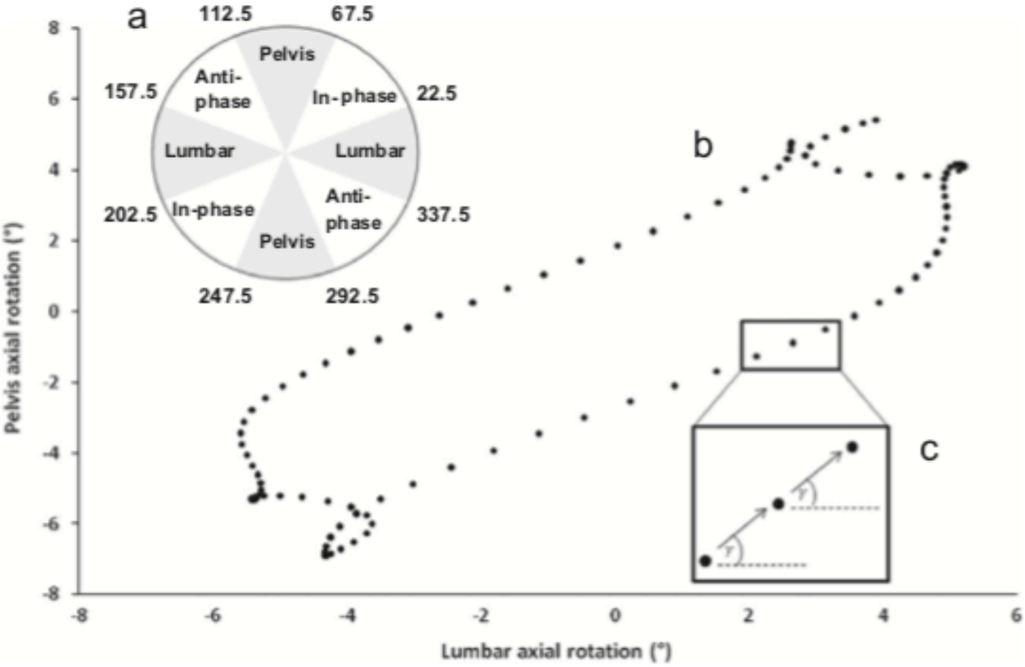


Figure 2.7. Modified vector coding with the addition of frequency bins by Chang et al., (2008). The vector angles are classified into frequency bins using the vector orientation to identify joint dominancy. This allows for the phase relationship to be classified into discrete analysis and meaningful interpretation. Adapted from Needham et al. (2014).

2.2.5. Quantifying Coordination Variability

Traditionally, variability was seen as inherent noise within the biological motor system (Schmidt and Lee, 1999). However, Lipsitz' (2003) 'loss of complexity hypothesis' proposed that a lack of variability may be a characteristic of dysfunction in performance or disease (Hamill et al., 2012). Biomechanically, the range of joint or segment coupling over a number of repetitions of trials is quantified, providing a measure of coordination variability (Coord$_{Var}$). Paradigms measuring Coord$_{Var}$ have subsequently identified differences between pathological and healthy populations (Hamill et al., 1999; van Emmerick and van Wegan, 2000) and skill levels within sport specific skills (Wilson et al., 2008; Cazzola et al., 2016) which has further framed the more purposeful view of biological variability. Coord$_{Var}$, as an implicit element of skill execution, can be separated into a functional and non-functional component (Hamill et al., 1999; Preatoni et al., 2013; Cazzola et al., 2016). From a dynamical systems perspective, Coord$_{Var}$ is functional to allow the motor system to adapt to perturbations within the task, individual or environment to facilitate consistent skill outcome (Chow et al., 2006; Robins et al., 2006; Mullineaux and Uhl, 2010). Consistency of skill outcome, in contrast, is considered non-functional for skill execution and referred to as performance variability (Perf$_{Var}$).

An integral component of the DST paradigm is the notion of skill exploration, aligning both with Bernstein's (1967) stages of motor learning and the emergence of new coordinated structures (Newell, 1985). Coord$_{Var}$, as an analytical tool, has been used to identify subtle changes in skill execution, finding differences between novice, skilled, and elite performance (Wilson et al., 2006; Cazzola et al., 2016; Williams et al., 2016). As an approach, Coord$_{Var}$ has even proven sensitive where conventional biomechanical approaches have failed to distinguish between patients with subtle pathologies such as patellofemoral pain syndrome (Hamill et al., 1999). Coord$_{Var}$ may, therefore, provide a tool to assess how an athlete is influenced by an intervention during the skill development process by quantifying exploration of the coordinative structures, and adhering to the stages of learning.

Coordination and coordination variability are inherently intertwined originating from similar measurement approaches and the related limitations. CRP is used mostly for cyclical motions, and requires a number of complex data decisions to be made, all of which radically alter the results (Mullineaux and Wheat, 2008). Further, it is inappropriate for applications to discrete skills as this violates the assumption of a sinusoidal distribution (Peters, 2003). Therefore, CRP is excluded from discussion here. To determine $\text{Coord}_{\text{Var}}$ using VC, circular statistics are employed to determine standard deviations of vector orientations over multiple trials (Chow et al., 2008; Vidal et al., 2018). The standard deviation of the vector angle (Heiderscheit et al., 2002) or standard deviation of both the vector angle and length (Tepavac and Field-Fote, 2002) provide a measure of $\text{Coord}_{\text{Var}}$, but both VC methods are susceptible to noise artefacts related to changes in vector length that can overinflate the variability output (Stock et al., 2018). This may explain that although $\text{Coord}_{\text{Var}}$ has found differences between cohorts (e.g. Hamill et al., 1999), when exploring subtle differences within cohorts such as pre and post in patellofemoral pain runners no differences in $\text{Coord}_{\text{Var}}$ were detected (Cunningham et al., 2014).

An alternative bi-variate data analysis method, CI2, allows for the statistical comparison of two time series data sets (Mullineaux, 2017) which could be modified to capture more global joint or segment variability during complex, discrete skills. The first stage of this approach applies ellipses to encompass multiple trials of bivariate data at each time point, with the ellipse axis scaled to 95% confidence intervals (95%CI). Stock et al. (2018) used these 95%CI ellipses to encase multiple trial angle-angle vector end points, identifying the area of these ellipses to be more robust to the statistical artefacts found using VC. CI2 uses quadrilaterals to connect consecutive ellipses to create 95%CI boundaries for the entire time series. The CI2 Matlab code provided by Mullineaux (2017) can be modified to extract the area of these quadrilaterals ($CI2_{Area}$) to provide a measure to statistically compare the spread, or $Coord_{Var}$, between any bi-variate time series.

2.3. Considerations for Feedback Design

The development of an effective KP intervention requires a number of key decisions around influential factors. Some of these may be logical, such as the relation between KP content and changes in skill required. Others may be more subtle, such as the focus of attention, the sensory channel chosen as a mode to transmit the augmented information. Finally, factors related to the timing at which feedback is given relative to the task, and how often, which are of clear importance from a practical perspective. This section will provide an overview of each of these areas in turn, with a specific focus on the KP literature.

2.3.1. Content

BFb content selection is arguably the most influential factor determining KP success toward influencing motor skill development. Information provided as BFb should have a direct link to the primary changes sought, either as empirical evidence linking the variables to performance (Newell et al., 1985; Fortier et al., 2005) or at least a close theoretical relationship to desired movements (Anderson et al., 2005). Secondary effects have also been shown on variables related to the targeted primary variables (Winchester et al., 2009; Rice et al., 2010; Noehren et al., 2011; Richards et al., 2018a). Manipulating simple variables can be used as BFb to target a less accessible secondary variable. For example, indirect feedback using trunk lean can be used to significantly reduce knee abduction moments in patients due to the empirical link between the two (Gerbrands et al., 2014). Reductions in loading rates have also been facilitated using BFb on foot strike type and step length during running gait (Baggaley et al., 2017). Secondary effects, however, are not guaranteed (Ford et al., 2015; van der Noort, 2015) and may even produce negative effects (Baggaley et al., 2017; Richards et al., 2018a). Therefore, it is important to establish a strong evidence base for required manipulations, and consider the most effective content to achieve these.

It is evident that equipment-based kinematics, external to the body, can be effective in altering performance in sports involving equipment manipulation. This has been shown in a variety of complex skills such as; wheelchair propulsion (Rice et al., 2010), rowing (Schaffert and Mattes, 2014; 2015), rifle shooting (Mononen et al., 2003; Kontinnen et al., 2004) and weightlifting (Winchester et al., 2009; Hwangbro, 2015). Similar to KR, externally focused KP allows for adjustments in performance outcome but it does not target the specific technique underpinning the movement for technical patterns to be encouraged. Additionally, a lack of appropriate retention tests in many of these KP investigations means that the permanency of these changes is not well known (Winchester et al., 2009; Schaffert and Mattes, 2014; 2015; Hwangbro, 2015). Mononen et al. (2008) and Kontinnen et al. (2004) both showed performance improvements with KP on barrel stability with retention shown at 10 and 40 days respectively, however these involved very intensive BFb schedules with 11-12 sessions over a 4-week period. The small changes within these studies suggest that the provision of external kinematics requires intensive practice and repetition. The provision of kinetics alongside the externally focused kinematics is more promising, with positive changes shown within just 1-2 sessions with wheelchair propulsion (Kotajarvi et al., 2006; Richter et al, 2011), and 4-weeks of rifle and postural stability KP (Mullineaux et al., 2012). While this type of feedback is clearly effective in implement-based sports, these still do not target specific movement pattern learning. Table 2.1 provides an overview of KP with an external focus alone, and with the addition of external kinetics.

The provision of external kinetics, such as ground reaction forces, is equally effective in skills where force output is of importance (Broker et al., 1993; Wulf et al., 1998, Abujaber et al., 2017). However, this shares similar issues with external KP in that specific technique is not prescribed and is left to the individual to self-organise. External kinetic KP research to date tends to emerge from motor learning paradigms with weight distribution during quiet standing (e.g. Bechly et al., 2013), ski simulator tasks (Wulf et al., 1998) or sit-to-stand (Abujaber et al., 2017). Within the sporting domain, the external kinetic KP research evidence base is limited. While cycling kinetics over two sessions has facilitated improvements which are retained after one week, the lack of a control group makes it difficult to separate BFb from practice (Broker et al, 1993). External kinetic KP research has failed to elicit improvements with the sprint start (Fortier et al., 2005), a skill underpinned by force generation, highlighting that technique may need to be incorporated in the KP.

Table 2.1. Overview of BFb research using externally (E) focused KP content on equipment kinematics, and also with the addition of external kinetics. Transmission mode is classified as auditory (Au) or Visual (Vi), while timing is either concurrent (C) or terminal (T). Schedules and retention time points are detail in days (d), weeks (wk) or months (mth). Number of BFb visits for each schedule, and time of retention are in brackets. ↑ / ↓ indicates increase / decrease.

Author	Year	Skill	BFb Content	Mode	Timing	Schedule	Improved	Retained	Key Findings
Konttinen et al	2004	Rifle shooting	Kinematic (E)	Au	C	4 wk (11)	Yes	Yes (10 & 40 d)	50% concurrent KP on rifle stability effective in increasing scores
Kotajarvi et al.	2006	Wheelchair propulsion	Kinematic (E) & Kinetic (E)	Vi	C	2 d (2)	Yes	N/A	KP ↑ velocity. Effective force did not. Stroke frequency indirectly decreased.
Mononen et al.	2008	Rifle shooting	Kinematic (E)	Vi	T	4 wk (12)	Yes	Yes (2 & 10 d)	100% KP on rifle stability ↑ shot accuracy, with 100% retained better than 50%.
Winchester et al.	2009	Power snatch	Kinematic (E)	Vi	T	4 wk (12)	Yes	N/A	KP improved barbell kinematics and had a secondary transfer to kinetic.
Rice et al.	2010	Wheelchair propulsion	Kinematic (E)	Vi	C	3 wk (3)	Yes	Yes (3 mth)	Stroke cadence ↓, and contact angle ↑, and secondary transfer to kinetics.
Richter et al.	2011	Wheelchair propulsion	Kinematic (E) & Kinetic (E)	Vi	C	1 d (1)	Yes	N/A	KP on maximal push variables led to ↑ in all variables and 255% ↑ distance.
Mullineaux et al.	2012	Rifle shooting	Kinematic (E) & Kinetic (E)	Au	C	4 wk (8)	Yes	Y (6-8 d)	KP on rifle stability and postural sway ↑ shooting score.
Schaffert & Mattes	2014	Rowing	Kinematic (E)	Au	C	2 weeks (1)	Yes	Yes (immediate)	Boat acceleration KP ↑ boat speed and positive acceleration period.
Hwangbro et al.	2015	Squat	Kinematic (E)	Vi	C	6 wk (6)	Yes	N/A	KP of patella trajectory in mirror ↑ vastus medialis and lateralis EMG.
Schaffert & Mattes	2015	Rowing	Kinematic (E)	Au	C	2 wk (7)	Yes	N/A	Boat acceleration KP ↑ boat speed and positive acceleration period.

Wearable technology has allowed for more specific information related to human movement to be relayed, however these have their own limitations. Accelerometers have been used in running (Crowell et al., 2010; Wood and Kipp, 2014; Creaby et al., 2016; Bowser et al., 2018; Zhang et al., 2019) and rowing (Anderson et al., 2005). Table 2.2 provides an overview of accelerometer research designs and key findings to date within the KP literature. Within running, accelerometers have shown excellent applications toward reducing tibial acceleration, with research showing up to 80% of individuals modifying impacts (Zhang et al., 2019). However, work still needs to be carried out to determine the accuracy of accelerometer measures using existing devices and the validity of impact load accelerations to loading of internal structures (Matijevich et al., 2019). Other wearable technology, such as EMG KP content, has been applied to increase muscle activation patterns. However, these have so far been limited to single DoF tasks, with mixed outcomes. EMG as KP has been shown to have little influence on bicep activation during elbow flexion (Gentil et al., 2017), however has been shown to be influential in increasing isolated knee extensor torque (Ekblom and Eriksson, 2012; Luc et al., 2016) and have transferable effects to opposing muscle groups (Luc et al., 2016). While wearable technology has certainly increased the range of available information for BFb provision and detail underpinning movement, more work is required to link the data obtained with performance.

Table 2.2. Overview of BFb research using wearable accelerometer KP content with a focus on segment kinematics. Transmission mode is classified as auditory (Au) or Visual (Vi), while timing is either concurrent (C) or terminal (T). Schedules and retention time points are detail in days (d), weeks (wk) or months (mth). Number of BFb visits for each schedule, and time of retention are in brackets.

Study	Year	Skill	Mode	Timing	Schedule	Improved	Retained	Key Findings
Anderson et al.	2005	Rowing	Vi	C	1 d (3)	No	N/A	More detailed BFb ↑ consistency, but no change in performance.
Crowell et al.	2010	Running	Vi	C	1 d (1)	Yes	N/A	Tibial accelerations greatly ↓, and retained with BFb withdrawal.
Wood & Kipp	2014	Running	Au	C	1 d (1)	Yes	N/A	KP target ↓ 10-15% of peak accelerations successful with 50% BFb.
Creaby et al.	2016	Running	Vi	C	1 d (1)	Yes	Y (1 d)	Both KP and clinician verbal BFb equally ↓ impacts in single session.
Bowser et al.	2018	Running	Vi	C	2 wk (8)	Yes	Y (1, 6 & 12 mth)	BFb on tibial accelerations ↓ range of impact variables. Retained over 1 year.
Zhang et al.	2019	Running	Vi	C	2 wk (8)	Yes	Y (1 wk)	80% of individuals ↓ peak tibial shock. Transfer to different gradients and outdoors.

Specific technique focused BFb, in the form of joint or segment kinematics, has received considerable attention in the literature, and is clearly the most effective content for altering specific movement patterns. Previous intervention schedules have ranged from a single week containing three sessions (Nunes et al., 2014), up to a more intensive four weeks containing 12 sessions (Kernodle and Carlton, 1992). Changes can happen relatively quickly, within just 1 day, however the permanency of these changes is not always guaranteed (Eriksson et al., 2011; Ericksen et al., 2015; Jackson et al., 2017). The vast majority of kinematic KP research has focused on cyclical movements (Baudry et al., 2006; Eriksson et al., 2011; Noehren et al., 2011; Shull et al., 2013; Jackson et al., 2017; Richards et al., 2018b), likely due to the simplicity in capturing data within a laboratory using ergometers, and the number of cyclical repetitions of the action for the participant to attend to the BFb. In contrast, discrete skills are relatively under-research within internal kinematic based KP designs (Thow et al., 2012; Nunes et al., 2014; Ericksen et al., 2015). This is surprising given the prevalence of discrete skills within sporting contexts and everyday movements, and the importance of objective data to support coaching practice (Giblin et al., 2016). Collectively, almost all of the longer term internal kinematic KP interventions demonstrate changes with no drop off in technique retention. This is irrespective of the time between the intervention and retention tests. Changes have been identified at one (Richards et al., 2018b), two (Baudry et al., 2006) and four weeks (Thow et al., 2012; Shull et al., 2013) following the main intervention. This highlights the potency of information related to specific technique, and the relative permanency of these effects (Schmidt and Lee, 2005). Limited research extends beyond four-week retention time points to identify whether or not these changes are indeed retained for longer. Surprisingly, despite Newell et al. (1985) advocating the importance of joint interaction information in motor learning, limited kinematic KP designs have presented information encompassing multiple joint interactions. Many kinematic KP designs on complex skills focus on one or two specific variables related to specific elements of the skill but do not assess whether or not these have a negative influence on other, related, joints (e.g. Eriksson et al., 2011). Successful gait retraining, therefore, should target multiple kinematic parameters simultaneously due to the linked kinetic chain evident in human movement (Gerbrands et al., 2014). For example, BFb induced changes in knee kinematics clearly influence other joints such as ankle frontal plane moments (Richards et al., 2018). Explorative research has assessed the whole arm with a wearable sleeve which provided temporal information on shoulder, elbow and wrist extension in netball shooting (Helmer et al., 2010). This research provided promising results in the form of increased shooting success, however has yet to be released outside of technology-based conferences. Other internal kinematic based KP research has attempted to manipulate coordination in a simple touch task (Fujii et al., 2016). However, beyond this, very little has been investigated. Multi-joint interaction BFb research, therefore, is required to enhance transferability to training and provide a more holistic approach to motor learning enhancement. Table 2.3 below provides a summative overview of the internal kinematic KP research designs to date, and key findings.

Table 2.3. Overview of BFb research using internal kinematics based KP content. Transmission mode is classified as auditory (Au), Visual (Vi) or Haptic (H), while timing is either concurrent (C) or terminal (T). Schedules and retention time points are detail in days (d), weeks (wk) or months (mth). Number of BFb visits for each schedule, and time of retention are in brackets.

Study	Year	Skill	Mode	Timing	Schedule	Improved	Retained	Key Findings
Kernodle & Carlton	1992	Throwing	Vi	T	4 wk (12)	Yes	Yes (2 d)	KP with cues and transitional information outperformed KR and KP alone.
Swinnen et al.	1997	Coordinated motion task.	Vi	C	2 wk (3)	Yes	Yes (2 d)	BFb facilitated new coordination patterns.
Cirstea et al.	2006	Stroke patient target reach	Au	C	2 wk (10)	Yes	Yes (1 mth)	KP on joint motion increased movement variables. KR, only improved KR variable.
Baudry et al.	2006	Gymnastics	Au	C	2 wk (6)	Yes	Yes (2 wk)	KP related to hip flexion ↑ body alignment on pommel horse rotations.
Helmer et al.	2010	Netball shot	Au	C	1 wk (4)	No	N/A	Interactive sleeve guided whole limb exploration, and ↑ throwing accuracy.
Noehren et al.	2011	Running	Vi	C	2 wk (8)	Yes	No (1 mth)	KP ↓ hip adduction angle. Secondary effects of ↓ vertical loading.
Eriksson et al.	2011	Running	Vi + Au	C	1 visit (1)	Yes	N/A	Fb altered stride length and frequency. (Stride length more). Visual better.
Secoli et al.	2011	Stroke recovery	Au + Ha	C	1d (1)	Yes	N/A	KP facilitated improvements in stroke patients, even with a distraction task.
Thow et al.	2012	Swim start	Vi + Au	T	4 wk (4)	Yes	Yes (4 wk)	KP on dive kinematics more effective than video or verbal coaching.
Etnoyer et al.	2013	Drop jumps	Vi + Au	T	1 d (1)	Yes	Yes (1 mth)	Video BFb significantly ↑ knee and hip flexion at contact.
Shull et al.	2013	Walking	Ha	C	5 wk (5)	Yes	Yes (1 mth)	KP ↓ knee abduction and linked with ↓ clinical pain scores.

Study	Year	Skill	Mode	Timing	Schedule	Improved	Retained	Key Findings
Nunes et al.	2014	Basketball free throw	Vb	T	1 wk (3)	Yes	Yes (1 d)	Qualitative 66% frequency KP better than 33% and 100% in elderly population.
Ericksen et al.	2015	Jump landing	Vi	C+T	1 visit (1)	Yes	N/A	Qualitative real-time + terminal BFb no more advantageous than terminal alone.
Jackson et al.	2017	Walking	Vi	C	1 d (1)	Yes	N/A	Peak knee adduction moment ↓ 20% from baseline.
Richards et al.	2018b	Walking	Vi	C	6 wk (6)	Yes	Yes (15mins)	KP altered foot orientation angle. Cognitive tests show link learning in participants.

With the advancement in computing, real-time joint kinetics, or joint moments, have become a popular form of BFb content in injury focused research (e.g. Ford et al., 2015). However, research to date has been limited to walking (Gerbrands et al., 2014; Richards et al., 2018a) and jump landings (Beaulieau and Palmieri-Smith, 2014; Ford et al., 2015), likely due to the theoretical link between knee abduction moments and increased injury risk in these actions. Conceptually, internal joint kinetics could be very beneficial to accelerating motor learning by providing information specifically related to muscular control, however procedures to calculate internal joint forces have a number inherent of assumptions in calculations (Challis and Kerwin, 1996) and interpretation (Zatsiorsky and Latash, 1993) which will be touched upon in more detail in section **2.4.7. Methods to Quantify the Kinematic Chain**. Therefore, joint segment kinematics remain the clearest option to modify specific technique.

2.3.2. Focus of attention

An external attention of focus has long been prescribed as more beneficial to motor learning than an internal focus of attention (Shea and Wulf, 1999). This has been attributed to the 'constrained action hypothesis' which holds that an external focus of attention allows an individual to develop their own motor solution to the task (Wulf et al., 2002). Allowing a system to self-organise rather than defining constraints (e.g. kinematic patterns) may be more useful in some cases, such as in novice motor learning (e.g. Wulf et al., 2010), however this is not useful for specific movement patterns as required in technique development (e.g. Etnoyer et al., 2013) or rehabilitation (e.g. van den Heuvel et al, 2016). Theoretical approaches emerging from focus of attention paradigms often directly contradict the evidenced success of internal focus KP feedback altering specific technique. A major distinction to separate these BFb and ‘focus of attention’ research approaches, which is often overlooked, is that the focus of attention literature is mostly based on instruction rather than feedback. Instruction informs performers of a required movement, while feedback specifically guides an individual on how to achieve this movement related to their performance. This is increasingly important when a specific technique is the focus of an intervention.

Further complications have been introduced with inherent misinterpretations across disciplines. Specifically**,** variables selected as BFb are not always biomechanically related to performance. This is explained with focus of attention predominantly being a psychological pursuit. For example, an external focus was shown to result in a greater jump height than internal focus (Wulf et al., 2010) however the internal focus was related to the fingertips. When repeated using the lower limbs as an internal focus, BFb has proven more effective at targeting specific movement patterns than both internal and external instruction (Keller et al., 2014). Therefore, it is likely that providing specific direction to learning is important when targeting specific movement patterns.

2.3.3. Feedback Sensory Channel

The modality used to transmit extrinsic information to a performer is both content and skill dependent. Data can be provided using visual (e.g. knee moments projected to a screen; Ford et al., 2015), auditory (e.g. pitch and tone to signify running impacts; Erriksson et al., 2011), or haptic sensory channels (e.g. walking plate vibrations; Shull et al., 2013) or any combination of the above (e.g. visual and auditory gait retraining; Richards et al., 2018a). Modality selection can be influenced by access to specialist technologies, such as a motion capture system allowing for a visual display of joint kinematics (Ford et al., 2015) or software to convert boat acceleration into sound (Schaffert and Mattes, 2015). However, the complexity of content to be portrayed, the environment and attentional capabilities of the skill should be the greater consideration as to the modality selected. For example, there is limited use encoding a complex tibial acceleration time-series curve into an auditory signal during locomotion, when visual presentation provides more detailed information in an environment where a performer can absorb information (Eriksson et al., 2011; Richards et al., 2018a). Variable selection for a skill should be of primary importance, and then the subsequent modality should be selected based on sensory availability, and preference of the performer (Richards et al., 2018a). The following section focuses on modalities used, and compares the strengths and weaknesses of each in turn.

Auditory feedback has a distinct advantage in that minimal attentional focus is required during an activity. BFb transmitted via an auditory channel has been applied to walking (Richards et al., 2018a), running (Eriksson et al., 2011; Wood and Kipp, 2014), and rifle shooting (Kontinnen et al., 2004; Mullineaux et al., 2012) as well as the pommel horse in gymnastics (Baudry et al., 2006) and netball shooting (Helmer et al., 2010). In all cases, auditory KP is applied concurrently, allowing for direct modifications to technique. Auditory information also has advantages in that it does not distract the user from using other implicit sensory sources, more readily complimenting the internal feedback sources, and can be easily linked with other available sources of information such as visual perception (Eriksson et al., 2011). Problematically, auditory KP requires technological capabilities to encode data to an interpretable format. For example, the provision of postural sway data (Mullineaux et al., 2012) and barrel sway (Konttinnen et al., 2004) in rifle shooting is useful, but requires that complex force signals and 3D kinematics are coded into changes in sound wave frequency. These are effective, but require specialist equipment and skill sets to apply. Further, more complex information requires more sophisticated solutions. Cyclical skills lend themselves well to auditory feedback due to the repetitive nature allowing for continual adjustments (Baudry et al., 2007; Eriksson et al., 2011). Limited attempts have been made to develop auditory equipment for complex, explosive skills. Interactive sleeves (Helmer et al., 2010) or leggings (Helmer et al., 2011) to stimulate changes in joint timing have been explored, however these products have yet to reach the consumer market or appear outside of conference abstracts.

Haptic BFb is feedback which invokes any sense of touch. Guided movement is an emerging specialism within clinical settings, blending robotics and exoskeletons with motor skill development (Timmermans et al., 2009). These rehabilitation technologies are generally applied to patients following neurological trauma to facilitate motor relearning (e.g. Secoli et al., 2011). However, these principles have been extended to more dynamic settings. For example, vibration sensors placed on left and right scapulas have successfully stimulated torso lean in gait retraining, and consequently reduced knee adduction moments (Shull et al., 2013). Within sport, sensors have also been placed in rowing oars, with vibration increasing with any deviations from a desired rowing path (Sigrist et al., 2013). While haptic feedback is promising, the requirement for technology embedded in equipment or specialist sensors still hold practical limitations which outweigh the benefits relative to traditional approaches.

Visual transmission is the most commonly used modality for the application of KP, both for concurrent and terminal BFb. The effectiveness of visual KP is clearly evident in a variety of skill and BFb content. For example, wheelchair propulsion has shown significant improvements (Kotajarvi et al., 2006; Richter et al., 2011) with single subject case study retaining kinematic changes for as long as three months (Rice et al., 2010). Other cyclical motions, such as running (Creaby et al., 2016; Bowser et al., 2018; and Zhang et al., 2019) have used visual displays of accelerometer traces to reduce tibia impact accelerations. These have ranged from a single session of BFb in one day (Creaby et al., 2016), to eight sessions in two weeks (Bowser et al., 2018). Importantly, the latter showed retention after 12 months. These studies highlight, collectively, that while changes can be quick, the alterations can be relatively permanent.

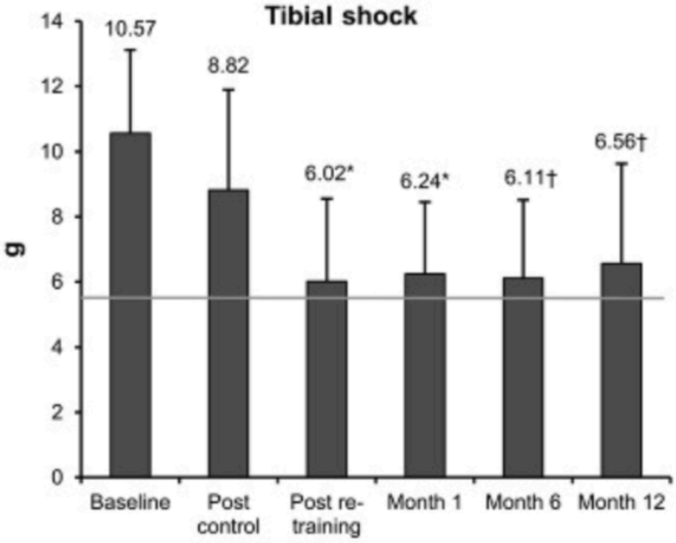


Figure 2.8. Reduction in tibial shock (g) following eight treadmill-based gait retraining sessions with visual BFb from a tibial accelerometer, and subsequent retention at 1, 6 and 12-month retention time points. The grey horizontal line represents normal values used as the gait retraining target. * and † indicate significantly different from post control (*p* <0.05 and 0.01 respectively). Adapted from Bowser et al. (2018).

Visual BFb has a further distinct advantage over other modalities in that complex information can still be successful if displayed correctly. Muscle activation patterns, for example, have been incorporated into rehabilitation programmes for stroke patients and facilitated improvements in tibialis anterior activation and strength (Tsaih et al., 2018). The specific type of plot used seemingly makes little difference when presenting BFb data, once adjusted into a presentable format (van der Noort et al., 2015; figure 2.9). This highlights the importance of transitional information to interpret data (Kernodle and Carlton, 1992). When not clearly explained, improvements are not always shown (e.g. Fortier et al., 2005). Grooms et al. (2018) emphasises this point by integrating four key injury-risk biomechanical variables (knee abduction moments, knee to hip moment ratio, lateral trunk flexion and vertical ground reaction forces) within a real-time deforming rectangle. While using a very complex presentation of variables, the incorporation of the BFb into an augmented neuromuscular training programme afforded transitional information to modify drop landing technique.

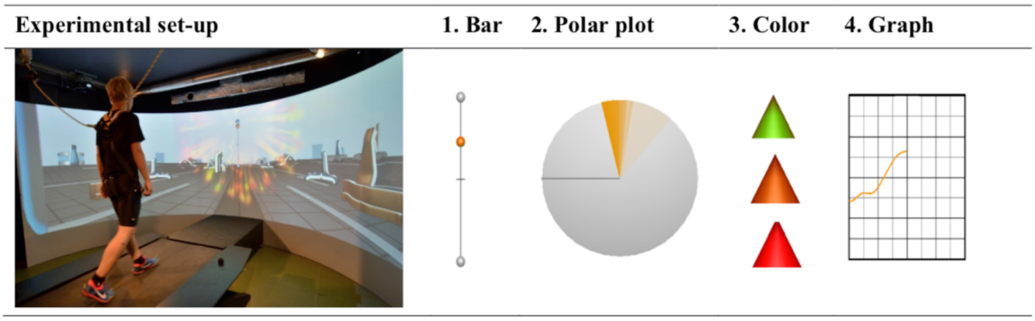


Figure 2.9. Experimental setup highlighting four different types of visual feedback used to present knee abduction moments of hip internal rotation angle. Adapted from van der Noort et al. (2015).

Visual BFb appears to be equally effective in terminal designs, with research demonstrating one (Thow et al., 2012), four (Winchester et al., 2009) and 12-week interventions (Viitasalo et al., 2005), incorporating four, 12 and 36 sessions, respectively. Only one of these tested for retention, but demonstrated positive outcomes with retention testing at four weeks (Thow et al., 2012). Indeed, visual KP has been shown to outperform auditory BFb in altering stride length and frequency in running (Eriksson et al., 2011). Further, visual KP has been identified as the preferred BFb modality in walking clinical patients (Richards et al., 2018a). Clearly, visual BFb is very powerful for motor skill development due to the flexibility for complex, multiple-variable BFb to be applied if refined into a presentable format.

2.3.4. Timing

Feedback timing is a critical factor underpinning motor skill retention. Generally, BFb can be provided concurrently during task execution, or following, and this timing is generally driven by the attentional demands of the movement. When performing a continuous task, concurrent is better as an individual can spend more time modifying the movement during the action (Broker et al., 1993; Park et al., 2000, Eriksson et al., 2011). With discrete skills, particularly explosive movements, the temporal window for adjustments is relatively small therefore attending to concurrent feedback would be difficult. In a BFb review, Sigrist et al. (2013) suggested that with increasing complexity concurrent BFb is more beneficial than terminal, however the research offered to support this is a simple pointing task. In reality, terminal feedback appears to be more effective in complex skills (Maslovat et al., 2009). Broker et al. (1993) found similar improvements in cycle force output between concurrent and terminal feedback groups, however the concurrent group received 18 KP sessions, while the terminal group with terminal feedback on the whole performance only received one. With little timing research using KP designs, KR literature has shown that a delay between action and receiving terminal BFb can influence skill retention (Swinnen et al., 1990). However, if no other trials occur between skill completion and BFb of the trial, then the influence of delay is negligible (Salmoni et al., 1984). With complex movement skills, a moderate delay can actually help intrinsic processes to be evaluated (Swinnen et al., 1990; Park et al., 2000), therefore allowing for increasing time between BFb sessions may be a beneficial strategy to enhance retention potential.

2.3.5. Frequency

The frequency of which augmented information is provided to an individual greatly influences performance acquisition and learning, and can have interesting effects on retention. Frequency is usually quantified as a relative percentage of total time (e.g. 100% equals every trial, 50% every other). Originally, KR interventions informed that a high volume of BFb was highly effective for transient performance changes, but detrimental to learning, explained by the guidance hypothesis (Salmon et al., 1984). However, it became apparent in early ski simulator experiments that this was not the case with KP and complex skills (Wulf et al., 1998). Complex skills require a higher level of frequency of BFb to guide learning (Wulf and Shea, 2002; Mononen et al., 2003; Wulf et al., 2010; Nunes et al., 2014 Fujii et al., 2016). Rifle shooters in Mononen et al. (2008) demonstrated more consistent performance outcomes with a high volume of BFb providing direction to learning. On a theoretical level, individuals receiving less than 100% BFb are encouraged to learn aspects of the task that enable them to execute the skill without BFb (Salmoni et al., 1984). However, more complex skills may require a higher volume of BFb to help to facilitate organisation of the greater DoF. As the information becomes more complex, and is related to coordinating multiple joints, 100% is more effective than 50% BFb (Fujii et al., 2016). Research contradicting that high volume BFb is detrimental for complex skills should be considered with caution. For example, Nunes et al. (2014) stated that 66% was the optimal BFb frequency with older adults learning the basketball free throw compared to 33% and 100%. However, the performance assessment was binary with one point for a basket but zero for all other outcomes. Previous research has scored on a 1-5 for shot quality (Helmer et al., 2010), which is sensitive to subtle technique changes. For example, a ball may hit the rim and bounce off, which is a performance improvement from complete misses in Nunes et al. (2014). Further, movement quality was qualitatively assessed and open to subjective error which may not be sensitive to subtle kinematic changes (Giblin et al., 2014). To enhance complex skill learning while avoiding the dependent properties of BFb research designs with 100% frequency have incorporated a faded, or reducing, BFb schedule (e.g. Shull et al., 2013; Bowser et al., 2018; Richards et al., 2018b). These designs allow for the extraction of the BFb over a number of sessions (e.g. 100%, down to 50% and then 25% for visit 1, 2 and 3 respectively). An alternative approach is to increase time between visits which allows for cognitive reinforcement to occur with time, enhancing permanency of learning (Parks et al., 2000).

2.3.7. Summary of Factors Influencing KP Effectiveness

It is apparent that KP can influence specific technique by focusing on performance determining components, but the content should be empirically supported. Historically, KP content has focused on a single joint, with simple skills. Most of these skills are also cyclical and continuous. For BFb to be useful in the vast array of applications in the real world, research focusing on discrete, complex skills, with whole limb joint interaction, is required.

To alter technique, KP content focusing on internal joint kinematics is essential. This can also produce secondary effects such as an increase in external ground reaction forces. With more complex information, such as data on a whole limb joint interaction, visual BFb affords the most effective solution to convey large volumes of complex information in a simple approach. During discrete tasks, the most effective timing for feedback presentation is following task execution, with complex skills requiring 100% frequency to facilitate retention and more permanent learning.

2.4. The Lower Limb Kinematic Chain in Human Movement

2.4.1. Whole Limb Movement

The human musculoskeletal system almost exclusively creates movement by translating joint rotations into linear motion (Bobbert and van Soest, 2001). For example, CoM forward rotation still occurs in vertical jumping with hip extension rotating the trunk which translated in to vertical propulsion (Bobbert and Zandwijk, 1999). This requires the coordination of many skeletal muscles around multiple joints to create the desired CoM translation (Gregoire et al., 1984; van Ingen Schenau, 1989a; 1989b; Zatsiorsky and Latash, 1993; Cleather et al., 2015). Successful bodily propulsion using whole limb contribution is achieved through kinematic sequencing of these joints, with research identifying a stereotypical joint sequencing pattern existing in explosive movements (e.g. jumping, Bobbert and van Soest, 2001; and sprinting, Jacobs et al.,1996).

According to Bunn's (1972) 'summation of speed principle' kinematic sequencing can augment an accumulation of angular velocities, generated in preceding segments, toward a distal endpoint. Large proximal segments are controlled by large force generating muscles (e.g. gluteus maximus), with smaller segments having smaller muscles with greater dexterity for control at the distal end of the chain (Mullineaux and Uhl, 2010). The proximal distal increase in angular velocity is due to 1) reducing moments of inertia with decreasing segment sizes, 2) power transfer mechanisms of biarticular muscles (Gregoire et al., 1984; Jacobs et al., 1996), and 3) stretch shortening mechanisms (Arnold et al., 2010). The sequential kinematic chain has been demonstrated in a number of open-chain movements where the most distal segment is unattached, thus free to move. Examples of this are, ball kicking (Putnam, 1993; Katis et al., 2015) handball throwing (Wagner et al., 2012), the tennis forehand (Landlinger et al., 2010), and the golf swing (Zheng et al., 2008; Tinmark et al., 2010).

In 'closed chain' movements, such as in jumping, the distal endpoint is fixed. Arguably, these are not always fully closed chains, with the proximal endpoint (the body) able to move in space, however inertia of the heavy trunk segment still imposes some resistance (Bobbert and van Soest, 2001). The movement requirements therefore may not be maximal segment end point velocity, but rather whole-body propulsion through greater force generation. In propulsive movements, such as jumping, the lower limb has also been shown to resemble a stereotypical proximal to distal sequence prior to take off (Jacobs et al., 1996; Bobbert and van Soest; Wong et al., 2016). This sequential action seemingly contradicts mechanical optimization principles, where simultaneous extension of the hip, knee, and then ankle plantar-flexion is suggested as optimal (Gregoire et al., 1984)**.** The neuromuscular anatomy of the lower limb, however, allows a proximodistal sequence to capitalise on the role of bi-articular muscles, allowing a transfer of energy between joints (Gregoire et al., 1984; Cleather et al., 2015). Theoretically this patterning is suggested to exploit the lower limb neuromuscular design in propulsive movements.

2.4.2. From Rotation to Translation

Almost all human movement is generated via rotations. The contribution of any individual joint rotation to translational movement is largely dictated by two joint constraints; a ***geometric constraint*** and an ***anatomical constraint*** (van Ingen Schenau, 1989a)***.*** The first adheres to simple geometric principles, in that a joint is much less effective in contributing to translational velocity at full extension. For example, in the context of knee extension, equation 2.1 demonstrates the translational separation of the hip and ankle (virtual segment HA) as a function of knee angle. This is defined as the interaction of the hip-knee vector (HK) and knee-ankle vector (KA). When differentiated with respect to time and rearranging terms, this becomes equation 2.2. The expression in equation 2.2 determines the transfer of joint angular velocity to translational velocity V_{HA}.

$$HA^2 = HK^2 + KA^2 - 2HK \cdot KA \cdot cos\theta \qquad \textbf{Eq. 2.1.}$$

$$v_{HA} = \Delta HA/\Delta t = [HK \cdot KA \cdot sin\theta/\sqrt{HA^2}] \cdot \Delta\theta/\Delta t \qquad \textbf{Eq. 2.2.}$$

Mathematically, this transfer function gradually decreases to zero at θ=180° (cos·180 = 0), with this relationship occurring with other joint combinations in the lower limb kinematic chain (Cleather et al., 2015). The second, ***anatomical constraint,*** holds that a joint has a limited range of motion to accelerate, and then successfully decelerate, before damaging hyper-extension occurs. This means that joint velocity is restricted at the extreme ranges of motion (RoM), with large body segments requiring antagonistic action to actively decelerate the joint following rapid extension (Bobbert et al, 2013). For example, during an explosive movement such as vertical jumping the knee joint must accelerate rapidly to maximal joint extension velocity (e.g. 10 rad·s^{-1}), and then decelerate back to 0 rad·s^{-1} prior to full extension. The alternative is passive structures absorbing this velocity, which could have disastrous implications such as singular or double cruciate ligament ruptures and bony oedema (Ali et al., 2018).

These constraints govern the translational contribution from individual rotational joints. Figure 2.10 demonstrates the translation in hip and ankle separation (V_{HA}) brought about by the knee joint in extension as depicted in equation 2.2. Due to both the **geometric** and **anatomical constraints** V_{HA} reaches its peak far before full extension. Peak V_{HA} can occur at a knee extension of 132°, much earlier than full extension (van Ingen Schenau, 1989a). This creates interesting questions when considering that take off often occurs much closer to full knee extension.

This incorporation of additional joints into this line of enquiry begins to explain the stereotypical sequential extension patterning in jumping. Bobbert and van Soest (2001) offer additional support to sequential patterning by building on work by van Ingen Schenau (1989a) in relation to the whole-body centre of mass (CoM) and premature take-off. If the vertical acceleration of the CoM is greater than -9.81 m·s^{-2} with a single joint contribution, then take-off will occur prior to full extension of that joint. The heavy trunk accelerating above the gravitational component will pull the lighter lower limbs up with it (van Ingen Schenau, 1989a; Bobbert & van Soest, 2001). A premature take-off, prior to full joint extension, is ineffective if the goal is to attain maximal vertical displacement, as only a small percentage of the lower limb musculature would have contributed. Timely extension of more distal segments, such as the knee and ankle, have been proposed as solutions to such a problem (Bobbert and van Soest, 2001). Referring to van Ingen Schenau's (1989a) model, the inevitable velocity decrease in V_{HA} is prevented by a rapid and timely extension of the knee, which in turn is supported by a timely ankle plantarflexion. This results in continued velocity of the hip relative to the ground (V_{HG}). While the above principles provide mathematical support for the occurrence of the stereotypical proximal to distal sequencing in jumping, the movements are driven by the underlying musculature and this have clear application to propulsion in multiple directions.

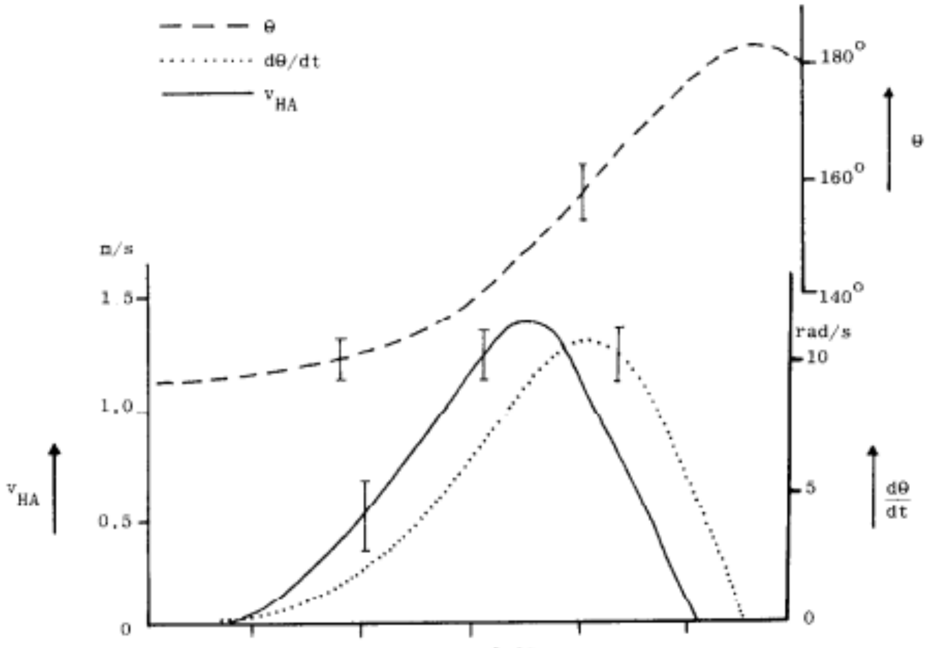


Figure 2.10. Velocity difference (V_{HA}) between hip and ankle during push off in speed skating. This velocity difference is not only determined by the knee angular velocity dθ / d*t* but also by the knee angle θ as demonstrated in equation 2.2. Note that dθ / d*t* is decelerated to 0 rad·s^{-1} prior to full extension according to anatomical constraints (Adapted from van Ingen Schenau, 1989a).

2.4.3. The Role of Biarticular Muscles

The explosive, whole limb, push-off is difficult to achieve if driven by mono-articular muscles alone. Research has identified that as much as 3000-4000 W of power is produced at the ankle in vertical jumping (Gregoire et al., 1984), with more conservative calculations still deriving values in excess of 2000 W (Bobbert and van Ingen Schenau, 1988). With simultaneous lower limb joint extension, the plantar flexors would have to generate the 2000-4000 W to propel the whole body alone (Bobbert and van Ingen Schenau, 1988; van Ingen Schenau, 1989a). Optimization models in vertical jumping show that the mono-articular plantar-flexors produce around 20% less peak force than the total peak force calculated at the ankle (Cleather et al., 2011). This additional force comes from bi-articular muscle contributions. Specifically, at the ankle this is the gastrocnemius with this muscle providing a dual functionality. Firstly, the gastrocnemius provides an antagonistic braking mechanism to knee extension, protecting the knee from the anatomical constraint by slowing excessive extension velocities. However, rather than wasting energy produced during knee flexion the gastrocnemius isometrically contracts, “locking” the bi-articular muscle (figure 2.11) and couples knee extension with plantarflexion of the ankle (Gregoire et al, 1984; van Ingen Schenau, 1989a, Cleather et al., 2011). In doing so, this coupling also allows the knee extensors to continue to contribute to the movement. As a transfer mechanism the gastrocnemius can contribute approximately 25-28% of total work delivered in the ankle in jumping and sprinting from knee extension (Jacobs et al., 1996).

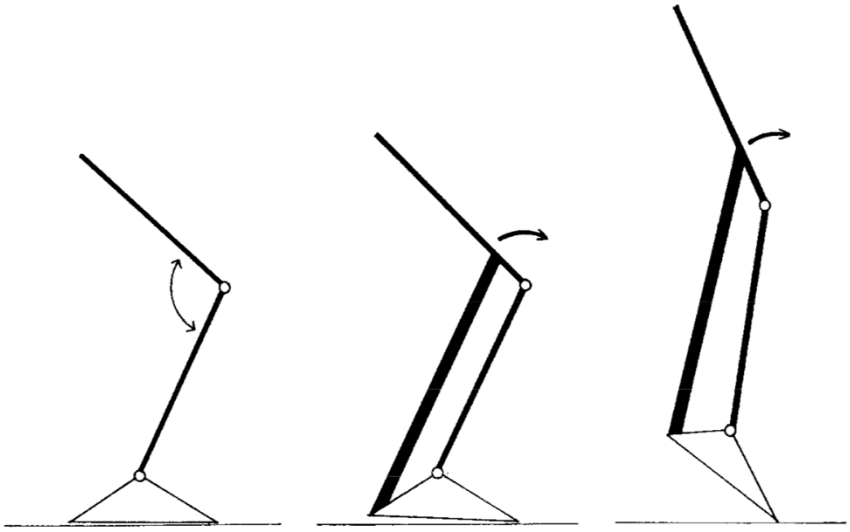


Figure 2.11. Gastrocnemius (thick black line) coupling knee extension to ankle plantar flexion. The far-left image depicts knee extension. The middle image includes a simplified model of the bi-articular gastrocnemius coupling knee extension with ankle plantarflexion. This overcomes both the geometric and anatomical constraints (adapted from van Ingen Schenau. 1989a).

The knee produces the most power in explosive whole limb leg extension (Jacobs et al., 1996; Cleather et al., 2015) making the knee-ankle coupling an extremely effective strategy for movement. The long flat muscle fusiform fibres of the vastii muscle group (vastus lateralis, medialis and intermedius) can produce isometric forces of around 4500 N (van Soest, 1993). This has been shown to equate to 43 J and 49 J of work in the last 90 ms of vertical jumping and the sprint 'push-off' respectively, compared to 24 J and 22 J in the mono-articular soleus for the same movement (Jacobs et al.,1996). The transference of power at the knee overcomes the geometric and anatomical constraints by transferring angular velocity, and power, to a more effective distal segment to contribute to take off as the CoM is accelerating upwards. Computer modelling has shown that changing the gastrocnemius into a mono-articular muscle decreases jump height (van Soest et al., 1993).

A more complex bi-articular muscle coupling relationship also occurs with the hip to knee by the bi-articular rectus femoris and hamstrings (Cleather et al., 2015). The hip extensors, primarily the gluteus maximus with a broad quadrilateral shape made up of thick bundles of parallel fibres, generates large forces to extend the heavy trunk (Bobbert and van Soest, 2001). The hamstrings are also activated to contribute to hip extension (Jacobs et al., 1996) but paradoxically create knee flexion via the bi-articular long head of the biceps femoris. Due to differing moment arm lengths at the hip and knee for both the hamstrings and rectus femoris, the net movement results in leg extension (Latash and Zatsiorsky, 1993). The mono-articular vasti muscle group helps to overcome this additional knee flexion torque (Cleather et al., 2015), along with the bi-articular rectus femoris coupling the powerful hip extension to knee extension and allowing for a net knee extension moment (figure 2.12). During single leg jumping, the rectus femoris has been calculated to transfer 21% of the work done in knee extension from the hip, and 31% in sprinting (Jacobs et al, 1996; figure 2.13).

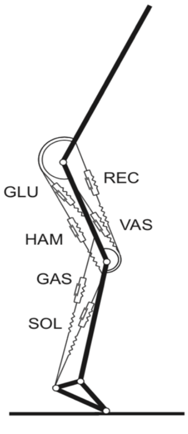


Figure 2.12. Model of the musculoskeletal system used in vertical jumping models. This demonstrates attachments for the mono-articular muscles crossing single joints for the gluteus maximus (GLU); vastii (VAS); and soleus (SOL), and the bi-articular muscle groups crossing two joints, of the rectus femoris (REC); hamstrings (HAM); and gastrocnemius (GAS). Adapted from Bobbert et al. (2013).

Taken in combination, recent modelling work has demonstrated that the human lower limb neuromuscular design is, in fact, optimal for jump performance (Wong et al., 2016). Clearly, the biarticular design offers an elegant solution to movement.

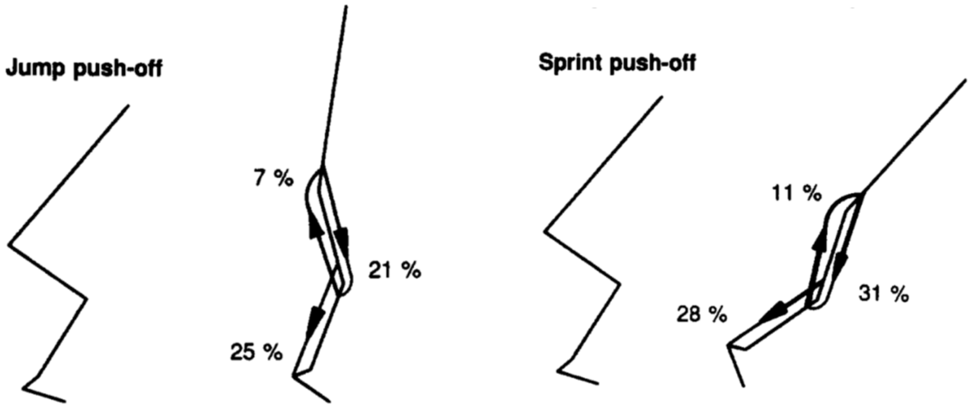


Figure 2.13. The relative work contribution of the biarticular muscles of the lower limb (hamstrings, rectus femoris and gastrocnemius) to the work done about a joint through power transfer, along with the direction of the transfer action. These values were calculated in the last 90ms of jump push-off (left) and the sprint push-off (right). Adapted from Jacobs et al. (1996).

An additional benefit of bi-articular muscles is a greater affordance of force direction solutions for motor tasks. Hof (2001) identified that mono-articular muscles produce a distal endpoint force vector primarily in the direction of one of the segments, whereas bi-articular muscles allow for a transverse component (figure 2.14). Therefore, it is clear that the traditional approach to assess joints individually, and not account for alterations in other related joints within the kinematic chain, is not always appropriate.

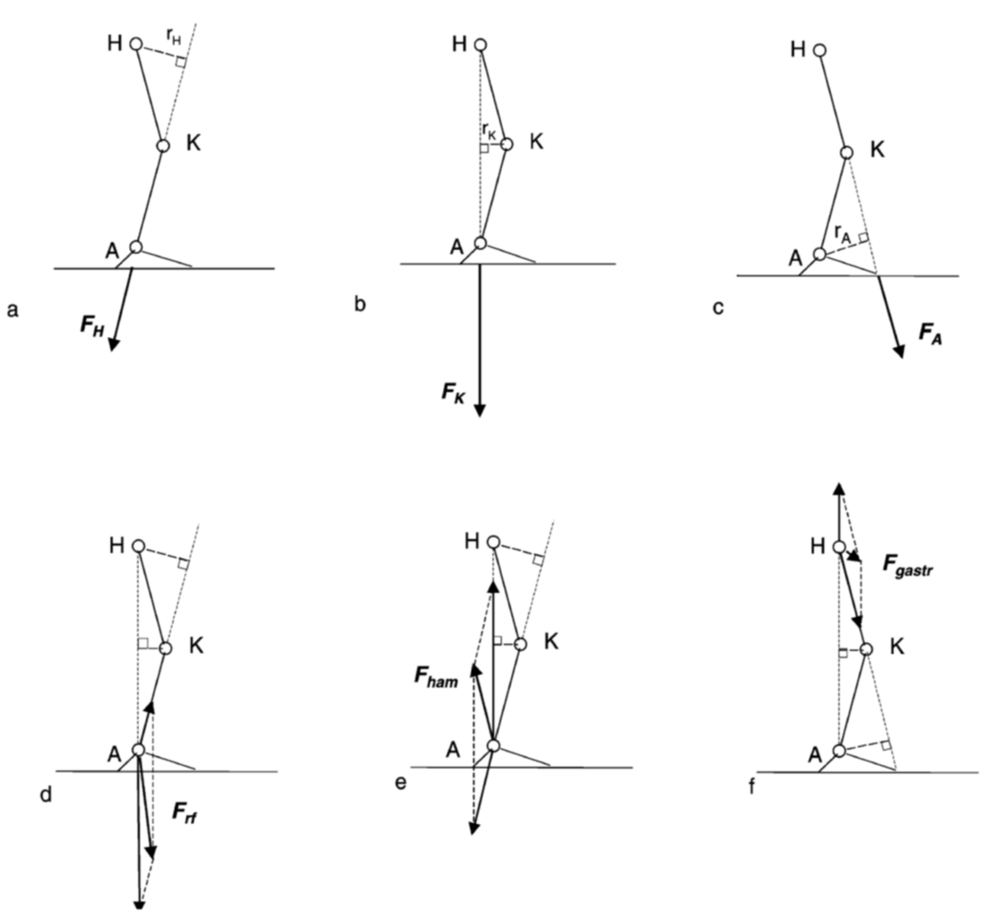


Figure 2.14. Ground reaction force vector orientations at the distal end point due to force of: a) monoarticular hip extensors (e.g. psoas); b) monoarticular knee extensors (vasti group); c) monoarticular ankle plantar flexor (soleus); d) biarticular rectus femoris; e) biarticular hamstrings; and f) biarticular gastrocnemius. Adapted from Hof (2001).

2.4.4. The Achilles tendon complex

The Achilles tendon is an efficient and advantageous biological component at the distal end of the kinematic chain. The long head of the bi-articular gastrocnemius and mono-articular soleus combine to form the longest tendon in the body which provides a mechanism to assist the small, distal segment plantar flexors to transfer the accumulated power from the whole limb to the ground for propulsion (Lichtwark and Wilson, 2006). The soleus, a very short muscle, can produce very little power at high velocities of shortening (van Ingen Schenau, 1984). The length and strength of the Achilles tendon facilitates the use of mechanical power accumulated in the kinematic sequencing described in earlier sections. Modelling research suggests that the elastic element of the triceps surae can act as a power 'amplifier', in retaining muscular work applied over the course of a relatively long contraction (Roberts and Azizi, 2011) which can then be released rapidly (see figure 2.15). This allows application of the same work in a shorter time, increasing power output (Bobbert, 2001; Roberts and Azizi, 2011). This is shown in the last 50-60 ms of vertical jumping, with kinetic energy of the CoM increasing by as much as 50%, in concert with rapid extension of hip and knee joints in the final push-off (van Ingen Schenau et al., 1989a) and a power return from the series elastic element of the Achilles tendon (Bobbert, 2001). Therefore, an increase in knee extension while maintaining a positive plantarflexion, leads to a greater transfer of mechanical power. The final extension contribution in the lower limb also puts the bi-articular muscles into lower, more favourable contractile velocities to produce force (Gregoire et al., 1984) with this additional accumulated work being transferred into the Achilles tendon. It is this elastic property that provides the advantage in explosive movements, which is exhibited with a fast and timely ankle plantarflexion.

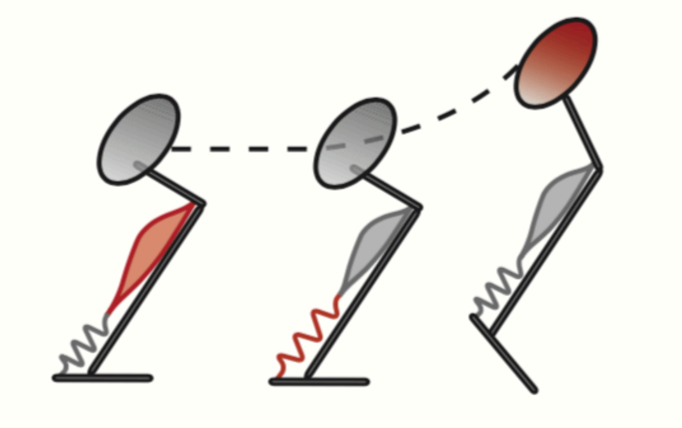


Figure 2.15. Schematic demonstrating power 'amplification' by the Achilles tendon. Work generated in the muscle is directly loaded and stored in the tendon, which can then be released rapidly into the body. If this energy is released more rapidly than it is stored, it is amplified. Adapted from Roberts and Azizi, 2011).

In running and walking, much of the work completed by the muscle tendon unit (MTU) is via isometric contraction of the plantar-flexors, with the Achilles tendon efficiently and repetitively returning elastic energy (Lichtwark and Wilson, 2006). In contrast, ultrasound imagining during squat jumping has shown that the triceps surae fascicles contract and shorten by 26%, stretching the tendon by 6%. This preloads the Achilles with 4.9 J of stored elastic energy, while the whole MTU does not change in length. Elastic energy is then released during the final 100 ms where the whole MTU shortens rapidly by around 5.3%, releasing higher peak elastic energy than that of fascicles alone (Kurokawa et al., 2001). Simulation models in counter movement jumps show that around 25% of peak power in plantarflexion is from the knee-ankle power transfer, with calf contraction providing 25%, and the remaining 50% from elastic recoil (Bobbert et al.,1986a; 1986b). Confirming these mathematical models, in vivo ultrasound demonstrates that both the soleus and gastrocnemius produce this elastic recoil in maximal vertical jumping (Farris et al., 2016), with this explosive catapult type recoil explaining how the ankle accumulates and utilises high velocities necessary in whole limb explosive movements (Hof et al., 1983). Further support is added to this with the 3000-4000 W of power produced in the ankle in vertical jumping (Gregoire et al., 1984) exceeding muscle fascia contractions capabilities alone (Roberts and Azizi, 2011; Farris et al., 2016). The compliant elastic tendon allows muscle fascicles to produce work at a more favourable velocity (Lichtwark and Wilson, 2006; Roberts and Azizi, 2011). Thus, as plantarflexion velocity increases, this tendon is capable of moderating and utilizing the additional velocity (Lichtwark and Wilson, 2006). Flexibility does exist within the system, however, with ankle strapping shown to have no effect on countermovement jump height (Abian-Vicen et al., 2008) which is most likely compensated for by knee extensors being prime contributing muscles in jumping (Jacobs et al., 1996) and able to overcome the more efficient Achilles tendon property deficit.

2.4.5. Joint timing

Timing of joint extensions is an important feature of the kinematic chain (Bobbert and van Soest, 2001). A simple physical model of a jumper (figure 2.16) can demonstrate the importance of joint timing in utilising bi-articular musculature. Experiments have explored relative timing using a trunk mass on a vertical rail, with a spring representing the mono-articular knee extensors and a wire of differing lengths representing the gastrocnemius. By varying the wire length, the timing of the gastrocnemius coupling knee extension to plantar flexion is manipulated. Using this model, an optimal length (reflecting an optimal timing strategy) has been shown to double height reached in the pseudo jump setup (Bobbert et al., 1987; van Ingen Schenau and Bobbert., 1988).

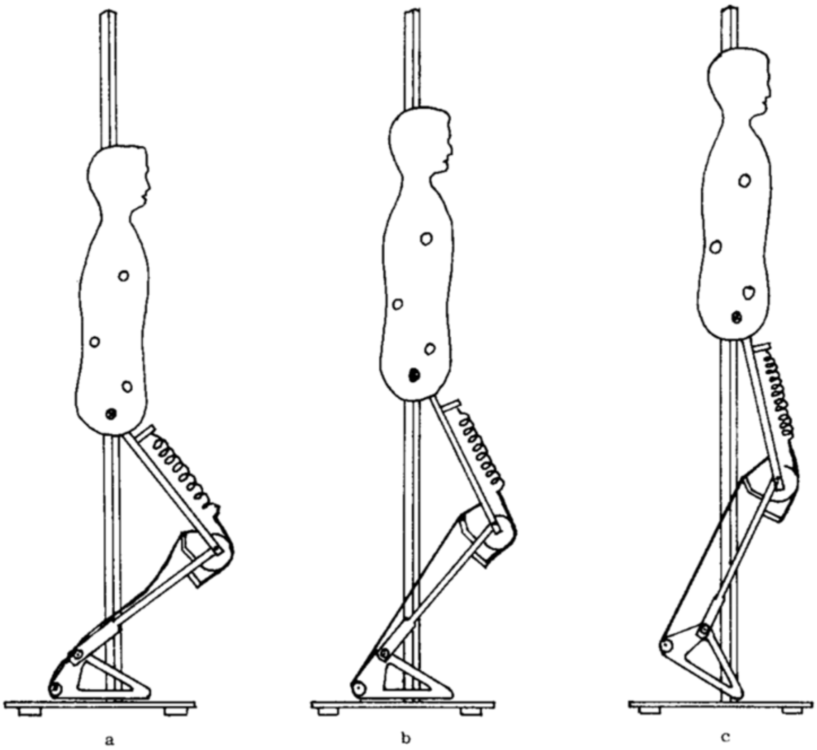


Figure 2.16. A physical 'jumping jack' model used to demonstrate the power transporting mechanism of the gastrocnemius. A spring represents the knee extensors which can be loaded with potential energy. Adjusting the length of the wire from the thigh to foot segment allows for manipulation of joint timing, as it represents the gastrocnemius coupling knee extension to ankle plantar flexion. At optimal timing the model jumps almost twice as high compared to jumps without coupling between these joints (26cm versus 14cm). Adapted from Bobbert and van Soest (2001).

The influence of jump timing has further been supported with mathematical simulations (Bobber and van Soest, 2001; Wong et al., 2016). Bobbert et al. (1987) showed that premature knee-ankle coupling resulted in the model losing contact with the floor prior to full knee extension meaning that the potential energy in the spring model was not fully utilised. This is analogous with the gastrocnemius and Achilles tendon spring like properties. Conversely, at an optimal wire length, thus timing, 90% of potential spring energy is converted into the vertical direction as ‘effective energy’. Bobbert and van Zandwijk (1999) suggested that hip, knee and ankle moments are sequential only due to the different timing it takes to activate these muscle groups. It has also been speculated that individuals in fact try to initiate all segment rotations simultaneously, but that inertial forces caused by the heavy trunk force the knee and ankle into additional, sequential, flexion (Hopper, 1973). However, simultaneous knee extension and plantar-flexion has been shown to impair activity of the gastrocnemius and increase activation of the mono-articular soleus in plantar flexion (Suzukiet al., 2014). This ultimately employs weaker musculature for the same movement. Bobbert and van Soest (2001) infer that foot timing is the most crucial as it has the lowest inertia for high velocity rotation, and due to distal positioning, it can continue to apply force following premature ‘take off’. Indeed, constraining muscle contractions of lower limb musculature to 100 ms after soleus reduced CoM jump height by 9 cm (Bobbert and van Soest, 2001).

2.4.6. Changes to the Force-Velocity Curve in Whole Limb Movement

Explosive tasks require the acceleration of the body’s CoM as quickly as possible (e.g. jumping, running). Success in these tasks is mostly driven by maximising power output of the lower limbs (Jacobs et al., 1996; Samozino et al., 2012; Samozino et al., 2014). From a neuromuscular perspective, power describes the physiological capabilities of skeletal muscle to generate force over a given velocity. Hill’s (1938) muscle model first described the hyperbolic force-velocity (F-V) relationship of isolated muscles (figure 2.17) and subsequent power generation. In movements involving a combination of joint rotations, however, the hyperbolic F-V relationship has been shown to be quasi-linear due to segmental interaction dynamics flattening this relationship (Bobbert, 2012; Jaric, 2015). The segmental interactions become an important consideration within interventions aiming to manipulate the force or velocity generating capacity of the system. However, it is important to note with these research updates that the velocity considered is related to segment or CoM velocity rather than isolated muscle shortening velocity as in Hill (1938).

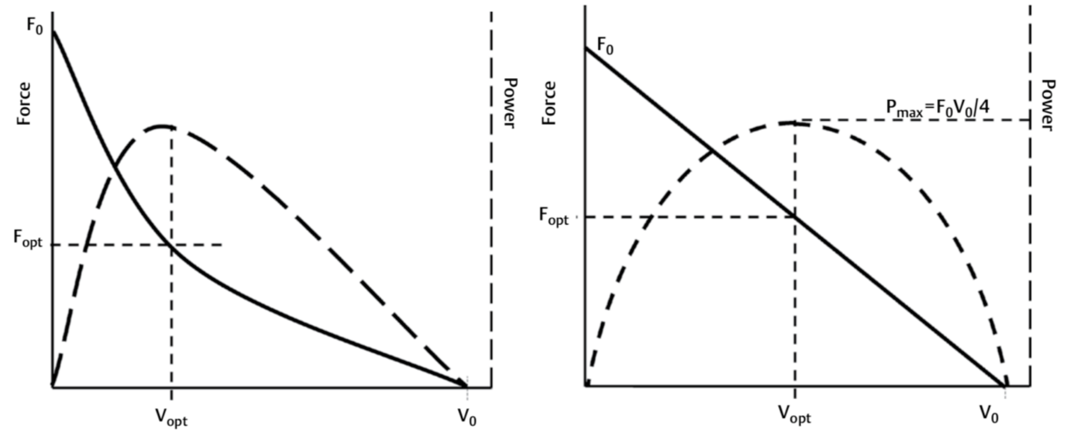


Figure 2.17. Typical force-velocity (solid line) and corresponding power-velocity (dashed line) relationship for a muscle or muscle group (left) and multi-joint task (right). The optimal force (F_{opt}) and velocity (V_{opt}) are the values which maximise power. Note, in whole limb movements P_{Max} occurs at higher velocities. Adapted from Jaric (2015).

The F-V relationship highlights important links between external force generation and power production, both at the individual joint level and propulsion of the whole-body CoM. The whole-limb quasi-linear relationship means that maximal power occurs at higher velocities than in the hyperbolic curve (Jaric, 2015). Whole limb propulsion, therefore, must be considered different to single limb profiles. In both cases, maximal power capabilities can be improved either by increasing the ability to deliver high force at low velocities, or low force at higher velocities. Generally, increasing force requires either physical adaptations over time (González-Badillo and Sánchez-Medina, 2011), or requires changes in technique, which can occur relatively quickly as discussed in earlier sections. Individual F-V profiles are relatively consistent over time, but still flexible (figure 2.18). Velocity has been shown to shift slightly with training, alongside increase in force production (González-Badillo and Sánchez-

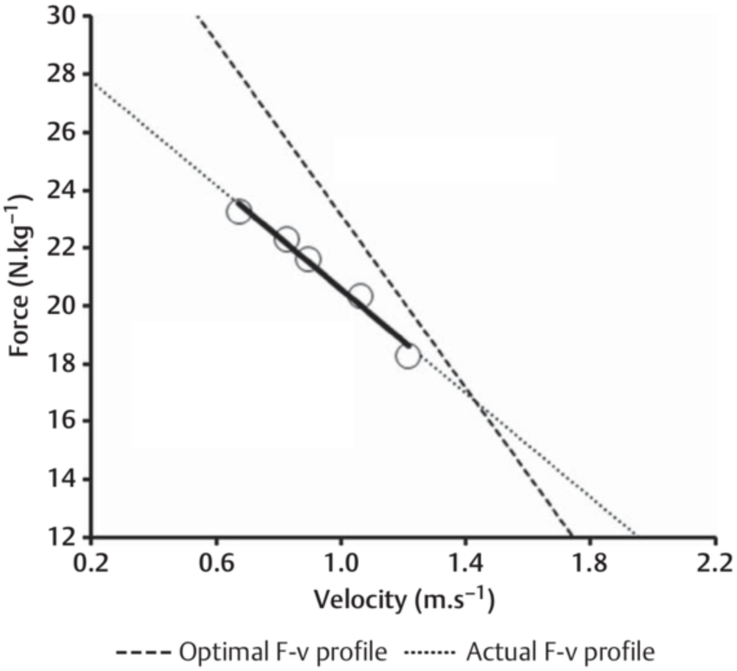


Figure 2.18. Typical linear normalized force-velocity relationship (solid line) obtained with squat jumps at given loads for one individual. The target adjusted force-velocity relationship is shown (dotted line) for this individual to maximise jump height, with no change in maximal power. Adapted from Samozino et al. (2014).

Medina, 2011). Indeed, individual F-V profiles can achieve the same maximal power output by theoretically manipulating the F-V relationship (Samozino et al., 2014). Jimémez-Reyes et al., (2019) identified that specific training directed at either force or velocity, dependent on individual deficits, can result in specific adaptations leading to greater jumping capabilities.

Individual joint roles need to be considered from the perspective of F-V profiles when targeting whole limb modifications. Specifically, the hip flexors have large force generating requirements to initiate movement and the heavy trunk (Bobbert and van Soest, 2001; Bobbert, 2012), therefore these muscles are likely to operate at a lower velocity. The knee, in contrast, contributes to an already accelerating CoM and therefore may be able to contribute more force at a higher, more favourable, velocity. The largest external force produced around the knee occurs at around 30° of flexion (Hahn et al., 2014), therefore orientation is also important. Finally, the ankle is seen to rotate the fastest, with the long compliant tendon of the plantar flexors acting like a catapult by causing the shortening velocity of the muscle tendon complex to be higher than that of the muscle fibres, allowing for fast plantar flexion in the final part of push off (Bobbert and van Soest, 2001). Maximal plantar flexion power is produced at around 80% maximal angular velocity in dynamic, non-isolated muscles, compared to 30% in isolated experiments (van Ingen Schenau et al., 1985).

2.4.7. Methods to Quantify Whole Limb Contribution

There are a number of approaches that have been applied to the quantification of the kinematic chain to explain contribution of the whole limb to movement. The motion of segments within the kinematic chain is dependent on how these segments interact (Putnam, 1993), therefore analysis methods need to assess all interrelating joints and segments.

Mathematical approaches can be used to explain whole limb kinematics (Putnam, 1991; 1993; Latash and Zatsiorsky, 1993), and how specific kinematic patterns emerge (Bobbert and van Soest, 2001). However, the complexity of these approaches makes using this information in an applied environment difficult. Similarly, computer simulations are useful to create predictive models to optimise future skill execution (Pandy and Zajac, 1991), or answer questions explaining the complexities of our neuromuscular design which are difficult to assess in vivo (van Soest et al., 1993; Bobbert, 2001; Bobbert, 2013; Bobbert et al., 2013; Wong et al., 2016). These models can also incorporate musculoskeletal data to explain the emergence of skill in detail (Bobbert and van ingen Schenau, 1988) or contributions of muscle groups (Gregoire et al., 1984; Jacobs et al., 1996) or specific muscle contributions (Bobbert et al., 1986b; Bobbert et al., 1986c; Hof, 2001). However, these approaches, again, are still overly complex for an applied practitioner to use.

The combination of kinematics and kinetics, through inverse dynamics analysis (IDA), provides useful information to explain whole system dynamics. Putnam (1993) suggests that a linked system can be completely explained by the joint moments if these match the available number of DoF in that system. Mathematically, combining segmental kinematics, known inertial properties and external ground reaction force data allows for the calculation of net joint torques, power and work around a joint (Hatze, 2002; Whittlesey and Robertson, 2014). The process involves solving the turning force acting on the distal segment first, and then solving the unknowns with the new known proximally up the chain in turn (Winter, 2009). While still a relatively complex approach, the reduction of complexity to net muscular actions allows results to be more intuitive. However, limitations of IDA are well documented (Challis and Kerwin, 1996; Cleather et al., 2011; Bezodis et al., 2013; Cleather et al., 2015). For example, derivative errors associated with joint centre location are amplified with each derivative (Challis and Kerwin, 1996), literature cannot agree on muscle moment arm lengths for joints (Cleather et al., 2015), and IDA does not take into consideration the impact of bi-articular muscles on adjoining segments (Latash and Zatsiorsky, 1993). Optimisation methods have been proposed, allowing for the incorporation of bi-articularity to IDA (Cleather et al., 2011), however this provides additional complication to an already overly complex approach. Therefore, a more simplified approach using kinematic contributions alone may be useful.

Three main approaches exist in defining kinematics of the whole kinematic chain contribution (Putnam, 1993). In maximal distal velocity-based movements (e.g. kicking), segment distal linear velocity endpoints are often used (van den Tillaar and Ettema, 2009; Landlinger et al., 2010). However, this method does not fully capture segment interactions, and does not relate the movements into an anatomical framework. The two alternative kinematic approaches used are the segment-based approach (Marshall and Elliot, 2000; Tinmark et al., 2010; Fargier et al., 2016) or joint based approach (van Ingen Schenau, 1985; Zheng et al., 2008; Liu et al., 2010; Wagner et al., 2011). It has been argued that using segments for the analysis of velocity accumulation provides an intuitively pleasing methodology (Putnam, 1993; Zatsiorsky and Latash, 1993). However, segment analysis may be conceptually difficult to understand for non-biomechanists, and can often require applications of inverse kinematics to refine joint centre locations for analysis. Joint angular velocity data, however, provide clear descriptions of proximal to distal sequencing, which also makes it easy to visualize the movement. Therefore, the joint based approach may actually be more intuitively pleasing for applied practitioners.

2.5. Sport Specific Literature: Vehicle for Feedback

To assess the influence of KP on a complex skill, a movement incorporating multiple interacting joints is required as a vehicle for research. Limited kinematic KP research has focused on explosive, discrete skills beyond research using single variables in jump landing (Ericksen et al., 2011), swim start glide performance (Thow et al., 2012) or qualitative KP with elderly populations in basketball throwing (Nunes et al., 2014). In addition, KP research to date has not incorporated whole limb contributions to movement in a complex skill beyond an interactive textile pilot study in netball (Helmer et al., 2010). Answering questions around a discrete, complex-skill, therefore, would provide a significant contribution to the BFb literature. There is limited information as to how a whole limb can be influenced using KP, particularly in a sport specific movement. The fencing attacking lunge was selected as a vehicle for analysis. This was, in part, due to the stationary start followed by whole body propulsion using the lower limbs and a clear outcome measurement of performance used in the literature around CoM velocity, but with accuracy required to make contact with a target restraining the movement. Research underpinning the fencing attacking lunge will be covered in more detail in the subsequent sections, with further reasoning as to the selection of this particular skill for the applications of KP.

2.5.1. The Fencing Attacking Lunge

The lunge is the most frequent attacking movement in fencing. A lunge has been shown to occur once every 23.9 seconds for males, and 20 seconds in females, in a national sabre tournament (Aquili et al., 2013), identifying the high prevalence of the

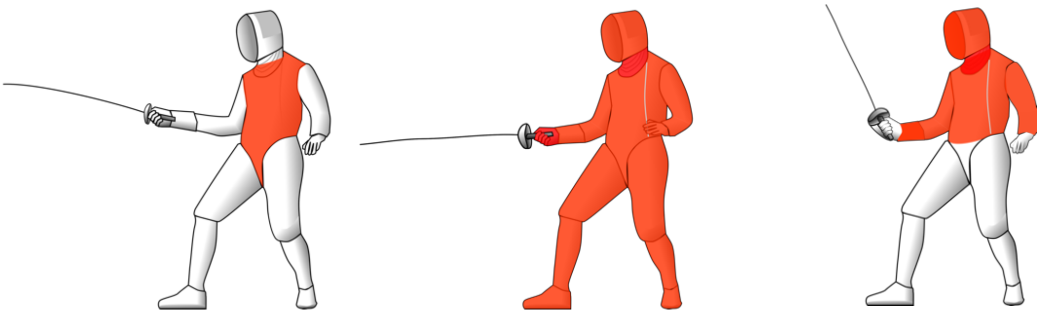


Figure 2.19. Point scoring zones for the foil (left), épée (middle) and sabre (right).

skill within the sport. Competition fencing is categorised by three weapons with differences related to how points can be scored (figure 2.19). The foil and epee are both thrusting weapons and can only score a point through contact using the tip of the blade. The sabre can use any part of the blade to register a hit as long as it is above the waist, controlling the need for accuracy. Regardless of the weapon discipline, the lunge remains the primary offensive movement with up to 140 attacking lunges per national competition, and around 21 per bout (Turner et al., 2014). A successful lunge tends to involve distance and speed (Gutierezz-Davilla et al., 2014). The primary objective of the fencing attacking lunge is to generate maximal sword velocity (Bottoms et al., 2013) to catch an opponent off-guard, or accelerate to make contact between the sword and a scoring body part by reacting to an opening in an opponent’s defence. In this regard research has investigated the influence of target change (Guitiérrez-Dávilla et al., 2013a; 2013b), uncertainty of target change requiring a defensive position mid-lunge (Guitiérrez-Dávilla et al., 2014), and dual task visual responses (Guitiérrez-Dávilla et al., 2017). The fencing movement involves the simultaneous thrust of the sword arm, with the lead foot kicking forward, followed by extension of the rear leg to propel the whole body (Yiou and Do, 2000).

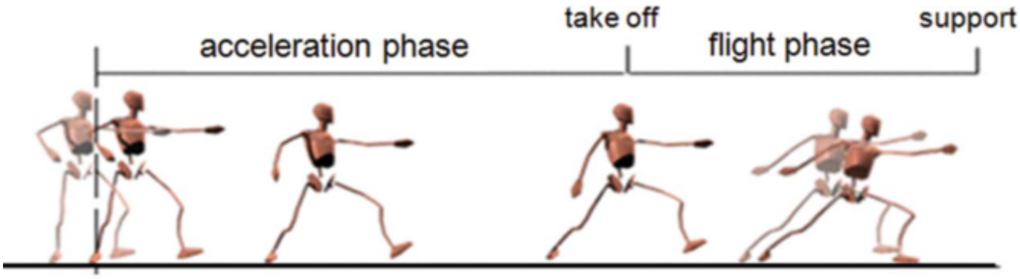


Figure 2.20. Schematic of the attacking lunge from the initiation of movement with extension of the sword arm and lead foot, followed by rear leg extension during the acceleration phase, to take off. Adapted from Guitiérrez-Dávilla et al. (2013b).

2.5.2. Biomechanical Determinants of the Attacking Lunge

It is clear that sword velocity is a key indicator of attacking lunge success. Considering the skill has multiple limb and joint coordination, much research has sought to identify the biomechanical variables leading to greater velocity. More skilled fencers coordinate timing of the lead leg kicking the foot out more effectively (Gutiérrez-Dávila et al., 2013). However, empirical evidence identifies the rear leg as the main propulsive drive within the fencing attacking lunge (Greshem-Fiegal et al., 2013; Bottoms et al., 2013; Guilhem et al., 2014). A perpendicular rear foot placement is recommended to generate maximal forward velocity and power in the explosive lunge (Gresham Fiegal et al., 2013). Bottoms et al. (2013) applied a forward stepwise multiple linear regression with sword velocity as the criterion, and found rear hip initial flexion (Adj. $R^2 = 0.24$) and rear leg knee range of motion (Adj. $R^2 = 0.35$) in the sagittal plane to be significant predictors (Adj. $R^2 = 0.35$). EMG has also shown that rear leg hip and knee extensors, and ankle plantar-flexors, are activated during the propulsive phase of the lunge (Williams and Walmsley, 2000; Guilheim et al., 2014). This is further supported with morphological adaptations found in elite fencers, with greater femoral cortical bone thickness and muscular cross-sectional area as a result of greater propulsive capabilities and impact attenuation upon landing (Chang et al., 2009). Drop jump scores and thigh cross-sectional area have also been shown as significant predictors of lunge speed (Tsolakis et al., 2010). These all lead to greater force generation to propel the body, with the lower limb kinematic chain as the propulsive driver.

Lower limb extensor musculature is linked to the kinematic contributions of the lower limbs. As suggested previously, the rear hip is likely important to contribute large force generation to move the heavy trunk and initiate movement (Bobbert and van Soest, 2001). In support of this, hip, knee and ankle moments have been shown to be larger in elite fencers versus non-elite, particularly the knee (Guan et al., 2018). This highlights the importance of the knee extensor musculature in this movement. Additionally, larger ankle range of motion is suggestive of a more effective power transfer mechanism of the kinematic chain (63 ± 6° compared to 51 ± 12°). These muscular activations, and kinematic movements, contribute to ground reaction forces, with greater force produced by more skilled fencers (Gutiérrez-Dávila et al., 2013b; Guan et al., 2018). It is clear that the movement is much more complex than one single joint, and that coordination is therefore a key element to the attacking lunge. Confirming this, Yiou and Do (2000) found no differences between expert fencers and novices when comparing sword velocity using arm extension alone or in combination with lower limb lunging. Surprisingly, limited fencing research has looked at the combined efforts of all three lower limb joints.

2.5.3. Application of KP to the Fencing Attacking Lunge

From the whole limb propulsive nature of the movement, the rear lower limb operates as a kinematic chain which would likely underpin successful CoM displacement. Therefore, BFb targeting the rear leg could, theoretically, lead to improvements in rear limb contributions. As changes to one joint in the kinematic chain can lead to negative changes to other linked joints within the kinematic chain (Richards et al., 2018a) it is important to assess if KP to the whole limb can be employed. However, as the success of BFb is linked to the importance of content to performance, it is clear that the whole limb mechanism underpinning attacking lunge success needs to be assessed prior to the provision of KP in the context of the fencing attacking lunge. In its simplest element, the fencing lunge is a discrete skill involving multiple joints within a single leg, for whole body propulsion. It has an aiming element, meaning that the task constraints require skilled, and refined, performance rather than just raw power, and it is relatively easy to determine if performance is successful with a target contact or not. Therefore, identifying how this provides propulsion using the whole limb is useful for performance, using a sport specific skill to assess the provision of KP BFb.

CHAPTER 3: UTILISATION OF THE WHOLE LIMB KINEMATIC CHAIN IN FENCING ATTACKING LUNGE PERFORMANCE

3.1. Introduction

Chapter 2 identified that the body of literature supporting applications of KP toward complex skills is limited, and to enhance the impact of BFb to real world settings is needed. Further, the majority of KP research has focused on the provision of information related to single joints, which may have detrimental effects on other limbs within the kinematic chain. Therefore, to enable the application of KP toward modifying a complex skill, whole limb joint interaction must be assessed within a complex skill. This chapter sought to investigate the kinematic chain as potential content for whole limb KP BFb, using the fencing attacking lunge as an example model, which provided empirical evidence for Theme 1.

Frequently in applied sports biomechanics, individual joints are singled out as determinants of performance (e.g. rear knee extension in fencing; Bottoms et al., 2013). With the inherent complexity of joint interaction within coordinated human movement, this single joint approach may be viewed as too simplistic. Approaches applying mathematical (Bobbert and Van Soest, 2001) and muscular modelling (Jacobs et al., 1996) on multiple joints combat this simplicity, however these theoretical approaches can be overly complicated for use in applied settings. In particular, these may be difficult to calculate and present to athletes as BFb within a short time frame, and athletes may have difficulty with interpretation. Other approaches, such as coordination paradigms (e.g. vector coding) may provide further insight into multiple joint interaction, but these methods only accommodate bivariate interaction, and thus cannot capture contributions of a third joint.

Quantifying the whole lower limb kinematic chain by overlaying joint angular velocities is a simple, yet useful method (Putnam, 1993; Marshall and Elliot, 2000; Landlinger et al., 2010). These simple visualizations help to identify athlete effectiveness in capitalizing on the whole lower limb kinematic chain to generate propulsion (Gregoire et al., 1984; van Ingen Schenau, 1989a; Zatsiorsky and Latash, 1993; Cleather et al., 2015). This approach also allows for the assessment of increased contributions in one joint having negative consequences on a distal joint (e.g. Richards et al., 2018a) due to segmental interaction (e.g. overcoming additional inertia). Such an approach could provide insight into components of skill that differentiate between athletic ability in harnessing a task specific strategy, such as forward propulsion of the body's CoM.

In the fencing attacking lunge, the objective is to generate maximal forward propulsion, covering ground quickly to strike an opponent with a sword (Bottoms et al., 2013; Guilhem, et al., 2014). Significantly greater sword velocity in elite fencers has been attributed to more than arm extension velocity alone, with sword arm movement in coordination with the lower limb lunge distinguishing skilled from novice fencers (Yiou and Do, 2000). Rear knee range of motion and peak rear hip flexion have been identified as significant predictors of sword velocity (Bottoms et al., 2013), however the relationship between the two has not been explored further, particularly in light of the sequential contributions as identified previously (Gregoire et al., 1984; van Ingen Schenau, 1989a; Zatsiorsky and Latash, 1993; Cleather et al., 2015). Kinematic and electromyographical data of elite fencers supports that the rear leg extensor muscles activate mainly in the propulsive phase of the attacking lunge (Guilhem et al., 2014), with this activation suggesting a temporal sequence in the rear leg with more distal muscles, such as plantar flexors in the ankle, firing later. These results allude to specific kinematic sequencing and suggest that skilled fencers harness a sequential kinematic chain to attain greater forward velocity. This would explain greater horizontal force generation by more skilled fencers (Gutiérrez-Dávila et al., 2013b; Guan et al., 2018). To alter technique, previous BFb research indicates that BFb success is influenced by its content, where the information given empirically links with performance.

Therefore, the specific aims of this chapter were to: a) identify differences in the kinematic chain associated with skill level, using the fencing attacking lunge, and b) demonstrate if these differences relate to a performance output such as forward sword velocity. Consequently, this chapter first addressed **RQ1. Can utilisation of the rear leg kinematic chain be used to distinguish between propulsive ability, in a sport specific skill?** Considering the importance of identifying if biomechanical variables linked to performance, **RQ2. Are kinematic differences in the rear leg kinematic chain associated with external kinetics and CoM propulsion?** was also addressed within this chapter. Three hypotheses were developed to address the research questions:

H_1: *Skilled participants will demonstrate clearer proximal to distal sequencing of the rear leg kinematic chain than novice participants through an accumulation of angular velocity magnitudes from the hip, knee and ankle joints in a proximal to distal pattern.*

H_2: *Skilled participants will demonstrate significantly greater external horizontal kinetics (peak ground reaction force and impulse) than novice participants.*

H_3: *Skilled participants will demonstrate significantly greater peak horizontal linear sword velocity than novice participants.*

3.2. Methods

3.2.1. Participants

Fifteen participants (mean ± SD; 8 novice; age 22 ± 10 years, height 1.74 ± 0.09 m, leg length 0.89 ± 0.06 m, mass 74.6 ± 16.2 kg, and; 7 skilled; age 24 ± 14 years, height 1.78 ± 0.07 m, leg length 0.95 ± 0.08 m, mass 72.0 ± 15.3 kg) agreed to take part in this study and provided informed consent. Group anthropometrics, as outlined above, were not significantly different (independent t-test, $p > 0.05$). All participants had a minimum of one year of experience fencing with a foil weapon (skilled 8.2 ± 7.6 years, novice 6.9 ± 12.2 years). Inclusion criteria for skilled grouping maintained that individuals were capable of lunging over one leg length in distance and could achieve a sword velocity of over 3 $m \cdot s^{-1}$ (Yiou and Do, 2000). Additional inclusion criteria to be classified as skilled was that participants had to be competitive at regional level or above, with three of the skilled participants having competed nationally and two internationally.

3.2.2. Procedure

A cross sectional study design was used to compare the novice and skilled fencers. Data collection took place at two institutions, with each participant visiting one of the two sites on one occasion. The multisite data collection was adopted to increase sample size. To avoid discrepancies between testing protocols, the same researcher conducted all data collection sessions at both sites. A similar mix of novice and expert fencers were also recruited at both sites.

All procedures were approved by the institutional ethics committee. At each site, testing took place in one day with participants completing seven lunges toward a 15 x 15 cm square target marked on the chest of the local fencing coach (figure 3.1), with the top of the target individually set at the height of the participant's sternal notch. Each participant wore tight fitting shorts (with females wearing a short vest top), along with their normal fencing shoes and competition foil. A total of 27 passive retro-reflective markers of 12.5 mm diameter were placed on the participant in anatomical landmarks for the rear leg, lead foot, pelvis, trunk and sword arm (figure 3.1.), with an additional three on the sword (5 cm distal from the base, middle of the blade and 5 cm from the tip) and four on the target.

Figure 3.1. Marker placement on the foil (left), demonstrating three markers placed on the blade (5 cm from the base, middle, and 5 cm from the sword tip) and the target (right) four markers 15 x 15 cm apart on the fencing coach, with a central point to direct accuracy.

The target centre was marked with visible tape for participants to direct their lunges (figure 3.1). Participants stood a self-selected distance (2.16 ± 0.07 m skilled and 2.01 ± 0.03 m novice; $p<0.05$) from the target, deemed their competitive attacking distance. With both feet on individual force plates, the participants were then requested to drop into the 'on guard' position and instructed to propel themselves forward as quickly as possible to strike the target centre upon reacting to an auditory signal. Only successful trials where the participant struck the target were analysed.

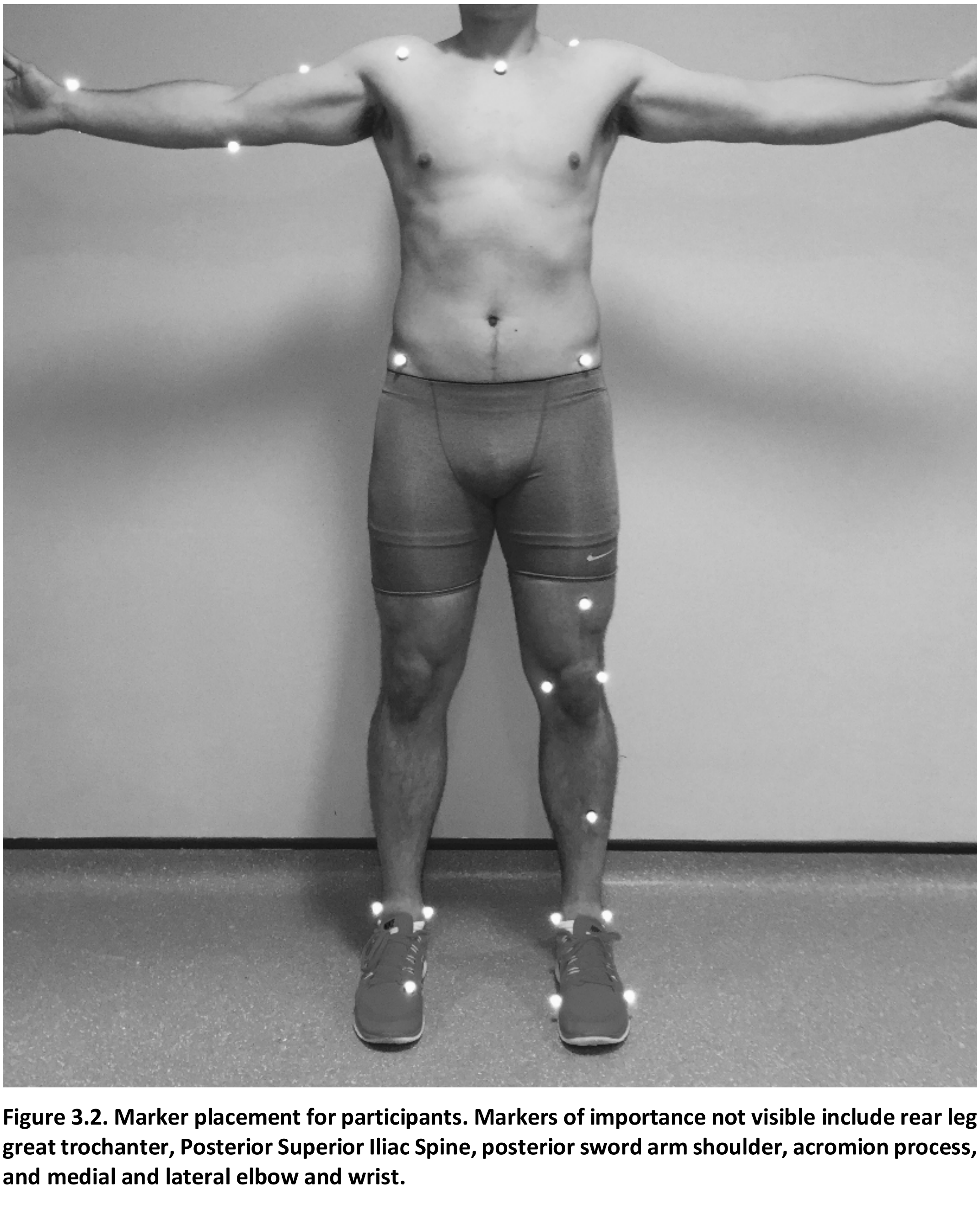


Figure 3.2. Marker placement for participants. Markers of importance not visible include rear leg great trochanter, Posterior Superior Iliac Spine, posterior sword arm shoulder, acromion process, and medial and lateral elbow and wrist.

Figure 3.3 shows a captured fencing attacking lunge trial. Marker tracking was completed at site one using 12 Raptor cameras operated through Cortex v5.0.2 software (Motion Analysis Corporation, Santa Rosa, CA), and at site two using 16 Vantage cameras operated through Vicon Nexus v2.0 (Vicon Motion Systems Ltd., Oxford, UK). Differences in kinematic collection setup were as a result of available resources at the respective institutions. Kinematic data at 200 Hz were synchronized at both sites with two Kistler force plates (Kistler type 9284, Kistler AG, Winterthur, Switzerland) via a standard analogue to digital synchronization cable, and sampled at 1000 Hz. The Y axis of the global coordinate system was orientated from the start position to the target, with the Z axis defined in the vertical direction and the X axis as the cross product of Y and Z.

Figure 3.3. Demonstrating the end of the attacking lunge position, with a successful trial upon making contact with the target.

3.2.3. Data Processing

A custom written MATLAB code (R2015a, Mathworks, Natick, MA) was used to analyze each trial. All data were smoothed using a zero lag, 4th order, low pass Butterworth filter at 10 Hz for kinematic and 50 Hz for kinetic data. Filter cut-off frequencies were selected based on previous fencing research for the kinematics (Guilhem et al., 2015), and visual inspection showed that 50 Hz allowed for the removal of electrical noise without affecting the kinetic data peaks. Kinetic data from the rear foot force plate were extracted based on two key events; onset of force (t_{FO}) and take off (t_{TO}). The variable t_{FO} was defined as the first instance the rear leg resultant force vector (F_R) was >20 N initial force, and t_{FO} as the first instance F_R was <50 N. Push off ($F_{PushOff}$) was the phase defined from t_{FO} to t_{TO} and time normalized to 101 data points using a cubic spline from for 0% to 100%. Prior to the calculation of impulse, body weight was removed from vertical ground reaction force (F_Z), and the mean of the first 10 frames of the horizontal ground reaction force (F_Y) of both plates extracted to offset to zero. The integral of both F_Z and F_Y were obtained using the trapezoidal method to calculate net vertical and horizontal impulse ($Impulse_Z$ and $Impulse_Y$ respectively). Kinetic variables were normalised to body mass to allow for comparison between participants ($Ns{\cdot}kg^{-1}$).

Each whole lunge movement was analysed from the onset of sword movement (defined as horizontal sword velocity >0.2 $m{\cdot}s^{-1}$), up until target contact. A virtual target centre was calculated as the mean of the four target markers and was used to identify sword impact, which was the instant at which peak acceleration of the target centre occurred. Total movement time was determined from first sword movement until target contact. Forward horizontal sword velocity was obtained from the most proximal sword marker. Peak sword velocity was the maximum value within each trial.

The sword arm shoulder virtual joint centre was calculated as the midpoint between anterior and posterior markers placed at estimated joint centres and horizontally posterior to the acromion process while the shoulder was abducted to 90°. Rear hip joint centre was calculated from relative anterior superior iliac spine breadth (14% medial, 19% posterior and 30% distal; Bell, 1990), shown as the most appropriate hip location method in fencers (Sinclair and Bottoms, 2013). Five further virtual joint centres were calculated for the sword arm wrist and elbow, as well as rear knee, rear ankle and lead ankle, as a midpoint between standard medial and lateral bony landmark markers. Lunge distance was determined as maximal forward displacement of the front foot virtual ankle joint centre in the sagittal (foot-target) plane, and normalized to leg length (vertical height of rear leg greater trochanter marker in the anatomical standing position).

Three dimensional joint angles and angular velocities were calculated as vectors between virtual joint centres. Hip angle was calculated as the angle between two vectors running from the virtual hip to the virtual shoulder and from the virtual hip to virtual knee respectively. Extension and plantar flexion was deemed as positive, with full extension defined as 180° for all joints**.** Series kinematic data were interpolated to 101 data points from F_O to F_{TO}, allowing presentation of angular velocities as a percentage of the push off phase, but with an additional 25 points of the early flight phase added for visual clarity (data presented as 0 to 125% time). Temporal variables were identified as local maxima events of joint angular velocity as percentages (relative to force application timing) for the sword arm elbow as well as the rear hip, knee and ankle. Initial pilot testing demonstrated that the lead foot left the ground in a kick out action almost at the initiation of the movement, thus contributed little to the propulsive ground reaction force. In addition, lead leg joint kinematics were highly variable between and within individuals, therefore the front leg was omitted from the analysis.

3.2.4. Statistical Analysis

All statistical tests were performed in SPSS (v.20; IBM, Armonk, NY). Normality was confirmed using a Shapiro-Wilk test ($p > 0.05$), hence data were presented as means ± standard deviation (SD) and between group differences were compared using independent t-tests with an alpha level set at 0.05. Rank scoring was assigned according to individual temporal sequence of maximal joint angular velocity extension for hip, knee and ankle respectively for each subject (e.g. first joint reaching maximal extension scoring 1; second joint scoring 2, last joint scoring 3) and presented as averages for both the skilled and novice groups. This allowed individual sequencing to be assessed. Pearson's product moment correlations were used to determine the relationship between peak ankle angular velocity, the distal endpoint of the chain, and the discrete kinetic variables of F_Y and $Impulse_Y$ as these directly underpin forward CoM propulsion.

3.3. Results

3.3.1. Performance Measures

There were no significant differences in total movement time (0.61 ± 0.11 s skilled versus novice 0.67 ± 0.17 s; *p=0.46*), yet the skilled group lunged further (1.15 ± 0.11 versus novice 0.86 ± 0.16 leg lengths; *p=0.02*). Peak horizontal sword velocity was significantly greater in the skilled group (skilled 3.24 ± 0.24 $m \cdot s^{-1}$ versus novice 2.69 ± 0.29 $m \cdot s^{-1}$; *p=0.02*).

3.3.2. Kinematic Measures

There were no significant differences in peak elbow extension velocities (skilled 5.38 ± 1.88 $rad \cdot s^{-1}$ versus novice 4.47 ± 1.62 $rad \cdot s^{-1}$; *p=0.21*), with a large spread of peak elbow extension timing shown with large standard deviations (skilled 70 ± 28% of $F_{PushOff}$ versus novice 86 ± 31%). As illustrated in table 3.1 there were no significant differences in hip angular velocities between the two groups (*p=0.24*). The skilled group demonstrated greater, but not significant, peak knee extension velocity (*p=0.17)* and significantly greater peak ankle extension velocity (*p=0.02*). There was a clear increase in magnitude in a proximal to distal sequence in both groups from hip to ankle angular velocities.

The skilled group's average joint peak extension times occurred earlier than the novice group, starting with hip angular extension velocities occurring at 80% of $F_{PushOff}$ for skilled compared to 84% for novice. Following maximal hip extension timing there was a general proximal to distal sequence in extension timing for both groups. The rank scoring shows that the skilled group all used a sequential pattern, of 1, 2 and 3 for hip, knee and ankle, whereas this was not the case with the novice group (table 3.1).

Figure 3.4 visually highlights differences in the rear leg kinematic chain between the novice (left) and skilled groups (right). The time series of the rear leg angular velocities show a clear sequential kinematic chain in both groups, yet more exaggerated and ending with a significantly greater ankle peak velocity in the skilled group. The sequential extension of the hip, knee and then ankle show an accumulative increase in joint extension magnitude, with the skilled group ankle plantarflexion seemingly continuing from the point of maximal knee extension.

Table 3.1. Rear leg kinematic variables for novice and skilled groups (mean ± SD) performing a fencing attacking lunge. Temporal sequencing is presented as percentage of push off phase (0% = F_{O}, 100% = F_{TO}). Percentage differences are presented relative to novice group results. T-test p values presented between groups.

Joint Kinematics	**Novice (n=8)**	**Skilled (n=7)**	**% Difference**	***p***
Peak Hip$_{\theta}$ (°)	161 ± 11	159 ± 14	-1.25	0.85
Peak Knee$_{\theta}$ (°)	165 ± 5	171 ± 6	3.57	0.71
Peak Ankle$_{\theta}$ (°)	121 ± 12	137 ± 12*	12.40	0.02
Peak Hip$_{\omega}$ (rad·s^{-1})	2.4 ± 0.9	1.9 ± 0.7	-23.25	0.24
Peak Knee$_{\omega}$ (rad·s^{-1})	4.6 ± 1.3	6.0 ± 2.4	26.42	0.17
Peak Ankle$_{\omega}$ (rad·s^{-1})	5.4 ± 2.9	9.1 ± 2.1*	51.03	0.02
Peak Hip$_{\omega}$ time (%)	84 ± 6	80 ± 17	-4.88	0.45
Peak Knee$_{\omega}$ time (%)	91 ± 4	88 ± 9	-3.35	0.14
Peak Ankle$_{\omega}$ time (%)	94 ± 3	94 ± 9	0.00	0.20
Hip rank scoring (target 1)	1.25 ± 0.50	1.00 ± 0.00	–	–
Knee rank scoring (target 2)	2.00 ± 0.80	2.00 ± 0.00	–	–
Ankle rank scoring (target 3)	2.75 ± 0.50	3.00 ± 0.00	–	–

***** $p<0.05$ between novice and skilled.***

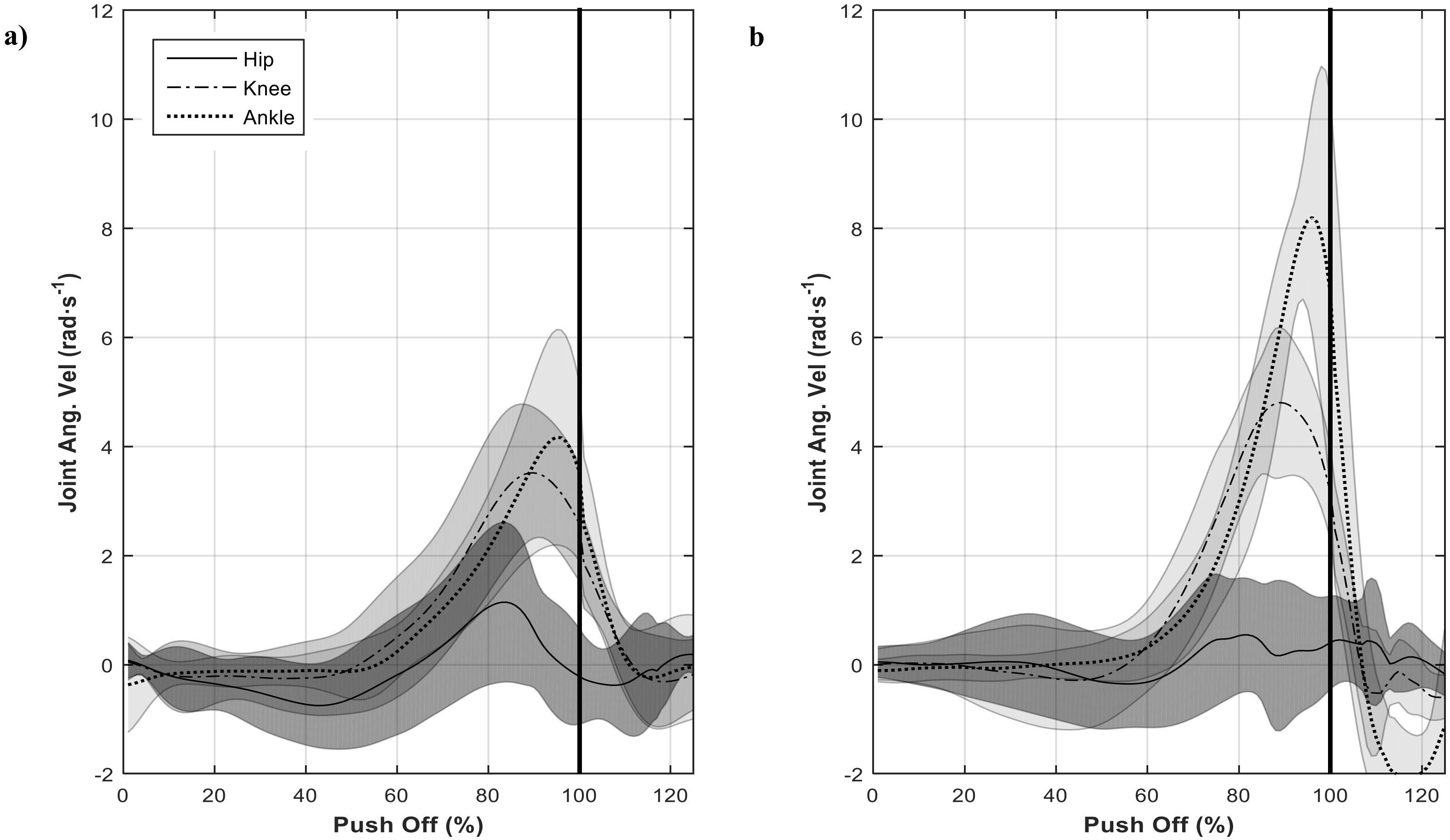


Figure 3.4. Mean (± SD shaded) joint angular velocity series data for novice (a) and skilled (b) groups performing a fencing attack lunge. Extension is positive. Application of force is from initiation of rear leg force (0%) to take off (100%). The solid vertical line at 100% signifies take off.

3.4.3. Kinetic Measures

There were no significant differences between group for normalised peak F_Z and normalised $Impulse_Z$ (table 3.2). Skilled participants demonstrated significantly greater normalised peak F_Y and $Impulse_Y$ than the novice group. Figure 3.5 highlights mean (± SD) horizontal force profiles for both the skilled and novice groups, demonstrating clear differences in horizontal force profile magnitudes, rather than timing, between groups.

Table 3.2. Kinetic variables for novice and skilled groups (mean ± SD) performing a fencing attacking lunge.

Kinetic Variable	Novice (n=8)	Skilled (n=7)	% Differences	*p*
Peak F_{Z} (N·kg)	9.09 ± 2.33	8.54 ± 1.72	-6.2	0.95
Peak F_Y (N·kg)	6.95 ± 1.92	8.48 ± 0.62*	20.0	0.01*
$F_{PushOff}$ Time (s)	0.51 ± 0.07	0.54 ± 0.08	5.7	0.40
$Impulse_Z$ ($Ns{\cdot}kg^{-1}$)	2.08 ± 0.39	2.08 ± 0.32	0.0	0.93
$Impulse_Y$ ($Ns{\cdot}kg^{-1}$)	1.92 ± 0.36	2.51 ± 0.25*	26.6	0.02*

***** ***p<0.05 between skilled and novice***

Pearson's product moment correlation indicated a strong positive correlation (r=0.81; *p<0.001*) between peak Peak $Ankle_\omega$ and Peak F_Y across all participants, yet a weak positive correlation between peak Peak $Ankle_\omega$ and $Impulse_Y$ (r=0.28; *p=0.31*). These results suggest a relationship between the most distal joint of the kinematic chain, and horizontal propulsion.

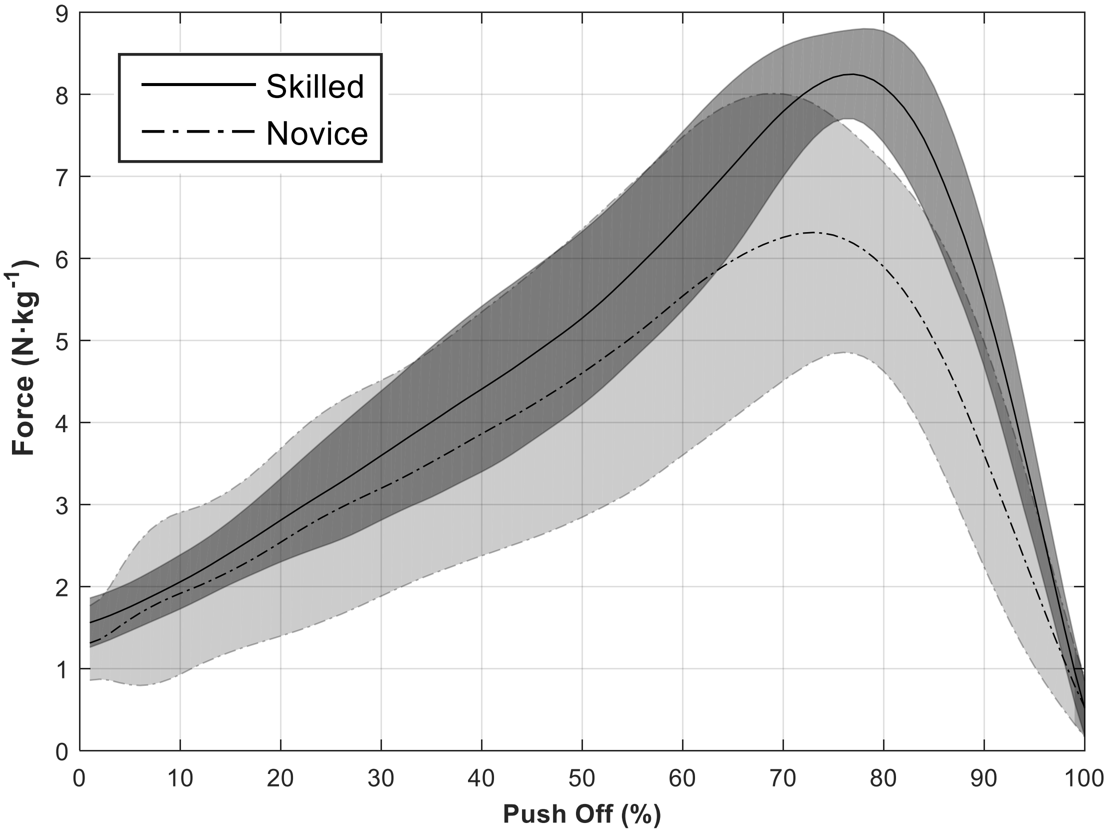


Figure 3.5. Mean (± SD shaded) normalised horizontal force data for both novice and skilled groups performing a fencing attacking lunge. Application of force is from initiation of rear leg force (0%) to take off (100%).

3.4. Discussion

This research examined the biomechanical characteristics of the fencing attacking lunge, focusing on skilled and novice fencers to identify differences in task dynamics related to successful lunge technique as a function of skill level. Specifically, this chapter assessed the rear leg kinematic chain, and resulting external ground reaction force kinetics, between the two groups. As such, the results of Chapter 3 will be addressed with a view to provide empirical evidence for Theme 1. The overall purpose of this research chapter was to provide a platform for the development of Theme 2.

The results of this chapter support the initial hypotheses that skilled participants demonstrate **H_1**) clearer proximal to distal sequencing of the rear leg kinematic chain, and greater accumulative angular velocity magnitudes in a proximo-distal pattern, **H_2**) significantly greater Impulse_Y and **H_3**) significantly greater sword velocity.

3.4.1. Kinematic Differences

The peak rear leg joint angular velocity ranking demonstrates that the skilled fencers use a proximal to distal sequential pattern to a greater extent than novices. This has been suggested as a more optimal use of a whole limb in propulsive movements (Gregoire et al., 1984; van Ingen Schenau, 1989a; Jacobs et al., 1996; Wong et al., 2016). With no differences shown between elbow kinematics between the groups, the significantly greater horizontal sword velocity (skilled, 3.24 $m \cdot s^{-1}$ compared to novice, 2.69 $m \cdot s^{-1}$; p=0.02) and lunge distance (skilled, 1.15 leg lengths compared to novice, 0.86 leg lengths; p=0.02) may be explained through a more effective utilization of the rear leg kinematic chain for greater forward propulsion. This is consistent with previous research demonstrating that additional sword velocity is developed through coordination of the lower extremities in the attacking lunge (Yiou and Do, 2000; Guilhelm et al., 2014). From the temporal analysis it appears that a sequential rear leg kinematic chain allows the skilled athletes to better harness a proximal to distal power transfer, as suggested with the increasing angular velocities here, thus developing greater forward propulsion of the system centre of mass (van Ingen Schenau, 1989a; Jacobs et al., 1996; Bobbert and van Soest, 2001; Cleather et al., 2015). The assessment of the kinematic chain demonstrated in this chapter appears to be an appropriate method to determine athletes' effectiveness in using the whole lower limb in propulsion, and may well underpin performance in an applied environment.

The large standard deviations of both groups' maximal elbow extension velocity timing (± 31% skilled versus ± 28% novice) demonstrate that there is considerable individual variability in elbow movement selection. This is perhaps explained with the arm controlling the aim of the sword, therefore the timing at which the elbow extends may be variable between participants to allow for adjustments so that accuracy can be maintained. According to mandatory "etiquette" in the discipline of fencing with foil, the sword arm must begin to extend prior to movement (Fédération Internationale d'Escrime (FIE), 2015) for an attack to be deemed valid. Therefore, the arm must always move first, whether this be via shoulder extension, abduction, elbow extension or a combination of these movements. The variable elbow strategies shown here, yet significant differences in performance indicators, support findings by Yiou and Do (2000) in that sword velocity is driven by more than the arm alone.

There was a clear proximal to distal increase of angular velocity magnitudes from the hip to knee in both groups. This was more pronounced in the skilled group (skilled, 1.9 to 6.0 rad·s^{-1} compared to novice 2.4 to 4.6 rad·s^{-1} for hip to knee, respectively), however there were no significant differences between groups when peak joint angular velocities were compared between groups for these joints (hip, *p=0.24*; knee, *p=0.17*). The lower hip angular velocity and resulting greater knee angular velocity in the skilled group can best be explained with the skilled fencers using a more advantageous position of the force-velocity curve of muscular contraction in the hip extensors (Feltner et al., 1999). Since relatively large force is required to overcome inertial properties of the heavy trunk segment compared to other joints, as well as a large extension and some abduction to move the body, the angular velocity of the hip will be the lowest in both groups. These larger forces would serve as greater input to the power transfer mechanism of the bi-articular rectus femoris (Gregoire et al., 1984; Jacobs et al., 1996**;** Bobbert and Soest, 2001)**.** It could be postulated that as joint power is a product of net joint moments and angular velocity, and net moment comprised of internal joint forces, the most effective power transfer from this larger muscle via bi-articular design may well be a larger force with the heavier trunk segment inhibiting extension velocity. Although power was not measured in this investigation, this could help to explain the lower, although not significant, hip velocity yet larger knee extension velocity in the skilled group.

A key difference in the skilled group was that the increase in angular velocity magnitude continued distally to the ankle resulting in a significantly greater ankle plantar flexion velocity (skilled 9.1 ± 2.1 rad·s^{-1} versus novice 5.4 ± 2.9 rad·s^{-1}; *p=0.02*). The skilled individual ranking averages scored 1.00, 2.00 and 3.00 for the hip, knee and ankle respectively, showing that on an individual level all of the skilled group followed a sequential proximal to distal movement pattern, initiated in the most proximal joint of the rear leg. The novice group rank averages scored 1.25 ± 0.5, 2.00 ± 0.80 and 2.75 ± 0.05 suggesting that the novice performers did not all follow a set sequential pattern. This clarifies the proximal to distal sequencing evident in the skilled group, and that this sequential patterning is likely important in generating high angular velocities. Mathematical modelling by Bobbert and van Soest (2001) demonstrated that extending the hip, knee and ankle in a sequential pattern is optimal in explosive jumping movements. In particular the timely extension of the ankle, the smallest and most distal segment with the lowest inertia, is pivotal in achieving maximal jump height. Earlier studies have calculated that 25% of the total work done about the ankle is due to a transfer action from the knee to ankle joint via the gastrocnemius (Bobbert et al., 1986) which is optimized with a timely transfer. This supports the findings of this chapter, with the skilled participants demonstrating better temporal sequencing in a proximal to distal manner. Although the previous findings are predominantly derived from vertical movements, work by Jacobs et al. (1996) has identified similarities in sequential patterning utilizing lower limb biarticular musculature in single leg jumps and the sprint start push off, suggesting that a closed kinematic chain in the lower extremities is transferable to the forward propulsive movement of the rear leg in the fencing lunge investigated in this study. As shown by Hof (2001), biarticular musculature opens up a greater range of affordances of external force orientations facilitating this transfer.

The timing of mean peak velocity was not statistically different between groups, although there were some noticeable differences in the variability of this timing. The skilled group showed greater variation with extension timing standard deviations (± 17% hip, ± 9% knee and ± 9% ankle for skilled, compared to ± 6% hip, ± 4% knee and ± 3% ankle for novice). This highlights that the skilled group had a larger range of individual extension timing strategies, which warrants investigation in future research on utilization of the kinematic chain during intervention induced changes.

3.4.2. Kinetic Differences

The addition of external kinetic data allows for an evaluation of the kinematic sequencing output to a propulsive task. No significant differences were found in normalised vertical kinetic variables (table 3.2). In contrast, significant differences were found in the normalised horizontal kinetic variables with the skilled group demonstrating both greater F_Y and $Impulse_Y$ than the novice group. This shows that the skilled group not only generated greater force to exploit the impulse-momentum relationship but were also more effective in transferring the rotational movement toward forward propulsion, without expending unnecessary force in the vertical direction. The strong positive correlation between ankle angular plantar-flexion velocity and normalised horizontal peak force ($r = 0.81$; $p<0.001$) across all participants could suggest that a greater ankle plantar-flexion velocity magnitude, obtained via an effective sequential kinematic chain, results in greater force generation. A strong positive correlation between ankle plantar-flexion velocity and Impulse_Y would strengthen the notion that an effective kinematic chain results in greater forward propulsion, due to the impulse-momentum relationship, however with a weak positive correlation ($r=0.28$; $p=0.31$), less effective timing of force application relative to take off may obscure this slightly with some individuals. For example, one novice participant had a large mean ankle plantar-flexion velocity (11.15 $\text{rad}\cdot\text{s}^{-1}$) which occurred at 101% F_{PushOff}, which is just after take-off. This pattern is best explained with some individuals achieving greater plantar-flexion velocity once body weight bearing down on the joint is no longer inhibiting the movement. In this regard, high plantar-flexion velocity may actually be a by-product of exerting large peak forces as a consequence of weight reduction occurring with take-off, therefore displaying strong correlations with the preceding force.

The primary limitations of this research may be the descriptive study design, along with the small sample size, however it does offer insight into effective kinematic sequencing toward propulsion in a sport specific skill, and provides some evidence of performance indicators related to whole limb sequential kinematics between skill levels. There could also be limitations associated with the multi-site research model (e.g. differences in data collection tool specifications). To combat this, collection methodologies were matched as closely as possible, and the same researcher conducted data collection at both sites.

Furthermore, although participant numbers at each site were different (site 1, n=9; site 2, n=6), grouping was equally proportioned at both.

The implementation of a longitudinal intervention to manipulate the kinematic chain and assess the changes in performance that arise as a result would allow for confirmation of the findings within this chapter. The provision of feedback on these variables may allow the athlete to subtly alter their kinematic chain and subsequently improve propulsion. In this regard, the causal relationship between the kinematic chain and horizontal propulsive force would be further confirmed.

3.5. Conclusion

This chapter has identified differences in the rear leg kinematic chain associated with greater sword velocity in the fencing attacking lunge. Key findings highlighted that skilled athletes use a temporal extension sequence from the hip, knee and to the ankle which results in a greater accumulation of extension velocity in the distal segments. Importantly, this study demonstrated that more effective utilisation of this rear leg sequential chain resulted in greater external horizontal kinetics, and was linked with greater propulsive ability in an explosive, ecologically valid, complex skill.

Generating a body of empirical evidence is important for the provision of BFb to modify technique to improve performance, and avoid detrimental effects of the BFb. The relationships shown here provide empirical support for the provision of extension velocities of a whole limb kinematic chain and sequential patterning to improve CoM propulsion in a whole limb, explosive complex skill. This information provides an evidence based for BFb content, addressing the first theme of this thesis, which can be built up on the next chapter in the implementation of a BFb intervention.

CHAPTER 4: MANIPULATION OF THE KINEMATIC CHAIN USING KNOWLEDGE OF PERFORMANCE BIOFEEDBACK

4.1. Introduction

Chapter 3 provides evidence for kinematic variables that may underpin explosive performance, identifying task dynamics as content for Theme 2. Based on these findings, there is empirical support for the use of the rear leg kinematic chain variables to be used as KP content for BFb toward an explosive lunge activity. Specifically, the provision of KP on rear leg kinematic chain joint extension magnitudes and sequencing. Questions arise as to whether the application of BFb on a specific performance determining variable can develop a novice performers' technique to a more desirable pattern, and in a relatively short space of time. Specifically, it remains to be seen whether a performer in an explosive lunge task demonstrating a rear leg kinematic chain pattern as demonstrated by novice fencers in chapter 3, can be developed toward a movement pattern seen in more skilled athletes with a BFb intervention, and subsequently whether these changes can be retained. This chapter seeks to provide empirical evidence underpinning applications of a KP intervention toward whole limb interaction in an explosive skill, using biomechanical principles, which addresses Theme 2 of this thesis.

This chapter seeks to address research question **RQ3. Can the provision of terminal KP BFb alter whole limb kinematics in a complex skill?** Changes in external kinetics, as an indirect result of BFb on joint kinematics, would further beneficial links in directing a KP intervention with kinematics to change propulsive ability. Thus, research question **RQ4.**

will be addressed **Do changes in the whole limb kinematic chain lead to changes to external kinetics during a discrete, complex skill?** Finally, to assess the relative permanence of these changes, **RQ5. Are changes in technique from a whole limb KP BFb intervention retained?** will be assessed within this chapter.

Feedback provides direction to skill exploration, helping to refine muscle coordination and identify efficient movement patterns during motor task learning. A range of modalities have been used to assess KP effectiveness in both continuous and discrete skills. These include visual (Swinnen et al., 1990), auditory (Mullineaux et al., 2011), and more recently haptic data (Sigrist et al., 2013). In cyclical tasks with concurrent feedback visual information displaying kinematic data has been shown to be more effective than auditory (Eriksson et al., 2011), with the visual presentation of data allowing a participant to objectively make specific adjustments. It has been suggested that audio BFb modalities are easier for a participant to attend to during an explosive task (Helmer et al, 2010), however visual KP has advantages in allowing for more complex information to be encoded than auditory (Ericksson et al., 2011; Sigrist et al., 2013).

The majority of KP research has focused on concurrent BFb toward cyclical skills. Continuous skills have many repetitions, thus allow the participant to modulate movement in real-time (e.g. rowing, Anderson et al., 2005; running, Eriksson et al., 2011; and wheelchair propulsion, Kotojarvi et al., 2006; Richter et al., 2011), however many sports involve explosive, discrete skills (e.g. the fencing attacking lunge), therefore further research into the effective application of objective KP toward these skills is required. During such ballistic skills, the temporal window for attention is short. In this setting post responsive, or terminal, visual KP has been shown to be beneficial (e.g. Etnoyer et al., 2013). Terminal KP allows for a more thorough evaluation of movement by the performer, processing new information that complement (or conflict) with internal BFb sources (Magill, 1994), thus facilitating adjustments in the subsequent trial. Terminal KP containing external kinematics, such as equipment trajectories, has been shown to improve performance (e.g. rifle shooting Mononen et al., 2003) but also indirectly influence related kinetics (e.g. Olympic weightlifting, Winchester et al. 2009). The constrained action hypothesis suggests that this external focus allows the participant to self-organise and produce an individual movement pattern (Wulf et al., 1998), however this may not be beneficial if a specific movement pattern is required. Targeting joint kinematics via objective, terminal KP can directly influence variables underpinning performance (Nunes et al., 2014), or indirectly if there is a strong relationship between these variables. For example, provision of KP on kinematics of volleyball spike landing indirectly resulted in a 23.6% decrease in vertical ground reaction force (Cronin et al., 2008). Hence, careful selection of these variables is important.

Many KP research designs target individual variables, which remain simple for the participant to understand (e.g. Richter et al., 2011). However, many sporting movements require coordination of multiple limb segments and joints. With the majority of early KP research focusing on simple skills in a laboratory setting, questions remain as to whether complex KP, in an effective design, can influence whole limb kinematics.

Use of the whole lower limb in a proximal to distal kinematic sequence has been linked with successful performance in jumping (Gregoire et al., 1984) and sprinting (Jacobs et al., 1996). Furthermore, mathematical modelling has identified the effectiveness of the lower limb rigid body chain in turning joint segment angular velocity into effective linear centre of mass velocity (Bobbert and van Soest, 2001; Wong et al., 2016). Since the human musculoskeletal system is a combination of mono-articular and biarticular muscles, spanning multiple joints in a complex interaction (Zatsiorsky and Latash, 1993; Cleather et al., 2015) effective KP should cater for this multi-joint interaction. Complex skills involving whole limb contributions may require more eloquent BFb solutions, such as interactive technologies (Helmer at al., 2010). Subjective, verbal KP can influence whole limb kinematics (Kernodle and Carlton, 1992), however more objectivity may be required to elicit specific, meaningful changes in line with theory underpinning proximo-distal sequencing (e.g. Putnam, 1993). With differences in the kinematic chain associated with skill level in Chapter 3, visual terminal KP may be an effective method to improve explosive lunge technique, by objectively relaying joint extension magnitudes and proximo-distal sequencing. This may allow the development of a novice movement pattern toward a more skilled pattern as identified in Chapter 3.

The aim of this research was threefold, to determine whether: 1) KP can be used to develop the whole lower limb kinematic chain in an explosive, complex, gross motor skill; 2) changes in the sequential kinematic chain lead to an increase in external kinetics, and; 3) if increasing joint extension magnitudes in the kinematic chain, and maintaining a proximal to distal sequence, would directly lead to greater propulsive ability. The following hypotheses were developed to address the research questions within this thesis:

- **H_5:** Terminal KP of the whole rear leg kinematic chain can directly facilitate an increase in joint extension velocity magnitudes, and maintain proximal to distal sequencing.

- **H_6:** Changes to the rear leg kinematic chain peak joint angular extension velocities, developed through a terminal KP intervention, are retained at 4-6 weeks.

- **H_7:** Terminal KP increasing rear leg kinematic chain joint extension velocities can indirectly facilitate an increase in external kinetics.

- **H_8:** Changes to rear leg external kinetics, developed through changes in the kinematic chain induced via a terminal KP intervention, are retained at 4-6 weeks.

- **H_9:** Increasing the rear leg kinematic chain accumulative velocities will lead to increased peak horizontal pointer velocity as a task performance measure.

4.2. Methods

4.2.1. Participants

Thirty-two healthy participants were recruited to take part in this research, with backgrounds in a variety of sports. The inclusion criteria were that they were physically active, injury free and aged 18-40 years old. Participants were also screened for red-green colour-blindness so that they could interpret the BFb if in the experimental group. Following informed consent, participants were randomly assigned into two groups; BFb group (n=16; 8 male, 8 female, means ± SDs; age 26 ± 5 years, height 1.71 m ± 0.08, mass 67.4 ± 10.76 kg, leg length 0.91 ± 0.04 m) and a control group (n=16; 8 male, 8 female, means ± SD's; age24 ± 4 years, height 1.72 m ± 0.10, mass 70.1 ± 14.9 kg, leg length 0.92 ± 0.06 m). The individual anthropometric characteristics of participants recruited in this study are included in table 4.1., along with their primary sport.

During the first session (S1) participants completed maximal horizontal countermovement jumps to ensure both groups were matched for jump distance, accounting for relative strength and explosive ability between groups. There were no significant differences between groups in jump distance ($p < 0.05$), meaning that both groups were physically matched on explosive ability.

Table 4.1. Anthropometric characteristics and primary sport of BFb (B#) and Control (C#) participants. Leg length is measured from GT vertical height in the anatomical position.

Participant ID	Age (y)	Height (m)	Mass (kg)	Leg Length (m)	Sport
B1	24	1.79	59.8	0.95	Camogie
B2	21	1.76	66.7	0.94	Basketball
B3	26	1.65	83.3	0.90	Basketball
B4	25	1.52	77.7	0.91	Squash
B5	21	1.78	54.8	0.82	Sprint Kayak
B6	19	1.76	66.0	0.94	Futsal
B7	25	1.71	56.0	0.94	Netball
B8	27	1.74	83.7	0.88	Rugby Union
B9	27	1.59	55.6	0.88	Gym User
B10	28	1.71	60.2	0.92	Gym User
B11	39	1.72	63.4	0.93	Triathlete
B12	21	1.71	62.0	0.92	Rugby Union
B13	28	1.60	56.8	0.84	Distance Runner
B14	28	1.80	83.4	0.98	Rugby Union
B15	28	1.76	80.0	0.95	Crossfit
B16	28	1.77	68.5	0.92	Crossfit
C1	23	1.68	93.1	0.9	Netball
C2	27	1.66	60.9	0.88	Field hockey
C3	23	1.77	70.5	0.94	Football
C4	23	1.58	55.2	0.89	Netball
C5	19	1.78	64.2	0.93	Rugby Union
C6	20	1.68	58.1	0.96	Squash
C7	21	1.54	41.8	0.83	Gymnastics
C8	21	1.60	52.7	0.83	Gymnastics
C9	26	1.71	64.2	0.9	Badminton
C10	22	1.81	80.3	0.94	Field hockey
C11	24	1.80	79.6	0.92	Rugby Union
C12	19	1.90	94.6	1.04	Crossfit
C13	32	1.72	84.4	0.87	Rugby Union
C14	29	1.67	66.9	0.88	Equestrian
C15	21	1.71	73.1	0.96	Football
C16	31	1.87	83.0	1.04	Football

4.2.2. Procedure

Participants visited the laboratory on three occasions in one week, with the first session (S) comprising of two parts (S1a + S1b), and the subsequent two sessions scheduled between 24-48 hours following the previous session (S2 + S3). This was the initial intervention week. Participants then returned at 4-6 weeks for a follow up retention (S4). Figure 4.1 outlines the study design for S1-S4. Each session was separated into multiple blocks, with each block comprising of six lunges.

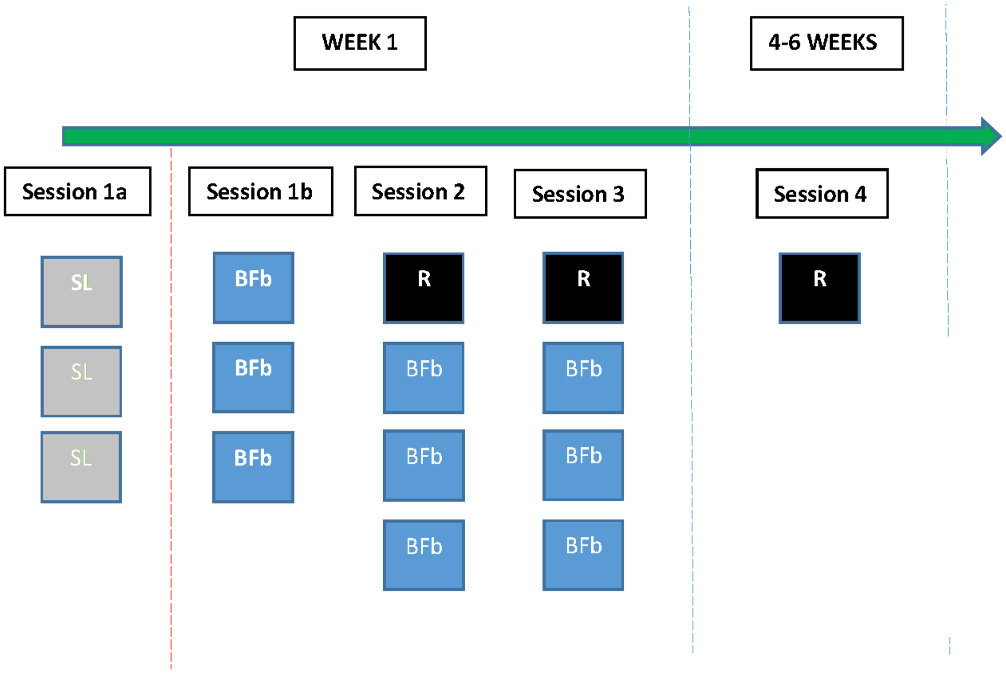


Figure 4.1. Schematic representation of the intervention data collection protocol. Each square represents one block of six lunges. SL = self-learning, where no BFb was provided; BFb = 100% BFb (or no BFb for controls) and R = retention block.

At the start of the first session (S1a) all participants were introduced to a novel lunge touch task, similar to an explosive attacking lunge in fencing but using a pointer in place of a sword. This allowed for a reduction in task complexity for non-fencing athletes, but retain the performance indicators of the propulsive element. The aim of the task was to use a 20 cm long pointer to strike a 15 x 15 cm target placed 1.5 leg lengths away from the front foot in a lunge start position, and at the height matching a marker placed on their sternal clavicular notch (figure 4.2.). During S1a all participants completed three blocks of ‘self-learning’, where they were provided with instruction of the starting position and the task. All participants were informed that the rear leg extension was the key to propulsive ability. The start position simulated an en-guarde stance adapted from fencing, with each foot on an individual force plate. The participants were instructed to flex their rear knee to 130° as shown in elite fencing performance (Bottoms et al., 2013) dropping them in to a preparatory stance. The front foot was pointed forward toward the target, with the rear foot placed perpendicular to the target as the most advantageous for rear leg power production in the fencing attacking lunge (Gresham-Fiegal et al., 2013). Once settled, upon receiving an audible command they were instructed to propel their body forward as quickly as possible and to strike the target centre. During the first three blocks, all participants were able to perform the required skill.

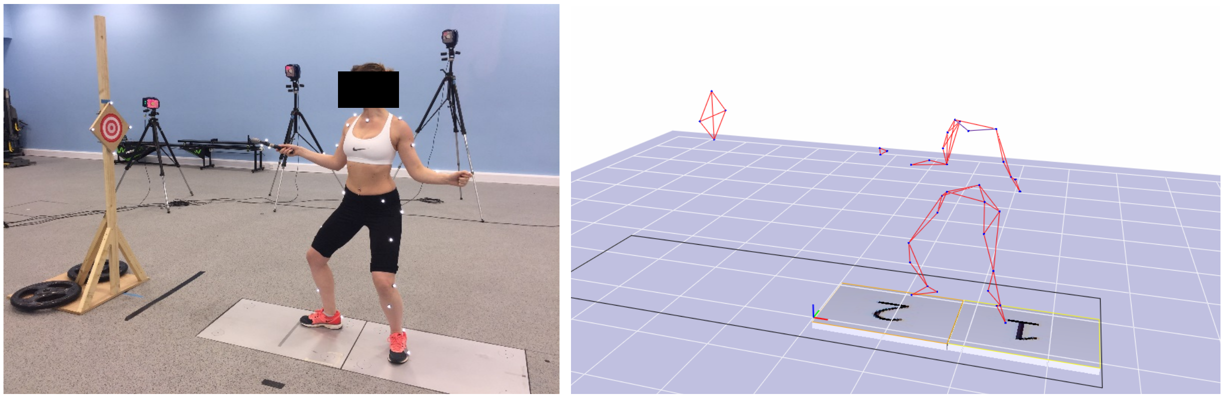


Figure 4.2. A participant in the ‘ready’ position in front of the target (left) and the motion capture data, visually displaying marker set up (right).

4.2.3. Biofeedback Content

Following the initial three blocks of self-learning, and prior to commencing S1b, participants within the BFb group were provided with standardised instructions on the BFb that was to follow (Appendix 1). The feedback consisted of a bar chart projected onto a large screen (figure 4.3). This displayed peak angular extension velocities for the rear leg hip, knee, and ankle in radians for following each trial. Along with magnitudes, a colour coding system was used to demonstrate joint sequencing information. Specifically, three green bars signified proximal to distal sequencing had occurred (e.g. hip, knee, and then ankle) whereas two red bars signified a non-sequential extension between the two joints in red (e.g. a temporal peak extension pattern of hip, ankle and then knee). Feedback was received within 10 s of completing a lunge for 100% relative frequency of the BFb lunge trials. Following the second trial, a red dotted line above each peak joint angular velocity displayed the participants 'personal best' (PB) value to provide motivation, and a form of error detection. The personal best trial was the trial which obtained the greatest ankle plantar-flexion maximal velocity during that session. Participants were instructed to try and beat the PB score each time, and to maintain all green bars for a proximal to distal sequence. Prior to each trial, for all participants, the verbal cue "extend your hip, knee, and then ankle" was given, along with the transitional information "to increase joint magnitude, open up the joint faster" following principles demonstrated by Kernodle and Carlton (1992).

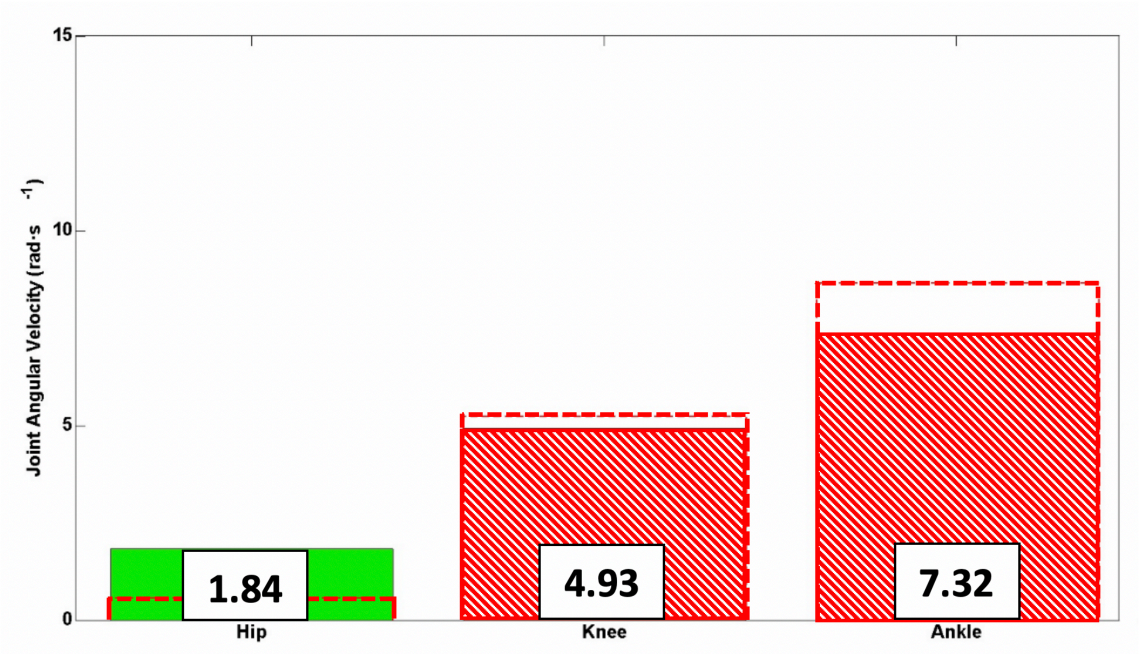


Figure 4.3. Biofeedback presentation on the magnitude and timing of rear leg hip, knee and ankle maximal angular extension velocity. The red-dotted line represents the session personal best trial for all three joints. Colour coding was used to display joint sequencing information, with patterns added here for visual clarity. All green (no pattern) signified proximal to distal sequencing, and red (striped pattern) identifying joints that were out of sequence (knee and ankle in this example). Values indicate joint angular velocity for the last trial completed.

4.2.4. Data Capture

Kinematic and kinetic data were captured using a 12-camera motion capture system (Motion Analysis Corporation, California, USA) sampled at 150 Hz, with two integrated force plates (9281E, Kistler, Switzerland) at 1500 Hz. Figure 4.4. demonstrates the motion capture setup. A total of 30 x 12 mm retro-reflective markers were placed on lateral anatomical landmarks, with a minimum of three per segment, and then an additional three on the pointer and four on the target (figure 4.2.). A lateral markerset was used to minimise marker occlusion, and facilitate tracking for the BFb.

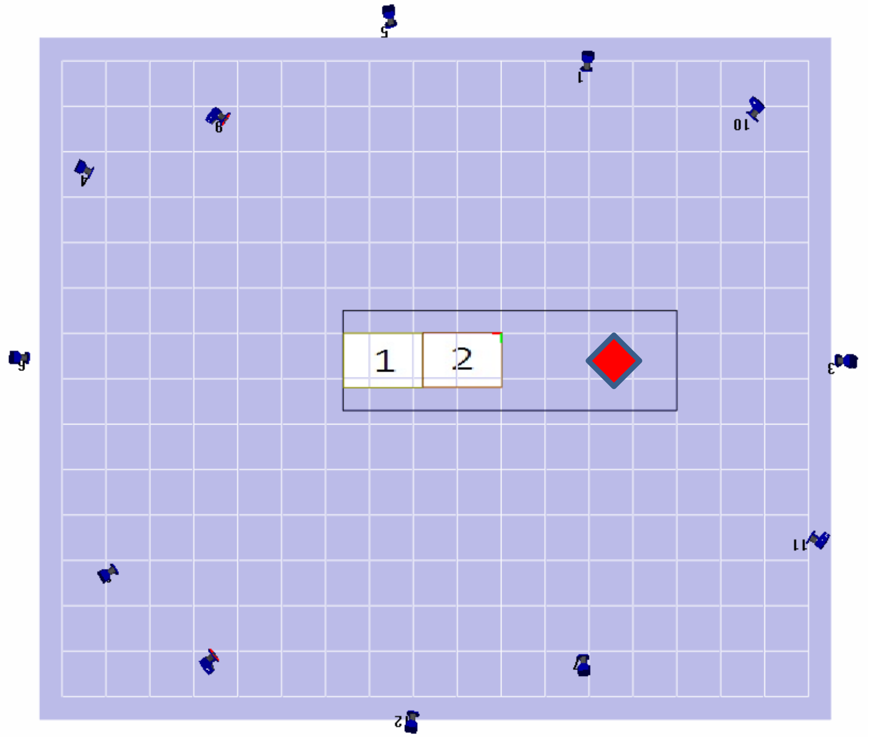


Figure 4.4. Motion capture coronal view, depicting the 12-camera setup. Each gridline square represents 0.5 m. The cameras represent the physical infra-red camera placement. Participants were placed on the forceplates 1 and 2, with target represented by the red diamond.

4.2.5. Data Processing

A custom written MATLAB code (R2015a, Mathworks, Natick, MA) was used to analyse each trial. All data were smoothed using the same approach as previously identified in chapter three. The remainder of data treatment was similar in a number of places, but some detail has been provided for clarity with the inclusion of variations.

Kinetic Data Treatment

Kinetic data from the rear foot force plate were extracted and interpolated to 101 data points to allow comparison with kinematic data as a percentage. Two key events were defined as in chapter 3; onset of force (t_{FO}) and take off (t_{TO}). However, for this data set t_{FO} was identified as the first frame that the rear leg resultant force was greater than 10% body mass of the combined front and rear leg force plates. The t_{TO} time event was identified by differentiating rear leg resultant force, and using the point that the differentiated force data crossed zero following peak force. This allowed a robust measure to identify a take-off event. Push off was the phase defined from t_{FO} to t_{TO} as previously identified and time normalized from 0% to 100% respectively. Peak vertical (Peak F_Z) and horizontal (Peak F_Y) forces were identified for each trial, along with the time that the peak forces occurred, and normalised to body mass to allow for comparison between participants. Rate of force development was calculated as the gradient of normalised peak force for vertical (RFD_Z) and horizontal (RFD_Y). Prior to the calculation of impulse, body weight was removed from vertical ground reaction force (F_Z). The integrals of both F_Z and F_Y were obtained using the trapezoidal method to calculate net vertical and horizontal impulse (Impulse$_Z$ and Impulse$_Y$ respectively). On an individual level, these were combined as a measure of Total Impulse to assess correlations between joint kinematics and propulsive ability.

Centre of Mass (CoM) velocities were calculated from the ground reaction force using mathematical derivation of Newton's second law of acceleration and the impulse-momentum relationship (equations 4.1 to 4.4).

$$F = m \cdot a = m \cdot \frac{\Delta v}{\Delta t} \qquad \textbf{Eq. 4.1}$$

$$\int F \cdot \Delta t = m \cdot \Delta v \qquad \textbf{Eq. 4.2}$$

$$\int F \cdot \Delta t = m \cdot (v_{final} - v_{initial}) \qquad \textbf{Eq. 4.3}$$

$$\int {}^{F \cdot \Delta t}\!/_{m} = v_{final} \qquad \textbf{Eq. 4.4}$$

Equation 4.1 depicts Newton's second law where *F* is force, *m* is a participant's mass, and *a* is CoM acceleration. Acceleration is the derivative of velocity (*v*) with respect to time (*t*). Rearranging this by time (equation 4.2), and then integrating both sides of the equation yields the impulse-momentum equation where impulse equals mass multiplied by the change in velocity (equation 4.3). As the task in this investigation is initiated from a stationary position, $v_{initial}$ can be assumed to be at zero. Therefore, impulse divided by mass yields the peak CoM velocities in both the vertical (CoM$_{VelZ}$) and horizontal (CoM$_{VelY}$) direction.

Kinematic Data Treatment

Kinematic variables were analysed for $F_{PushOff}$ of each lunge. 3D joint angles were calculated for the rear leg hip, knee and ankle. Specifically, the thigh was defined from the greater trochanter (GT) marker to the lateral femoral condyle, the shank from the lateral femoral condyle to the lateral malleolus, and the foot from the lateral malleolus to the 5th metatarsal. The hip joint was defined as the angle from the thigh segment relative to the horizontal to account for trunk lean as it was seen to obscure rear leg contributions in pilot testing with athletes new to the task. The knee joint was defined from the thigh to the shank, and the ankle from the shank to the foot. Extension was deemed as positive for all three joints. 3D joint angles and angular velocities were calculated for the rear leg hip, knee, and ankle. Peak joint extension angles (Hip_{θ}, $Knee_{\theta}$, $Ankle_{\theta}$), peak extension angular velocities (Hip_{ω}, $Knee_{\omega}$, $Ankle_{\omega}$) were extracted for analysis. Alongside these, joint ranges of motion (RoM) were determined, as well as the timing of peak extension velocities presented as percentage of $F_{PushOff}$. Time series kinematic data were interpolated to 126 data points providing a kinematic profile relative to external kinetics for $F_{PushOff}$. Therefore, time series kinematic data were presented as in chapter three, from 0-125% of $F_{PushOff}$.

4.2.6. Statistical Analysis

For all variables, block means were calculated for each participant, along with standard deviations which were then meaned by group. This provided group means for each block along with standard deviations for group analysis. For analysis of the BFb intervention in this chapter, block 3 was taken as pre-intervention (Pre$_{\mathrm{Int}}$), block 14 as post-intervention (Post$_{\mathrm{Int}}$) and block 15 at the four-six-week retention (Ret$_{\mathrm{Int}}$). For comparison purposes, peak joint extension angular velocities were also assessed as percentage changes relative to block 3 (Pre$_{\mathrm{Int}}$ = 0%).

As defined in chapter three, rank scoring was assigned to the rear leg angular velocity peak timings to determine individual sequencing. All statistical tests were performed in SPSS (v.20; IBM, Armonk, NY). Normality was assessed using a Shapiro-Wilk test. Interaction effects were investigated across variables using a 2 x 3 mixed method ANOVA design (Group x time; Pre$_{\mathrm{Int}}$, Post$_{\mathrm{Int}}$ and Ret$_{\mathrm{Int}}$). Non-normally distributed data were tested using the repeated measures approach due to robustness of the 2-way repeated model, and a lack of appropriate non-parametric equivalent. Significant interaction effects were then investigated further using a post-hoc Wilcoxon signed rank for non-normal distributions. The alpha level was set at 0.05 for all statistical analysis.

4.3. Results

4.3.1. Kinematic Changes

Table 4.2 summarises the rear leg kinematic variables, presenting mean ± SD values. There were significant interaction effects in Peak Hip$_{\omega}$ ($F=4.781$; $p=0.02$) and Knee$_{\omega}$ ($F=14.302$, $p<0.001$) between the groups and time points. Participants in the BFb group show significant increases in Peak Hip$_{\omega}$ and Knee$_{\omega}$ from Pre$_{\text{Int}}$-Post$_{\text{Int}}$ sessions ($p=0.04$ and $p=0.01$ for Hip$_{\omega}$ and Knee$_{\omega}$ respectively), with these changes being retained for 4-6 weeks at Ret$_{\text{Int}}$ with no significant differences between Post$_{\text{Int}}$-Ret$_{\text{Int}}$ ($p=0.75$ and $p=0.78$ for Hip$_{\omega}$ and Knee$_{\omega}$ respectively). In contrast, the Control group showed no significant increases in Peak Hip$_{\omega}$, and Knee$_{\omega}$ ($p=0.58$ and $p=0.14$ for Hip$_{\omega}$ and Knee$_{\omega}$ respectively) between Pre$_{\text{Int}}$-Post$_{\text{Int}}$. This shows that the BFb seemingly improved hip and knee extension velocities, and that these were retained up to 4-6 weeks. No significant interaction effects were found between the groups and time points for Peak Ankle$_{\omega}$ ($F=1.537$, $p=0.23$) absolute magnitudes.

No interaction effect was shown between Peak Hip$_{\theta}$ ($F=0.170$, $p=0.98$) and Peak Knee$_{\theta}$ ($F=1.180$, $p=0.30$) extension angles, or with the RoM at these joints ($F=1.499$, $p=0.23$ for Hip$_{\text{ROM}}$; $F=0.187$, $p=0.83$ for Knee$_{\text{ROM}}$), showing that there were no changes in angular displacement, despite the changes in extension velocities. A significant interaction effect was shown in plantarflexion kinematics of Peak Ankle$_{\theta}$ ($F=10.915$, $p=0.00$) and Ankle$_{\text{ROM}}$ ($F=9.543$, $p<0.001$). Both variables increased in the BFb group from Pre$_{\text{Int}}$-Post$_{\text{Int}}$ ($p=0.00$) for both Peak Ankle$_{\theta}$, and Ankle$_{\text{ROM}}$), which were retained at Ret$_{\text{Int}}$. Therefore, although

Peak Ankle$_{\omega}$ absolute magnitude did not change, there were significant increases in ankle displacement kinematics.

There were significant interaction effects for all three maximal joint extension velocities when normalised as a percentage change from the Pre$_{\text{Int}}$ time point (F=3.746, p=0.03 hip; F=10.241, p=0.01 knee; F=3.397, p=0.04 ankle). In the BFb group the hip, knee and ankle joints increase by 34 ± 38%, 25 ± 24% and 33 ± 47% respectively. These increases were retained at 28 ± 41%, 24 ± 27% and 24 ± 36% at the retention time point. Comparatively, the Control group displayed marginal improvements through practice alone with an increase of 9 ± 29%, 6 ± 20% and 8 ± 28% for the hip, knee and ankle respectively at the post time point. These changes were retained with 5 ± 27%, 2 ± 25% and -4 ± 31% for the same joints at retention.

Table 4.2. Rear leg kinematic variables for BFb and Control groups (mean ± SD) performing the lunge task. Temporal sequencing is presented as percentage of push off phase (0% = t_{FO}, 100% = t_{TO}). *denotes significant differences Pre$_{Int}$-Post$_{Int}$, †denotes significant differences Post$_{Int}$-Ret$_{Int}$, ‡ denotes significant differences Pre$_{Int}$-Ret$_{Int.}$

BFb (n=16) Joint Kinematics	Pre$_{Int}$	Post$_{Int}$	Ret$_{Int}$	Interaction
Peak Hip$_\omega$ (rad·s^{-1})	2.71 ± 0.78	3.48 ± 0.95*	3.34 ± 0.97‡	S
Peak Knee$_\omega$ (rad·s^{-1})	8.83 ± 2.00	10.78 ± 2.01*	10.69 ± 2.15‡	S
Peak Ankle$_\omega$ (rad·s^{-1})	8.83 ± 3.66	10.10 ± 1.59	9.40 ± 1.53	NS
Peak Hip$_\theta$ (°)	90 ± 7	92 ± 10	91 ± 7	NS
Peak Knee$_\theta$ (°)	168 ± 6	171 ± 4	171 ± 5	NS
Peak Ankle$_\theta$ (°)	146 ± 9	157 ± 8*	153 ± 6‡	S
Hip$_{ROM}$ (°)	36 ± 6	43 ± 10	40 ± 7	NS
Knee$_{ROM}$ (°)	74 ± 18	75 ± 16	77 ± 13	NS
Ankle$_{ROM}$ (°)	52 ± 11	51 ± 7*	51 ± 7‡	S
Peak Hip$_\omega$ time (%)	69 ± 16	73 ± 19	77 ± 10	NS
Peak Knee$_\omega$ time (%)	72 ± 15	74 ± 20	79 ± 9	NS
Peak Ankle$_\omega$ time (%)	75 ± 17	74 ± 19	80 ± 9	NS
Hip rank scoring (target 1)	1.75 ± 0.86	1.91 ± 0.97	2.31 ± 0.95‡	NS
Knee rank scoring (target 2)	1.63 ± 0.62	1.69 ± 0.60	1.53 ± 0.50	NS
Ankle rank scoring (target 3)	2.63 ± 0.62	2.41 ± 0.71	2.16 ± 0.77	NS

Control (n=16) Joint Kinematics	Pre$_{Int}$	Post$_{Int}$	Ret$_{Int}$	Interaction
Peak Hip$_\omega$ (rad·s-1)	2.49 ± 0.64	2.64 ± 0.70	2.56 ± 0.81	S
Peak Knee$_\omega$ (rad·s-1)	9.50 ± 2.29	8.54 ± 1.39	8.92 ± 1.44	S
Peak Ankle$_\omega$ (rad·s-1)	8.99 ± 2.07	9.33 ± 1.45	8.16 ± 1.83	NS
Peak Hip$_\theta$ (°)	89 ± 9	92 ± 10	91 ± 9	NS
Peak Knee$_\theta$ (°)	168 ± 8	171 ± 4	171 ± 5	NS
Peak Ankle$_\theta$ (°)	148 ± 15	147 ± 13	147 ± 14	S
Hip$_{ROM}$ (°)	36 ± 6	38 ± 10	36 ± 8	NS
Knee$_{ROM}$ (°)	70 ± 15	74 ± 14	75 ± 13	NS
Ankle$_{ROM}$ (°)	52 ± 8	53 ± 5	51 ± 8	S
Peak Hip$_\omega$ time (%)	65 ± 13	77 ± 17*	72 ± 15	NS
Peak Knee$_\omega$ time (%)	72 ± 15	79 ± 14	80 ± 14	NS
Peak Ankle$_\omega$ time (%)	73 ± 15	81 ± 13	83 ± 14	NS
Hip rank scoring (target 1)	1.56 ± 0.89	1.69 ± 0.95	1.31 ± 0.70	NS
Knee rank scoring (target 2)	1.75 ± 0.45	1.63 ± 0.50	1.94 ± 0.25	NS
Ankle rank scoring (target 3)	2.69 ± 0.60	2.69 ± 0.49	2.75 ± 0.68‡	NS

There were no significant interaction effects between groups or time points for any kinematic temporal variables. This is shown on a group joint level, as demonstrated by Peak Hip_{ω} time (*F*=1.301; *p*=0.42), $Knee_{\omega}$ time (F=0.412; p=0.66) or $Ankle_{\omega}$ time (F=0.946; p=0.39). Additionally, the individual rank scoring shows that there were no differences between the two groups with respect to altering the proximal to distal sequence on an individual basis as a consequence of adhering to the BFb intervention.

The angular velocity time series data in figure 4.4a, depicting standard deviations from the mean with grey shading, show distinct changes in the extension magnitudes of the BFb hip, knee and ankle angular velocities. There is a distinct increase in extension velocity magnitudes of all three joints from pre to post time points with no changes in timing. The increased gradient of velocities mean that joint acceleration extension must increase. These changes are retained in the retention time points. Most notably, the hip demonstrates a greater peak in the post and retention time points. Knee extension velocity also increases. The ankle angular velocity mean is notably smaller in magnitude than the corresponding knee series plots in the BFb intervention group. The Control group (figure 4.4b) show no noticeable changes in joint extension between the Pre_{Int} and $Post_{Int}$ time points. The standard deviations do visually demonstrate a decrease in group distribution from the mean, suggesting that the control group all converge on a movement pattern of similar joint extension velocities. The joint patterns did not differ substantially in the Pre_{Int}, $Post_{Int}$, or Ret_{Int} time points for the Control group, shown in the joint kinematic chain joint velocity time plots.

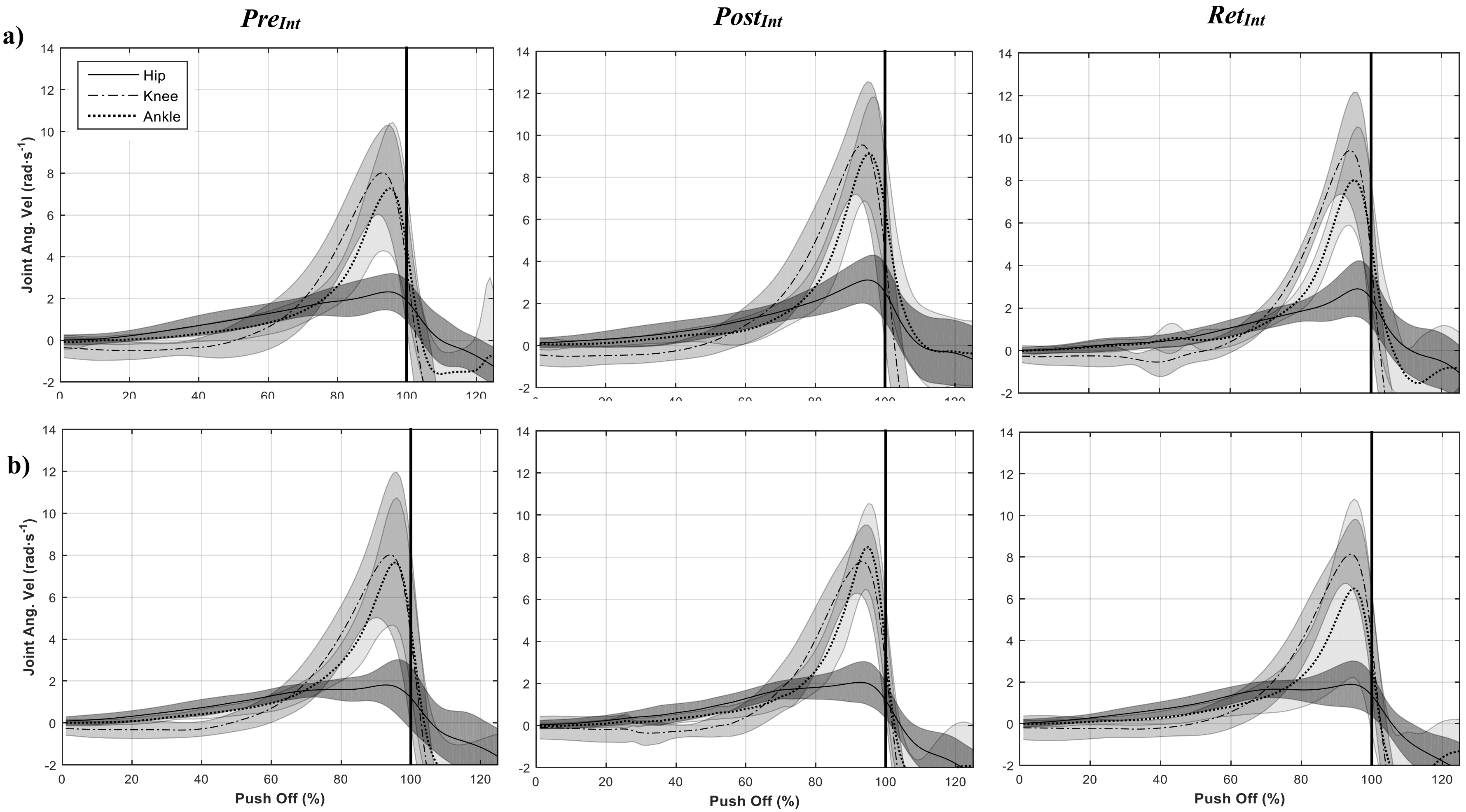


Figure 4.5. Mean joint angular velocity series data for BFb (a) and Control (b) for Pre_{Int}, $Post_{Int}$ and four-six week Ret_{Int} time points performing the lunge task. Standard deviations are plotted either side of each mean, with grey shading depicting the data spread. Extension is positive. Push off phase is from initiation of rear leg force (0%) to take off (100%). The thick vertical line at 100% signifies take off.

4.3.2. Kinetic Changes

There were no significant interaction effects between any external kinetic variables, shown in Table 4.3. Peak F_Z showed no change, highlighted with a lack of significant interaction effect (F=0.597, p= 0.55). The horizontal component Peak F_Y, increased from Pre_{Int}-$Post_{Int}$, however this was seemingly lower in the Ret_{Int}, with a lack of significant interaction showing no tangible changes (*F*=1.364, *p*=0.26). The timing of these peak force occurances also yielded no significant interaction, with mean values comparable across groups, and with no changes across the three time points in either (*F*=1.137, *p*=0.26 for Time of Peak F_Z; and *F*= 0.545, *p*=0.64 Time to Peak F_y). With the interaction between kinetic magnitude and timing, there were no interaction effects in either RFD_Z (*F*=1.105, *p*=0.34) or RFD_Y (*F*=1.879, p=0.16).

No significant interaction effects in Imp_Z (*F*=0.208, *p*=0.72) support the notion that there were no changes in the vertical propulsive ability. Both groups showed an increase from pre to post Imp_Y, however there was no significant interaction effects to support these changes (*F*=0.516, *p*=0.57). No interaction in the duration of force application ($F_{PushOff}$ Time; *F*=1.1768, *p*=0.18) also highlights that there were no reductions in the amount of time that impulse was generated, thus further demonstrating no changes in external kinetic variables. Figure 4.5 shows normalised horizontal force series data for the Pre_{Int}, $Post_{Int}$, and Ret_{Int} time points for both the BFb and Control group means, with respective SDs in shading. There were no visible changes in the normalised discrete peak horizontal force means for either groups across any time points. However there were substantial differences shown with individual responses in the BFb group, with large standard deviations in the Post_{Int} session. This variability was not evident in the Ret_{Int}.

Table 4.3. Kinetic variables for both BFb and Control groups (mean ± SD) performing the lunge task. *Note, there are no significant interactions (NS) or differences throughout these results.

BFb Kinetic Data	**Pre_{Int}**	**Post_{Int}**	**Ret_{Int}**	**Interaction**
Peak F_Z ($N\cdot kg^{-1}$)	1.06 ± 0.19	1.02 ± 0.24	1.02 ± 0.16	NS
Peak F_Y ($N\cdot kg^{-1}$)	0.75 ± 0.15	0.83 ± 0.25	0.67 ± 0.16	NS
Time of Peak F_Z (s)	0.37 ± 0.12	0.36 ± 0.13	0.39 ± 0.05	NS
Time of Peak F_Y (s)	0.41 ± 0.12	0.40 ± 0.12	0.42 ± 0.06	NS
RFD_Z ($N\cdot kg^{-1}\cdot s^{-1}$)	3.59 ± 1.87	3.80 ± 2.32	2.96 ± 0.59	NS
RFD_Y ($N\cdot kg^{-1}\cdot s^{-1}$)	2.17 ± 0.89	2.49 ± 1.19	1.80 ± 0.49	NS
Impulse_Z (Ns)	154 ± 53	152 ± 47	150 ± 36	NS
Impulse_Y (Ns)	139 ± 46	152 ± 50	128 ± 30	NS
F_{PushOff} Time (s)	0.52 ± 0.11	0.52 ± 0.14	0.56 ± 0.06	NS

Control Kinetic Data	**Pre_{Int}**	**Post_{Int}**	**Ret_{Int}**	**Interaction**
Peak F_Z ($N\cdot kg^{-1}$)	1.04 ± 0.22	1.05 ± 0.22	1.02 ± 0.19	NS
Peak F_Y ($N\cdot kg^{-1}$)	0.69 ± 0.16	0.74 ± 0.17	0.72 ± 0.18	NS
Time of Peak F_Z (s)	0.37 ± 0.1	0.42 ± 0.12	0.41 ± 0.09	NS
Time of Peak F_Y (s)	0.41 ± 0.09	0.41 ± 0.10	0.43 ± 0.09	NS
RFD_Z ($N\cdot kg^{-1}\cdot s^{-1}$)	3.39 ± 1.61	2.91 ± 1.33	2.91 ± 0.86	NS
RFD_Y ($N\cdot kg^{-1}\cdot s^{-1}$)	1.92 ± 0.69	1.90 ± 0.68	1.83 ± 0.66	NS
Impulse_Z (Ns)	145 ± 43	141 ± 53	146 ± 41	NS
Impulse_Y (Ns)	128 ± 41	141 ± 39	131 ± 29	NS
F_{PushOff} Time (s)	0.52 ± 0.11	0.59 ± 0.11	0.58 ± 0.09	NS

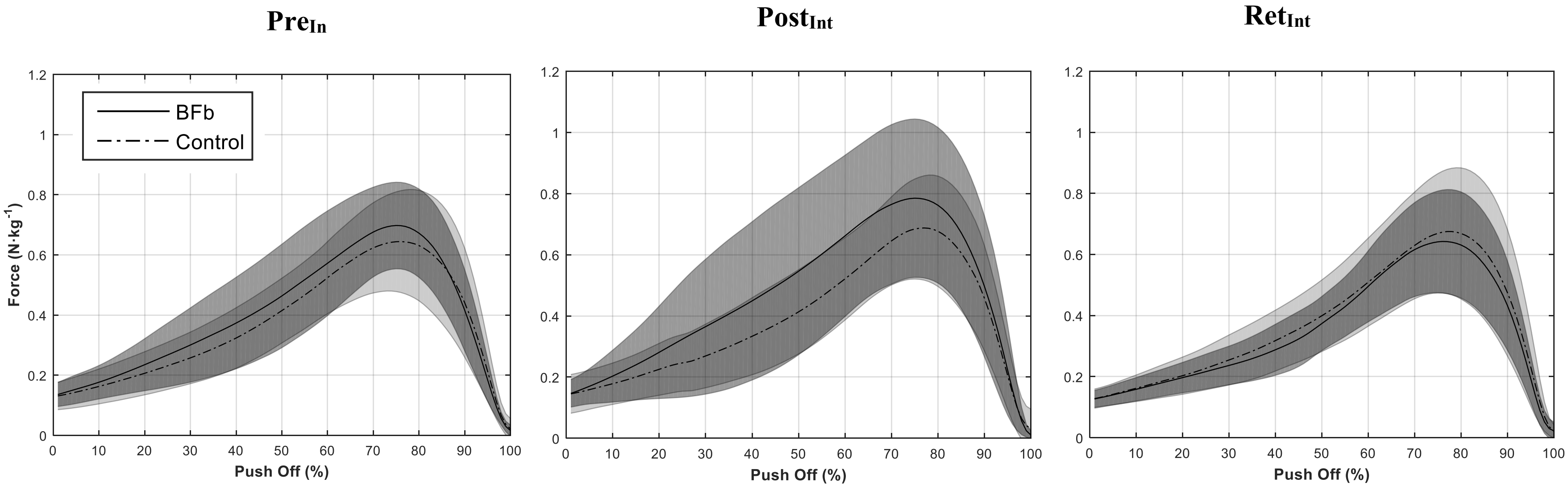


Figure 4.6. Mean normalised horizontal force data for both BFb and Control groups performing the lunge task. Standard deviations are plotted either side of each mean, with grey shading depicting the data spread. Push off phase is from initiation of rear leg force (0%) to take off (100%).

4.3.4. Kinematic Transfer to External Kinetics

Correlations between individual peak joint extension kinematics and Total Impulse using the individual lunge dataset (n=4416) demonstrating no significant correlations between the joint extension parameters and CoM propulsion. This is visually highlighted in below (figure 4.6) with Peak Ankle$_{\omega}$ demonstrate no correlation with Total Impulse (R= -0.08, p=0.00). In addition, no correlations were shown with Hip$_{\omega}$ and Total Impulse (*r*=0.02, *p*=0.15) and Knee$_{\omega}$ with Total Impulse (*r*=0.11, *p*=0.00). As a thought experiment, individual Hip$_{\omega,}$ Knee$_{\omega}$ and Ankle$_{\omega}$ were also combined to create a total rear leg kinematic chain angular velocity, and correlated with Total Impulse. This relationship was also insignificant, with no correlation (*r*=0.02; *p*=0.21), thus confirming no correlational relationship between peak joint extension velocity magnitudes and CoM propulsion.

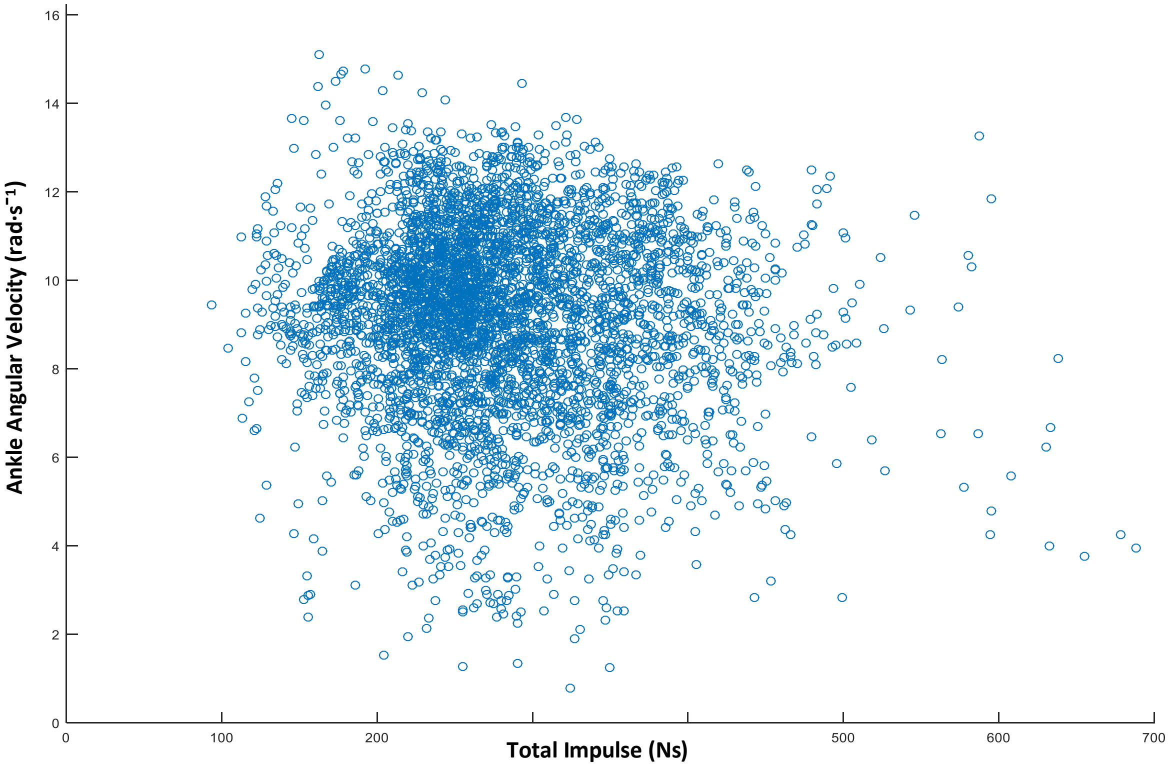


Figure 4.7. Scatter plot of individual lunge peak ankle angular velocity versus total impulse (Imp$_Z$ + Imp$_Y$) for entire data set (n=4416) performing the lunge task. Plantarflexion is positive.

4.3.5. Performance Variables

There were no significant interaction effects in any performance variables. Specifically, there was no interaction effect with Pointer Vel_Y (*F*=0.761, *p*=0.47), demonstrating that changes in kinematic chain extension did not facilitate an increase in peak linear point velocity. Additionally, no interaction effects were shown with CoM Vel_Z (*F*=0.279, *p*=0.67) or CoM Vel_Y (*F*=0.854, *p*=0.43), demonstrating further that propulsive ability did not change. The performance kinematics are depicted in table 4.4. The intervention did not appear to alter propulsive kinematics of the explosive lunge task.

Table 4.4. Kinematic performance variables for BFb and Control groups (mean ± SD).

Performance Parameters	**Pre_{Int}**	**$Post_{Int}$**	**Ret_{Int}**
BFb CoM Vel_Z ($m \cdot s \cdot ^{-1}$)	2.22 ± 0.48	2.19 ± 0.50	2.17 ± 0.28
BFb CoM Vel_Y ($m \cdot s \cdot ^{-1}$)	2.02 ± 0.47	2.21 ± 0.72	1.87 ± 0.34
BFb Pointer Vel_Y ($m \cdot s \cdot ^{-1}$)	4.47 ± 1.42	4.63 ± 0.79	4.53 ± 0.74
Control CoM Vel_Z ($m \cdot s \cdot ^{-1}$)	2.13 ± 0.37	2.06 ± 0.60	2.17 ± 0.40
Control CoM Vel_Y ($m \cdot s \cdot ^{-1}$)	1.89 ± 0.47	2.11 ± 0.49	2.01 ± 0.51
Control Pointer Vel_X ($m \cdot s \cdot ^{-1}$)	4.36 ± 0.85	4.79 ± 1.12	4.80 ± 0.99

4.4. Discussion

The purpose of this chapter was to address Theme 2 by investigating the effectiveness of an objective, terminal BFb intervention, using KP to develop whole limb kinematics in a complex skill performed by novices. Specifically, this chapter focused on the rear leg in an explosive lunge movement. Kinematic BFb based on rear leg hip, knee, and ankle extension magnitudes and sequencing was provided to athletes following each trial of the modified lunge-touch task. The KP intervention was provided over three sessions during one week, with a retention session after 4-6 weeks. A matched, randomised control group completed the same number of lunges throughout. From the kinematic and kinetic data collected during this period, this chapter sought to evaluate changes in technique and performance characteristics in a complex motor skill task brought about through applications of feedback directed toward the whole limb kinematic chain.

4.4.1. Kinematic Changes with Biofeedback

The results of this chapter show that an objective, terminal KP intervention, focusing on rear leg kinematic chain peak extension velocity magnitudes and sequencing, was effective in altering whole limb kinematics. This allows the acceptance of the first hypothesis addressed in this study; ***H_5) Terminal KP of the rear leg kinematic directly facilitates an increase in joint extension velocity magnitudes, and maintains proximal to distal sequencing.*** Findings in this chapter demonstrate that KP allows improvements beyond self-learning, with the provision of augmented information not readily available to the participant (Magill, 1994).

The significant interaction effect in Peak Hip_ω and Peak $Knee_\omega$ demonstrates that KP induced changes in the two most proximal joints of the rear leg kinematic chain. Specific changes occurred with significant increase for both Hip_ω and $Knee_\omega$ from Pre_{Int}-$Post_{Int}$, in the BFb group (2.71 ± 0.78 to 3.48 ± 0.95 $rad \cdot s^{-1}$ for hip; and 8.83 ± 2.00 to 10.78 ± 2.01 $rad \cdot s^{-1}$ for knee; $p < 0.05$). In comparison, the Control group showed no significant increases from Pre_{Int}-$Post_{Int}$ points in hip or knee joints (2.49 ± 0.64 to 2.64 ± 0.70 $rad \cdot s^{-1}$ for hip; and 9.50 ± 2.29 to 8.54 ± 1.39 $rad \cdot s^{-1}$ for knee; $p < 0.05$), demonstrating that the changes that did occur in rear leg kinematics were due to the KP intervention. Significant changes in hip and knee kinematics have been shown in KP interventions offering video based BFb, facilitating an increase in joint flexion during drop landing (Etnoyer et al., 2013) and volleyball spike landings (Cronin et al., 2008). Manipulation of hip extension in an explosive task is beneficial due to the large force generating capacity of this joint. Research demonstrates that the largest joint torques of the lower limb are generated in the hip extensors in jumping and sprinting, relative to the knee extensors and ankle plantarflexors (Jacobs et al., 1996). This large hip extensor contribution is necessary to initiate movement of the heavy trunk segment and to produce large muscular forces to input into bi-articular power generation of the lower limb (Jacobs et al. 1996; Bobbert and van Soest, 2001; Cleather et al. 2015). This lower limb power transfer mechanism has been shown to generate the largest forces in the proximal segment which in turn are transferred to the knee through isometric contraction of the bi-articular rectus femoris. Therefore, this hip extension contributes to knee extension (Gregoire et al., 1984; van Ingen Schenau, 1989; Jacobs et al., 1996). Increasing the contribution of the hip joint alone should prove beneficial, however this should also be paired with additional contraction of the large mono-articular vastii group to counteract excessive knee flexion, a bi-product of the bi-articular hamstrings role in hip extension (Cleather et al., 2015). Thus, in this study, it is important that knee extension showed increases alongside hip extension with the BFb. The increase hip and knee extension support this notion.

Objective visual KP has been shown to be very effective in manipulating knee kinematics with these changes also transferring to other discrete skills. For example, KP on knee kinematics altering knee abduction in squatting has shown successful transfer to drop landing mechanics aiding injury prevention (Ford et al., 2015). Thus, it appears that the knee is a joint that individuals have the capacity to manipulate in discrete skills. In less explosive tasks, such as walking, knee abduction has been reduced by 20% with just one session of KP (Jackson et al., 2017), showing that knee kinematics are malleable in many movement patterns, and these changes can occur early on. However, a lack of retention testing beyond one day makes it difficult to speculate on the permanency of these changes. These studies collectively support that the knee can be manipulated effectively with immediate feedback. This effectiveness may stem from the role the lower limb joints each individually play in the summation of force. The hip extensors generate large forces, with a primary objective to move the trunk and develop force (Bobbert and van Soest, 2001). The knee must combat the bi-product of knee flexion from the hamstring contributions to trunk extension (Cleather et al., 2015), and contribute further extension with the vastii muscle group demonstrating the largest muscular force contribution in jumping (Jacobs et al. 1996). In addition, the knee contributes to Achilles tendon loading

(Malvankar and Khan, 2011; Farris et al. 2016), pivotal in ankle plantarflexion. Thus, the knee is a very effective joint to target via BFb in explosive, whole limb activity as a linking segment and a large contributor.

Interestingly, there were no significant changes in Peak Ankle$_{\omega}$ in either BFb or Control groups (see table 4.2). Mathematical modelling demonstrates that excessive extension of the more proximal segments (e.g. the hip and then the knee) may impair ankle plantarflexion with the smaller segment unable to counteract the larger inertia generated (Bobbert and van Soest, 2001). Logically, however, as the ankle is positively extending during the propulsive phase, with no significant decrease, it is tolerating and transmitting the preceeding joint velocities and therefore should be able to generate and transmit larger plantarflexion forces. Following this notion, increasing proximal joint extension, at the detriment of increased plantarflexion, may still be an effective strategy. The force generating soft tissue structures at the ankle, such as the Achilles tendon, play an active role as a loaded spring mechanism (Malvankar and Khan, 2011). Ultrasound measurements during countermovement jumping show a pre-loading strategy with the biarticular gastrocnemius and mono-articular soleus muscle fibers shortening, and stretching the Achilles tendon during the downswing phase of a counter movement jump, which subsequently produce a spring recoil force (Kurakowa et al. 2003). Participants in this chapter may be attempting to plantarflex, but be inhibited by the large increase in knee extension. This may explain no change in the absolute ankle plantarflexion velocities in this study, but the greater Ankle$_{RoM}$ and Ankle$_{\theta}$. The extension kinematics may occur once the CoM has begun to unweight, thus BW on the distal joint is lifted. Although the changes of $\text{Ankle}_{\text{RoM}}$ and Ankle_{θ} are small, they may be meaningful as they still increase positively, enough for a statistical significance to highlight and confirm the common group strategy.

The intervention BFb demonstrated in this chapter targeted multiple joint interaction in a gross complex motor skill, with applications previously not addressed using objective feedback methods. The simultaneous changes in hip and knee extension, without detriment to the ankle, demonstrate that it is indeed possible to attend to multi-joint feedback. Kernodle and Carlton (1992) initially portrayed capabilities of participants to attend feedback on complex, multiple joint interaction, however success was reliant on correct transitional information being provided to inform participants on how to achieve this. Later research strengthened this theoretical standing, demonstrating alterations in limb interaction with concurrent feedback (Swinnen et al., 1997). Further, KP can direct a multitude of kinematic variables in a seated reach and touch task in stroke patients (Cirstea et al, 2016), showing our cognitive ability to process complex data on multiple joints simultaneously. With the inhibition that may have occurred at the ankle, future work should seek to investigate whether a targeted strategy could optimise and isolate specific movement parameters that allow the ankle to change. Considering the cognitive capabilities to attend to multiple levels of BFb, it is plausible that there is an optimal extension of the knee that fits in with the sequential action without inhibiting changes in the ankle.

There were no significant changes in temporal sequencing. This was demonstrated with no group changes in Peak Hip_{ω}, $Knee_{\omega}$ or $Ankle_{\omega}$ percentage timings, nor on an individual level shown with individual joint extension rank scoring. This can be explained simply in that timing was not specifically targeted with the BFb intervention, beyond maintaining proximal to distal sequencing. This allowed individuals to self-select joint timings within acceptable bandwidths, with a single constraint (e.g. a sequential pattern must be obtained). Therefore, this was not significantly altered by participants. Interactive textiles with embedded sensors have shown promise in altering temporal sequencing in whole limb movements, with real time auditory BFb in a modified netball shooting task (Helmer et al. 2010). Auditory beat patterns directed skill exploration by participants to find their individual task solution, while also guiding specific proximal to distal timing. This shows that it is possible to alter specific timing of joint kinematics if targeted, however, if prescribing specific timing patterns there needs to be a sufficient body of evidence to underpin prescription.

Much of literature underpinning temporal patterns in lower limb propulsion uses double leg counter movement jumps, or squat jumps, as a vehicle for hypothesis testing (e.g. van Ingen Schenau, 1989; Jacobs et al, 1996; Bobbert and van Soest, 2001). These movements occur in around 0.3 seconds in duration, thus are much quicker than the movement pattern assessed in this chapter. The quicker movement speed can be accounted for by the use of both legs, and with the incorporation of a stretch shortening cycle. For example, Jacobs et al. (1996) incorporated analysis of single leg sprint starts with single leg jumping, showing that both movements differ from this experiment by eliciting a stretch shortening contribution and thus occur in a much shorter time frame. The starting position of knee flexion at 130° in this thesis negated any stretch shortening cycle contributions, in an attempt to isolate pure propulsive capabilities. This may in actuality be a limitation in removing natural mechanisms taking advantage of force generating physiology.

Bobbert and van Soest (2001) demonstrated sequential patterning of the lower limb joint initiation relative to take off, with hip, knee and ankle extension initiating at 0.33-0.19 s, 0.05 s and 0 s (take off) respectively. Mathematically, this patterning demonstrated effective use of segmental rotation toward vertical jumping. When this is compared to a single leg propulsive task as seen in this chapter, it can be seen that the movement is slower when a single leg is working to propel the whole body laterally. This is evidenced with group average $F_{PushOff}$ Times ranging from 0.52-0.59 s which are similar to previously identified acceleration phase times in the fencing attacking lunge (Gutierrez et al., 2014). Extending this argument, with conservative values of 0.55 s $F_{PushOff}$, and using modest hip, knee and ankle extension timings of 70, 75 and 80% for each respectively, a different, more simultaneous, extension pattern occurs. Offsetting the ankle to 0 s would result in 0.06 s for the hip and 0.03s for the knee with 5% of relative timing equating to 0.03 s. This demonstrates participants in this movement, on average, were closer to simultaneous hip and knee extension, yet still technically sequential. This further adds to the notion that excessive knee flexion inhibits the ankle. Future work, targeting further manipulation of this timing, may yield different results.

The reduction of complex information of time series data for three joints to singular local maxima values and timings may be too simplistic. Joint timings published by Jacobs et al. (1996) and Bobbert and van Soest (2001) identify joint initiation patterns as well as movement, thus it may be that the simplification of joint sequencing to one point is too simplistic, in that the movement as a whole should be taken into consideration. One such method could be the coordination between joints in achieving the sequential patterns.

4.4.2. Kinematic Retention

The kinematic changes elicited during the one-week intervention, containing just three sessions, were maintained at the 4-6-week Ret_{Int} time point. This was demonstrated with no significant changes between $Post_{Int}$-Ret_{Int} for both Peak Hip_{ω} and Peak $Knee_{\omega}$ (Hip, p=0.75; and Knee, p=0.78) absolute values. Further verification is demonstrated with significant differences between these two joints shown between the Pre_{Int}-and Ret_{Int} conditions (Hip, p=0.05; and Knee, p=0.01), highlighting that variables at Ret_{Int} were sustainably increased from baseline, indicative of relatively permanent changes (Kontinnen et al., 2004; Noehren et al., 2011). Since no significant interaction effect were evident with Peak $Ankle_{\omega}$ this was not assessed Pre_{Int}-and Ret_{Int}.

When normalised to percentage change, all rear leg lower limb joints demonstrated a retention of the significant Pre_{Int}-$Post_{Int}$ increases, with no significant difference from $Post_{Int}$-Ret_{Int} (Hip, p=0.44; knee, p=0.81; and ankle, p=0.51). This was also further supported with significant increases between Pre_{Int}-and Ret_{Int} (Hip, p<0.01; knee, p<0.01; and ankle, p<0.01). In contrast, there were no significant interaction effects between any of the rear leg joint angular velocities in the control group, thus it can be concluded that while the control group did not change as a function of practice or time, the BFb intervention group were not only able to attend to the biofeedback to develop at a rate beyond the practice alone, but were also able to retain these changes. These changes in rear leg joint strategies in the rear kinematic chain, maintained at the 6-week retention point allow for the acceptance of ***H_6*: Changes to the rear leg kinematic chain, developed through a terminal biomechanical KP intervention, are retained at 4-6 weeks.***

These findings provide evidence supporting the notion that short interventions can indeed lead to retention in the long term. Previous research has highlighted permanent changes in assessments at 4 weeks, following interventions with large volumes of contact time (e.g. 10 sessions in two weeks by Cirstea et al., 2006; and four sessions in one week by Thow et al., 2012), however few studies have investigated retention with less contact time such as Etnoyer et al. (2011) demonstrating a single session being retained over a four-week period. As suggested in this chapter, if changes can be accrued with few sessions in a short time frame, and retained with relative permanency, this has big implications toward motor learning effectiveness. Single case study evidence has demonstrated retention of up to three months in wheelchair propulsion (Rice et al., 2010). The work in this chapter re-affirms that learning can indeed be retained for longer time periods, demonstrated through a larger sample size.

Additional kinematic changes in the intervention group, such as Ankle_θ were also retained, showing that the BFb group established greater plantarflexion as a strategy following the intervention. Retention in the changes of $\text{Ankle}_{\text{ROM}}$ further support these findings. The meaningfulness of the small magnitude of change needs to be evaluated with further analysis of the external kinetics elicited as a result of these changes, however it does further provide evidence that individuals may have been further exploring joint movements in an explosive task.

4.4.3. Kinetic Changes

Across the discrete kinetic variables, there was no significant interaction effects or changes between either groups. This shows that external kinetics did not indirectly change as a product of the kinematic BFb intervention. With the changes in kinematic joint extension velocities, while also maintaining individual sequencing, it is surprising that there were no significant interaction effects in any of the external kinetic variables. Therefore, these findings lead to ***H_7: Terminal KP increasing rear leg kinematic chain joint extension velocities can indirectly facilitate an increase in external kinetics*** being rejected***.*** As there were no changes to be retained, **H_8** is also rejected in this research; ***Changes to rear leg external kinetics, developed through changes in the kinematic chain induced via a terminal KP intervention, are retained at 4-6 weeks.***

Research has demonstrated that it is possible to provide kinematic information alone, and still facilitate changes to external kinetics in the performance of sporting skills. Applications of BFb in Olympic weightlifting movements have shown that the provision of barbell trajectories can increase external kinetics with changes in peak vertical ground reaction forces (Winchester et al., 2009) however, in the weightlifting research participants were operating at less than 90% of their 1 repetition maximum weight. This means that external kinetics could possibly be increased with the application of more effort at a submaximal load. In contrast, participants in the present research design were instructed to operate at 100% maximal explosive effort. The same explanation can be offered toward drop jump tasks (Cronin et al. 2008; Ford et al. 2015), performed within submaximal parameters. Similarly, significant adjustments in hip adduction in running, maintained after 1 month, have not produced significant changes in kinetic loading variables (Noehren, et al., 2011). These studies, paired with the current research, collectively suggest that BFb effectiveness can rely on the specificity of the BFb itself, or the cause and effect relationship that exists between variables.

Direct applications of kinetic BFb in sprinting have also failed to elicit changes (Fortier et al., 2005). These further confound evidence on BFb capabilities to manipulate kinetics, however potential limitations could have masked feedback effectiveness. For example, Fortier et al. (2005) used exceedingly low frequency BFb (three block starts per week). Further, the intervention involved presenting whole ground reaction force traces, to change very specific discrete kinetic variables, a complex array of information. Limited transitional information may have prohibited BFb interpretation (Kernodle and Carleton, 1993). Other research approaches have removed complex kinetic variables in pilot experiments prior to the main intervention, with participants demonstrating difficulty interpreting the rate of applied force (Richter et al. 2011) further highlighting this issue. Where the link between kinematic and kinetic variables is more intuitive, success is more evident in continuous skills (e.g. swing amplitude and exerted force on a ski simulator;

Shea and Wulf, 1999). The lack of changes in resulting external kinetics in this chapter may therefore be explained with the participants operating at maximal explosive capacity, and a disconnect in linking kinematic changes with external kinetics in skill execution. Future research in explosive, discrete skills, therefore, should look to create tangible links to incorporate kinetic changes that directly underpin the task.

Perhaps internal kinetics, using inverse dynamics, are the link between kinematic manipulations resulting in changes to external ground reaction forces. Incorporating kinematic data with kinetics through joint moments, the product of angular displacement and perpendicular force, has been shown to be effective in reducing knee abduction in drop jump landing (Ford et al., 2015). Specifically, participants receiving band width BFb on knee abduction moments during squat training were able to reduce knee moments in a transfer task, more so than participants just receiving knee adduction angle. This research was effective in a drop jump landing task, but may not be effective in maximal extension due to differing anatomical constraints (van Ingen Schenau, 1989). Practical issues arise in the provision of real time joint torques due to the large volume of separate data inputs required (e.g. force vectors, centre of pressure orientation, segmental inertial parameters, and 3D marker locations; Challis and Kerwin, 1996), along with a large number of markers to determine segment orientation and rotation. Further limitations of this method pertain to confidence in small changes in joint torques that may in actuality be due to measurement error, and the quantification of net torques on one joint that may result from this bi-articular muscle power transfer (Zatsiorsky and Latash, 1993; Jacobs et al., 1996; Cleather et al, 2015). Future work should seek to identify a method that incorporates simple kinematics and kinetics, aligning to work in an applied performance or clinical setting.

4.4.4. Kinematic Transfer to External Kinetics

The disassociation shown between kinematic changes and no changes in external kinetics is surprising. The original “summation of speed principle” proposed by Bunn (1972) relates to effective force being a sum of segmental forces applied in a correct sequence. More recently, this kinematic and kinetic association has been demonstrated in sprinting (Jacobs et al. 1996) and jumping (Bobbert and van Soest, 2001; Wong et al., 2016) with bi-articular transfer mechanisms showing a clear link through joint net power measurements. However, commonly, the research underpinning the kinematic chain in whole limb propulsion has not manipulated the kinematic chain with an intervention. Therefore, the relationship between changing kinematics and kinetics is not known.

Findings in chapter 3 supported the notion that a greater sequential kinematic chain, with accumulated distal joint angular velocity correlated with horizontal impulse generation between novice and skilled fencers (r=0.81; $p<0.001$). However, findings in this chapter show that this may not be the case with the general athletic population analysed in this intervention. Figure 4.6 highlights that there is no correlation between peak joint angular extension velocities, and impulse when using a large data set (n=4416 lunges). There are two plausible reasons that support this disconnect. Firstly, that the increase in Peak Hip$_{\omega}$, and Peak Knee$_{\omega}$, yet no significant change in Peak Ankle$_{\omega}$ could be due to some form of dampening mechanism by the distal joints. For example, on an individual level, an increase in joint extension velocities could suppress the next distal joint with additional inertia (Bobbert and van Soest, 2001). The Achilles tendon, in particular, could be absorbing and dissipating force (Kurokawa et al, 2003; Malvankar and Khan, 2011). With system complexity across three joints, and a vast array of soft tisssue structures, this could be the case throughout the kinematic chain, in which a simplistic model may not be fit for purpose.

Secondly, as mentioned previously, the summation of speed principle (Bunn, 1972) relates to magnitude and timing of joint extensions.This chapter focused on increasing joint extension magnitudes, but not dictating timing beyond a proximo-distal sequence. Previous theoretical models have proposed the accumulative nature of correct timing, in that the distal segment should begin extension at the point of the proximal joints peak extension for the most effective velocity transfer (Putnam, 1993; Wagner et al., 2012). No such research, to the authors knowledge, has evaluated this timing in a whole lower limb, propulsive activity. Therefore, it is difficult to ascertain as to what “optimal” extension timings are, beyond a sequential pattern. Therefore future research should seek to understand the threshold between a simultanous joint extension “push” pattern, and a proximo-distal sequence that would utilise additional joint velocities fully.

As there were no changes in external kinetics, there were no changes in performance parameters for CoM velocities, or pointer velocities. This provides evidence for rejection of ***H_9*: Increasing the rear leg kinematic chain accumulative velocities, will lead to increased peak horizontal pointer sword velocity as a task performance measure.***

4.5. Conclusion

This chaper has assessed a KP BFb intervention focused on manipulating whole limb kinematics of the rear leg kinematic chain during a simplified propulsion lunge task. Using content identified in the fencing attacking lunge Chapter 3, it was shown that the information on peak hip, knee and ankle extension angular velocities and proximal to distal sequencing was able to faciliate changes in a complex skill. Specifically, hip, knee and ankle angular extension velocites, normalised as percentages, showed siginificant increases which were retained at 4-6 weeks. Surprisingly, the altering kinematics did not elicit any changes in the external kinetics. Supporting this link, 4416 trials were used to reject the correlational findings in Chapter 3 between rear leg kinematics and external ground reaction forces, providing strong evidence for no links between the two changes.

While findings in this chapter highlight that BFb during a complex task can develop whole limb kinematics, it is clear that these changes can be specific and that secondary influences cannot be assumed. The lack of kinetic changes could be due to segmental dynamics, which require further investigation. Further, limited information exists as to explain how BFb specifically guides explorative processes.

CHAPTER 5: LONGITUDINAL ANALYSIS OF WHOLE LIMB COMPLEX SKILL CHANGES USING A REDUCING VISUAL KNOWLEDGE OF PERFORMANCE BIOFEEDBACK SCHEDULE

5.1. Introduction

Short term BFb interventions applied to improve sporting performance (Broker et al., 1993; Eriksson et al., 2011), reduce injury risk (Crowell et al., 2010; Ford et al., 2015; Creaby and Smith, 2016) and in clinical rehabilitation (van den Heuvel et al, 2016) have shown changes to occur within just a few visits, but there is limited information on how influential or permanent these changes are. Long and high frequency interventions are, however, time and resource intensive. From a theoretical perspective, the guidance hypothesis considers that while BFb is beneficial to direct motor learning, too much BFb can lead to dependency and prevent autonomous exploration processes (Salmoni et al., 1984; Sadowski et al., 2013). This dependency may encourage learners to bypass other important sources of feedback information needed to develop intrinsic error detection and correction mechanisms (Park et al., 2000). To reduce any dependency, BFb frequency over time can be reduced (e.g. Richards et al., 2018b) and time between visits can be increased throughout a longitudinal intervention design. BFb dependency is typically evidenced with a drop-off in retention once BFb is removed (Maslovat et al., 2009), and is considered to be skill specific (Sigrist et al., 2013; Wulf and Shea, 2002). No methods have currently been used, however, to directly assess changes in skill adaptation during the intervention period. Many BFb research designs do not have theoretical support for the time frames selected, with limited research underpinning the appropriate number of visits for feedback scheduling for complex skills, or indeed a method to identify when changes occur within a programme of BFb. Schedule selection is often driven by applied practice or replicating previous designs which have been shown to be effective. Few studies seek to identify at what point feedback has had the desired effect in altering technique, only that it is successful.

Coordination paradigms assessing joint couplings provide insight into system organization. This is particularly useful in assessing the emergence of skill which can be difficult to quantify using traditional single joint analysis (Hamill et al., 1999). Much of the research underpinning how individuals interact with feedback originates from simple tasks with limited degrees of freedom, thus limited complexity. Complex skills involve the interaction of multiple segments, joints and musculature as occurs in many sporting movements. Newell (1985) proposed three stages of motor learning related to changes in coordination; the emergence of coordination, control of the motor system, and finally the emergence of skill where the performer is able to use and manipulate environmental constraints. These are not dissimilar to Bernstein's (1967) original notions of freezing the multiple degrees of freedom (DoF) in the initial stages of learning and then freeing as the skill is learnt, prior to an exploitation of the reactive phenomena within the task and environment. In principle, the analysis of coordination profiling alone would provide insight into the stages of motor learning. Joint coupling analysis is proven to separate contrasting or specific populations, such as sex and expressed anterior knee pain

(Rodrigues et al., 2015) and noticeably different phases of movement (Vidal et al., 2018). However, current coordination methodologies are not always successful in distinguishing between generic injury populations (Ferber et al., 2005) or between skill levels where subtle differences exist (Williams et al., 2016). Therefore, in a propulsive skill, comparing coordination changes in a non-specific athletic population may yield inconclusive results. Research related to the kinematic chain highlights the effectiveness of the proximal to distal sequencing (Jacobs et al., 1996; Bobbert and van Soest, 2001). The increased peak extension velocity of both the hip and knee during the lunge task in Chapter 4 would suggest greater in-phase coupling with segments working together. Conversely, the lack of change in external kinetics could be related to greater anti-phase coupling with the additional knee extension, suppressing ankle plantarflexion (Hopper, 1973). To address this, this chapter sought to assess research question **RQ6. Does the provision of whole limb terminal KP BFb influence joint coupling coordination during a complex skill?**

Intra-participant variability of coordination patterns ($\mathrm{Coord}_{\mathrm{Var}}$) may be a useful tool to identify differences where coordination is not sensitive enough (Hamill et al., 1999; Rodrigues et al., 2015). Traditionally viewed as inherent noise within the motor system, a concurrent perspective highlights the functional role of movement variability in skill exploration and maintaining a consistent performance outcome (Mullineaux and Ulh, 2010). This closely aligns with theoretical underpinning that BFb can enhance the development of motor skills by guiding skill exploration processes (Lauber et al., 2013).

The notions of freezing and freeing $\text{Coord}_{\text{Var}}$ also underpins stages of learning by (Bernstein, 1967; Newell, 1985). However, of importance in concurrent variability paradigms is that $\text{Coord}_{\text{Var}}$ is a functional component to enhance consistent performance (Hamill et al., 2012; Preatoni et al., 2013), often depicted as low performance variability (Perf_{Var}). Indeed, research has shown how skill learning can manifest in more proximal joints, with distal joints allowing for system flexibility to achieve a more consistent outcome (Robins et al., 2006). Hamill et al. (2012) identify that both $\text{Coord}_{\text{Var}}$ and Perf_{Var} need to be integrated in any functional analysis. Therefore, both variability components together could prove to be an effective approach to assess the effectiveness of BFb to facilitate motor learning.

$\text{Coord}_{\text{Var}}$ has been shown to be an effective analysis method to differentiate between populations where conventional biomechanical approaches lack sensitivity (e.g. patellofemoral pain syndrome; Hamill et al., 1999). Similarly, this approach has been adopted in complex skills and successfully identified differences between closely aligned skill levels such as elite and sub-elite athletes in triple jump (Wilson et al., 2008), swimming (Seifert et al., 2010; Seifert et al., 2011), and race-walking (Cazzola et al., 2016). $\text{Coord}_{\text{Var}}$ has also been used to identify changes in movement patterns throughout complex skill development within individuals (Williams et al., 2016). However, conflicting methodologies used to quantify this $\text{Coord}_{\text{Var}}$ can influence the interpretation of findings (Silvernail et al., 2018). Identifying small intra-individual

Coord$_{\text{Var}}$ differences using vector coding can prove difficult where point-point vectors have similar orientations, such as in the propulsive phase of a skill (as shown in chapter 2). Similarly, recent research has identified vector coding can produce erroneous statistical artefacts (Mullineaux and Uhl, 2010) related to short vectors (Stock et al., 2018). Therefore, the adaptation of a coordination technique that also encapsulates the space encompassed by the time series may be more effective (Mullineaux, 2017). This chapter sought to modify a bi-variate 95% confidence intervals approach to also calculate the area for angular velocity phase plots, thus providing a discrete value for Coord$_{\text{Var}}$. This method may prove to be particularly useful for longitudinal analysis, and to assess the explorative capacity facilitated by augmented BFb. Additionally, individuals demonstrate different motor learning rates (Chow et al., 2008), thus identifying individual BFb progress is of great importance. Analysis of Coord$_{\text{Var}}$, therefore, could be used to identify stages of learning during BFb interventions for each individual which would prove to be beneficial for practitioners. The final research question addressed was **RQ7. Does KP BFb facilitate an increase in joint coordination variability?**

To summarise, the aims of this chapter were to determine; 1) if a longitudinally reducing BFb schedule can negate effects of the BFb dependence; 2) how early changes in the sequential kinematic chain occur in attending to BFb; 3) if there are alterations in the rear leg joint coupling coordination instigated with BFb, and; 4) if the provision of BFb encourages the exploration of skill. The following hypotheses were developed to address the research questions within this chapter:

- H_{10}: *A longitudinally reducing biofeedback schedule will facilitate the retention of kinematic changes over a 26-week period.*

- H_{11}: *Changes to the rear leg peak joint angular velocities will increase in the first two sessions of the BFb intervention for all three rear leg joints.*

- H_{12}: *The BFb group will show an increase of in-phase joint coupling for the hip-knee angular velocity modified vector coding joint couplings with the BFb.*

- H_{13}: *The BFb group will show an increase of antiphase-phase joint coupling for the knee-ankle angular velocity modified vector coding joint couplings with the BFb.*

- H_{14}: *The BFb group will have an increased joint coupling variability within the Hip-Knee and Knee-Ankle when attending to the BFb compared to Control.*

- H_{15}: *Performance variability will not change in either BFb or Control groups.*

- H_{16}: *Individual joint coupling variability can be used to identify individuals in a state of exploration while attending to BFb.*

5.2. Methods

Chapter 4 detailed the participants and data collection of the kinematic and kinetic data also used in this chapter (section 4.3). The same 32 participants gave informed consent to take part in the additional longitudinal element in this chapter as part of the original BFb intervention. One of the BFb group was not included in the longitudinal data analysis due to a missing block of data. The data collection protocol was the same as detailed in chapter 4, which will be briefly summarised in the subsequent sections, but with additional detail where relevant.

5.2.1. Participants

The 32 participants from the previous chapter, with the same institutional ethical approval and written informed consent, were kept in two equal groups of BFb and Control. They returned for an additional two visits following the retention visit at weeks 4-6. All 32 participants were used for the group level analysis. For the individual variability analysis, one participant from each group was removed due to missing number of trials for one of the BFb participants interfering with the CI2 (Mullineaux, 2017) calculation thus interfering with regression analysis. One of the Control group participants was randomly omitted from the presented table in the results section for data visualization simplicity.

5.2.2. Procedure

Following the intervention as detailed in the previous chapter (chapter 4), participants returned for a further two visits, with the total intervention undertaken over a 26-week period. After the one-week intervention, with three visits spaced 24-48 hours apart, participants returned at the 4-6-week mark for the Retention$_{Wk4}$ block as detailed earlier. Following this block with no BFb, participants were provided with BFb for three additional blocks, as per the intervention week. This visit, totalling four blocks, was then repeated at 13 weeks, and then concluded with a final visit for a single retention block at 26 weeks. In total, participants visited the laboratory on six occasions over a six-month period structured as a faded schedule with increasing duration between each visit (e.g. 24 hours up to 12 weeks between S5 and S6). The control group matched all lunges without feedback. Each block was labelled sequential from 1-23 (block 3 being the last block of self-learning and 23 being the final retention block) for analysis. Figure 5.1 provides schematic detail of the longitudinal reduced BFb schedule design.

Figure 5.1. Schematic representation of the longitudinal data collection protocol. Each square represents one block of six lunges. SL = self-learning, where no BFb was provided; BFb = 100% BFb (or no BFb for controls) and R = retention block.

5.2.3. Data Capture and Analysis

Kinematic data were collected using the same motion capture and integrated two forceplate setup as detailed in chapter 4. The rear leg was again the focus of the analysis, with the same marker-set as the main intervention. For all variables, block means were calculated for each participant, along with standard deviations, allowing for individual analysis over time. Block means were then grouped into BFb or Control, providing group means for each block along with standard deviations for group analysis. For the longitudinal analysis, block means for the hip, knee and ankle were expressed as percentages relative to block three ($\text{Pre}_{\text{Int}} = 0\%$).

5.2.3.1. Identification of Kinematic Changes

Retention time points were assessed for changes across kinematic variables at $\text{Retention}_{\text{Wk4-6,}}$ $\text{Retention}_{\text{Wk13}}$ and $\text{Retention}_{\text{Wk26}}$ and between groups to assess for learning between groups. A piecewise linear regression method was used to determine the session in which a change in learning, or breakpoints (S_{BP}), occurred for the three rear lower limb joint percentage differences over each respective longitudinal time series. For this specific analysis retention points were removed to avoid any characteristic drop in retention performance interfering with the linear regression fit. This S_{BP} identified the session during which the increase in joint extension angular velocity ceased. The below equation (Eq. 5.1) shows how this was calculated where the sum of squares (SS) is determined by identifying the best fit between two segments of data using two linear regressions per assessment. This equation iteratively applies a linear regression from the start of the data set (Pre_{Int}) to S_{BP}, and then simultaneously from the final retention block (Ret_{23}) back to S_{BP}. Therefore the data is separated into two segment components (1:r and the reverse of r:n). By minimizing the sum of squares of the differences between the data segments and the linear regressions a best fit is found for both linear regressions.

$$S_{BP} = S\{\min[SS_{s=1:r} + SS_{s=r:n}]\} \qquad for\ r\ =\ 2, \ldots, n - 1 \qquad \textbf{Eq. 5.1}$$

The intersect of these two regression lines is the breakpoint, thereby allowing for identification of where independent and dependent variable relationships change. This process allows for the identification of where improvements in skill plateaued when attending to the BFb over a longitudinal period.

5.2.3.2. Joint Coordination

Coordination patterns were calculated throughout the push off phase, with 0-100% of joint kinematics corresponding to the period of $F_{PushOff}$, defined from the onset of force (F_O) to take off (F_{TO}) as identified in the previous chapter. Coordination was quantified using a modified vector coding technique (Chang et al, 2008; Needham et al., 2014), which allows for quantification of coordination patterns into frequency bins. First the projected 3D joint bi-variate angular velocity plots were created for the rear leg hip-knee and knee-ankle joint couplings. Then the coupling angle, which describes the relative motion between the segments, was quantified by calculating the angle created by the vector joining two successive time points and the right horizontal for each angle-angle plot. Equation 5.2 below shows this process, where $0° \leq Y \leq 360°$ is the coupling angle bound from 0° to 360° and *i* is each data point as a percentage of $F_{PushOff}$ for the *j*th trial. Since these angles are directional in nature, circular statistics were used to calculate mean coupling angles (*Ŷ)* for each block of 6 lunges.

$$\gamma_{j,i} = \tan^{-1}\left(\frac{y_{j,i+1} - y_{j,i}}{x_{j,i+1} - x_{j,i}}\right) \qquad \textbf{Eq. 5.2}$$

The coupling angle can then be used to identify instantaneous spatial relationships between joints, classified with four unique coordination patterns (Chang et al., 2008; Needham et al., 2014). These correspond to: 1) anti-phase, 2) in-phase, 3) proximal joint phase, 4) distal joint phase. These four patterns can be identified using the bi-variate angular velocity plot orientations, corresponding to the vertical, horizontal and 45° diagonals. For example, when coupling angles are 45° and 225° (a positive diagonal) the coordination is *in-phase* meaning that in that instant both joints are moving in the same direction (i.e. simultaneous extension). Conversely, at 135° and 315° (a negative diagonal) the coordination is *antiphase* meaning that both joints are moving in opposite directions (e.g. knee extension with ankle dorsiflexion). When coupling angles are parallel to the horizontal axis (*Y = 0*° or 180°) then there is movement of the proximal joint, but no movement in the distal joint, therefore a *proximal joint phase*. Therefore, when coupling angles are parallel to the vertical (*Y = 90*° or 270°) the proximal joint is locked while the distal joint moves exclusively, thus it is a *distal joint phase*. When a coupling angle deviates from the vertical, horizontal or diagonal vectors the movement patterns are less pure to the above definitions. However, the mean coupling angles can be categorized into 45° frequency bins as per table 5.1, where the dominant movement pattern can be identified during the propulsive movement.

5.2.3.3. Coordination Variability

Hip, knee, and ankle joint velocity time series data were used to assess $\text{Coord}_{\text{Var}}$. Angular velocities were selected for analysis as the primary variable targeted by the BFb. Due to two missing blocks of data, one BFb participant was removed from the $\text{Coord}_{\text{Var}}$ analysis. Hip-knee and knee-ankle joint couplings $\text{Coord}_{\text{Var}}$ were quantified using a modification of a bivariate analysis method (CI2, Mullineaux, 2017) to extract the CI2 area (CI2_{Area}). The first three stages of CI2 were from code provided by Mullineaux (2017) to: 1) calculate 95%CI ellipses around the cluster of joint coupling angular velocity data points for each frame; 2) join the centres of consecutive ellipses to define the direction vector, and; 3) create convex quadrilaterals to provide 95%CI borders along the entire time series (figure 5.2). CI2_{Area} extracts the area encompassed by these quadrilaterals throughout Push_{Off} calculated using the Matlab function 'polyarea'. A larger CI2_{Area} demonstrates a greater exploration of the joint angular velocity coupling.

Table 5.1. Coordination categories for modified vector coding (Adapted from Chang et al., 2008).

Coordination Pattern	Coupling Angle Definitions
Anti-phase	$112.5^\circ \leq Y < 157.5^\circ$, $292.5^\circ \leq Y < 337.5^\circ$
In-phase	$22.5^\circ \leq Y < 67.5^\circ$, $202.5^\circ \leq Y < 247.5^\circ$
Proximal joint phase	$0^\circ \leq Y < 22.5^\circ$, $157.5^\circ \leq Y \leq 202.5^\circ$, $337.5^\circ \leq Y < 360^\circ$
Distal joint phase	$67.5^\circ \leq Y < 112.5^\circ$, $247.5^\circ \leq Y < 292.5^\circ$

The $CI2_{Area}$ was calculated for each block during the propulsive phase of movement, determined as the onset of force (t_{FO}) and take off (t_{TO}) as described in the previous chapter. $CI2_{Area}$ provided a discrete value for each block, for each participant, for the entire 26-week intervention as a measure of $Coord_{Var}$. To determine change in $Coord_{Var}$ across the 26 weeks, a simple linear regression was fitted to the group mean $CI2_{Area}$ for both coordination couplings thus providing a gradient to quantify changes in variability over time ($CV_{Gradient}$). Group 95% confidence intervals of the Control $CV_{Gradient}$ were also calculated ($95\%CI_{Slope}$) to provide comparative data for individual analysis. Simple linear regressions were then used at an individual level to determine if BFb had led to an increase in joint coupling variability by assessing if the individual regression slopes were greater than the $95\%CI_{Slope}$ upper bound. Performance variability ($Perf_{Var}$) was quantified using the coefficient of variability of the CoM_{Vel}, as calculated in Chapter 4, at both the individual and group level. Linear regressions were also applied to these data to provide an indication of change over time ($PV_{Gradient}$) also compared to Control group $95\%CI_{Slope}$ upper bound to test for group changes.

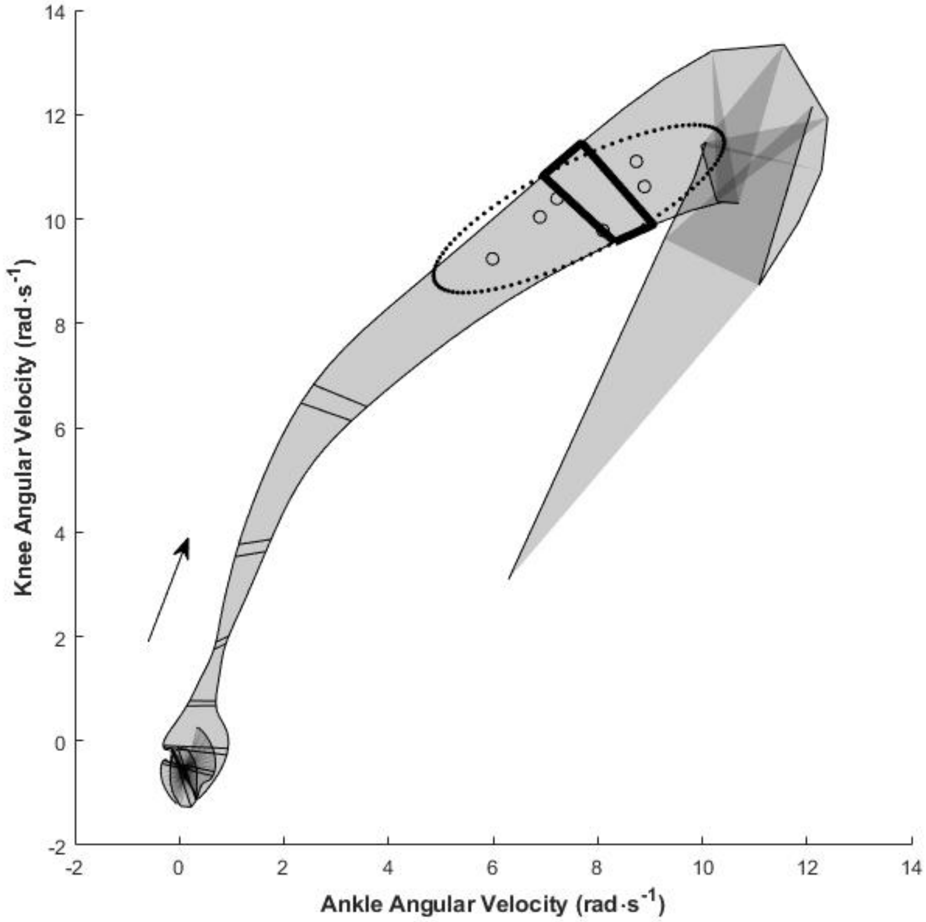


Figure 5.2. Example of CI2$_{Area}$ applied to the knee-ankle angular velocity joint coupling. The quadrilateral at every 10% time points are illustrated for 6 trials, with the ellipse at 80% included for visual purposes. The 95% confidence ellipses encompass the data points throughout the data series, with the ellipse centres joined to create the direction vector. The points of the ellipse border perpendicular to the direction vector for two consecutive ellipses are then used to create quadrilaterals for the whole time series, with the area of the quadrilaterals being CI2$_{Area}$.

5.2.4. Statistical Analysis

Normality was assessed using a Shapiro-Wilk test. Interaction effects were investigated across variables using a 2 x 3 mixed model ANOVA (Group x Retention blocks). Non-normally distributed data were still tested using the mixed model ANOVA where interaction effects were assessed due to robustness of the ANOVA model, and a lack of appropriate non-parametric equivalent. Significant interaction effects were then investigated further using a post-hoc Wilcoxon signed rank for non-normal distributions. $Post_{Int}$ to $Retention_{4\text{-}6Wk}$ percentage differences were assessed using a Wilcoxon signed rank to assess for a retention drop off in this variable. Statistical analysis was completed in SPSS (v.22, IBM, Armonk, NY) with an alpha level of 0.05. Data were presented as means ± SDs.

5.3. Results

5.3.1. Longitudinal Kinematic Retention

Participants show no interaction effects in any of the kinematic measures at $Retention_{4\text{-}6Wk}$, $Retention_{13Wk}$ and $Retention_{26Wk}$ (table 5.2). The group block mean time series percentage change data (figure 5.3) shows that the BFb group, relative to Pre_{Int} (block 3; 0%), significantly increased $Post_{Int}$ (block 14) hip (40.0%), knee (24.8%) and ankle (28.9%), angular velocities following the BFb intervention. Over the same period, the control group showed no significant changes in any joint angular velocities. After a period of 4-6 weeks, these changes were retained across all rear leg joints as exemplified by no significant differences between $Retention_{Wk4\text{-}6}$ (block 15) and the previous block ($Post_{Int}$) as identified above. The BFb group were able to retain the kinematic changes induced by the BFb conditions throughout the 26-week intervention with no decrease in kinematic percentage differences. The breakpoint was identified in the second session for all three joints in the BFb group (block 9, 8 and 8 for hip, knee and ankle joints respectively). The Control group, in contrast, did not show any change over time.

Table 5.2. Rear leg kinematic variables for BFb and Control groups (mean ± SD) for the 4-6 week, 13 week and 26 week retention time points (Retention$_{4\text{-}6\text{Wk}}$, Retention$_{13\text{Wk}}$ and Retention$_{26\text{Wk}}$, respectively) Temporal sequencing is presented as percentage of push off phase (0% = F$_{O}$, 100% = F$_{TO}$). There were no significant interaction effects between group and retention time points.

BFb (n=16) Joint Kinematics	Retention$_{4\text{-}6\text{Wk}}$	Retention$_{13\text{Wk}}$	Retention$_{26\text{Wk}}$
Peak Hip$_{\theta}$ (°)	91 ± 7	93 ± 8	92 ± 12
Peak Knee$_{\theta}$ (°)	171 ± 5	172 ± 3	171 ± 5
Peak Ankle$_{\theta}$ (°)	153 ± 6	153 ± 5	152 ± 6
Hip RoM (°)	40 ± 7	42 ± 10	42 ± 13
Knee RoM (°)	77 ± 13	78 ± 15	79 ± 18
Ankle RoM (°)	51 ± 7	52 ± 9	52 ± 8
Peak Hip$_{\omega}$ (rad·s^{-1})	3.34 ± 0.97	3.54 ± 1.08	3.50 ± 1.18
Peak Knee$_{\omega}$ (rad·s^{-1})	10.69 ± 2.15	10.62 ± 2.03	10.83 ± 2.28
Peak Ankle$_{\omega}$ (rad·s^{-1})	9.40 ± 1.53	10.48 ± 3.94	9.81 ± 1.94
Peak Hip$_{\omega}$ time (%)	77 ± 10	80 ± 13	76 ± 11
Peak Knee$_{\omega}$ time (%)	79 ± 9	81 ± 11	76 ± 11
Peak Ankle$_{\omega}$ time (%)	80 ± 9	82 ± 11	78 ± 11

Control (n=16) Joint Kinematics	Retention$_{4\text{-}6\text{Wk}}$	Retention$_{13\text{wk}}$	Retention$_{26\text{Wk}}$
Peak Hip$_{\theta}$ (°)	91 ± 9	93 ± 11	92 ± 14
Peak Knee$_{\theta}$ (°)	171 ± 5	172 ± 4	171 ± 4
Peak Ankle$_{\theta}$ (°)	147 ± 14	147 ± 11	147 ± 15
Hip RoM (°)	36 ± 8	36 ± 10	36 ± 7
Knee RoM (°)	75 ± 13	77 ± 16	77 ± 12
Ankle RoM (°)	51 ± 8	52 ± 6	52 ± 8
Peak Hip$_{\omega}$ (rad·s^{-1})	2.56 ± 0.81	2.41 ± 0.81	2.61 ± 0.71
Peak Knee$_{\omega}$ (rad·s^{-1})	8.92 ± 1.44	9.42 ± 1.71	9.56 ± 1.33
Peak Ankle$_{\omega}$ (rad·s^{-1})	8.16 ± 1.83	8.95 ± 1.75	8.96 ± 1.50
Peak Hip$_{\omega}$ time (%)	72 ± 15	70 ± 14	69 ± 19
Peak Knee$_{\omega}$ time (%)	80 ± 14	78 ± 11	77 ± 14
Peak Ankle$_{\omega}$ time (%)	83 ± 14	79 ± 11	78 ± 15

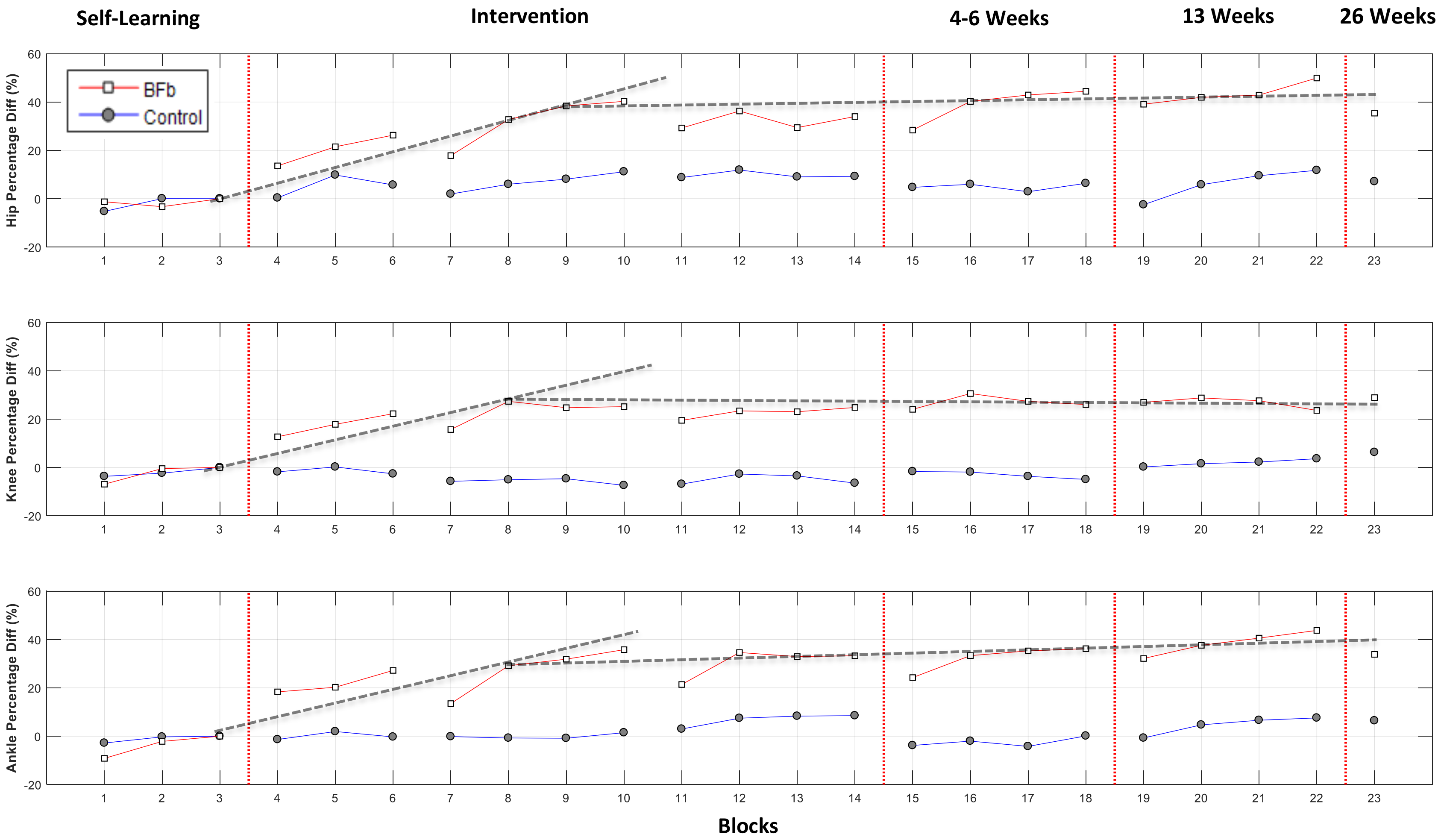


Figure 5.3. Mean percentage change of joint angular velocities from 0% in block 3 for participants performing a lunge task. Each shape represents one block. The red dotted vertical lines separate between sessions (Self learning, Intervention, 4-6 Weeks, 13 Weeks and 26 Weeks). Black dashed lines represent least square product regressions that depicted breakpoint in percentage change as detailed in methods. No breakpoint was observed for the control group, so this was omitted.

5.3.2. Coordination Coupling Changes

There were no obvious changes in the joint angle-angle coupling kinematic plots for the BFb group in both the hip-knee and knee-ankle angle-angle coupling plots (figure 5.4). The BFb group seemingly decreased initial knee angle at force onset for the final retention block (120° to 112°). The ankle in the BFb knee-ankle plot shows greater plantarflexion following at $\text{Retention}_{\text{Wk26}}$. Interestingly, the Control group showed a decrease in the hip-knee coupling plot along the hip axis, showing a slightly reduced hip range of motion from visual inspection at $\text{Retention}_{\text{Wk26}}$. There were no changes in the Control group knee-ankle coupling plot.

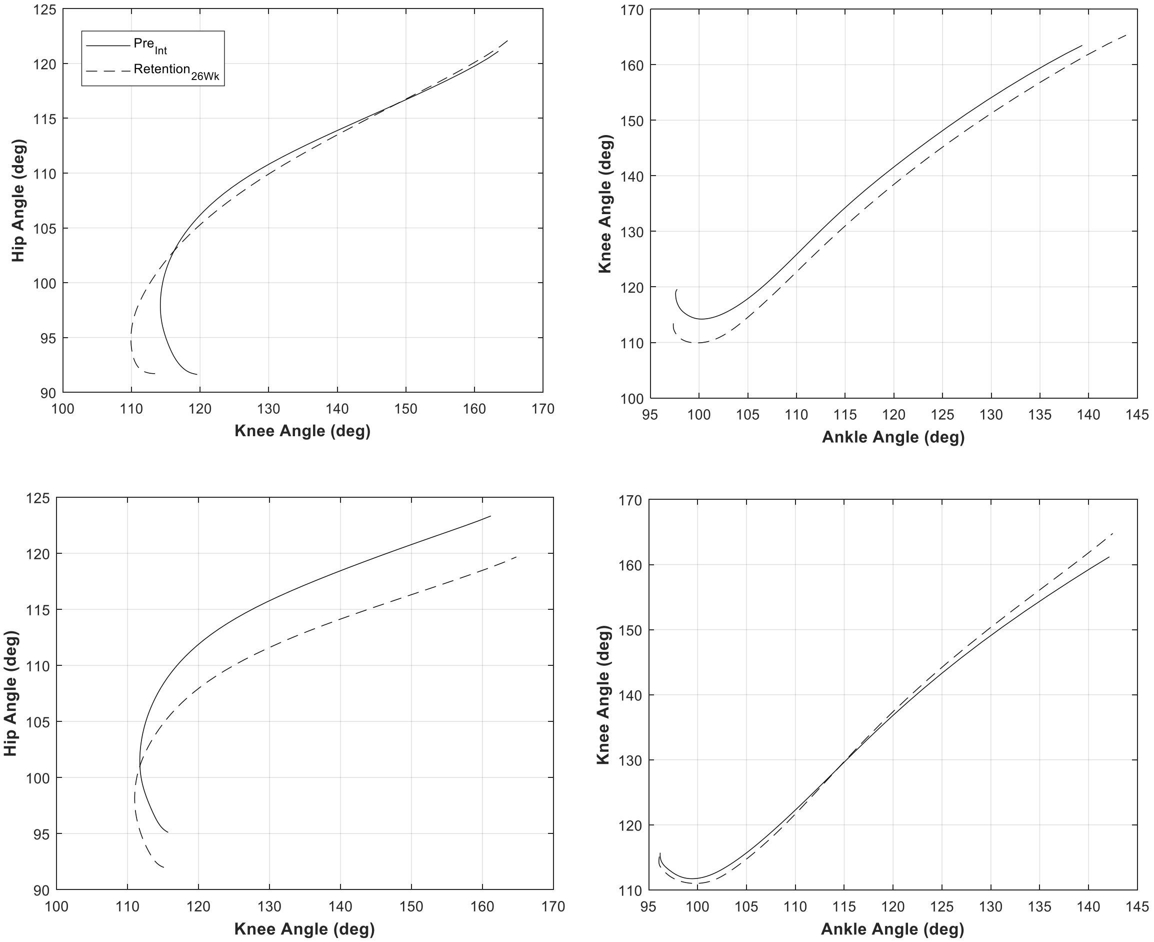


Figure 5.4. Mean angle-angle plots for hip-knee (left) and knee-ankle (right) joint couplings for BFb (top) and Control (bottom) groups at Pre_{Int} and $\text{Retention}_{\text{26Wk}}$ performing a lunge task.

There were clear differences between angular velocity plots in both the hip-knee angular and knee-ankle velocity coupling. Both BFb hip-knee patterns show a shift toward greater hip-knee angular velocity magnitudes but a slight shift toward simultaneous extension from Pre_{Int} to $\text{Retention}_{\text{26Wk}}$. The knee-ankle coupling shows larger magnitudes in both axes for the BFb group. The Control group show an interesting hip-knee angular velocity pattern which differs to the BFb at both time-points, but more importantly has not altered throughout the 6-month intervention. The Control group knee-ankle angular velocity plot shows moderate increases in the knee axis with no real changes in coordination.

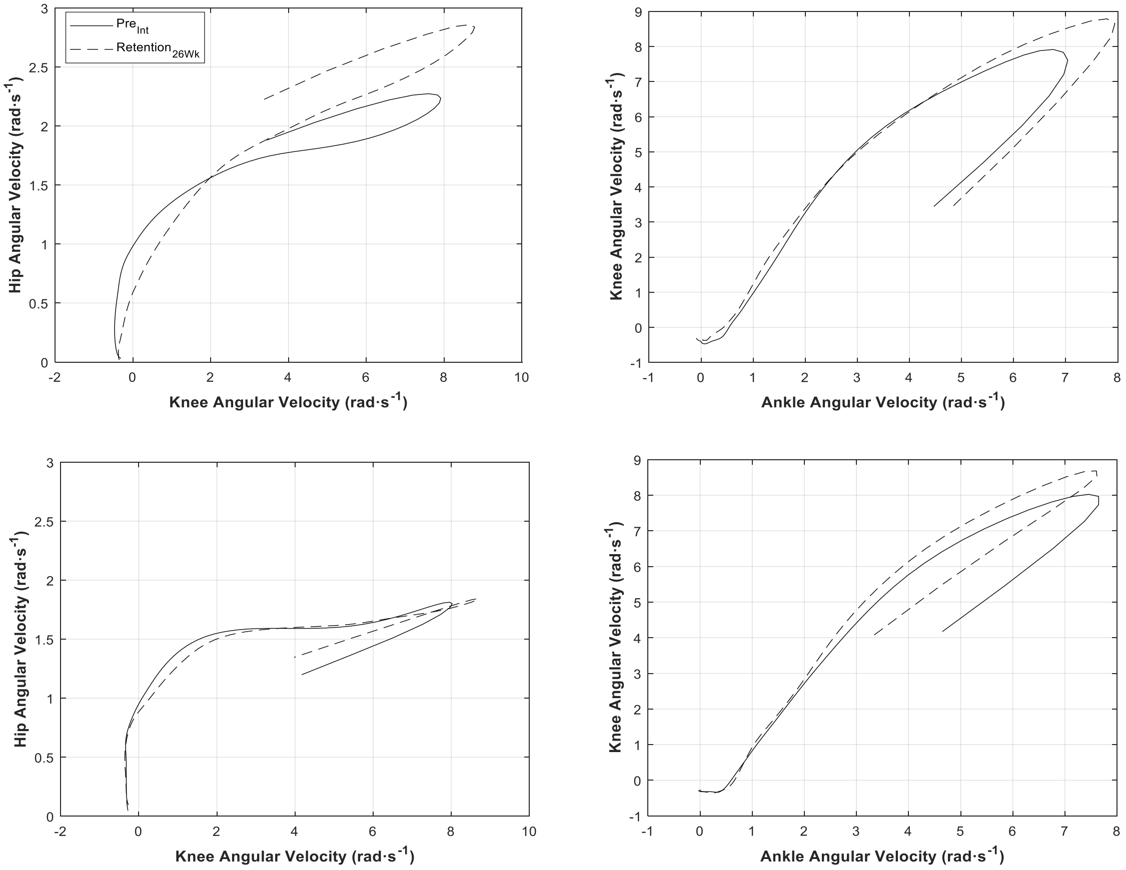


Figure 5.5. Mean angular velocity-angular velocity plots for hip-knee (left) and knee-ankle (right) joint couplings for BFb (top) and Control (bottom) groups at Pre_{Int} and $\text{Retention}_{\text{26Wk}}$. during a lunge task.

There was no significant interaction effect between group and time in the hip-knee in-phase coordination coupling (*F* (3, 87) = 0.610, *p* = 0.61). As a general trend the BFb group had larger in-phase coupling throughout all time points with a between group interaction (*F* (1, 29) = 7.150, *p* = 0.01). Post-hoc analysis revealed that at Pre_{Int} there were no significant differences between groups (*p* = 0.17), but there were significant differences at $\text{Retention}_{\text{4-6Wk}}$ (*p* = 0.02), and $\text{Retention}_{\text{Wk13}}$ (*p* = 0.02) with the Control group mean decreasing. $\text{Retention}_{\text{26Wk}}$ showed no significant differences between groups (*p* = 0.16) with a slight decrease in BFb mean in-phase and increase in the Control group in-phase. There were no significant interaction effects shown for anti-phase (*F* (3, 87) = 1.266, *p* = 0.29), although as a trend the Control group increased this throughout the intervention with a classic interaction decrease over time in the BFb group. Specifically, the BFb group decreased anti-phase coupling following the intervention at $\text{Retention}_{\text{Wk4-6}}$ and also $\text{Retention}_{\text{Wk26}}$ but a singular increase at $\text{Retention}_{\text{Wk13}}$ likely influenced the interaction significance. The BFb group show an increase in hip dominance throughout the intervention relative to the Control group, however this was not significant (*F* (3, 87) = 2.070, *p* = 0.11). Both groups decreased knee dominance with no significant interaction identified (*F* (3, 87) = 0.645, *p* = 0.59), although, again the BFb group mean shows a crossover increasing between $\text{Retention}_{\text{13Wk}}$ and $\text{Retention}_{\text{26Wk}}$ while the Control decreased.

Table 5.3. Coordination frequency bins calculated from modified vector coding for hip-knee angular velocity coupling. Each group of frequency bins is the group block mean (± SD). Data is a % of propulsion phase. *Signifies a significant main effect between groups across all time points included.

Hip-Knee	Pre$_{\text{Int}}$		Retention$_{\text{4-6Wk}}$		Retention$_{\text{13Wk}}$		Retention$_{\text{26Wk}}$	
	Control	**BFb**	**Control**	**BFb**	**Control**	**BFb**	**Control**	**BFb**
In-phase*	34 ± 10	40 +13	29 ± 14	40 ±10	30 ± 10	40 ± 10	32 ± 14	38 ± 10
Antiphase	16 ± 8	17 + 8	17 ± 9	12 ± 7	17 ± 12	15 ± 10	19 ± 12	12 ± 8
Hip	22 ± 8	19 + 12	24 ± 10	27 ± 12	23 ± 8	27 ± 13	22 ± 9	29 ± 10
Knee	17 ± 8	16 + 10	16 ± 10	14 ± 10	14 ± 9	12 ± 7	11 ± 7	13 ± 9

Table 5.4. Coordination frequency bins calculated from modified vector coding knee-ankle angular velocity coupling. Each group of frequency bins is the group block mean (± SD). Data is a % of propulsion phase. *Signifies a significant main effect between groups across all time points.

Knee-Ankle	Pre$_{\text{Int}}$		Retention$_{\text{4-6Wk}}$		Retention$_{\text{13Wk}}$		Retention$_{\text{26Wk}}$	
	Control	**BFb**	**Control**	**BFb**	**Control**	**BFb**	**Control**	**BFb**
In-phase	9 ± 6	9 ± 5	11 ± 7	8 ± 5	8 ± 5	9 ± 5	10 ± 9	9 ± 4
Antiphase*	21 ± 9	32 ± 14	21 ± 8	28 ± 8	22 ± 11	28 ± 9	25 ± 15	27 ± 14
Knee	45 ± 12	38 ± 13	47 ± 13	44 ± 9.2	48 ± 9	42 ± 11	46 ± 13	45 ± 12
Ankle	16 ± 11	12 ± 8	14 ± 8	14 ± 9	14 ± 7	14 ± 8	11 ± 7	14 ± 10

There was also no significant interaction effect between groups and time in the knee-ankle in-phase coordination coupling (*F* (3, 87 = 1.307, *p* = 0.28). The BFb group showed a trend of greater anti-phase knee-ankle coupling at all time-points (*F* (1, 29) = 4.420, *p* = 0.04), with this decreasing throughout the intervention in the BFb group over time. The Control group, in contrast, show an increasing trend of anti-phase knee-ankle coupling throughout. Post-hoc analysis revealed that this was significantly larger than the BFb group at Pre$_{\text{Int}}$ (*p* = 0.01) and Retention$_{\text{Wk4-6}}$ (*p* = 0.03), but then no difference at Retention$_{\text{Wk13}}$ (*p* = 0.15) and Retention$_{\text{Wk26}}$ (*p* = 0.67). The Control group showed an increase in in-phase coupling from Pre$_{\text{Int}}$ and Retention$_{\text{Wk4-6}}$ which was also prominent at Retention$_{\text{Wk26,}}$ however there were no significant interaction effects shown (*F* (3, 87) = 0.951, *p* = 0.42). There was also no significant interaction shown between groups for knee dominance (*F* (1, 29) = 0.315, *p* = 0.58). Generally, the BFb group showed lower knee dominance throughout relative to the Control group apart from at Retention$_{\text{13Wk}}$, but this was not statistically significant between groups (*p* = 0.17). Ankle dominance showed a classic interaction with BFb increasing and the Control group decreasing over time, however this was also not significant (*F* (3, 87) = 1.292, *p* = 0.28).

Large standard deviations relative to each group mean show that there were large individual variations to coordination patterning in both groups. This was demonstrated in the hip-knee coordination patterns as well as the knee-ankle coupling.

5.3.3. Group Joint Coupling Variability

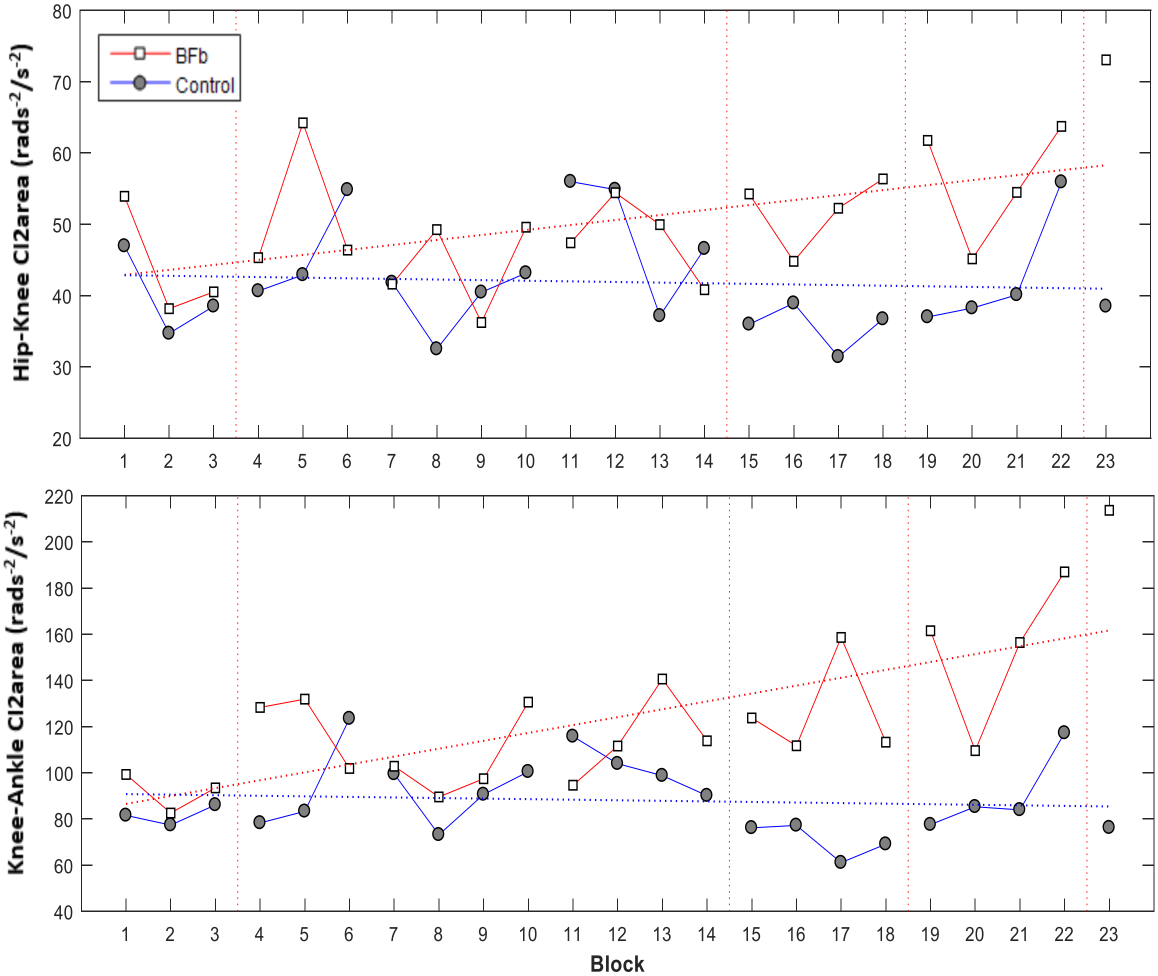


Figure 5.6. Hip-knee (top) and knee-ankle (bottom) coupling CI2 area variability profiles for BFb and Control groups over 23 blocks, spanning 26 weeks. The vertical red dotted lines separate between sessions (Self learning, Intervention, 4-6 weeks, 13 weeks and 26 weeks). Dashed lines are simple linear regressions fitted to each group.

As a group the BFb group showed a continual increase in $CI2_{Area}$ over time in both the hip-knee (BFb $CV_{Gradient}$ = 0.7 versus -0.9 Control), and knee-ankle joint coupling variability (BFb $CV_{Gradient}$ = 3.14 versus -0.24 Control), relative to the Control group (figure 5.6). The increase in variability did not plateau over time from visual inspection. $CV_{Gradient}$ was larger in the more distal joint coupling of the knee-ankle relative to the hip-knee.

Group $\mathrm{Perf}_{\mathrm{Var}}$, as a measure of task performance variability, was unchanged over the 6-months in both groups (BFb $\mathrm{PV}_{\mathrm{Gradient}}$ = BFb -0.01 versus Control 0.00).

5.3.4. Individual Joint Coupling Variability

On an individual level, 7 out of 15 BFb participants showed greater increases in hip-knee coupling variability throughout the reduced schedule biofeedback intervention relative to the control group ($95\%\mathrm{CI}_{\mathrm{Slope}}$ lower bound, -0.63; upper bound, 0.57), while 9 out of 15 BFb individuals showed a greater increase in knee-ankle variability than the control group ($95\%\mathrm{CI}_{\mathrm{Slope}}$ lower bound, -2.04; upper bound, 1.45). $\mathrm{Perf}_{\mathrm{Var}}$ did not alter over time for almost all participants, with only two of the BFb group's $\mathrm{PV}_{\mathrm{Gradient}}$ gradients exceeding the control group $95\%\mathrm{CI}_{\mathrm{slope}}$ (0.26 and 0.21 for each participant; Control lower bound, -0.11; upper bound, 0.12).

Table 5.5. Individual $CV_{Gradient}$ determined from $CI2_{Area}$ for hip-knee and knee-ankle couplings. *Signifies BFb individuals with gradients greater than Control group 95%CI upper bound.

	Hip-Knee $CV_{Gradient}$		**Knee-Ankle $CV_{Gradient}$**	
Group #	**Control**	**BFb**	**Control**	**BFb**
1	0.26	5.13*	-0.19	18.97*
2	0.09	0.54	0.05	10.39*
3	0.39	1.58*	1.43	1.64*
4	-0.17	0.49	-0.15	-3.46
5	-0.11	-0.81	-0.88	-1.05
6	0.95	-0.10	3.28	-1.51
7	-1.94	1.58*	-7.90	12.54*
8	-0.12	1.26*	1.44	-0.56
9	1.33	2.24*	-0.12	4.97*
10	-0.43	-0.06	-0.62	3.40*
11	-1.46	-1.62	-3.49	-3.53
12	-0.54	-0.02	0.29	-1.56
13	-0.37	1.62*	3.34	6.37*
14	-0.05	-0.80	-1.42	1.83*
15	1.67	1.34*	0.54	7.80*
95%CI Upper	0.57	**95%CI Upper**	1.45	
95%CI Lower	-0.63	**95%CI Lower**	-2.04	

5.4. Discussion

The purpose of this chapter was firstly**,** to assess the longitudinal retention of the kinematic changes, and investigate when significant changes occurred. Assessment of the longitudinal data would provide a deeper level of understanding to support findings within Theme 2. Secondly, by applying a dynamical systems approach, this chapter aimed to examine longitudinal exploration strategies arising with attention to a KP BFb intervention over a 26-week intervention. Therefore, this chapter also sought to examine changes in coordination and coordination variability over time, addressing Theme 3 of this thesis.

5.4.1. Longitudinal Kinematic Retention

This chapter demonstrates that a reducing biofeedback schedule is effective in negating dependency effects of BFb (Salmoni et al., 1984), whereby learning occurred ($p < 0.05$) but with no significant decrease in retention throughout the 26-week intervention. Specifically, no significant reduction in rear leg hip, knee and ankle retention kinematics following the initial intervention week support the notion that an 'extraction' technique, whereby augmented feedback contact is reduced over time, is effective in facilitating relatively permanent learning (Schmidt and Lee, 2005). Previous research has shown effective retention at one month after just one day of BFb (Etnoyer et al., 2013) which is a less intensive intervention however these findings were demonstrated in a relatively simple drop landing task with simple BFb. Results in this chapter show that a BFb intervention with just three sessions in one week, followed by two sessions within a fading schedule can be as effective as more time intensive interventions (e.g. Viitasalo et al., 2001) while also ensuring the skill is retained over a six-month period. The notion that a high volume of initial BFb is effective in a more complex task to compensate for the more complex movement information (Sigrist et al., 2013) holds true in this research by using a reducing schedule with four sessions in one week and then intermittent 'top up' visits separated with increasing time periods of 4, 8 and then 12 weeks. This supports ***H_{10}*: A longitudinally reducing biofeedback schedule will facilitate the retention of kinematic changes over a 26-week period** and provides evidence to underpin BFb interventions on complex skills.

The breakpoint analysis revealed that the BFb intervention was effective in eliciting changes in the whole limb rear leg kinematic chain early on, with peaks in skill targeted variables shown within just two sessions. This aligns closely with a paucity of research demonstrating changes in performance after one visit (Richter et al., 2011; Ford et al., 2015; Eriksson et al., 2011; Baggaley et al., 2017; Jackson et al., 2017), however none of these studies have retention tests to identify if these technique alterations were temporary alterations in performance or learnt. Other, more intensive BFb protocols, have shown that four weeks populated with 11 sessions can improve a complex skill such as rifle shooting with 10- and 40-day retentions showing that these changes were maintained (Kontinnen et al., 2004). Findings in this chapter show that changes can be developed with a less intensive BFb intervention and then maintained with a reducing schedule. There is limited research on complex skill development and retention using KP beyond one month, bar a three-month retention in a single subject case study (Rice et al., 2010) therefore this research provides significant insight into successful complex skill retention. These findings support ***H_{11}*: *Changes to the rear leg peak joint angular velocities will plateau within the first three sessions of the BFb intervention for all three rear leg joints.***

Questions arise as to why the skill learning stopped at 40, 24.8 and 28.9% increase in hip, knee and ankle extension velocities. As discussed in chapter 2, there is a point where joint extension must reach a maximum according to van Ingen Schenau's (1989) anatomical constraint. For example, in this experiment the knee accelerates from 0 rad·s^{-1} when flexed at 120°, up to around 10 rad·s^{-1}, but then must decelerate back to 0 rad·s^{-1} by full extension to avoid damaging hyperextension. Participants may have reached an anatomical constraint within this task. Research also supports that the muscular capability to generate greater contractile velocities at the same force output would perhaps allow this rapid acceleration-deceleration relationship to develop further (González-Badillo and Medina 2010). Muscular activity is not measured within the scope of this research, however it would is possible that there is a maximal threshold for each joint driven by the muscular capabilities (van Ingen Schenau, 1989; Bobbert and van Soest, 2001). Additionally, with motor learning tasks the individual is attempting to develop a skill by attending to the individual, environmental and task constraints (Bernstein, 1967; Turvey 1990). It could be argued, therefore, that the participants were constrained by the closeness of the target once the task of covering the distance had been satisfied (e.g. adequately capable of lunging across the target distance to strike the target). This may have become a limitation of this research after a number of sessions.

Indeed, within the coaching literature research suggests that once an individual has acquired a skill it is appropriate to develop the task to allow for further skill progression (Farrow and Robertson, 2017), therefore in future it may be of interest to extend the distance as each individual appears to reach a breakpoint in learning. This is difficult to do without an appropriate paradigm to identify at which point a participant is still exploring a complex skill and needs the constraints to be altered. These findings are useful in guiding applied approaches to skill development and working with athletes in longitudinal development cycles.

Traditional paradigms of motor learning indicate that there is a subsequent drop off at retention following the skill development intervention (e.g. Rice et al., 2010). The lack of significant differences between the last intervention measure (block 14) and subsequent $\text{Retention}_{\text{4-6Wks}}$ show that this paradigm may not be applicable to explosive complex motor skills in a sporting context. Indeed, additional provision of 'top up' BFb with an extracting visit schedule over 26 weeks, as demonstrated in this study, appears to be an effective approach to reduce this negative response of a drop in performance at retention, and perhaps aids long term retention (i.e. learning). This is supported with the moderate dips in all three joint extension magnitudes (figure 5.3) followed by a return to intervention week values with the first block of feedback (block 16). These findings are useful in guiding applied approaches to skill development and working with athletes in longitudinal development cycles.

5.4.2. Lower Limb Coordination and Joint Coupling

There were no significant changes in the BFb group mean coordination patterns for the hip-knee and knee-ankle joint couplings relative to the Control group. This highlights that the augmented biomechanical feedback intervention in chapters 4 and 5 did not elicit permanent alterations in joint coupling strategies of the lower limb kinematic chain in the BFb group rear leg kinematic chain. The overall lack of changes in coordination strategies is perhaps surprising, but can be supported with a number of reasons which will be addressed in more detail in the following sections. Following this, separate joint coupling responses will be discussed in more detail.

5.4.2.1. Explanations for Lack of Coordination Changes

The longitudinal BFb intervention in this thesis focused on the influence of KP feedback directed toward increasing joint angular velocity magnitudes of the rear leg kinematic chain in an explosive movement, whilst also **maintaining** proximal to distal sequencing. In this regard the feedback was effective in facilitating an increase in joint extension magnitudes, as shown in chapter 4; the primary effect that the BFb was targeted toward. An underlying assumption in this research was that the kinematic chain coordination patterns would alter to achieve these magnitude differences; a secondary effect. Previous research to reduce loading rates via the provision of running kinematics has shown success in altering the primary and secondary variables, but in addition to negative effects of variables associated with injury risk such as increased ankle joint internal forces (Baggeley et al., 2017). Caution must be taken regarding secondary effects. In this research, the BFb worked in altering the desired variables, however the coordination pattern to achieve this goal was not significantly changed.

The lack of adaptation in the coordination patterns in this explosive task adds weight to the notion that the stereotypical pattern of the sequential kinematic chain as seen in sprinting (Jacobs et al., 1996) and jumping (Gregoire, 1984; Cleather et al., 2015) may indeed be an optimal movement pattern in whole limb human propulsion (Bobbert and van Ingen Schenau, 2001; Wong et al, 2017). In this regard, the BFb design in this thesis was directed at increasing the magnitudes of this pattern, and only encouraging that the movement was within the stereotypical proximal to distal sequential order, not specific boundaries. Future research manipulating the sequential kinematic chain temporal aspects would provide useful insight in this respect. If the new coordination pattern were different to the stereotypical proximal to distal extension pattern, and these changes did not lead to increased force generation then it would support that humans have evolved to use biarticular musculature in the most efficient manner (Wong et al., 2016).

Quantification of coordination in human movement has inherent limitations related to the methodology chosen. Modified vector coding adapted the original methodology proposed by Sparrow et al. (1987) into a more accessible approach using coordination frequency bins referring to joint dominancy (Chang et al., 2008) and then inferential histograms providing visual clarity for practitioners (Needham et al., 2014; 2015). This modified method has proven applications between specific populations (Rodrigues et al., 2015), or vastly different phases of a skill (Vidal et al., 2018). A limitation of this approach lies in the sensitivity of the coordination bins to pick up minor alterations to coordination coupling in the temporal domain. This is not necessarily something that a "count" of vector angle orientation would pick up. The research in this study is perhaps a prime example of this. Looking at the BFb group hip-knee angular velocity plot, it is clear to see that magnitudes have marginally increased for both joints, but with no real change in the vector orientations. However, there is clearly a shift in the data in the temporal domain. Modified vector coding may therefore not be sensitive enough to compare coordination patterns within or between similar populations or movement patterns. Methods that capture these temporal changes in bi-variate data plots, such as CI2 (Mullineaux, 2017), may be more effective in identifying these changes. This could be an appropriate direction of future research in discrete skills focusing on specific components of the movement, such as the propulsive phase of the explosive lunge explored in this study.

5.4.2.2. Hip-Knee Joint Coupling Frequency Bins

There were no statistically significant interaction effects between group and time for the hip-knee joint coupling coordination. This results in rejecting **H$_{12}$:** ***The BFb group will show an increase of in-phase joint coupling for the hip-knee angular velocity modified vector coding joint couplings with the BFb***. There were, however, some interesting patterns shown in hip-knee coordination couplings via the modified vector coding frequency bin analysis. In the context of hip-knee coupling in the kinematic chain, a significant increase of hip-knee in-phase coordination would suggest that both joints are simultaneously extending, and thus contributing toward propulsion via full leg extension, however this would contradict theoretical and mathematical modelling of the kinematic chain, where simultaneous leg extension is not optimal (Bobbert and van ingen, 2001; Wong et al., 2016). It would be more beneficial if hip dominance and knee dominance (isolated extensions) increased meaning that each joint utilising a greater range of motion to generate angular velocity around a subsequent segment, sequentially (Bobbert and van Ingen Schenau, 2001). This may be slightly masked in that no joint is truly fixed within the sequential kinematic chain, with each distal segment building on angular momentum of the more proximal segment, by definition (Bunn, 1972; Putnam 1993). Therefore, a moderate increase in knee extension may not be evident as a knee dominant movement if the hip has moderate movement simultaneously (i.e. in-phase). An increase in hip dominance would be suggestive of increased recruitment of the larger hip extensor muscles for greater propulsive force generation in the lunge movement (Guilheim et al., 2014). Table 5.2 shows an increase from 22 to 29% in the BFb group hip dominance from Pre_{Int} to $\text{Retention}_{\text{26WK}}$, with the Control group demonstrating relatively little change (maintaining around 22%) apart from a small peak at $\text{Retention}_{\text{13Wk.}}$ This peak likely obscures statistical significance of a plausible interaction effect. Both groups showed a decrease in knee dominance which also supports the importance of the hip extensor musculature in this movement when combined with a moderate BFb group increase in hip dominance. Anti-phase movement, with one joint extending while the other is in flexion, would be suggestive of one joint collapsing in the sequential kinematic chain in a propulsive task. As a general trend it appears that the BFb group decrease in anti-phase coordination over time (17% - 12%) with the Control group maintaining their anti-phase frequency (between 16 and 19%), which indeed supports the above conceptualization, but again these findings were not supported with a statistically significant interaction effect.

Although there were no significant interaction effects, a significant main effect was shown between the two groups. The BFb group demonstrated significantly greater in-phase patterns during propulsion throughout the 26 Week intervention. This difference was prevalent from the initial Pre_{Int} measurement, which may obscure results with interaction effects. With traditional discrete variables, this can be corrected via offset normalization (e.g. set Pre_{Int} to 0%) but this is less meaningful when dealing with a variable such as a modified vector coding frequency bins. The data for each joint has already been differentiated from displacement to angular velocity, coupled with another joint, vector coded, meaned via circular statistics, and then counted into frequency bins as a percentage (Chang et al., 2008; Needham et al., 2014). Offset normalization may add further unnecessary complexity providing a percentage difference of a percentage. A more appropriate experimental design would be to match groups according to coordination patterns prior to addressing the research question, however this is difficult to achieve in reality with the vast range of inter-individual coordination strategies depicted in the same skill (Seifert et al., 2011). This was beyond the original scope of this research, whereby groups were matched on propulsive ability as a measure of athleticism. It is prudent, therefore, that research investigating small changes in coordination within components of a discrete complex skill should attempt to account for these group differences prior to intervention onset.

5.4.2.3. Knee-Ankle Joint Coupling Frequency Bins

The knee-ankle joint coupling showed no significant interaction effects across any of the modified vector coding frequency bins for group by time, although there were interesting coordination patterns that emerged. There was a trend that the BFb group showed a decrease in anti-phase knee-ankle coupling throughout the intervention (Pre_{Int} 32% to $\text{Retention}_{\text{Wk26}}$ 27%) relative to the Control who increased marginally (21%-25%). Despite these trends, the findings support rejection of the hypothesis $\mathbf{H}_{\mathit{13}}$: ***The BFb group will show an increase of antiphase-phase joint coupling for the knee-ankle angular velocity modified vector coding joint couplings with the BFb***. There was, however, a significant main effect between groups in the anti-phase coupling with the BFb group showing significantly greater anti-phase dominance throughout the intervention. This could obscure any interaction effect with overlapping group data between the two groups as discussed previously. If the Pre_{Int} time points were offset to the same values (e.g. 0%) as stated in the previous section, or indeed recruitment based on similar coordination patterns, this research may have empirically supported the notion of the ankle joint being forced into dorsi-flexion with the additional hip and knee extension velocity accumulation directed toward the proximal ankle (Gregoire et al., 1984; Jacobs et al., 1996; Bobbert and Van Soest, 2001; Cleather et al., 2015). The group differences in anti-phase could explain the lack of change in kinetic variables throughout the intervention as shown in chapter 4, with joints acting as dampening mechanisms with opposing actions. Equally, as discussed in chapter 2 the foot complex is often negated from lower limb analysis and modelled as a single segment for simplicity (e.g. Wong et al., 2016). The architectural structure of the foot serves as both a dampening and a propulsive function depending on environmental and task constraints (Welte et al., 2018). This is a limitation of the rear leg kinematic chain concept when the foot, the most complex segment which facilitates contact and force distribution to the ground, is assumed to be non-deforming and negated from coordination profiling. Future research should consider the inclusion of foot coordination, similar to the rearfoot sub-talor joint motion being coupled with forefoot intertarsal joints as in Chang et al. (2008),

There were no statistically significant interaction effects in the knee-ankle coupling **in-phase** frequency bins. There was also no significant main effect between groups. As a general pattern both groups show little change throughout the intervention with the in-phase dominant pattern. This lack of change in simultaneous knee extension and ankle plantar-flexion adds weight to the preceeding arguments that simultaneous extension is not an optimal propulsive strategy in the lower limb biological design (Gregoire, et al., 1984; Wong et al., 2016). Interestingly, both groups show an increase in knee dominancy with the coordination coupling (BFb group 38% to 46%) relative to the Control group of maintaining 45% to 46%, however this was not significantly different in the between groups main effect. These findings support the notion of knee dominance being beneficial in explosive whole lower limb movements due to the long flat fusiform fibres of the vastii group capable of producing relatively high forces in knee extension (van

Soest, 1993) which helps to generate net leg extension in combination with the bi-articular hip-knee coupling (Cleather at al., 2015). Changes in the ankle dominancy frequency bins show the inverse pattern of the knee dominancy frequency. The BFb group maintain similar ankle dominancy values of between 12% at $\mathrm{Pre}_{\mathrm{Int}}$ and 14% at $\mathrm{Retention}_{\mathrm{Wk26}}$, while the Control group showed a moderate decrease in ankle dominancy from 16% at $\mathrm{Pre}_{\mathrm{Int}}$ to 11% at $\mathrm{Retention}_{\mathrm{Wk26}}$. Although these changes were not statistically significant, collectively the individual joint dominancy coupling results suggest that during the intervention the BFb group focused on increasing knee extension, and maintaining ankle plantarflexion. In similar movements, this joint coupling strategy has been shown to be extremely beneficial in loading the Achilles tendon to efficiently return elastic energy in propulsion (Lichtwark and Wilson, 2006). The lack of significant interaction effects to support this in this research is perhaps surprising given the theoretical underpinnings addressed throughout this chapter, however it is plausible that a more specific research design to identify these changes in coordination patterns, as previously mentioned, would allow for these findings to be empirically supported in future.

5.4.3. Biofeedback and Coordinated Variability

The BFb intervention encouraged skill exploration in both the hip-knee and knee-ankle coupling $\mathrm{Coord}_{\mathrm{Var}}$. The BFb group $\mathrm{Coord}_{\mathrm{Var}}$ continually increased in both joint couplings throughout the 6-month period reducing schedule BFb intervention, while comparatively the Control group remained constant displaying no change. This allows for the acceptance of ***H_{14}*: The BFb group will have an increased joint coupling variability within the Hip-Knee and Knee-Ankle when attending to the BFb compared to Control.*** The use of $CI2_{Area}$ method was able to highlight the exploration of the lunge skill through changes in $Coord_{Var}$ while attending to the terminal KP intervention. It is apparent that $Coord_{Var}$ is effective in successfully identifying differences in skill execution between groups where coordination alone cannot (Cazzola et al, 2016; Williams et al., 2016). This also demonstrates that the proposed $CI2_{Area}$ method was sensitive enough to identify changes between groups and also over time.

The BFb appears to guide skill exploration which adheres to previous theoretical suggestions (Lauber et al., 2013). This continual exploration is in line with Bernstein's (1967) stages of motor learning, with participants initially freezing the coordinated DoF in the self-learning blocks (1-3), and then freeing joint coupling variability to continually explore task execution throughout the 26 weeks in both joint couplings. This is also in line with concepts observed by Newell (1985) in that the BFb group selected a coordination pattern organizing the system to adhere to constraints fairly early on. This has been suggested as a common finding in selecting tasks where a skill is not completely novel (Newell and Vaillencourt et al., 2001). An athletic individual will often use a whole limb for propulsion as evidenced by the 'stereotypical' sequential pattern as shown in Gregoire et al. (1984). This is further supported with both the BFb and Control groups demonstrating similar $Coord_{Var}$ during the 'self-learning' phase (blocks 1-3) prior to the intervention. From a motor learning perspective, once the participants receive the BFb they appear to be freeing DoF as a skill exploration strategy (Bernstein, 1967; Newell and Vaillancourt, 2001). This appears to be a relatively quick response facilitated by the BFb. $\mathrm{Coord}_{\mathrm{Var}}$ remained constant in the Control group who were free to self-explore in finding their own motor pattern throughout the entirety of the intervention.

According to Newell's (1985) framework of learning, it would be fair to postulate that the BFb group had gained control of the coordination dynamics and were in a state of exploration around the task constraint but not quite categorized as skilled. The increasing $\mathrm{Coord}_{\mathrm{Var}}$ scores would also suggest the continued freeing of DoF throughout the 26 weeks. (Bernstein, 1967). However, when pairing the $\mathrm{Coord}_{\mathrm{Var}}$ profiles with the breakpoint analysis the skill dynamics were satisfied within two sessions. Therefore, it could be argued that the increasing $\mathrm{Coord}_{\mathrm{Var}}$ from this point is exploiting reactive phenomenon (Bernstein, 1967) after satisfying task demands, and exhibiting skilled behavior (Newell, 1985). It is difficult to confirm this theoretical standpoint without an inverse dynamics analysis to separate the contribution of active and passive forces, that could be explored in future research.

A possible limitation is in the selection of linear statistics used. However, visually it is clear that the $\mathrm{Coord}_{\mathrm{Var}}$ increased linearly as a whole which highlights that participants remained in a functional state of technique exploration or skill exploitation. Questions arise as to when this increase would plateau, or reduce, as prescribed in Bernstein (1967) and also Newell's (1985) theoretical frameworks, and those of reaching a stable coordination state. These suggest that $\mathrm{Coord}_{\mathrm{Var}}$ would decrease when a skill was mastered, but still allow a level of functional variability to maintain a stable and successful performance outcome. It can be postulated that the volume of BFb (which totaled around six hours per individual) kept the BFb individuals in a continual state of exploration during the BFb extraction. Therefore, perhaps more BFb would have helped to solidify learning without effects of dependency and exhibited in a plateau of $\text{Coord}_{\text{Var}}$.

Throughout the entirety of the BFb driven skill exploration, the performance output variability (Perf_{Var}) remained consistent in both groups. This allows for the acceptance of ***H_{15}: Performance variability will not change in either BFb or Control groups***. Only two of the BFb group's Perf_{Var} exceeded the control group $95\%\text{CI}_{\text{slope}}$ with minor gradient changes, thus supporting no changes in Perf_{Var}. This links to theoretical frameworks that support the functional role of $\text{Coord}_{\text{Var}}$ flexibility allowing for a consistent performance output (Hamill et al., 2012; Preatoni et al., 2013). It is also of interest to note that $\text{Coord}_{\text{Var}}$ was larger in magnitude in the more distal joint coupling. This is in line with previous research underpinning whole limb sequential coordination strategies, with the more distal joints offering a compensatory strategy for movement errors in more proximal segments (Robins et al., 2006; Mullineaux and Ulh, 2010). This also aligns with previous BFb complex skill development research demonstrating a proximal to distal learning strategy with learning over time (Carleton and Kernodle, 1992). The implications of these findings suggest that applied practitioners should consider directing BFb toward more proximal joints in the initial stages of learning as suggested in literature, but with considerations of individual differences which is often overlooked.

5.4.4. Individual Coordinated Variability

The individual results highlight that there are varied individual responses to the BFb intervention as a whole. This highlights the need to individualise applied paradigms. Relative to the Control hip-knee $CI2_{Area}$ over the 6 months, 7 out of the 15 BFb group individual $CV_{Gradient}$ scores were greater than the upper bound $95\%CI_{Slope}$ of the Control group. This means that nearly half of the BFb group explored the rear leg propulsion pattern by increasing hip-knee coupling exploration strategies. In addition, 9 out of 15 BFb individuals had knee-ankle coupling $CV_{Gradient}$ scores which exceeded upper bound $95\%CI_{Slope}$ of the Control group. Looking at both joint couplings across individuals, it appears that the same individuals with greater hip-knee coupling variability also had greater knee-ankle coupling variability. This also seems to suggest that certain individuals have greater $Coord_{Var}$, which may be as a strategy in response to the BFb. This could warrant further investigation in future research to individualise BFb approaches, and also to focus BFb on more easily manipulated joints. These findings support ***H_{16}: Individual joint coupling variability can be used to identify individuals in a state of exploration while attending to BFb.***

It is evident that BFb encourages skill exploration, and that there are individual response rates to the augmented information provided (Chow et al., 2008; Seiffert et al., 2010; Seiffert et al., 2011). Individual differences in this chapter demonstrate that it is possible to use $Coord_{Var}$ to tease out these individual differences, particularly using the $CI2_{Area}$ methodology as proposed here. It is important that a paradigm is able to identify individual differences that allow a practitioner to monitor motor learning to modify task and or environmental constraints to continue learning progression (Farrow and Robertson, 2017). Those individuals with low $CV_{Gradient}$ demonstrate low levels of $Coord_{Var}$ within the intervention meaning that the BFb is not directing skill exploration (Lauber et al., 2013). This could highlight individuals that require an alteration to the BFb content, modality or indeed a change in the task itself. Without these alterations, individual skill progression may be limited. Further, the method demonstrated here allows for an evaluation of an individual rate of learning, and for the real time analysis of skill development during a BFb intervention. Future research should assess the robustness of this proposed paradigm in applications to other complex sporting movements and ecological settings.

5.5. Conclusion

Visual KP was found to increase rear leg hip and knee extension velocities in a complex skill, in the form of an explosive lunge task. These changes were retained over a total period of 26 weeks, using intermittent return visits with increasingly larger time periods in between. There were no significant alterations to coordination strategies as a response to feedback, supporting the specific effects of BFb on targeting variables. This investigation highlighted that the provision of BFb guided and directed skill exploration, but without altering performance consistency. The new longitudinal approach adds evidence to the functional nature of coordination variability to better satisfy task demands during practice. In future, to assess effectiveness of feedback provision, the coordination variability paradigm offered here may offer insight that is of use to the applied practitioner. Specifically, exploring coordination variability could potentially identify the stages of learning during individual skill development cycles, further enhancing training and skill development.

CHAPTER 6: GENERAL DISCUSSION

6.1. Introduction

Limited, coherent guidelines exist to inform knowledge of performance (KP) based biofeedback (BFb) interventions. Through merging traditional biomechanical analysis techniques with a dynamical systems approach, this thesis longitudinally examined the influence of BFb on complex skill development. Research informing the application of BFb has predominantly emerged from the KR literature, focusing on simple skills (Newell et al., 1983; Swinnen et al., 1990; Smith and Loschner, 2002; Snodgrass et al., 2010; Schaffert and Mattes, 2014; Albuquerque et al., 2014; Simon and Bock, 2016). However, findings derived from simple skills are not necessarily generalisable to complex skills (Wulf and Shea, 2002). A discrete explosive skill, specifically the fencing attacking lunge, was used as a vehicle to investigate application of BFb to complex skills.

Emerging KP literature has begun to focus on complex skills, but most investigations provide BFb on individual, isolated variables (e.g. Creaby et al., 2016). Problematically, changes elicited in a single joint within a linked kinematic chain can have an adverse effect on related joints (Noehren et al., 2011; Richards et al., 2018a). Therefore, research focusing on the application of KP BFb to manipulate the whole limb is required to enable successful skill development using KP BFb. The aim of this thesis was **to identify the effectiveness of KP BFb on influencing a whole limb complex motor skill, and the subsequent longitudinal retention.**

To address the overall aim of this thesis, research questions were generated within three key themes to provide a theoretically structured approach. These themes were;

1) I**dentify** biomechanically relevant **content** for biofeedback
2) **Assess** the effectiveness of **biofeedback** applied to whole limb technique
3) **Examine learning** through the perspective of Dynamical Systems Theory

This chapter will first address each research question in turn, answering progressive questions in line with the three thesis themes. Following this, a critical appraisal of the methodologies undertaken in this chapter with the key limitations addressed and considered. Finally, this chapter closes with novel contributions and practical applications arising from this body of work and future directions, ahead of a thesis conclusion.

6.2. Addressing the Research Questions: An Overview

KP BFb has proven effectiveness in directly modifying individual variables underpinning technique (Baudry et al., 2006; Eriksson et al., 2011; Thow et al., 2012; Ford et al., 2015; Richards et al., 2018b), and to influence secondary influences on related variables (Winchester et al., 2009; Rice et al., 2010; Noehren et al., 2011; Richards et al., 2018a). However, limited research has attempted to modify whole limb performance in complex skills. Chapter two highlighted that BFb content is a highly influential factor when modifying technique. Therefore, chapter 3 addressed **Theme 1** of this thesis and related research questions by assessing the whole limb kinematic chain in a complex, explosive movement.

6.2.1. Theme 1: Identifying Biomechanically Relevant Content for Biofeedback

Research on the lower limb neuromuscular design has identified the effectiveness of our bi-articular neuromuscular design as a power transfer mechanism (Gregoire et al., 1984; Van Ingen Schenau, 1989a; Bobbert and van Soest, 2001; Wong et al., 2016) allowing for more effective CoM propulsion (Jacobs et al., 1996). The fencing attacking lunge was identified as a vehicle to biomechanically assess and interpret contributions of the whole limb movement toward propulsion in chapter 3, addressing the first two research questions. This skill was selected due to sword velocity being linked to the extension of multiple lower limb joints (Bottoms et al., 2013; Guilhem et al., 2014), generated using more coordinated movements as shown in skilled athletes (Yio and Do, 2000).

RQ1. Can utilisation of the rear leg kinematic chain be used to distinguish between propulsive ability, in a sport specific skill?

A cross sectional study design was implemented, using a total of fifteen fencers separated into novice and skilled groups. Distinctions of skill level were based on experience, lunge distance and sword velocity (Yiou and Do, 2000). Seven of these were classed as skilled competing at regional level, with three competing nationally and two internationally. Kinematics and kinetics of the fencing attacking lunge were captured using a 3D motion analysis system and two synchronised force plates. Performance variables confirmed differences between the two groups performing the skill, with the more skilled participants lunging further and achieving significantly greater sword velocity (skilled 3.24 ± 0.24 $m \cdot s^{-1}$ versus novice 2.69 ± 0.29 $m \cdot s^{-1}$; $p<0.00$).

The skilled group demonstrated larger rear leg angular extension velocities, accumulating in a proximal to distal sequence. This accumulation resulted in significantly greater ankle plantarflexion angular velocity. These findings are in line with previous research implicating the evolution of bi-articular musculature as an evolutionary mechanism allowing for whole limb contributions to CoM propulsion (Gregoire et al., 1984; Jacobs et al., 1996; Bobbert and Soest, 2001; Cleather et al., 2015; Wong et al., 2016). This confirmed that greater utilisation of the rear leg kinematic chain was a distinguishing feature between skill levels in a sport specific skill. To confirm these findings were linked with propulsive abilities, kinetic variables were compared between groups, and correlations between distal segment kinematics (Peak $Ankle_{\omega}$) and external kinetics (Peak F_Y and $Impulse_Y$) were sought to answer the second research question.

RQ2. Are kinematic differences in the rear leg kinematic chain associated with external kinetics and CoM propulsion?

The skilled fencers demonstrated significantly greater normalised horizontal kinetics (Peak F_Y and $Impulse_Y$) than the novice athletes. Further, strong positive correlations were found between Peak $Ankle_{\omega}$ and Peak F_Y and a positive, but weak, correlation between Peak $Ankle_{\omega}$ and $Impulse_Y$. These correlations were important, as the ankle is the most distal joint within the kinematic chain which is vital link to deliver the accumulated power to the floor (Jacobs et al., 1996; Bobbert and van Soest et al., 2001). Ankle plantar-flexion is assisted by the long, elastic Achilles tendon (Kurakowa et al.

2003; Lichtwark and Wilson, 2006) which acts as a power amplifier (Robert and Azizi, 2011). Importantly, the correlation between the kinematic chain accumulated velocity and external kinetics provides a theoretical link underpinning faster sword velocities in the more skilled participants in the fencing attacking lunge (Yio and Do, 2000; Bottoms et al., 2013; Gresham-Fiegal et al., 2013; Guilhem et al., 2014). These were also in the horizontal direction, with biarticular muscles facilitating vector orientation (Hof, 2001). Therefore, this provided empirical support for quantification of the rear leg kinematic chain to form BFb content for a KP based intervention to facilitate changes in performance.

6.2.2. Theme 2: Assessing the Effectiveness of Biofeedback on Whole Limb Technique

The second theme built on the findings of Theme 1 (Chapter 3) by assessing the effectiveness of whole limb kinematics as KP BFb to develop the rear limb kinematic chain, and CoM propulsion, though addressing three research questions.

RQ3. Can the provision of terminal KP BFb alter whole limb kinematics in a complex skill?

Chapter 4 provided answers to research questions RQ3-RQ5. Thirty-two healthy participants from a range of different sports were recruited and randomly assigned into a BFb or Control group. They were introduced to a simplified attacking lunge task, and following self-learning practice the BFb group received visual KP based on joint extension magnitudes and sequence. The intervention was structured over three visits during one week, while kinematics and kinetics were collected for each trial. Retention was assessed with participants returning at 4-6 weeks.

The provision of terminal KP BFb on whole limb kinematics was successful in altering technique in the complex, novel lunge task assessed within this thesis. All three joints of the rear-leg kinematic chain showed a significant increase in kinematic contributions. Specifically, Hip_{ω} and $Knee_{\omega}$ significantly increased in the BFb group, while no changes occurred in the Control group. While $Ankle_{\omega}$ increased there were no significant interaction effects, but there was an increase in $Ankle_{RoM}$ suggesting changes in the ankle. When normalised as a percentage of change, however, there were significant interactions across all three joints, with increases in normalised Hip_{ω}, $Knee_{\omega}$ and $Ankle_{\omega}$. Changes in the hip and knee are in line with previous BFb research in discrete skills (Etnoyer et al., 2013; Ford et al., 2015), with the proximal joints being great power generators of the lower limb (Jacobs et al., 1996; Wong et al., 2016).

The lack of obvious changes in the ankle highlight the importance of considering how changes to joint kinematics within a kinematic chain, such as increasing knee extension, can influence related joints. Previous findings have highlighted negative interactive effects on one joint following BFb directed at another (Baggaley et al., 2017; Richards et al., 2018a). From a BFb perspective, it may be difficult to cognitively focus on information related to three joints during task execution (Richards et al., 2018b) which could explain non-clear changes in a third joint. However, with changes to the $Ankle_{RoM}$ and percentage normalised $Ankle_{\omega}$ differences, it seems likely that greater variability at the distal joint may mask changes (Mullineaux and Uhl, 2010) at both a group and individual level. More likely, the increase in inertial forces caused by the heavy trunk forced the ankle into additional flexion (Hopper, 1973). KP research has previously shown changes to knee kinetics to negatively impact ankle kinetics (Richards et al., 2018a). It is clear that the provision of multiple joint kinematics requires careful consideration beyond the immediate changes sought.

Newell et al. (1983) anticipated that information on joint movements would be beneficial in tasks requiring the coordination of multiple degrees of freedom. The answer to RQ3 supports this statement. KP is beneficial for complex skills as it can cater for the increasing skill complexity with multiple joint interactions (Kernodle and Carlton, 1992; Viitasalo et al., 2001; Kontinnen et al., 2004; Richards et al., 2018a; 2018b). Additionally, it has been shown that transitional information and cues to provide direction are important (Kernodle and Carlton, 1992). Therefore, it was determined that KP BFb needs to facilitate clear instructions. Without these, changes may not occur (Fortier et al., 2005) or BFb may result in undesirable outcomes (Richards et al., 2018a).

RQ4. Do subsequent changes in the whole limb kinematic chain lead to changes to external kinetics during a discrete, complex skill?

Despite changes to rear leg kinematics, there were no significant changes shown in external kinetics across any of the variables in Chapter 4. This was a surprising finding, and at odds with the kinematic chain literature focusing on explosive tasks (Gregoire et al., 1984; Bobbert, 1986a; 1986b; 1986c; Jacobs et al., 1996; Cleather et al., 2011; Fargier et al., 2016). The transverse component of biarticular muscles has been proposed as a mechanism to allow for horizontal force generation (Hof, 2001), therefore increasing the theoretical effectiveness of the kinematic chain transfer should have resulted in kinetic increases. In response to contradictions with existing research, this is the first research to manipulate the kinematic chain, with previous work being theoretical or cross-sectional designs therefore the reality could be more complex than theory suggests. Chapter 3 identified links between a more effective kinematic chain and greater kinetic capabilities. However, a stronger experimental design in Chapter 4, with a randomised controlled intervention, provided data from 4416 trials which confirmed that the kinematic-kinetic relationship is not as clear as it first appears in this research.

From a biofeedback perspective, these results demonstrate that secondary effects are not always guaranteed, and require strong empirical evidence if sought indirectly through applying a KP intervention. The body is more complex than rigid body models in the literature, and oversimplification can be problematic. For example, the foot is often modelled as a rigid body in inverse dynamics analysis, however it is a flexible segment made of multiple joints and soft tissue structures (Welte et al., 2018). Therefore, the causal relationship of increasing kinematics directly being transferred to an increase in force not as clear as proposed in previous research.

An alternative consideration relates to the force-velocity (F-V) relationship of lower limb musculature. It could be argued that increasing velocity would reduce the force generating capabilities of the muscle due the F-V curve derived from individual muscle tendon unit properties (Hill, 1938). However, in whole limb interactions this curve is flattened out and appears linear (Bobbert, 2012; Jaric, 2015), and is also malleable (González-Badillo and Sánchez-Medina, 2011; Jimémez-Reyes et al., 2019). So, a shift in velocity leading to no change in external kinetics may actually produce greater lower limb power, but it is likely that the intrinsic dynamics of the lower limb mask this (Bobbert, 2012) with the interaction between the knee and ankle, or energy dissipation and absorption through soft tissue structures (Zelik and Duo, 2010).

RQ5. Are changes in technique from a whole limb KP BFb intervention retained?

It is clear from the intervention of Chapter 4, and the subsequent retention test, that changes in technique facilitated by the visual KP BFb were retained. While four-six weeks does not appear to be a long period to ascertain the permanency of learning, a vast quantity of KP research has not included retention tests (Kotajarvi et al., 2006; Eriksson et al., 2011; Richter et al., 2011; Secoli et al., 2011; Hwangbro et al., 2015; Schaffert and Mattes, 2015) or limited retention testing to within 24 hours (Nunes et al., 2014; Schaffert and Matters, 2014; Creaby et al., 2016). Chapter 4 findings were in keeping with KP literature, with kinematic changes following intensive interventions retained at four-weeks (Thow et al., 2012), or up to one year (Bowser et al., 2018). However, the intervention in Chapter 4 demonstrate the successful manipulation of three joints simultaneously within a complex, discrete skill within just three visits, which were still retained at four-six weeks. While the guidance hypothesis states too much BFb fosters dependence (Salmoni et al., 1984), the results of Chapter 4 confirm that high frequency BFb is effective in complex skills, without compromising retention (Wulf and Shea, 2002).

Chapter 5 contributed to this theme by extending the intervention to 26 weeks, with a time fading schedule, in that two single BFb sessions were increasingly spaced out at 4-6 and 13 weeks, with a 26-week retention point. Results showed that kinematic changes were retained at 26-weeks. Breakpoint analysis was applied to percentage changes of the hip, knee and ankle, and highlighted that BFb group changes occurred within session two for all three joints, and did not decrease throughout the rest of the intervention.

6.2.3. Theme 3: Examining Learning through the Perspective of DST

Chapter 5 focused on longitudinal changes over 26 weeks to address Theme 3. To date, research incorporating longitudinal data through stages of learning is limited. Incorporating longitudinal analysis enhances insight into skill development processes (Newell, 2003). Therefore, a dynamical systems approach was integrated into the longitudinal framework to provide a deeper level of analysis of emergent behaviours brought about by the guiding properties of the KP based BFb.

RQ6. Does the provision of whole limb terminal KP BFb influence joint coupling coordination during a complex skill?

In order to answer this question, intra-limb coordination was quantified using a modified vector coding technique (Chang et al., 2008; Needham et al., 2014) to assess for changes in hip-knee and knee-ankle angular velocity coupling of the rear leg kinematic chain during the propulsive phase of the lunge task throughout a 26-week intervention.

There were no significant changes in coordination in either the hip-knee or knee-ankle couplings throughout, in both groups. A lack of significant changes in coordination is initially surprising, and in contrast to previous literature with KP BFb manipulating coordination patterns (Hatze, 1976; Swinnen et al., 1997; Fuji et al., 2016). However, two key differences offer reasonable explanations. Firstly, KP research manipulating coordination to date has focused on the manipulation of simple skills, such as manoeuvring automated levers (Swinnen et al., 1997) or reaching tasks (Fuji et al., 2016). Secondly, although the skill presented to the athletes was novel, completion of the task required the use of a stereotypical movement in a sequential rear leg kinematic chain extension (Jacobs et al., 1996; Bobbert and van Soest, 2001; Wong et al., 2016). Considering the BFb targeted an increase in joint extension, and not a manipulation of joint timing, the lack of coordination changes seemed reasonable as the temporal relationships were not directly manipulated, rather individuals were asked to simply extend joints at a faster rate, and to retain sequential pattern.

RQ7. Does KP BFb facilitate an increase in joint coordination variability?

Answering this question required the development of a new coordination variability ($\mathrm{Coord}_{\mathrm{Var}}$) method, $\mathrm{CI2}_{\mathrm{Area}}$, as variability derived from vector coding techniques has been shown to be susceptible to noise artefacts in data with fast changes in vector orientation (Stock et al., 2018). $\mathrm{CI2}_{\mathrm{Area}}$ was also shown to be advantageous for longitudinal analysis as it provided a discrete measure of $\mathrm{Coord}_{\mathrm{Var}}$ for each block of practice, which allowed for changes over time to be analysed using a simple linear regression. Comparing the BFb $\mathrm{Coord}_{\mathrm{Var}}$ slope to the Control group confidence intervals allowed for a new and unique approach to assess group changes in coordination variability.

Following a brief reduction in hip-knee and knee-ankle $\mathrm{Coord}_{\mathrm{Var}}$ with the first three self-learning blocks in both groups, $\mathrm{Coord}_{\mathrm{Var}}$ increased in both joint couplings following introduction of the BFb. Further, this increase in variability continued for the entirety of the 26-week intervention. The initial decrease in variability with self-learning, followed by a continual increase in variability following the introduction of BFb as guidance, fits with both Bernstein's (1967) stages of learning, and Newell's (1985) coordination-control-skill framework. While both theoretical approaches appear contradictory, they can in fact be complimentary. The initial reduction of DoF links with Bernstein's (1967) first stage of learning (Newell and Vaillancourt, 2001) which, accordingly, mirrors Newell's (1985) transition from the first stage of discovering coordination, to the second stage of acquiring control once the coordination pattern is established. Following this, the multiple DoF are released (Bernstein, 1967; Newell and Vaillancourt, 2001) while the increase in ability to control segment dynamics allows for more explorative behaviour (Newell, 1985) guided by the BFb (Salmoni et al., 1984).

BFb was shown to facilitate an increase in functional $\text{Coord}_{\text{Var}}$, with the reducing biofeedback schedule over time continually encouraging exploration throughout the intervention. While it is difficult to compare hip-knee to knee-ankle $\text{CI2}_{\text{Gradient}}$'s due to different data ranges, it appears that the more distal coupling of the knee-ankle is more variable than the proximal hip-knee. This is in line with research suggesting that the more distal segments make compensatory changes to ensure a more persistent skill outcome (Mukllineaux and Uhl, 2010). Throughout this functional exploration, Perf_{Var} remained unchanged in both groups, demonstrating theoretical concepts of functional variability allowing for consistent performance (Preatoni et al., 2013).

Qualitatively, figure 5.5 highlights the postulated changes in variability through stages of learning which have only previously been identified in cross-sectional designs (e.g. Wilson et al., 2008). The longitudinal approach applied here provides new insight into the stages of learning (Newell, 2003), with BFb proving a useful tool to accelerate the skill development process.

RQ8: Can a longitudinal method to quantify coordination variability detect individual differences in skill exploration strategies?

The ability to detect individual responses to interventions is crucial for application of theory into practice (Glazier and Mehdizadeh, 2018). Therefore, the answer to RQ8 was an essential component to underpin the successful application of BFb. To answer this research question, the Control group $CI2_{Area}$ regression gradient ($CI2_{Gradient}$) was determined for both hip-knee and knee-ankle coupling for the 26 weeks, along with 95% confidence intervals ($95\%CI_{Slope}$). Then, individual BFb $CI2_{Gradient}$ were calculated and compared to the Control group $95\%CI_{Slope}$ upper bound. Using this method, it was identified that seven of the BFb participants hip-knee $CI2_{Gradient}$ were greater than the comparative Control group upper $95\%CI_{Slope}$, and nine BFb participants knee-ankle $CI2_{Gradient}$ were greater than their Control counterpart $95\%CI_{Slope}$ upper bound. This method demonstrated individual responses to BFb by identifying individuals demonstrating increasing exploration strategies during the intervention. Six participants demonstrated increases in $CI2_{Area}$ over time in both joint couplings, highlighting individuals who appeared to be responsive to the BFb, engaging and exploring new coordination patterns.

It became apparent that the new and novel $CI2_{Area}$ approach was able to detect individual responses to BFb. This has important implications, as it offers a solution to identify individual responses to an intervention targeting skill development.

6.2.4. Research Question Summary

Table 6.1. An overview of the research questions (RQ1-8) addressed throughout this thesis, and key findings to the respective questions.

Research Question	Key Findings
RQ1	Use of the rear leg kinematic chain can distinguish between skill levels in a complex task, involving whole limb propulsion.
RQ2	Differences in the rear leg kinematic chain in the fencing attacking lunge were associated with differences in external kinetics.
RQ3	The provision of complex, whole limb kinematics as KP BFb can be used to manipulate the whole limb kinematic chain in a complex skill.
RQ4	Changes in whole lower limb kinematics do not necessarily result in changes to external kinetics.
RQ5	Kinematic changes were retained at 4-6 weeks, and up to 26 weeks with a time fading BFb schedule.
RQ6	Joint coupling coordination did not alter with the addition of while limb KP BFb provided.
RQ7	The provision of KP BFb facilitates an increase in coordination variability as a function of guided skill exploration over time.
RQ8	A new coordination method was successfully used to identify individual responses to the KP BFb over time.

6.3. Critical Appraisal of Methodologies

6.3.1. Study Designs Employed During this Thesis

Chapter 3 used a cross-sectional (C-S) design to investigate differences between novice and elite athlete populations. C-S designs are one of the most common scientific approaches, using contrasting groups to try to identify performance determining variables (Glazier and Mehdizadeh, 2018). While C-S research allow for logistically simple data collection, useful for hard to access groups (e.g. elite athletes), it has limitations in that it only allows for single time point analysis. Individual technique can vary, even with elite performers (Bartlett et al., 2007), meaning that extrapolation of results from single time points to other time points or populations is restricted. To help increase representability of technique in Chapter 3, ten trials were collected per individual, which is above practical recommendations within biomechanical research (Mullineaux et al., 2001).

The limitation of a C-S design as used in Chapter 3 is exemplified with the correlation between ankle kinematics and external kinetics which was later shown to be less clear with a stronger research design in Chapter 4. However, other explanations that could have explained the differences in force production between groups in Chapter 3 was the possibility that elite athletes simply could have been stronger, thus produce greater force. This was later controlled for in the subsequent Chapters 4 and 5 with jump testing to ensure propulsive capabilities were matched.

Chapter 4 incorporated a randomised, controlled trial (RCT) protocol, applying content from Chapter 3 as a BFb intervention to manipulate whole limb kinematics. The level of evidence arriving from RCT is stronger, and usually facilitate the identification of causation by manipulating the variable of interest, and comparing to the matched control group. Additionally, the use of a baseline and three additional time points in Chapter 4 increases the strength and confidence of findings. Chapter 5 expanded the RCT design by doubling the experimental visits and incorporating a longitudinal element spanning 26 weeks. Longitudinal RCT designs are one of the strongest forms of scientific evidence, and in the context of motor learning can provide invaluable information on skill development cycles (Nouritt et al., 2003; Newell, 2003; Deschamps et al., 2004). Few longitudinal investigations exist within motor control and biomechanics, with the majority being longitudinal CS designs, likely due to the demanding nature of data collection protocols. Newell (2003) advocates that to better understand how skills are learnt, then true longitudinal research covering the stages of motor learning is required. The incorporation of multiple research designs building upon each chapter in this thesis, provides depth and progression of knowledge within the main research topic.

6.3.2. Choice of Biofeedback Delivery

There are a multitude of options and decisions underpinning the development of a successful BFb intervention, as covered in Chapter 2. Research has previously suggested that auditory is the most effective BFb channel for discrete skills, as it compliments, rather than detracts from other sensory processes (Park et al., 2000; Erikssen et al., 2011). However, acoustic BFb has limitations regarding the volume of information that can be portrayed. Further, technological restrictions confine the selection of data that can be used (Sigrist et al., 2013).

Visual BFb, in contrast, allows for a greater variety of data presentation (Noehren et al., 2011; Grooms et al., 2016; Richards et al., 2018a) which is useful for complex skills. For example, if the BFb intervention applied in Chapters 4 and 5 used an auditory transmission channel instead of visual, it is likely that individuals would have had difficulty interpreting the information. Each BFb presentation had peak angular extension velocities of three joints simultaneously, proximal-to-distal sequencing, and personal best summary information of the session overlaid. The simultaneous manipulation of auditory signal traits (e.g. volume, frequency, and tone) would have been difficult for an athlete to comprehend (Sigrist et al., 2013). The use of different drumbeats has been applied to manipulate whole limb temporal sequencing in netball throwing with mixed success (Helmer et al., 2010), which contains less information than in this thesis. Therefore, it appears that visual BFb is logically the better selection to convey a high volume of complex information.

Colours were used to encode sequential pattering within the visual BFb of Chapters 4 and 5, with green depicting joints were in sequence, and red for out of sequence. A limitation that arose during testing is that binary colour choices do not provide the athlete with detailed error detection information on how close they were to task success. Error information assists in correctional behaviours with movement (Anderson et al., 2005), therefore a greater range of colours could be useful in future research using visual BFb.

Research within this thesis primarily manipulated joint extension velocity magnitudes whilst also ensuring proximal to distal sequencing of joint extensions were maintained. However, a specific timing extension pattern was not defined. The kinematic chain has been suggested to rely on 'optimal' timing (Bobbert et al., 1987; van Ingen Schenau and Bobbert., 1988), however it is difficult to prescribe optimal zones when these are not clearly known. Future work, using individual mathematical modelling, could perhaps provide this data. This individualisation of data is both time and labour intensive, and as it is only applicable to individual athletes, practical applications are hindered.

6.3.3. Biofeedback Content

During Chapter 3 it was identified that the athletes with higher sword velocities and superior lunge distance had a greater increase of proximal-to-distal angular velocity in the rear leg kinematic chain. Further, ankle kinematics were significantly correlated with horizontal propulsive forces. However, in Chapter 4 the rear leg kinematic chain was manipulated to enhance the proximal-to-distal joint extension magnitude and sequential patterning with a view that this would also enhance external force generation. The expected finding was supported within the kinematic chain literature (Jacobs et al., 1996; Hof, 2001; Wong et al., 2016), Achilles tendon research (Bobbert, 2001; Roberts and Azizi, 2011) and BFb literature (Winchester et al., 2009; Rice et al., 2010; Mullineaux et al., 2012). While utilisation of the rear leg kinematic chain was enhanced there were no significant changes in any of the external kinetric measures. Further, Chapter 4 confirmed the lack of a correlation between rear leg angular extension magnitudes and Impulse_Y (n=4416). In contrast to the published literature, the body of evidence generated within this thesis suggests that primary BFb variable alterations do not necessarily produce indirect secondary changes to external GRF kinetics.

Chapter 2 discussed the importance of an empirical link between BFb content selection and the targeted variables. When focusing on secondary influences of BFb from kinematics to kinetics, a simplified model of the human body is built on musculature manipulating rigid segments (Winter, 2009). Clearly, human anatomy is more complex. Therefore, if kinematic and kinetic changes are sought the provision of both movement and the resulting forces may be required. Combining the two data sources can be achieved using one of two main methods; 1) the provision of joint kinetics, or 2) external kinematics with a secondary kinetics variable incorporated, either as a ‘condition’ or additional information. The selection of either options is dependent on the skill being used and the specific changes sought. Inverse dynamics analysis is clearly useful if looking to manipulate internal kinetics linked with injury prevention or disease (Ford et al., 2015; Jackson et al., 2017; Richards et al., 2018b), but from a performance perspective a multitude of joint torques can create the same technique (Latash and Zatsiorsky, 1993). Therefore, in cases where a prescriptive technique is required to generate specific external ground reaction forces, then combining both kinematic and related kinetic variable outcomes is probably better.

6.3.4. Group and Individual Analysis Techniques

Biomechanics, as a discipline, tends to use group-based contrasts (e.g. skill, gender, injury) to summarise general technique (Bartlett et al., 2007). Group-based analysis often masks differences within and between different athletes (Hunter et al., 2004; Glazier and Mehdizadeh, 2018). Technical models established from group-based contrasts is often then applied to individuals to facilitate skill changes toward this general technique, observed at the group level. Considering that inter-individual technique is variable, the idea of a group 'optimal technique' may be unfounded. Even elite athletes have individual technical idiosyncrasies due to training status, injury history and differing anthropometrics (Bartlett et al., 2007). The group-individual led approach has been termed the 'ecological fallacy', as general statements may not actually be applicable to specific individuals (Piantadosi et al., 1988). It poses interesting questions on the limitations of biomechanical BFb when derived from group responses. However, group responses make it possible to identify performance trends and provide insight into general technique which is needed as an initial starting point to see if modifications can be made (Lees, 2002; Glazier and Mehdizadeh, 2018).

To combat these limitations, this thesis incorporated both group and individual analysis approaches, providing a more holistic approach to understand skill development as a result of BFb. Chapter 3 applied a group contrast approach to identify technique-based differences. However, 10 trials were collected for each individual, meaning that individual means would have been more representative of true performance (Mullineaux et al., 2001). One supporting argument for the group analysis in this thesis is that the bi-articular morphology of the lower limb is an inherent component of the human neuromuscular design, with stereotypical patterns both on an individual (Wong et al., 2016) and group level (Wagner et al., 2011). Further, individuals were instructed to increase their own extension magnitudes, rather than to match a group derived value.

Chapter 4 maintained a group analysis approach to identify changes in technique with statistical confidence, and for results to be generalisable beyond the confines of this thesis. Problematically, averaging individual responses treats inter-individual variability as movement noise and essentially smooths out trends (Bartlett et al., 2007) therefore individual non-responders could have masked the true effect of BFb. Indeed, the inter-individual variation in hip, knee and ankle angular velocity was large enough to mask changes in Ankle_{ω}, but normalising intra-individual responses as a percentage of baseline, allowed these changes to be more clearly evaluated.

To allow for the identification of individual responses to the BFb within this thesis, Chapter 5 culminated in the development of a new methodology (CI2_{Area}) to identify individual technique exploration as a result of the BFb. CI2_{Area} used higher order variables by quantifying global coordination variability kinematics of two segments. Changes to the individual CI2_{Area} was analysed using linear regressions over the longitudinal time period with the gradient compared to the Control group’s 95% confidence interval upper bound. The use of 95% confidence intervals is equivalent to 1.96 SDs which means that if an individual’s data exceeded this limit, then a true change is more likely to have occurred. Using this approach, this thesis was able to evaluate individual responses to BFb.

A methodological issue which arose within the BFb intervention of Chapter 4 and 5 related to individual responses of the distance selected for target placement for the adapted lunge skill. The target was placed 1.5 leg lengths away, in fitting with previous fencing research (Yiou and Do, 2000; Bottoms et al., 2013), and pilot testing. However, it became apparent with a few individuals that they were able to satisfy the task demands of propelling their CoM with in excess of 1.5 leg lengths within a few sessions which meant that the target became a limiting factor to propulsive capabilities. In an applied setting the target would have been moved further based on individual progression, however as this did not happen with all participants the distance was maintained to uphold scientific rigour. Research has argued that multiple, individual baselines should be used in biomechanical research (Stergiou and Scott, 2005). However, given the novel nature of this research, individual thresholds are difficult to ascertain. Ultimately, it cannot be ruled out that external kinetics did not increase further once propulsion was inhibited by target placement.

6.3.5. Quantification of the Kinematic Chain used as Biofeedback Content

Several approaches have been applied to quantify the kinematic chain, but not all of these are suitable as BFb content. For example, mathematical models are overly complex, and coordination coupling may be difficult for individuals to interpret. Linear end point velocities could be applied, and are often used in high distal velocity movements (Putnam, 1993; Lees et al., 2010), however these are limited without being able to provide anatomical orientations for technique. In this regard, joint angular velocities are useful, as used in this research, because they allow for an assessment of the intrinsic biomechanical dynamics of the task.

Inverse dynamics analysis (IDA) provides data which is anatomically relevant, and the incorporation of kinetic information allows for the net contribution of muscle groups to movement to be ascertained (Winter, 2009). However, the IDA approach does not take bi-articular musculature into account (Cleather et al., 2011) which is paramount to the theoretical argument underpinning the research within this thesis because bi-articular muscles influence the rotation of segments that they are not directly attached to (Latash and Zatsiorsky, 1993). Further, IDA requires a multitude of data inputs, including a large number of retroreflective markers to capture segment dynamics. For this research to remain applied, a reduced lateral marker set was used which meant that the motion capture could seamlessly identify an individual and provide information within a few seconds of each trial. This also allowed for the potential of future technological applications to build from this work in terms of a BFb sensor using accelerometers for applied assessments. The lateral markerset does, however, have limitations in that long axis rotation is missed, which is considered a contributing factor in high velocity movements (Marshall and Elliot, 2000).

6.3.6. Quantification of Coordination and $Coord_{Var}$

Chapter 5 applied a modified vector coding technique (Chang et al., 2008; Needham et al., 2014) to quantify lower limb coordination between two joint couplings. The modified technique is advantageous as it allows for joint coupling coordination to be quantified into four frequency 'bins' which allow for simple characterisation of segmental relationships during movement. As identified in Chapter 5, VC binning is not sensitive to small changes in vector orientations due to the use of frequency bins with thresholds, meaning that slight changes in technique are not detected.

Currently, a greater limitation when quantifying coordination of the lower limb kinematic chain is that existing methods only account for two mechanical degrees of freedom. The kinematic chain is an interaction of three joints in both the upper (Wagner et al., 2011; 2014) and lower limb (Gregoire et al., 1984; Putnam, 1993; Jacobs et al., 1996; Bobbert and van Soest, 2001; Cleather et al., 2011; Cleather et al., 2015). Research has offered conceptual approaches to qualitatively assess three joint interactions (Irwin et al., 2018) but has not yet offered a quantifiable measure of coordination of three joints. Work in running has investigated three joint synchronisations (Diss et al., 2019) but this approach only provides a single discrete value, which is not anatomically relevant for practitioners altering technique.

It was identified in Chapter 2 that vector coding (VC) is susceptible to noise artefacts with changes in vector length (Stock et al., 2018). Therefore, Chapter 5 led to the development of a new technique to quantify coordination variability between two joints ($CI2_{Area}$). $CI2_{Area}$ offers a simple solution to quantify global $Coord_{Var}$ of two joints. However, while $CI2_{Area}$ appears to be a reliable tool, as a new method this still requires evaluation in regards to the validity in a range of different individuals, groups, and skills. For instance, increased variability was assumed to represent exploration, but further empirical studies would provide stronger evidence to support this assumption.

6.4. Novel Contributions to Knowledge and Practical Applications

This thesis has provided novel contributions surrounding both the practical and conceptual applications of biomechanical biofeedback toward modifying whole limb technique. In addition, this body of work has advanced understanding of skill development through a dynamical systems framework, and proposed a new methodology for future research and assessment of skill development in applied settings. Through the thematic framework guiding the approach of this thesis, the conceptual and practical applications of BFb were enhanced. The following sub-sections cover the salient contributions arising from this body of work.

6.4.1. Assessment of the Whole Limb Contributions to Movement

Human movement utilises bi-articular musculature, and whole limb coordination, to create movement (van Ingen Schenau, 1989). Research has shown that manipulating components of this kinematic chain can influence other, related variables (Baggely et al., 2017). While the kinematic chain has been assessed in a variety of sporting movements, Chapter 3 highlighted that often the kinematic chain is not assessed as a whole with many biomechanical investigations focusing on specific, individual joint variables. Theme 1 of this thesis provided a novel contribution by demonstrating how quantifying the whole lower limb allows a more holistic overview of technique, using the fencing attacking lunge skill as an example. This approach provides practical guidelines and considerations for the applied practitioner should consider secondary effects when attempting to develop complex skills.

6.4.2. Practical Contribution on BFb to Whole Limb Technique Changes

Chapter 2 focused on refining a large volume of information related to the provision of BFb to provide guidelines and considerations to developing successful KP interventions. Through these guidelines, and building on the content identified in Chapter 3, Theme 2 (Chapter 4) created a BFb intervention focusing on the development of whole limb technique. While reviews of BFb literature exist (Magill, 1994; Ericksen et al., 2011; Sigrist et al., 2013; Lauber and Keller, 2014) these offer limited guidance as to how to directly create an intervention to target specific variables. High frequency, terminal, visual KP BFb designs could increase angular velocities of three joints, and maintain a sequential pattern, in a propulsive whole limb complex skill.

Demonstrating effective changes, and the decisions supporting the intervention creation, supports important contributions to KP BFb literature. BFb research transcends disciplines, as a culmination of knowledge from multiple disciplines (e.g. biomechanics, Mullineaux et al., 2012; motor control, Newell, 1985; psychology, Wulf et al., 1998; neuroscience, Grooms et al., 2016; and coaching practice, Etnoyer et al., 2014). While advantageous to have multiple discipline viewpoints, this has led to conflicting literature in many cases (e.g. Wulf et al., 2010 and Keller et al., 2014). Chapter 4 demonstrated application of a BFb intervention to modify whole limb kinematics developed using a body of evidence presented in Chapter 2 and 3. This Theme offers findings derived from guidelines, and practical recommendations, that have clear implications to enhance and frame future applied practice.

6.4.3. Conceptual Understanding of BFb Influence on Skill Development

By combining two distinct, yet complementary approaches, of traditional biomechanical analysis and DST, Chapters 4 and 5 enhanced understanding of the influence of BFb on complex skill development. Findings in Chapter 4, as addressed previously, demonstrated the effectiveness of the BFb approach used within this thesis. Chapter 5 applied a linear breakpoint analysis technique to the longitudinal hip, knee and ankle angular velocity data. Findings highlighted that changes occurred relatively early on, providing evidence that complex skill interventions may need regular review in application to ensure continual skill progression. While previous interventions have highlighted changes in single variables, with just a few visits (Swinnen et al., 1997; Etnoyer et al., 2013; Nunes et al., 2014; Creaby et al., 2016), no research to date has quantified how quickly these changes can actually occur within an intervention. The breakpoint analysis is a useful practical tool to monitor changes in long term skill development for athletes, coaches, and clinical practitioners.

Complementing the breakpoint analysis, Theme 3 was further addressed in Chapter 5 through incorporation of coordination and coordination variability analysis from a DST approach. Findings highlighted that while coordination patterns did not change as a result of the BFB, as quantified by modified vector coding techniques, coordination variability did. While BFb has been postulated to guide skill development processes in simple skills (Lauber et al., 2013), this thesis provides novel evidence using a complex skill. Participants were seen to initially reduce coordination variability during self-learning, and then to significantly increase exploration strategies as guided by the BFb.

These findings offer support for frameworks of motor learning (Bernstein, 1967; Newell, 1985), with strong evidence established from a longitudinal data set from a skill development intervention through the stages of learning (Newell, 2003). Not only does this thesis offer novel insights into complex skill motor learning, it highlights the potential application of BFb as a tool to accelerate the skill development process for future research.

6.4.4. Development of a New Method of Coordination Variability, and a Practical Approach to Identify Individual Skill Development

Existing methods are well established to quantify $\text{Coord}_{\text{Var}}$ using vector coding approaches. The standard deviation of the vector angle (Heiderscheit et al., 2002) or standard deviation of both the vector angle and length (Tepavac and Field-Fote, 2002) provide a measure of $\text{Coord}_{\text{Var}}$, but both VC methods are susceptible to noise artefacts related to changes in vector length that can overinflate the variability output (Stock et al., 2018). Within Chapter 5 a new method to quantify $\text{Coord}_{\text{Var}}$, CI2_{Area}, was developed which avoids the statistical noise artefacts inherent within the VC methods. An additional advantage of CI2_{Area} over VC based methods is that it can be applied to identify the spread, or variability, of any bi-variate data, as it builds on the bi-variate analysis technique, CI2 (Mullineaux, 2017). This means that as an approach CI2_{Area} offers a wide range of practical solutions for time series analysis.

$\text{CI2}_{\text{Area,}}$ also offers a distinct advantage over previous $\text{Coord}_{\text{Var}}$ in that it allows for statistical comparisons between group and individual levels using a discrete value, whereas VC based variability methods provide time-series data that only summarises vector orientations. $CI2_{Area}$ envelopes all vectors in a given data set, and essentially summarises the area covered by the spread with a discrete value. Chapter 5 expanded on this approach by incorporating longitudinal data over a 26-week intervention and applying linear regression analysis. This novel approach, using $CI2_{Area}$, provides a method for longitudinal assessment of skill development, and offers an invaluable insight into stages of learning (Newell, 2003). As a relatively simple method, this approach has the potential to allow sport scientists, coaches, athletes and clinical practitioners to monitor variability over time. In short, $CI2_{Area}$ can be used to assess skill development in relation to motor learning (Bernstein, 1967; Newell, 1985; Newell and Vaillancourt, 2001), potentially distinguish between dysfunction in performance or disease (Lipsitz, 2003; Hamill et al., 2012) and be used in support of injury prevention.

By comparing individual $CI2_{Area}$ gradients ($CI2_{Slope}$) to group $CV_{Gradient}$ 95% confidence intervals, an approach to quantify individual learning rates was created. Within the context of this thesis, Chapter 5 applied this method to identify individuals that responded to the BFb in both hip-knee and knee-ankle joint $Coord_{Var}$. The development of the individual approach is important to allow an intervention to be accessed in catering for individuals, rather than the statistical many, with group means not washing out individual data trends (Bartlett et al., 2007). This methodological approach has potential for rehabilitation and clinical settings to assess an individual’s deviations from the group, or indeed their own normative values, allowing for individual case analysis.

6.5. Directions of Future Research

Through a critical appraisal of the methodological approaches and findings within this thesis there are a number of future research directions that can build on this body of work. These relate to BFb, future applications of $CI2_{Area}$ as an applied tool, and the need to better understand neuromuscular control arising through the application of BFb.

6.5.1. Linking Kinematic and Kinetic Content in BFb

While Theme 2 established that the visual BFb was able to manipulate whole limb kinematics, the lack of secondary effects on external GRF kinetics was a surprising result which warrants further investigation. The theoretical relationship between changing kinematic variables and subsequently influencing GRF kinetics exists (Winchester et al., 2009; Rice et al., 2010; Mullineaux et al., 2012), however confounding variables may interfere with secondary influence of kinematic BFb to alter external GRF. These could be related to intricacies of the internal soft tissue structures (Bobbert, 2001; Roberts and Azizi, 2011) and internal dynamics (Bobbert et al., 2012), the content selection of BFb (Richards et al., 2018a), or the implicit task dynamics inhibiting additional propulsion (e.g. target distance). This warrants future research which should seek to build on existing BFb approaches to investigate whether the BFb content within this thesis were an inhibiting factor.

It seems reasonable, that more detailed information relating to specific joint timing could be influential in the power transfer mechanism (Bobbert et al., 1987; van Ingen Schenau and Bobbert., 1988; Bobbert and van Soest, 2001). Pertaining to future research building from the findings of this thesis, however, the incorporation of kinetics into a whole limb BFb intervention and a control group without kinetic BFb would allow for a distinction between the task not facilitating secondary changes to kinetics, or the BFb content. This approach could incorporate kinematics and external kinetics, or using joint kinetics as a combination of the two data sources which has shown success in anterior cruciate ligament injury prevention programmes (Beaulieu and Palmier-Smith, 2014; Ford et al., 2015; Grooms et al., 2018).

6.5.2. Confirmation of $CI2_{Area}$ Validity and Reliability

The development and application of $CI2_{Area}$ proved to be an effective method to analyse longitudinal changes of $Coord_{Var}$ in Theme 3. While it appears to demonstrate strong face validity, as a new approach future research should seek to assess the construct validity of $CI2_{Area.}$ As an approach, $CI2_{Area}$ has many similarities to vector coding, but with subtle differences in how $CI2_{Area}$ encapsulates data. Comparisons between the two prevalent vector coding techniques (Heiderscheit et al., 2002; Tepavac and Field-Fote, 2002) and another vector encapsulating approach have been shown to be robust to statistical noise (Stock et al., 2018), but this was applied to simulated data. Therefore, research should seek to apply $CI2_{Area}$ to a range of different movements, individuals and data sets and compared to more conventional methods quantifying coordination variability (e.g. continuous relative phase or vector coding). From a practical perspective, the application of $CI2_{Area}$ using different inputs, such as accelerometer data, would also be a useful venture.

6.5.3. Application of $CI2_{Area}$ to Determine Intervention Modifications

Chapter 5 advanced $CI2_{Area}$ to create individual linear regression slopes, allowing for individual identification of $Coord_{Var}$ changes over time ($CI2_{Slope}$). The new methodology was then able to identify whether or not individuals were exploring coordination patterns as a function of the BFb guidance. Within this research, this approach was used to essentially identify whether individuals responded to the BFb. From a DST perspective, coordination variability has been proposed to increase with explorative learning, and then decrease as skill is formed, before finally increasing again once an individual has acquired a consistent outcome and can manipulate the environment to be more efficient (Bernstein, 1967; Newell and Vaillancourt, 2001; Wilson et al., 2008). Within this thesis a linear regression was applied to $CI2_{Area}$ profiles as it fit the data, however additional curve fitting techniques could also be incorporated which would cater for trends in $Coord_{Var}$ associated with stages or learning. Regardless, applications of longitudinal variability analysis extend toward any intervention which involves alteration in movement dynamics as an assessment tool. Therefore, future research applying this technique into a range of sports, clinical settings and biological paradigms is warranted using changes in $CI2_{Area}$ over time as a criterion threshold to alter intervention provisions.

6.5.4. Incorporation of Muscular Control into BFb Research

Throughout this thesis, the research themes focused on the contribution of the kinematic chain to CoM propulsion (Theme 1), the assessment of BFb to manipulate the kinematic chain (Theme 2), and explorative strategies of the kinematic chain. This body of work operated on assumptions from a body of literature supporting the power transfer mechanisms of bi-articular musculature of the lower limb (Gregoire et al., 1984; van Ingen Schenau, 1989; Jacobs et al., 1996; Bobbert and van Soest, 2001; Cleather et al., 2011; Cleather et al., 2015; Wong et al., 2016). However, changes in muscle recruitment and activation were mostly ignored. The scope of this thesis was to investigate the use of KP BFb to manipulate complex skills, which proved to be successful. The incorporation of surface electromyography (sEMG) could be used to investigate changes is muscular recruitment with BFb. Taking this one stage further, techniques and technology to decompose a sEMG signal have recently emerged (Contessa et al., 2016), offering a methodology to quantify neuromuscular control. EMG decomposition could be incorporated into future research to analyse changes in motor unit recruitment within the lower limb as a response to whole limb BFb, offering a physiological explanation as to how BFb influences the emergence of complex skills.

6.6. Thesis Conclusion

The aim of this thesis was to identify the effectiveness of KP BFb on influencing a whole limb complex motor skill, and the subsequent longitudinal retention. By combining traditional biomechanical approaches with a dynamical systems framework to learning a more holistic understanding around the influence of BFb of movement was developed. An explosive, complex skill was used as a vehicle for analysis throughout.

To achieve this aim, a series of research questions were developed which underpinned three progressive themes; 1) **identify** biofeedback content which encapsulates whole limb contributions to movement, 2) **assess** the effectiveness of biofeedback to manipulate whole limb technique, and 3) **examine** learning as a consequence of biofeedback guidance through the perspective of Dynamical Systems Theory.

The first methodological approach identified that elite fencers utilised the rear leg kinematic chain to a greater extent than novices, with larger proximal to distal joint angular extension velocities resulting in greater propulsive capabilities. The second methodological approach used the kinematic chain content as BFb to successfully manipulate whole limb kinematics, although no kinetic changes were shown in external kinetic measures. Finally, a longitudinal 26-week intervention was used to assess how BFb influenced learning. Biomechanical changes occurred within just two visits, however exploration strategies, measured using a new coordination variability method, continued throughout the entirety of the BFb intervention in the BFb group. Throughout both BFb interventions, the Control group showed no significant changes.

This thesis has provided novel contributions surrounding both the practical and conceptual applications of biomechanical biofeedback toward modifying whole limb technique. Through the progression of the three themes, this body of work has advanced understanding of skill development, incorporating a dynamical systems framework, offering guidelines for future BFb application, and proposed a new methodology for the assessment of skill development in applied settings.

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APPENDICES: Appendix 1

Biofeedback Explanation Sheet

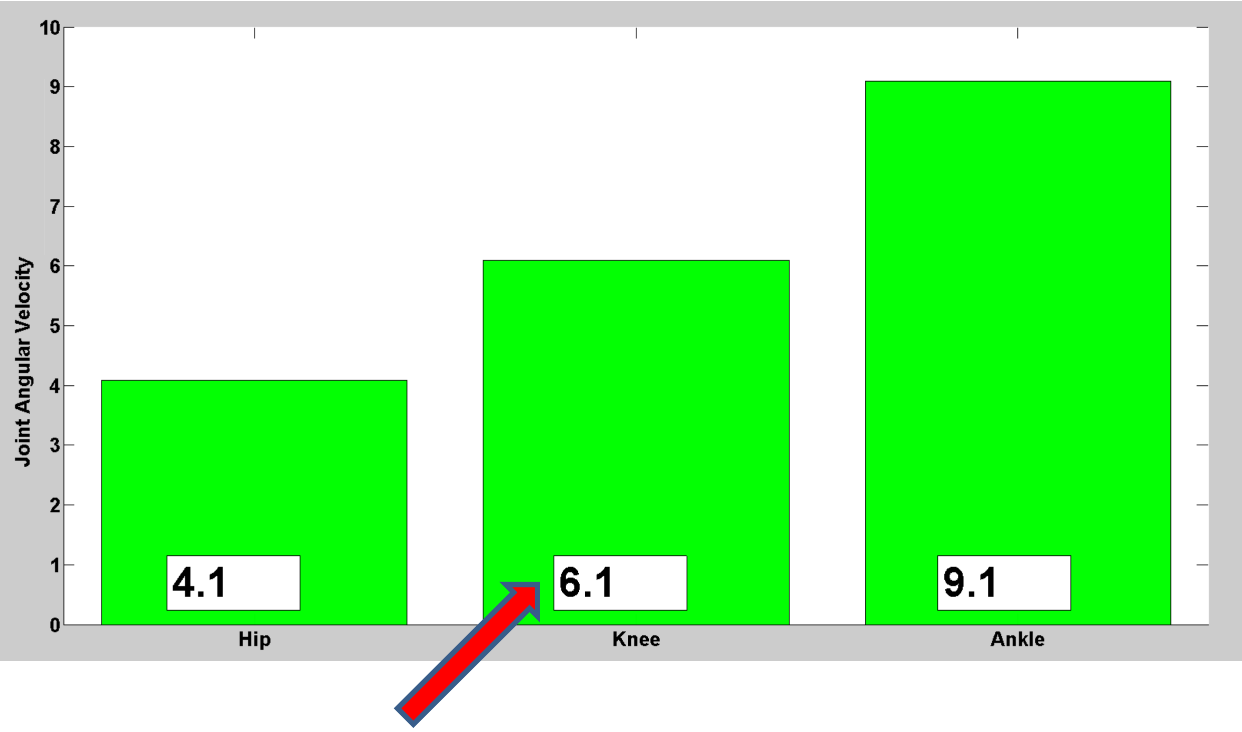
This study is investigating ***"the provision of key information on the quality of movement, to achieve a performance outcome",*** *termed Biomechanical Biofeedback.*

Biomechanical Biofeedback Used in this Research:

During this research project, you will receive information on hip, knee and ankle joints of one leg. This will be the limb responsible for your forward propulsion.

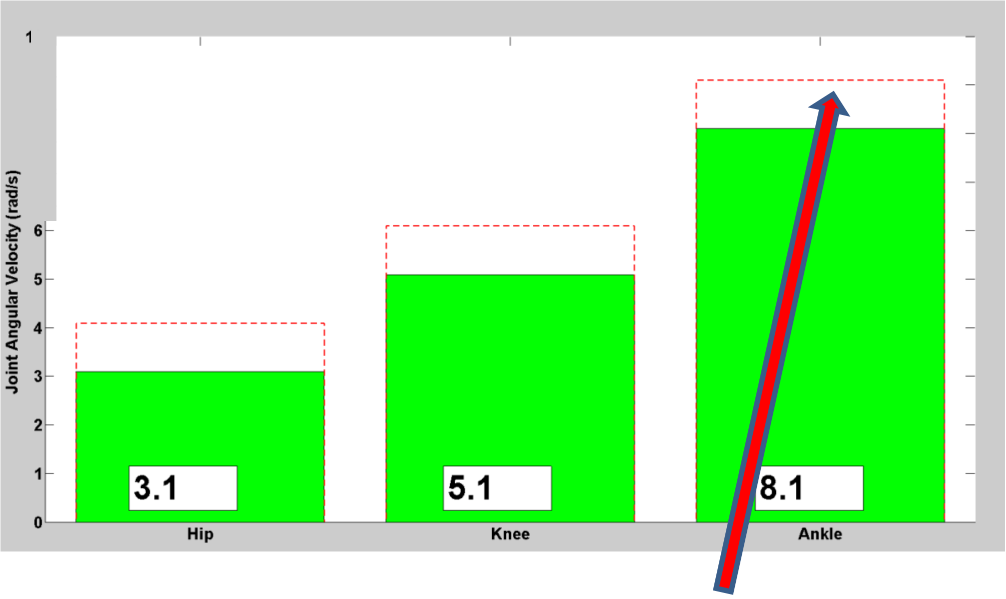
The information you receive will be on the straightening velocity of each joint.

THE BIOFEEDBACK:



The bar height is displayed in the in the middle of each bar. The velocity should increase in magnitude from hip – knee – ankle. This is visually displayed with bar height.

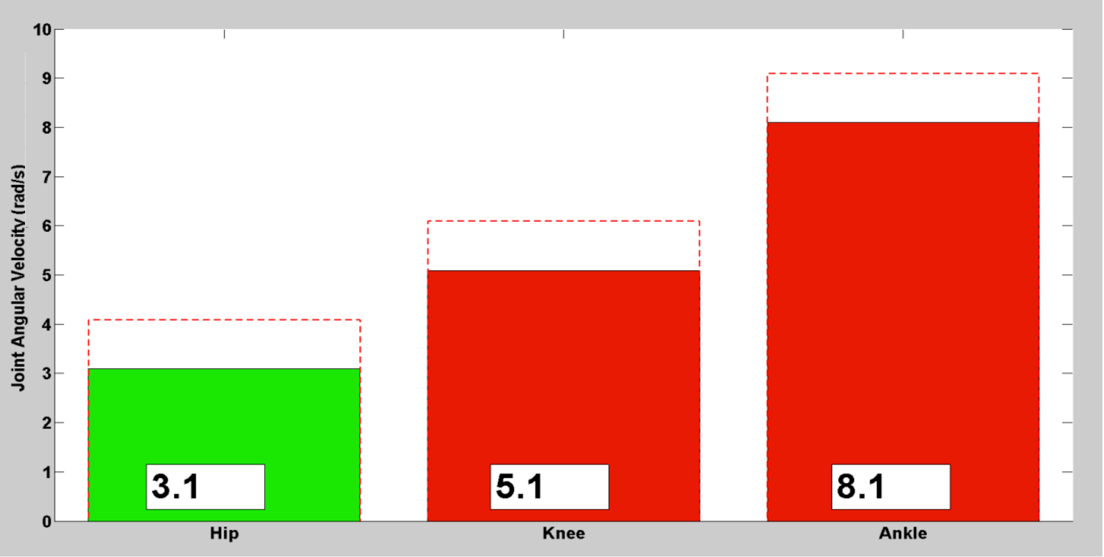
PERSONAL BEST VALUES:



Following each subsequent trial, a red dotted line will appear on each bar. This is the ***maximal velocity*** achieved at each joint. This is your ***personal best*** from all of your trials.

***You need to try and beat this every trial**

JOINT ORDER / MOVEMENT SEQUENCE:



Optimal sequence in the rear leg joints for propulsion extends from ***hip to knee to ankle***. If your sequencing is correct, all of these will be green.

If your sequence is out of order (e.g. ***hip – ankle – knee***) then the out of sequence joints will be red. ****You need to aim for all of these to be green***

IN SHORT

Propel yourself forward as quickly as possible, aiming for:

1) The height of each bar to be above dotted red line.
2) All bars to be green, indicating you moved each joint in the right order.