COORDINATION OF PLACE KICKING IN RUGBY UNION

by

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DECLARATION

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SUMMARY

Place kicking is a crucial skill in rugby as more than 40 per cent of the points scored in professional rugby matches are achieved by means of place kicks. Research in rugby kicking has mainly focussed on isolated segment position or movement, with limited literature on segments moving relative to each other. The aim of this study was to identify characteristics of place kicking technique from a coordination and coordination variability perspective.

Ten male kickers performed five trials from three different distances (40 m, 32 m, and 22 m) in a range that proficient kickers should convert successfully 80 per cent of the time. An optoelectronic motion capture system consisting of ten cameras were used for capturing total body kinematic data. Data collection took place outdoor, on a rugby field. Data reductions included normalisation of kicking phases, extracting discrete kinematic variables, joint angles, joint and segment coordination patterns (hip-knee, knee-ankle, and pelvis-torso), and coordination variability measures. ANOVA comparisons were made on discrete data, while statistical parametric mapping repeated measures ANOVA analysis was used for continuous variables to determine differences groups differences. Coordination patterns were determined by means of vector coding technique. A bivariate method of calculating the area of the ellipse at each time point was used to determine the coordination variability. A hierarchal cluster analysis was performed on sagittal plane angles at kicking events to determine different technique profiles.

Parameters such as greater hip extension and external rotation during the backswing ($p=0.001$, $p=0.015$) as well as increased pelvic external rotation ($p=0.015$) in the 40 m kicks compared to the 22 m and 32 m kicks are related to the formation of the tension arc in attempt to increase foot speed by means of the stretch-shortening cycle. The 40 m kicks had increase knee flexion ($p<0.001$), increasing the pre-stretch in the thigh muscles. Both factors allow greater force to be applied to kicking foot over greater distance during forward swing.

During the forward swing a period of in-phase is reported as both the hip and the knee were flexing, creating a whip-like action. During the backswing the pelvis and thorax worked together to create a tension arc, while during the forward swing, the anti-phase with pelvis dominancy was seen. The pelvis was main mover for tension arc release, while the thorax stays more stable. Even though absolute changes in joint angles were seen, no changes were reported for the coordination patterns when kicking at different distances (22 m, 32 m, 40 m). An investigation into coordination variability found no differences between groups, indicating no change in movement strategy when kicking at different intensities. The cluster analysis revealed three clusters of sagittal plane kinematics describing a knee-dominant, hip-dominant as well as a combination technique.

Stemming from the above, place kick training can benefit by coaching cues and drills focussing attention on tension arc formation, and the rhythm of movements. These results impart the knowledge that different distances require similar movement coordination strategies.

Keywords: place kicking technique, inter-segment inter-joint coordination, vector coding, coordination variability

OPSOMMING

Die stelskop in rugby is ‘n kritiese vaardigheid aangesien meer as 40 persent van die punte aangeteken in ‘n professionele rugbywedstryd te danke aan stelskoppe is. Navorsing in rugby skoppe het meestal geïsoleerde fokus op indivduele segmente, beperkte navoring focks op hoe segmente beweeg relatief tot mekaar. Die doel van die studie was om te eienskappe van stelskoppe te identifiseer vanuit ‘n koördinasie en koördinasie veranderlikheid perspektief.

Tien manlike skoppers het elk vyf skoppe vanaf drie verskillende afstande (40 m, 32 m, en 22 m) was vanaf die pale uitgevoer in area waar goeie skoppers 80 persent skopsukses het. Toerusting wat gebruik is vir data-insameling sluit ‘n tien-kamera bewegings analise sisteem in. Data was verwerk deur die normalisering van skop fases, onttrekking van diskrete kinematiese veranderlikes, gewrigshoeke, gewrigskoppelinge (heup-knie, knie-enkel, pelvis-torso), en koördinasie veranderlikheids maatreëls. ANOVA vergelykings is gedoen op die diskrete data, terwyl statistiese parametriese kartering herhaalde metode ANOVA analise uitgevoer is op die kontinue data om beduidende verskille tussen groepe te bepaal. Koppelingshoeke is bepaal deur hoek-hoek plotte en vektorkodering om koördinasie patrone te bepaal. ‘n Tweeverandelike metode is gebruik om die area van die ellips te bereken om die koördinasie variasie te bepaal. ‘n Klusteranaliese was uitgevoer om sagittalevlak skop tegnieke te bepaal.

Veranderlikes gekoppel aan spanningsboog formasie, insluitend grooter heup ekstensie en eksterne rotasie gedurende ($p=0.001$, $p=0.015$) is verhoog in 40 m skoppe in vergelyking met die 22 m en 32 m skoppe, sowel as meer eksterne rotasie van die pelvis ($p=0.015$). Die 40 m skoppe het ook verhoogde knie fleksie ($p<0.001$) getoon in vergelying met die kort afstand skoppe. Beide faktore verhoog krag toegepas oor ‘n groter afstand, op die skopvoet.

Koördinasie patrone vir die heup-knie koppeling toon dat die knie die primêre beweger is gedurende die terugswaai. Gedurende die vorentoe swaai kom daar ‘n periode van in-fase voor waartydens die heup en knie albei fleksie ondergaan, wat 'n sweepslag aksie van die onderste ledemaat tot gelvog het. Gedurende die terugswaai werk die pelvis en toraks saam om 'n spanningsboog te vorm, terwyl tydens die vorentoe swaai word anti-fase met pelvis dominansie gesien. Die pelvis was dus die primêre beweger vir die vorentoe swaai wat oorseenstem met die vrylating van die spanningsboog, terwyl die toraks meer stabiel bly. Alhoewel absolute verskille gesien is met skoppe vanaf verskillende afstande, bly die koördinasie patrone konstant. 'n Ondersoek rakende die koördinasie variasie het geen verskille tussen groepe gevind nie wat daarop dui dat daar geen verandering in die bewegings strategie was wanneer geskop word met verskillende intensiteite nie. Dit word vermoed dat die skoppers goed ingeoefende bewegings patrone gehad het vir skoppe vanaf al die afstande.

Gebaseer op die bogenoemde resultate, kan navorsingsresultate afrigters help om op spanningsboog, ritmiese koördinasie patrone en die tydsberekening van bewegings te fokus. Die resultate van die studie dui daarop dat geen verandering in bewegings pattrone nodig is nie wanneer daar geskop word met verskillende afstande vanaf die pale.

Sleutelwoorde: stelskop tegniek, intersegment intergewrig koördinasie, koördinasie variasie, vektorkodering

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ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
BC	Ball contact
ADD/ABD	Adduction/Abduction
Anti	Anti-phase
CA	Coupling angle
CAF	Central Analytical Facilities
CAV	Coupling angle variability
CRP	Continuous relative phase
cm	centimetre
CV	Coordination variability
deg/s	Degrees per second
Dist	Distal phase
F/E	Flexion/Extension
FIFA	Fédération Internationale de Football Association
In	In-phase
IR/ER	Internal Rotation/External Rotation
KL	Kicking leg
KLTO	Kicking leg initial foot-off
m	Meter
m/s	Meters per second
MS	Movement strategies
MV	Movement variability
NKS	Non-kicking side
NoRMS	normalised root mean square
Prox	Proximal phase

ROM	Range of motion
SPM	Statistical parametric mapping
SPSS	Statistical Package for Social Sciences software
SL	Support leg
SLC	Support leg contact
SLTO	Supporting leg foot off
TA	Tensions arc
TOB	Top of backswing

DEFINITIONS

Joint coupling	Coordination between two joints during a movement.
Coordination	Relative timing and movement of interacting body segments.
Movement execution	Refers to the way in which a task is performed (joint angles and segment positions).
Movement outcome	The outcome of a movement pattern (foot speed at ball contact).
Performance outcome	The outcome of the kick; it would be successful if the ball passes over the crossbar.
Movement strategy	The neuromuscular reaction to perform a movement under specific conditions and altering parameters of the environment, organism or task (such as altering kicking intensity/distance from posts).

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

Rugby Union (commonly referred to as “rugby”), including the recent variations of the traditional game, have become one of the most popular sports in the world. The attendance at the 2015 Rugby World Cup was amongst the highest of any single sports event, only preceded by the FIFA (Fédération Internationale de Football Association) World Cup (Arnold & Grice, 2015). Worldwide about 9.1 million men, women and children play the sport in World Rugby member unions (World Rugby, 2018). In rugby players fulfil position-specific roles within the 15-player team. Place kicking has become a specialised skill where a team would typically have one player performing the place kicking role.

Successful place kicking can contribute significantly to a team’s prospect of winning a match. A place kick to convert a five-point try is worth two points, and a place kick for a penalty is worth three points. An analysis of 582 international rugby matches showed that, if the place kicking performance was reversed, the outcome would be different in 14 per cent of the matches (Quarrie & Hopkins, 2015). Therefore, successful kicking could contribute significantly to winning a match. As rugby is becoming more professionalised, teams are turning to scientific, evidence-based research to provide them with the competitive edge.

Although, the place kick in rugby is regarded a vital part of the game, relatively little scientific research has investigated the skill of place kicking, specifically from a biomechanical perspective. Studies reporting on specific angles, velocities, and ranges of motion, provide a detailed understanding of the place kick. In order to collect this type of information for a rugby place kick, a full-body, three-dimensional (3D) motion analysis is essential (Davids, Lees & Burwitz, 2000) as the movement occurs across three planes of movement with involvement of lower- and upper body segments (Bezodis, Willmott, Atack & Trewartha, 2014). In rugby research, the place kicking technique has been investigated in recent years using 3D motion analysis.

The place kick is a complex movement involving multiple segments, joints, and muscles requiring quantitative investigation. Studies reporting on specific angles, velocities, and ranges of motion, provide a detailed understanding of various movements. The execution of a place kick is divided into five distinct phases, namely: 1) an approach towards a stationary ball, 2) planting of the support leg next to the ball, 3) backswing of the kicking leg, 4) the forward swing of the kicking leg to hit the ball with maximal endpoint velocity by the kicking foot, and 5) the follow-through after ball contact where the slows down (Atack, Trewartha & Bezodis, 2014; Zhang, Liu & Xie, 2012).

Research has mainly focussed on the kicking leg, including the hip and knee joints in isolation, focussing on angles and angular velocities. The kicking leg has been identified in research an important aspect as knee extension is reported to be the most significant contributor to foot speed at ball contact (Atack, Trewartha & Bezodis, 2017; Sinclair, Taylor, Atkins, Bullen, Smith & Hobbs, 2014; Zhang *et al.*, 2012). The kicking leg follows a specific kinematic sequencing pattern, where the kicking leg moves from the top of the backswing towards ball contact. The hip flexion velocity reaches a peak velocity first during the downswing, then starts to decelerate, and thereafter, the knee extension reaches peak velocity just prior to ball contact, termed "proximal-to-distal sequencing" (Atack *et al.*, 2014; Bezodis, Atack, Willmott, Callard & Trewartha, 2018; Bezodis *et al.*, 2014; Bezodis & Winter, 2014; Koike & Bezodis, 2017; Zhang *et al.*, 2012). Other than the description of peak velocities, the patterns of lower limb joint movements relative to each other has not been investigated in rugby kicking.

It is not only the function of the kicking leg that was deemed important but also proximal segments up the kinetic chain. Investigations into upper body segments include the angle of the pelvis relative to the torso, as well as the angular position of the non-kicking side arm. A larger relative pelvis-to-torso angle (termed "tension arc") aids in kicking foot velocity by means of the stretch-shortening cycle, but needs to be controlled as it may influence kicking accuracy (Atack, Trewartha & Bezodis, 2016, 2019; Green, Kerr, Olivier, Dafkin & Mckinon, 2016). The non-kicking side arm aids in the relative pelvis-to-torso rotation and contributes to performance by stabilizing the body in the mediolateral direction by opposing the momentum of the kicking leg (Atack *et al.*, 2014; Bezodis, Trewartha, Wilson & Irwin, 2007; Green *et al.*, 2016). Again, no research in rugby place kicking investigated the movement of the pelvis relative to the thorax across the entire kicking phase.

Adding to the complexity of place kicking, a trade-off exists between the performance objectives of accuracy and distance (Green *et al.*, 2016). The ball must be kicked with enough velocity to ensure that the ball has the required distance to pass over the crossbar, as well as with proper direction to pass in between the two upright posts. A variety of muscles and joints are required to work together to execute a successful kick. The rugby place kick occurs from various positions on the field during a match and the ability of the kicker, to convert successfully from various distances is advantageous. In Australian rules football, foot speed at ball contact, as well as shank angular velocity are two of the three best predictors of distance kicking, along with ball position at ball contact (Ball, 2008). Other factors related to increased kicking distance in Australian rules football include larger step length and approach velocity (Ball, 2008, 2011). Increasing approach velocity was identified as a very easy way for a kicker to achieve greater foot velocity (Ball, 2011). The kicker, therefore, needs to coordinate their joints and segments to hit the ball with enough velocity and to achieve an optimal direction.

Coordination refers to controlling the multiple degrees of freedom in order to complete a task (Li, Alexander, Glazebrook & Leiter, 2016). In other words, the quantification of how joints and segments move relative to each other, and the timing of these movements are essential aspects of coordination. It could be argued that coordination may be the key to performance in rugby kicking as it could provide insight into the movement strategies used by the kicker to perform a kick. Analysis of coordination allows the researcher to evaluate how joints or segments work together to achieve a goal.

Coordination variability gives an indication of the amount of change of movement patterns used to perform a specific task and could provide information on the flexibility of the motor system (Hafer & Boyer, 2017). Coordination variability has been related to expert performance and injury prevention

(Preatoni, Hamill, Harrison, Hayes, van Emmerik, Wilson & Rodano, 2013; Stock, Wilson, Mcleod & Emmerik, 2017), but has not been investigated in rugby place kicking. This study will investigate coordination and coordination variability in place kicking at different distances from the posts (22 m, 32 m and 40 m).

As the place kicking skill in rugby is complex and crucial to the success of a team, the sport is modernizing and becoming more scientifically driven, where place kicking is being researched with high-tech equipment. The novelty of this study includes a full body analysis, on an outdoors rugby field, with the correct target space (distance to the posts) and multiple kick distances. This study addressed the limitations of doing indoor, laboratory-based testing protocols, namely incorrect footwear and distance from the target as the kickers are usually are asked to kick into a net, potentially having a psychological effect on the effort level. This study utilizes modern coordination analysis instead of traditional kinematic measures of amplitude using discrete values, which adds to the novelty

1.2 PROBLEM STATEMENT

It is clear from literature that the place kicking technique has been investigated, with mainly an isolated focus on the segments or areas of interest. Place kicking requires the coordination or interaction of multiple segments of the human body and timing of each segment relative to the other. Several performance indicators of place kicking have been identified; such as peak knee extension velocity and relative pelvis-to-torso ROM. However, the question arises whether coordination may be the primary key to performance in kicking. The only feature of coordination reported in literature is the kinematic sequencing pattern of peak velocities in a proximal-to-distal manner.

Quantifying coordination could provide insight into the movement strategies used in different types of kicks, such as a hip-dominant or knee-dominant movement strategy. Coordination includes the organisation of joint- and segment interaction in goal-directed activity (Li *et al.*, 2016). The coupling angle is a time-continuous outcome measure that can be used to quantify coordination between two moving elements of the musculo-skeletal system and could be used to get more insight into different coordination strategies used under different task constraints.

Based on scientific evidence, coaches are currently unsure whether kicking technique should change with kicking close- and long-range kicks. This programme of study will, therefore, investigate how kicking characteristics change when a kicker is asked to kick at various distances from the posts. The study is novel and unique as data were recorded in an outdoor, field-based environment with rugby posts to replicate a realistic place kick situation and provide the kicker with the opportunity to execute the movement as naturally as possible. As opposed to the laboratory-based studies, kickers were able to 1) wear their own boots, 2) visually see the posts (the size and distance from the target), and 3) set themselves up in a way they would on the field. Kickers were instructed to kick the ball from three different kicking distances, by moving the posts closer or further.

1.3 SIGNIFICANCE AND MOTIVATION

The purpose of this research study was to determine how movement execution differs when a kicker is asked to kick from various distances from the posts and consequently, contribute to the scientific pool of knowledge on the biomechanical analysis of place kicking in rugby. Adding information on coordination- and movement variability (MV) regarding the place kicking technique at different distances might provide insight into the change in a kicker's movement pattern in order to solve task demands such as achieving long-range kicks. Improving the knowledge and understanding of coordination- and coordination variability in the place kicking technique might contribute to evidence-based training programs regarding the place kicking skill. Evidence-based research is crucial to support the coach in creating drills and to identifying kicking technique characteristics to focus on for a favourable results, such as increased kicking distance (Bezodis & Winter, 2014). An example could be cues such as *Stretch-Plant-Snap*, for kickers to focus on tension arc formation and release as well as the rhythm associated with these motions.

1.4 SCOPE

This research study investigated the discrete kinematic variables, continuous coordination variables, and coordination variability of place kickers in association with performance outcomes and kicking intensities. A successful place kick consists of accuracy and distance. However, the study focussed mainly on movement execution. Kicking success was recorded and used to distinguish between successful and unsuccessful trials. Accuracy was not recorded nor used to corroborate the trade-off between distance and accuracy.

The main focus of the study was to determine differences in kicking kinematic when asked to kick at different distances perpendicular to the posts (22 m, 32 m and 40 m). The study does not investigate the effect of kicking at different angles. This research study investigates the kicking technique of general rugby kickers (university and club level), not professional kickers and should be considered when interpreting the results. Data was segmented into backswing and forward swing phases only, with ball contact terminating the phase. The approach as well as the follow-through was not investigated.

1.5 RESEARCH AIMS, OBJECTIVES, AND HYPOTHESES

Research aims

The aim of the study was to identify characteristics of place kicking technique from an inter-joint and inter-segmental coordination and coordination variability perspective in male university and club level place kickers. The objectives were to compare the differences between place kicking attempts at 22 m, 32 m, and 40m from the posts, respectively in terms of variables listed in Table 1.

Table 1: Objectives of the research study related to the first aim of the study

Objective One	Objective Two	Objective Three	Objective four
Discrete kinematic variables	**Joint angle and angular velocity curves**	**Segment couplings (Coupling Angle)**	**Coordination variability**
Angles at ball contact, ROM and peak velocity for: • Ankle in sagittal plane • Knee in sagittal plane • Hip in sagittal plane • Pelvis in transverse plane • Thorax in transverse plane	Knee (KL) Hip (KL) Thorax Pelvis	Hip-knee joints Knee-ankle joints Pelvis-torso segments	Hip-knee joints Pelvis-torso segments
Foot speed at ball contact			

KL: Kicking leg

The second aim of the study was to determine if different forward swing techniques or movement strategies exist in a group of male university and club level place kickers. The fifth objective was to evaluate the sagittal plane angular position of the knee, hip and thorax at various kicking events.

Hypothesis One

It was hypothesised that there would be no significant difference in discrete kinematic variables between place kicks at 22 m, 32 m, and 40 m from the posts.

Hypothesis Two

It was hypothesised that there would be (a) no significant difference in joint angle curves, and (b) no significant difference in angular velocity curves between place kicks at 22 m, 32 m, and 40 m.

Hypothesis Three

It was hypothesised that there would be no significant difference in segment couplings between place kicks at 22 m, 32 m, and 40 m.

Hypothesis Four

It was hypothesised that there would be no significant difference in coordination variability between place kicks at 22 m, 32 m, and 40 m.

Hypothesis Five

The final hypothesis was that there would be distinct movement patterns can be identified based on the angular position of the knee, hip and thorax at three forward swing events.

1.6 ASSUMPTIONS

This research study assumed that variation in movement is fundamental and would be observable in coordination variability measures. It was assumed that changes in coordination measures are as a result of manipulating the distance. It was furthermore assumed that the equipment used within the ambit of this study elicited reliable measures. It was also assumed that the participants had a sincere interest in participating in the study and therefore performed the kicking tests to the best of their abilities.

1.7 OVERVIEW OF DISSERTATION

Chapter Two provides a presentation of the current literature regarding the kinematic analysis of place kicking in rugby as well as coordination and coordination variability and how it can be applied to research on kicking. In Chapter Three provides an overview of the methodological procedures used within the ambit of this research study. Chapter Four presents the results of the research, with Chapter Five providing a discussion of these results including the conclusions are drawn and future research areas recommended.

CHAPTER TWO: LITERATURE REVIEW

2.1 INTRODUCTION

This chapter provides an overview of the current literature available on rugby place kicking with reference to other kicking disciplines such as soccer and Australian football. Firstly, an introduction is given about rugby and the significance of the place kicking skill. Thereafter studies focussing on kinematic analysis of place kicking are presented in terms of 1) the approach, 2) planting of the support leg, 3) the lower body kinematics including the kicking leg knee and hip, 4) the upper body kinematics including the pelvis, thorax and non-kicking side arm, and 5) the trade-off between accuracy and distance. Coordination and movement variability are then described as well as methods used to calculate these measures. Finally, task constraints are presented within the ambit of this study.

2.2 RUGBY AND PLACE KICKING

Rugby Union (hereafter referred to as “rugby”) has become more popular than ever before. The 2015 Rugby World Cup drew a record number of 2.47 million spectators to the tournament (Arnold & Grice, 2015). In recent years, rugby has grown to a global sport, with 121 counties making up more than 9.1 million players (World Rugby, 2017). World Rugby has seen unprecedented growth from 16 teams participating in the first World Cup in 1987 to 95 teams in 2015 (Arnold & Grice, 2015). Rugby is one of the most popular sports in South Africa and has an estimated 603,455 players (World Rugby, 2017).

The place kick in rugby is a critical aspect of the game, as it allows teams to gain points after a try is scored or when a penalty is awarded. With the place kick, the ball is stationary and positioned on a kicking tee. The kicker is allowed a short run-up to execute the kick. The ball must travel between the two upright posts and over the crossbar to be awarded points.

The place kick can be split into three phases, namely: 1) the approach, 2) kicking phase, and 3) follow-through (see Figure 1). The kicking phase can further be divided into a backswing with hip extension until a peak is reached – this is commonly referred to as “top of backswing”. Thereafter, the forward swing follows to ball contact (Atack, 2016).

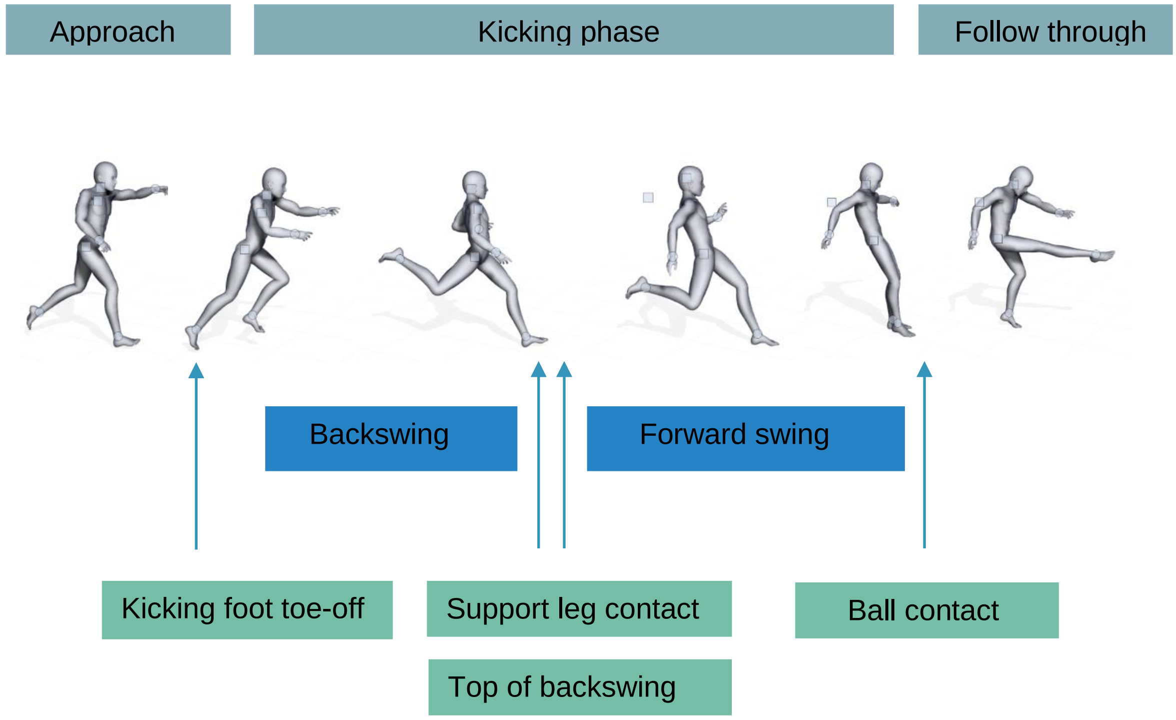


Figure 1: Kicking events and phases for a right-footed kicker
Source: Author, 2019

An analysis of 582 international rugby matches from 2002 to 2011 reported that the place kick contributed to 45 per cent of the total points scored in a match (Quarrie & Hopkins, 2015). Highlighting the importance of the place kick, Quarrie and Hopkins (2015) added that if the kicking accuracy by the two teams was reversed, the outcome of the match would have changed in 14 per cent of the matches. Despite the importance of the place kick, little research has focused on the technical analysis of place kicking (Zhang *et al.*, 2012).

Rugby kicking, similarly to soccer instep kicking, consists of a run-up towards to ball, increasing the speed of the centre of mass of the body to achieve an optimal velocity of the foot at ball contact. Approaching the ball at an angle will allow the pelvis and kicking leg to move through a large ROM in order to achieve a high velocity at ball contact (Davids *et al.*, 2000). After the approach, the general characteristics of the kick include the support leg that is planted on the ground next to the ball. The backswing of the kicking leg creates a greater ROM to generate more force and leg speed before ball contact potentially. The thigh then moves forward, followed by the shank moving passively through the knee. Finally, the quadriceps contract to extend the knee in order for the shank to achieve maximum speed at ball contact, while the thigh is decelerating (Zhang *et al.*, 2012).

Recently, the kinematics of kicking in rugby has received some attention in the literature. Research focussing on 3D analysis is explained in further detail in the following section.

2.3 KINEMATIC ANALYSIS OF THE PLACE KICKING MOVEMENT IN RUGBY

Although scarce, some research has focused and highlighted specific elements of the place kicking movement pattern such as 1) the approach, 2) support leg, 3) kicking leg, 4) pelvis and trunk, 5) non-kicking side arm, 6) kinematic sequencing, and 7) trade-off between accuracy and distance. These studies will be discussed in more detail below.

2.3.1 APPROACH

The approach is an individualised aspect of rugby place kicking, with very little scientific research available within the field of rugby. In contrast, the instep kick in soccer has been widely researched. With regards to the approach of soccer instep kicking (kicking of a stationary ball, comparable to rugby place kicking), some primary aspects of the approach have been studied (see Figure 2). A curved approach consisting of two to four steps was proposed to be optimal for performance (Lees, Asai, Andersen, Nunome & Sterzing, 2010). Andersen and Dörge (2011) reported on the influence of different run-up speeds on the maximal speed of the ball executing the kick of a stationary ball. Maximal ball speed was achieved during the self-selected approach speed. The authors concluded that an approach of self-selected speed would lead to kicking success in terms of distance; however, accuracy was not accounted for.

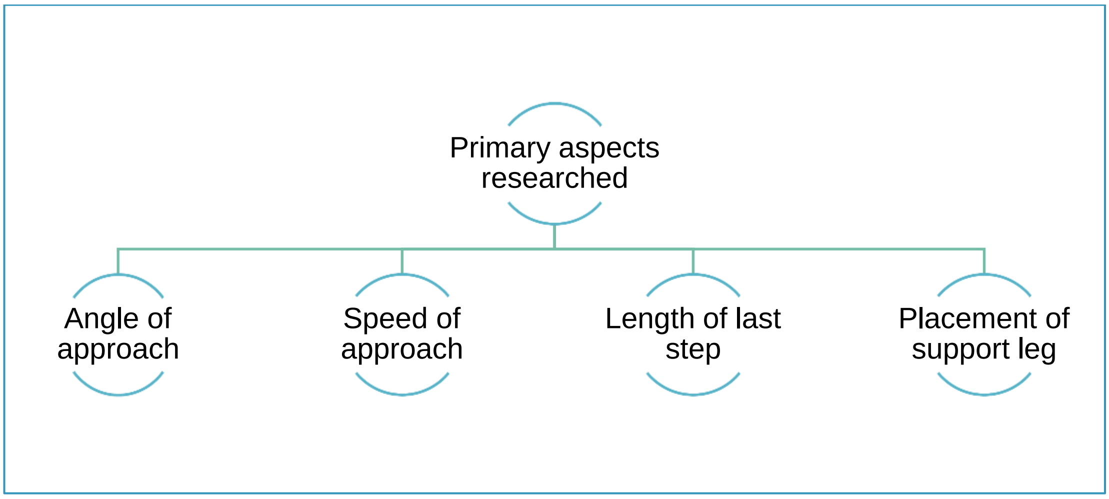


Figure 2: Primary aspect of the approach featured in kicking
Source: Author, 2019

In rugby, the final steps of the approach of 15 elite kickers were investigated (Cockcroft & Van Den Heever, 2016). Each kicker was asked to perform ten kicks toward a target in a laboratory, rating the comfort of the kick after each attempt. Large variability in the approach angles was reported (inconsistency mean of 1.6 m), as well as the foot positioning of the penultimate two steps before final planting of the support leg with and inconsistency mean of 0.023 m for the penultimate step (Cockcroft & Van Den Heever, 2016). These findings support the concept that the approach characteristics are largely individualised, however some approach variables have been linked to kicking success.

The length of the last step has been identified as a critical characteristic of rugby kicking performance. Cockcroft and Van Den Heever (2016) described the length of the last step to be 1.523m (± 0.124m). A more substantial final step will provide a greater ROM at the hip of the kicking leg, enabling higher speed generation at ball contact. A large last step was also found to be used for distance kicking (Ball, 2008). Lees and Nolan (2002) indicated that for soccer instep kicking, increasing the length of the last stride of the approach was associated with longer range kicks. It was hypothesised that the increase in the length of the stride leads to greater pelvic retraction, thus allowing for more pelvic protraction while executing the kick (Lees & Nolan, 1998; Zhang *et al.*, 2012).

Similarly, it has been reported that greater ROM at the hip of the kicking leg, during the backswing, the more leg speed can ultimately be generated at ball contact (Zhang *et al.*, 2012). With the pelvis being rotated backwards, a longer final step will allow for greater ROM of the kicking leg – the foot can be taken back a further distance and can thus have greater acceleration up to ball contact (Davids *et al.*, 2000). This theory was also supported by research conducted in Australian football where it was reported that hip angular velocity decreases towards ball contact, while pelvis angular velocity continues to increase to ball contact. It was suggested that rather than hip extension, the length of the last step leads to greater pelvis ROM, thus allowing increased pelvis angular velocity at ball contact (Falloon, Ball, Macmahon & Taylor, 2010).

2.3.2 SUPPORT LEG PLANTING

The planting of the support leg next to the ball represents the end of the approach phase (Zhang *et al.*, 2012). With a minimal sample size, the effect of different instep foot positions on ball velocity was investigated (Baktash, Hy, Muir, Walton & Zhang, 2009). Three university-level players were asked to plant their support leg at four different positions. No significant difference was found in ball velocity with the four different foot positions. Therefore, no ideal foot position was reported. Accuracy may have been influenced but was not measured. It was speculated that the player could compensate for the different foot positions by shifting his body weight (Baktash *et al.*, 2009). Methodological limitations were present in this research study, namely the small sample size of three kickers, competency of the kickers, testing environment, lack of trials, as well as footwear that were not externally valid. In the study conducted by Baktash *et al.* (2009), kickers were forced to place their support leg on predetermined positions. Cockcroft and Van Den Heever (2016) found the natural foot placement of 15 professional rugby kickers to show little inter-subject variability (33 cm ± 3 cm lateral to the tee and 3 cm ± 7 cm behind the tee) indicating a consistent movement across the sample of elite kickers, similar to findings in soccer chip kicking (Chow, Davids, Button & Koh, 2005). Baktash *et al.* (2009) found no difference in foot speed when players were asked to place the support leg in different positions relative to the tee; however, Cockcroft and Van Den Heever (2016) found a similar natural position in a sample of elite kickers. In the study conducted by Baktash *et al.* (2009), three university level kickers were selected, whereas Cockcroft and Van Den Heever (2016) investigated a substantial amount of elite kickers. Both studies were conducted in a laboratory-based environment, where the kickers kicked into a net. Neither studies reported any accuracy measures, however Baktash *et al*. (2009) included ball velocity results of between 18.5 and 20.9 m/sec. Finally, no instructions to the kicker were reported in either study.

2.3.3 LOWER BODY

2.3.3.1 KICKING LEG

The kicking leg has received the most attention in research and has been investigated in terms of quantifying leg joint mechanics, contributions to foot speed, critical differences between kickers achieving different outcomes and determining the planarity of the kicking foot trajectory. Studies in kicking across football disciplines focussing on the kinematics of the kicking leg will be discussed below.

Kinematics of the kicking leg was described for the backswing, from the kicking leg toe-off to support foot contact, and forward swing to ball contact (Atack *et al.*, 2014) (see Figure 3). Thirteen players of various levels of play (community to international) were asked to complete six maximal kicks towards a target. For the kicking leg, hip extension is reported for the backswing while hip flexion is seen in the forward swing. The angular velocity of the hip decreases before ball contact (Atack *et al.*, 2014). Knee flexion is found during the backswing and continues up to 50 per cent of the forward swing phase; thereafter, knee extension occurs until before ball contact, where a knee flexor moment is observed (Atack *et al.*, 2014). The ankle stayed in a relatively plantar-flexed position, dorsiflexing just before ball contact (Atack *et al.*, 2014).

Similar findings were reported by Zhang *et al.* (2012), who found that thigh angular velocity increases up to peak values prior to peak shank angular velocity and then quickly decreases before ball contact. This was reported to be evidence of the proximal-to-distal sequence.

A clear link exists between foot velocity and ball velocity (Atack *et al.*, 2017; Kellis & Katis, 2007); therefore, a key performance indicator of a place kick is the generation of the high end-point velocity of the kicking foot at ball contact. The most efficient way of achieving an optimal end-point velocity of a linked system is with a proximal-to-distal sequencing pattern (Putnam, 1993).

Kicking foot velocity at ball contact is reliant on the movement of the distal segment, as well as proximal segments further up the kinetic chain (Zhang *et al.*, 2012). It was described that at the instance of ball contact, the contribution of the proximal segments to foot velocity would be small to zero. However, when looking at the time history of the proximal segments, they provide a substantial contribution. It is, therefore, essential to investigate the entire movement as the instant of ball contact will provide limited information (Putnam, 1993). During kicking, several segments interact in a proximal-to-distal sequence to transfer momentum to the kicking foot (Putnam, 1993), also called the “summation of speed” principle where maximal velocity will be reached at the most distal end-point (Putnam, 1993). Therefore, end-point speed could increase by increasing the speed of the proximal segments (De Witt & Hinrichs, 2012).

By means of Euler joint angle traces and angular velocities of the hip and knee joint, many researchers identified a proximal-to-distal sequencing pattern in peak knee and hip velocities for the kicking leg in rugby kicking (Atack *et al.*, 2014; Bezodis & Winter, 2014; Zhang *et al.*, 2012), as well as soccer kicking (Naito, Fukui & Maruyama, 2010; Nunome, Ikegami, Kozakai, Apriantono & Sano, 2006; Putnam, 1993) contributing to optimal end-point velocity of the foot at ball contact. The movement starts at the most proximal segment and progresses to the most distal segment for maximal speed at this segment. The proximal-to-distal sequencing pattern was observed with the forward swing of the kicking leg where the angular velocity of the thigh increases until it reaches a peak during the forward swing, then decreasing rapidly before ball contact. The forward velocity of the shank reaches a peak at ball contact (see Figure 3) (Atack *et al.*, 2014; Davids *et al.*, 2000; Zhang *et al.*, 2012). A proximal-to-distal sequence should maximise the velocity of the distal segment.

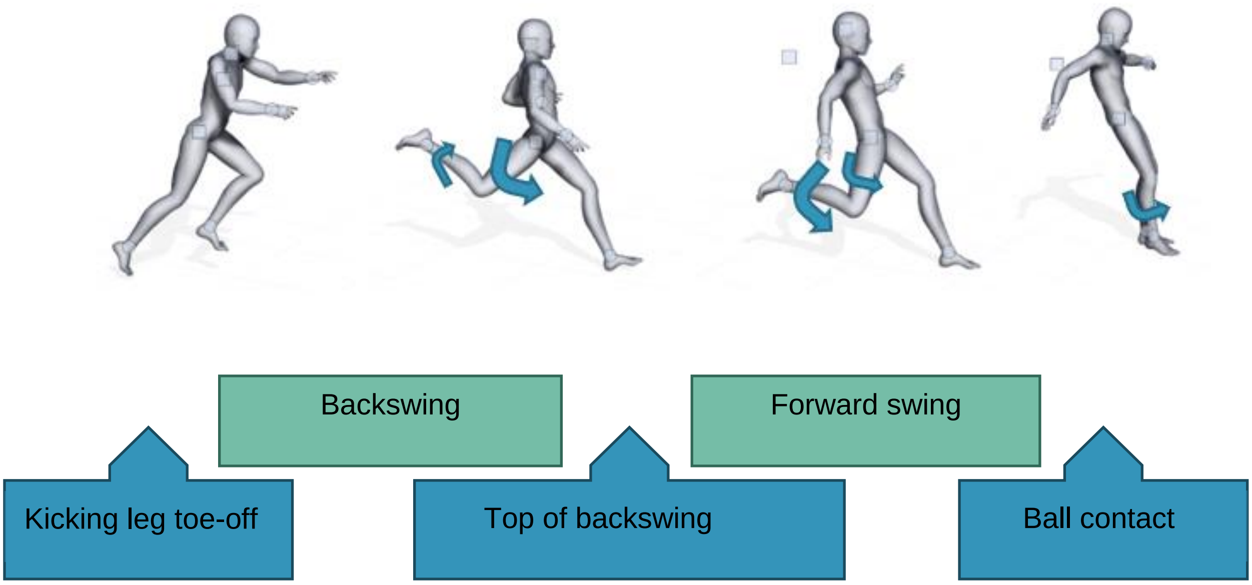


Figure 3: Angular trajectories during a rugby kick
Source: Author, 2019

In soccer kicking, Witt and Hinrichs (2012) commented that in achieving the greatest end-point velocity, the summation of speed principle is used where increasing the speed of the proximal segments will lead to transferred momentum from proximal-to-distal endpoint, increasing the speed of the foot at ball contact. However, Shan and Westerhoff (2005) reported that after the forward swing, the kicking phase is characterised by two distinct phases, namely: 1) the hip flexion angular velocity, and 2) stable hip angle where hip angular velocity is equal to 0. In the first phase, the hip undergoes flexion while the knee angle decreases to a minimum, then the knee angle starts to increase, with the ankle staying in a relatively consistent position (Shan & Westerhoff, 2005). The second phase (stable hip) contains the fastest rate of knee extension and dorsiflexion of the ankle, with a constant hip position. Hip flexion takes place first, thereby initiating the kicking action. Thereafter, knee extension takes over, with ankle dorsiflexion occurring at the same time (Shan & Westerhoff, 2005). Ball contact occurred with maximum deceleration of spine flexion and maximum deceleration of anterior pelvic rotation, indicating that pelvis- and hip motion comes to a halt at ball contact. This indicates zero angular velocity of the hip at ball contact, providing a stable platform for foot-ball interaction (Langhout, Weber, Tak & Lenssen, 2015; Lees *et al.*, 2010; Shan & Westerhoff, 2005).

In terms of the contributions of segments to the speed of the foot during a rugby kick, the most significant contributors to foot speed were knee extension, hip flexion, pelvis velocity and pelvis rotation (Zhang *et al.*, 2012). However, contributions were not constant during the entire kick. Each phase of the kick described different contributors to foot velocity. Firstly, during the backswing, hip and knee flexion was the primary contributor, while linear velocities of the pelvis and pelvic rotation negatively contributed to foot velocity. Then, during the first half of the forward swing phase, the linear velocities of the pelvis were the main contributors. Lastly, during the final half of the downswing phase, knee flexion was the primary contributor (Zhang *et al.*, 2012)**.** In terms of percentages, the most substantial contribution to foot velocity was made by the knee (75% ± 8%), followed by hip flexion (13% ± 2%), pelvis velocity (9% ± 1%), and pelvic rotation (2% ± 1%), while hip adduction/abduction, and internal/external rotation was negligible (Zhang *et al.*, 2012).

Similarly, research reported that knee extension angular velocity of the kicking limb at ball contact was the only significant predictor of ball velocity (Sinclair *et al.*, 2014). Supporting the importance of knee extension by means of comparisons, substantially more knee extension work is done by kickers achieving consistently greater distance compared to kickers achieving less than 32 m kicks (Atack *et al.*, 2017). Peak relative knee velocity, knee velocity, peak thigh segmental angular velocity, as well as foot centre of mass velocity were critical factors in creating high ball velocity. It was also reported that not only the events at impact are essential, but also events preceding ball contact, emphasising the importance of intersegmental coordination (De Witt & Hinrichs, 2012).

The concept of the motion-dependent moment was suggested, representing the action of the proximal adjacent and distant joints and how they are coupled to each other (Lees *et al.*, 2010; Nunome, Ikegami, *et al.*, 2006). It implies that kinetic sources other than the muscle moments are somewhat responsible for the pattern of segmental motion during kicking. When the hip and trunk musculature contributes to foot speed at ball contact, it will exceed the inherent force-velocity limitation of the muscles (Lees *et al.*, 2010). Improving the motion-dependent moment can result in an improvement of kicking performance (Nunome, Ikegami, *et al.*, 2006) and consequently, emphasises the importance of coordination as an aspect of successful place kicking (Bezodis & Winter, 2014; De Witt & Hinrichs, 2012).

A study investigating differences in kicking techniques between kickers achieving different outcomes described various dissimilarities in kicking leg kinematics (Atack *et al.*, 2019). When comparing the kickers performing successful in 32 m kicks with kickers who fell short (but with proper direction), it was found that the "short kickers" had decreased foot velocity (17.0 ± 1.5 m/s), compared to "long kickers" (20.3 ± 1.0 m/s) (Atack *et al.*, 2019). Slower foot speed was speculated to be due to less hip flexion and knee extension work during the forward swing, based on proximal-to-distal energy transfer. The "long kickers" had greater ball velocity than the "short kickers", while the kickers missing to the non-kicking side presented greater longitudinal spin, resulting in the ball veering off to the left. Kickers missing to the non-kicking side had more hip flexion and less knee extension (Atack *et al.*, 2017). It was speculated that the differences might be due to decreased strength capabilities, or the kickers might have decided to kick in a more controlled fashion in order to prioritise the accuracy constraint (Atack *et al.*, 2019; Sinclair, Taylor, Smith, Bullen, Bentley & Hobbs, 2017). Kickers were able to achieve a reasonable distance of 32 m from the posts, but failed in accuracy (missing the posts to the non-kicking side) and presented more positive hip flexion work and less positive knee extension work compared to kickers who were successful in the 32 m kicks. These findings can be aligned with Australian Rules Football, where two distinct groups of kickers were identified – the "thigh strategy" and "knee strategy" groups (Ball, 2008). Both groups achieved the same kicking foot velocity but used different movement patterns to achieve the outcome (Ball, 2008). In both studies, a dominant knee technique was desired for accurate kicking, possibly due to more control of the kicking foot direction (Atack *et al.*, 2019; Ball, 2008).

Current literature identified the importance of analysing the kinematics. It is suggested that increased peak hip extension angle and peak knee extension velocity are linked to improved performance by increasing foot speed at ball contact. There are no research (to the author's knowledge) reporting the inter-joint coupling between the hip and knee during rugby place kicking. The current study therefore aimed to address the gap by determining the motion of the hip and knee joint relative to each other, for the entire backswing and forward swing phase of the kick.

2.3.4 UPPER BODY

2.3.4.1 PELVIS AND TRUNK

Research has also paid attention to segments further up the kinetic chain. In an investigation of place kicking technique differences between successful and non-successful kickers, the hip and knee joint kinetics were calculated, as well as the orientation of the pelvis and the thorax, and rotation of the pelvis relative to the thorax. Kickers were grouped based on their performance outcome (ball clearing the crossbar, 32 m away). Kickers achieving more than 32 m were labelled as "long kickers", if the ball projectile was wide to the left or right, kickers were labelled as "wide kickers", and lastly, the kickers achieving less than 32 m were labelled "short kickers" (Atack *et al.*, 2017).

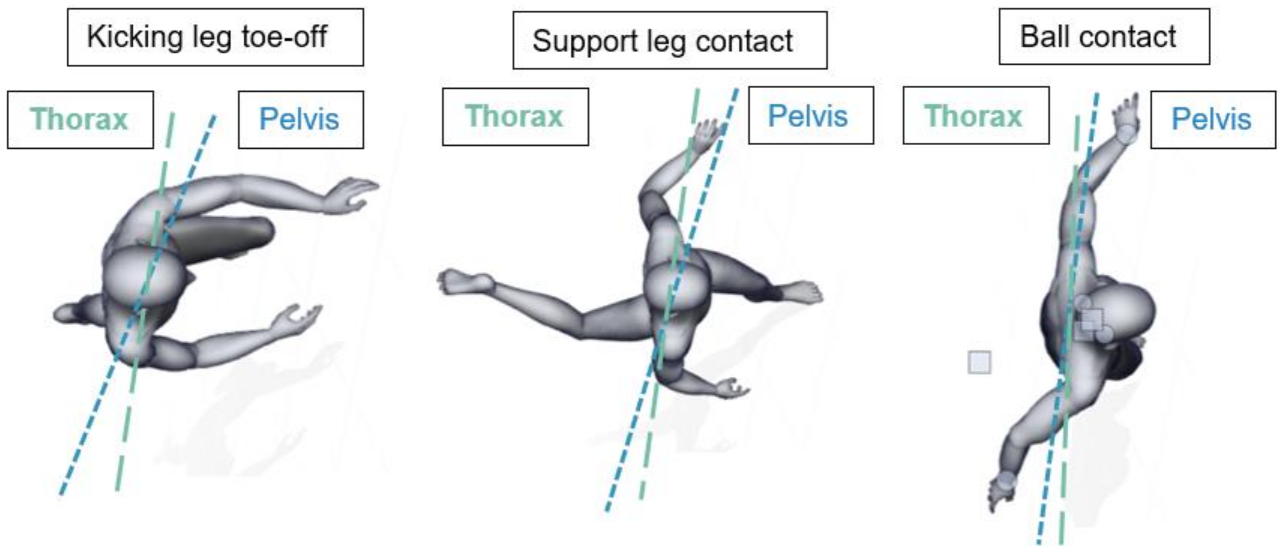


Figure 4: Top view of *a* kicker from kicking leg toe-off to support leg contact to ball contact
Source: Author, 2019

It was reported from the top of the backswing to initial ball contact (i.e., the forward swing) that all three types of kickers (short, long, and wide to the non-dominant side) had their pelvis and thorax faced toward the dominant side of the goalposts. The pelvis and thorax position (when viewing the kicker from the top) is graphically depicted in Figure 4. Short kickers had a more front-on position relative to the posts with less hip protraction, thus inhibiting kicking performance. Wide left kickers had similar pelvis motion; however, a significantly greater pelvis-to-thorax angle was noted with the thorax being more front-on. The large relative angle may, therefore, correlate with greater foot speed generation, but negatively influences accuracy (Atack *et al.*, 2017).

Green, Kerr, Olivier, Dafkin and Mckinon (2016) reported good to excellent correlations between trunk rotations (involving the shoulder action), pelvis rotation, and the distance of the kick when investigating the trade-off between accuracy and distance. Twelve university first team kickers kicked at the goal five times, recording data with an 18-camera OptiTrack, and AMASS (ADTech Motion Analysis Software System). It was speculated that the kinetic chain sequence starts at the trunk, followed by the rotation action of the pelvis. Other research supporting this hypothesis includes that trunk rotation could lead to greater knee extension velocities, thereby increasing foot speed (Naito *et al.*, 2010), trunk rotation has a small effect on foot velocity, emphasising the transfer of energy from the trunk to the legs (Zhang *et al.*, 2012), and greater pelvic retraction on the kicking side, generating more energy, thereby improving foot speed called the “tension arc” (Shan & Westerhoff, 2005) or X-factor. The tension arc has been described in soccer research and is related to the stretch across the upper body in accordance with the kicking leg backswing (Shan & Westerhoff, 2005). The body winds up before releasing during the forward swing, and can be quantified at maximal hip extension (top of backswing) using variables such as ROM of hip extension, spine extension, spine rotation to the non-kicking side, and anterior tilt in the pelvis (Langhout, Tak, Van der Westen & Lenssen, 2017). Fullenkamp, Campbell, Laurent and Lane (2015) showed the importance of the X-factor in generating ball velocity. However, Green *et al.* (2016) found that the X-factor stretch (the difference between shoulder- and pelvic movement) must be decreased for more accurate kicking, relating to the function of the non-kicking side arm.

2.3.5 ARMS

2.3.5.1 NON-KICKING SIDE ARM

In an investigation regarding the role of the non-kicking side arm, five university first team kickers were analysed on an eight-camera VICON system (Bezodis *et al.*, 2007). Each kicker completed seven kicks for accuracy as well as seven kicks for distance. It was reported that flexion and adduction of the non-kicking side arm are widely used in skilled payers before ball contact. This, however, was not the case with amateurs. It was found that additional arm movement resulted in an increase in ball speed in skilled players (Bezodis *et al.*, 2007). At support leg contact the non-kicking side arm and the kicking foot move as far as possible apart from each other and the support leg, causing a stretch across the body known as the tension arc, and follows the principle of the stretch-shortening cycling, allowing a quick forward swing (Bezodis & Winter, 2014).

Kicking is a 3D movement, confirmed by momentum occurring around all three axes and the non-kicking side arm moving in multiple planes. The shoulder moves mainly through flexion and adduction at ball contact (Bezodis *et al.*, 2007). It is, therefore, useful to describe the movement of the non-kicking side arm in absolute X, Y and Z components and emphasise the need for using 3D analysis when describing a kicking technique (Bezodis *et al.*, 2007).

The non-kicking side arm displayed minimal angular momentum in the front plane. Sagittal plane angular momentum displayed a peak close to ball contact. Greater non-kicking side arm sagittal plane angular momentum correlates with a greater whole-body anti-clockwise angular momentum in the sagittal plane at ball contact. The kickers with greater sagittal plane angular momentum also had greater accuracy. Kickers with greater sagittal plane angular momentum had increased trunk lean towards the kicking side at ball contact and decreased the distance between the kicking leg and support leg ankle joint centre at ball contact, improving the accuracy of the kick. A theory was developed that the kicking leg and non-kicking side arm interact to maintain balance in the mediolateral direction at ball contact (Bezodis *et al.*, 2007). Total transverse plane angular momentum is reduced by the clockwise momentum of the non-kicking side arm, opposing the anti-clockwise transverse angular momentum of the kicking leg, preventing over-rotation of the body (in the transverse plane) around the Z-axis (Bezodis *et al.*, 2007). Shan and Westerhoff (2005) also indicated the importance of the arm movement as they reported skilled players to have more effective upper-body movement compared to less skilled players, possibly related to balance/shifting of the centre of mass (Shan & Westerhoff, 2005).

Kicking performance can be improved by non-kicking side arm motion as greater kicking leg transverse momentum can be utilised without over-rotating the body. Transverse-axis rotation might be beneficial for distance kicking, but detrimental for accuracy kicking, as it is less controlled (Bezodis *et al.*, 2007; Green *et al.*, 2016).

Bezodis *et al.* (2007) referred to the importance of the timing of movement of segments as this will ensure that the non-kicking-side arm and kicking leg angular velocity peaks interact for kicking performance. In other words, if the velocity of the non-kicking-side arm and kicking leg peak at the same time, the body would be stabilised in the transverse plane.

2.3.6 TRADE-OFF BETWEEN SPEED AND ACCURACY

Ball speed has mainly been used as an indicator of success (Kellis & Katis, 2007), but the accuracy (direction) of the kick also needs to be considered to provide a successful outcome (Atack, 2016). Therefore, the two primary performance objectives of kicking in soccer or rugby are 1) kicking the ball with the most considerable amount of speed, 2) as accurately as possible. However, a trade-off between accuracy and distance have been identified by Andersen and Dörge (2011), Green *et al.* (2016) and Kellis and Katis (2007). Andersen and Dörge (2011) examined the influence of an accuracy constraint on the speed of the ball during a penalty kick. The average speed of the ball was between 28.60 and 34.48 m/s for kicks with no accuracy constraints, when the accuracy constraint was placed on the kicker, the ball speed decreased to 85 per cent of above-mentioned values. Lees & Nolan (1998) also found that ball speed and joint velocities, as well as hip and knee joint ROM, decrease when a kicker is instructed to perform their most accurate kicks.

The trade-off between accuracy and distance was also reported as some kinematic variables were positively correlated to distance and negatively correlated to accuracy, particularly pelvis and torso rotation (Green *et al.*, 2016). Supporting the above, other studies also reported a trade-off in rugby (Bezodis *et al.*, 2007), speculating that the torso rotation is the variable distinguishing between distance and accuracy (positive correlation with distance and negative correlation with accuracy).

Torso rotation had a small effect contribution to the overall distance of the kick (pelvis rotation being the principal determinant), but more torso action might place the kicker at risk for over-rotation (Bezodis *et al.*, 2007).

The upper body plays an important role in kicking success by formation of the tension arc producing a stretch across the body, which is released during the forward swing, contributing to increased foot velocity at ball contact. The pelvis and thorax segments are involved in tension arc formation where an increased relative pelvis-thorax angle corelates with increased kicking distance. In addition to the pelvis-thorax range of motion, it is evident that the non-kicking side arm aids in tension arc formation as well as stabilizing the total body momentum in the transverse plane, by limiting over rotation caused by the kicking leg. No studies in rugby kicking has investigated the motion between the pelvis and the thorax relative to each other. Only one study investigated pelvis-thorax coupling in soccer research, however, 2D analysis was used. The current study used a 3D motion analysis system, to ensure accurate data collection. Ecological valid data collection on a rugby field is important where the kicker is allowed to wear his rugby boots, allowing the support leg of the kicker to be planted in a stable position and creating energy transfer to the pelvis and thorax. Laboratory based studies, where kickers are wearing running shoes, is questionable as the player might slip or subconsciously control the support leg action to maintain balance.

2.3.7 METHODS USED IN THE ANALYSIS OF THREE-DIMENSIONAL RUGBY PLACE KICKING RESEARCH

Rugby kicking has gained more interest in the global scientific community. Initially, 2D video analysis was used to quantify the mechanics of place kicking (Aitchison & Lees, 1983). However, a sagittal and frontal view is insufficient as rugby kicking is a tri-planar, complex movement (Bezodis *et al.*, 2014). With the advances in technology, 3D movement analysis equipment became more popular. Differences in research methodologies, research questions, and variables investigated, make comparison across studies challenging. Table 2 represents the methods, variables, and data processing used by various studies that focus on the kinematics of rugby kicking.

Table 2: Study design and methods used in rugby kicking kinematic research

Reference	Aim	Population	n	Measurement	Trials	Equipment	Model	Distance/direction/Instructions
(Atack *et al.*, 2014)	Quantify and explain kicking leg joint mechanics	Different levels of play (community to international)	13	Indoor – 3D motion analysis (rugby boots)	6 Maximal kicks	10- or 11-camera VICON MX3 and MX3+, 240Hz (also GRF with Kistler, 960Hz)	Clusters	Maximal kicks
(Atack *et al.*, 2017)	Identifying differences in key kinetic and kinematic technique features between groups of kickers achieving different outcomes	Amateur to senior international	33 total: 18 long, 4 short, 8 wide	Indoor – 3D motion analysis	At least 5 maximal distance kicks	VICON MX3,240Hz, Kistler 9287BA force platform 960Hz	Clusters	Kickers grouped based on their performance (short, long, wide). Calculation of distance – would it clear 32m? Maximal effort
(Baktash *et al.*, 2009)	Investigation into four different foot position: Next to, Wide, In front, Behind	University (some experience)	3	Indoor – 3D motion analysis (incorrect footwear)	3 Trials in each foot position	8-camera VICON 612, 250Hz	Plug-in-Gait	Unclear
(Bezodis *et al.*, 2007)	How the NKS arm contributes to generation and control of whole-body momentum	University first team (at least five years of experience)	5	Indoor – 3D motion analysis	14 (7 accuracy, 7 distance)	8-camera VICON, 120Hz	Plug-in-Gait	7 accuracy, 7 distance (as far as they can kick)
(Bezodis *et al.*, 2014)	Determine the planarity of the kicking foot trajectory, and assessing two techniques of different data treatments	Community to age group international	13	Indoor – 3D motion analysis (own boots)	5 – 6 kicks	10- or 11-camera VICON MX3 or MX3+ 240Hz		
(Bezodis *et al.*, 2018)	Investigate how the properties of the kicking foot swing plane differ between accurate and inaccurate kickers + differences in SL and pelvis kinematics to improve performance	Skilled male (amateur to senior international)	33	Indoor – 3D motion analysis (own boots)	Only the best kick of each kicker was used	10-11 camera VICON MX, 240Hz & force plate (960Hz)		Successful vs Non-successful (Would it clear 32m?)
(Cockcroft & Van Den Heever, 2016)	Variation in step alignment and support foot positioning in a group of place kickers	Elite	15	Indoor – 3D motion analysis (incorrect footwear)	10	8 camera VICON, 200Hz. Bertec force-plate 1000Hz	Plug-in-Gait	Mid-range kicks (submaximal)
(Green *et al.*, 2016)	relationship between kinematic factors and kicking accuracy and distance	University first team	12	Outdoor – 3D motion analysis	5 maximal kicks	18 camera Optitrak flex,100Hz, AMASS	Plug-in-Gait	Kicks performed from midway on the halfway line
(Koike & Bezodis, 2017)	Determining the dynamic contributions to kicking foot speed in rugby place kicking.	Japanese male	3	Indoor – 3D motion analysis	5-8 kicks, far and straight, only 1 used for analysis	14 camera VICON, 250Hz, Kistler force plate, 1000Hz		Instruction to kick as far and straight as possible

(Sinclair *et al.*, 2014)	Identify important technical aspects of in-step rugby kicking pertinent to the generation of ball velocity	University first-team level (minimum of three years experience)	20	Indoor – 3D motion analysis	20	8 Camera (Qualisys), 500Hz. Force platform (Kistler)	Clusters on thigh, shank and pelvis	Unclear
(Sinclair *et al.*, 2017)	Differences in kicking kinematics when kicking towards a target and kicking for maximal velocity, in an attempt to identify the trade-off between accuracy and distance	University first team	10	Indoor – indoor 3D motion and Xsens	Unsure	500Hz optoelectrical motion capture system 8-camera (Qualisys)		Max: kick ball as hard as you can, Accuracy: kick ball into 0,5m by 0,5m square
(Zhang *et al.*, 2012)	Examining movement sequencing and contributors of motions of individual segments, to the velocity of the foot	University players (skilled)	7	Indoor – 3D motion analysis	12 trials Max kicking (3-5 practise)	8-camera VICON, 250Hz	Plug-in-gait	Maximal effort

Source: Author, 2019

Table 3: Variables used in rugby kicking kinematic research

Reference	Variables									Outcome
	Pelvis	Hip	Knee	Foot	Ankle	KL	SL	NKS arm	Trunk	Whole body	
(Atack *et al.*, 2014)		Angle, angular velocity, momentum, joint power	Angle, angular velocity, momentum, joint power		Angle, angular velocity, momentum, joint power						
(Atack *et al.*, 2017)	Pelvis orientation around longitudinal axis	Hip flexor work	Knee extensor work						Torso orientation around longitudinal axis	Relative pelvis-thorax rotation	
(Baktash *et al.*, 2009)		Angles and moments (X-, Y- and Z-direction) around BC	Angles and moments (X-, Y-, and Z-direction) around BC								Resultant ball velocity
(Bezodis *et al.*, 2007)						Angular momentum (X-, Y- and Z-direction)	Angular momentum (X-, Y- and Z-direction)	Angular momentum (X-, Y- and Z-direction)	Angular momentum (X-, Y- and Z-direction)	Angular momentum (X-, Y- and Z-direction)	Accuracy, ball speed (average 5m/s at 35 degrees above horizontal)
(Bezodis *et al.*, 2014)				Time-histories of kicking foot centre of mass							

(Bezodis *et al.*, 2018)				Kicking foot CoM, SL placement (CoM)						Whole body CoM	
(Cockcroft & Van Den Heever, 2016)				Foot positioning of the final three steps before BC							
(Green *et al.*, 2016)	Pelvis rotation		Knee extension (SL, KL)		Ankle extension (SL, KL)			Arm abduction (SL, KL). Elbow flexion (SL, KL)	Back flexion, Lateral bend, Torso rotation	Head rotation, Head flexion, X-factor,	Distance, Accuracy
(Koike & Bezodis, 2017)		Hip (KL, SL) F/E, Hip KL A/A	Knee KL F/E,	Time-histories of KL foot speed	Ankle KL P/D flexion				Torso I/E rotation		
(Sinclair *et al.*, 2014)		SL and KL Angle at BC, Peak angle, Angular velocity at BC and peak angular velocity (in X, Y and Z direction)	SL and KL Angle at BC, Peak angle, Angular velocity at BC and peak angular velocity (in X, Y and Z direction)		SL and KL Angle at BC, Peak angle, Angular velocity at BC and peak angular velocity (in X, Y and Z direction)						Ball velocity (mean 26.64, SD 1.60, Launch angle 33.7, SD 2.17
(Sinclair *et al.*, 2017)		Angle (F/E, ADD, INT) @BC, Peak, ROM, Angular velocity (F/E, ADD, INT) @BC, Peak	Angle (F/E, ADD, INT) @BC, Peak, ROM Angular velocity (F/E, ADD, INT) @BC, Peak	Angle (DF, IN, INT) @BC, Peak, ROM Angular velocity (DF, IN, INT) @BC, Peak							Max velocity vs Accuracy
(Zhang *et al.*, 2012)	Rotation, velocity	Angle, angular velocity (ADD, F/E, I/E rotation)	Angle, angular velocity (F/E)	Velocity (and ball velocity)							

Source: Author, 2019

Table 4*:* Data processing methods in rugby kicking kinematic research

Reference	Data processing	Filtering	Statistics
(Atack *et al.*, 2014)	14-segment model reconstructed – global optimisation approach.	4th-order Butterworth, Zero-lag, (18Hz), XYZ Cardan rotation sequence	Mean and SD
(Atack *et al.*, 2017)	14-segment model	Motion data: 4th-order Butterworth, Zero-lag, (18Hz) and segmental kinetics reconstructed using an inverse kinematics approach.	Only the best kick (max distance) was used for analysis. Mean and SD were calculated for each group. 90% confidence intervals, smallest important effect. Time-histories were compared between the groups using a statistical parametric mapping two-tailed independent samples t-test with an alpha-level of 5%.
(Baktash *et al.*, 2009)			2 tailed T-tests
(Bezodis *et al.*, 2007)	10-segment kinematic model (plug-in-gait – Head, trunk, u-arm, forearm, thigh, shank)	Data smoothed using a generalised cross-validatory spline Woltering filter.	T-tests (Mean and SD)
(Bezodis *et al.*, 2014)		Data representations as 1/240 s in time and at every 0.05m in displacement	Root mean square difference between swing plane and raw foot centre of mass coordinates to determine goodness of fit of each plane Mean and SD, Pearson product correlation between swing plane properties
(Bezodis *et al.*, 2018)	14-segment rigid body model	18Hz low pass (Butterworth, 4th-order)	Effect size (Cohen's d)
(Cockcroft & Van Den Heever, 2016)		Vicon Nexus Woltering filter	Pearson correlations
(Green *et al.*, 2016)	15-segment model		Pearson correlation (Mean and SD), stepwise multiple linear regressions
(Koike & Bezodis, 2017)	15 rigid-linked segments		
(Sinclair *et al.*, 2014)	Joint angles were created using X,Y,Z Cardan sequence referenced to co-ordinate systems created about the proximal end segment.	Filtered at 50Hz using zero-lag low pass Butterworth 4th-order filter. 20 trials were averaged for each participant	Multiple regression analysis (dependent = ball velocity; independent = kinematic parameters) – stepwise forward procedure. Pearson correlation
(Sinclair *et al.*, 2017)	Rigid clusters on pelvis, thighs, and shank	15Hz zero lag low pass Butterworth 4th-order	Paired t-tests, Bonferroni. Effect size partial eta^2, Cohen's d, Shapiro-Wilk for normality. SPSS
(Zhang *et al.*, 2012)	Rotations of segments represented by Euler angles in X,Y,Z order (F/E, ADD/ABD, I/E rotation order) and linear velocity based on differentiating time-series coordinates of the markers	Butterworth low-pass filter (12Hz)	Foot velocity determined by a velocity decomposition method. Percentages calculated.

Source: Author, 2019

Unlike the vast research reflected in Table 2 above, data in the current study were collected outdoors. The joints and segments of interest within this research study include the ankle, knee, hip of the kicking leg, pelvis, and thorax. The foot speed at ball contact was collected, and accuracy was recorded based on the outcome of the kick. In this research study, a 15-segment rigid body model was constructed and an 18Hz zero-lag Butterworth filter utilised similar to previous rugby specific kicking research investigating angle and velocity curves (Atack *et al.*, 2014).

Using ball speed as the only outcome variable is insufficient, as accuracy (direction) is an essential factor of rugby place kicking performance (Atack, 2016). In some instances, no information was provided on the outcome of the kicks (accuracy or distance) or the instructions given to the kicker (Baktash *et al.*, 2009; Sinclair *et al.*, 2014). It is important to state the specific task constraints required, as it may influence the coordination pattern used by the kicker. It has been shown that kicking leg dynamics, including foot- and ball speed, decreased when kickers were asked to kick for accuracy as opposed to kicking for distance. Other limitations of the research include the small sample size, incorrect footwear, and methods not always reported on. Challenges/differences exist between laboratory settings and outdoor environments. Outdoor data collection has an advantage of the players being in their natural environment, wearing their own boots, and being able to see the goalposts and orientate themselves on the field. The advantage of an indoor setting is that it is more isolated and controlled, avoiding the influence of the weather, and you can easily make use of force platforms to obtain information on support leg impact. Various research studies state that although data collection was conducted in an indoor environment, kickers were able to wear their own rugby boots.

Most studies focused on the lower body mechanics, specifically describing the hip and knee angles, velocities, and moments in the X-, Y-, and Z-direction (Table 3). Some research also identified the values at specific points of interest. Upper body dynamics have only been reported by a few studies, such as Bezodis *et al.* (2007) when describing how the non-kicking side arm influences the whole-body angular momentum. Green *et al.* (2016) investigated the correlation between the kicking kinematics – including the arm, head, and torso – and kicking accuracy and distance. Atack *et al.* (2017) investigated the torso mechanics and relative pelvis-thorax rotation, amongst others, in describing the differences in successful and non-successful kickers. Lastly, torso rotation is also mentioned by Bezodis *et al.* (2014) when determining the planarity of the kicking foot trajectory.

In terms of data processing (Table 4), there is some variation in the processes used. In some cases, the subject reconstruction was not fully reported on; however, a 14-15 segment model was mostly used. A fourth-order low-pass Butterworth filter was used in most cases with a cut-off frequency between 12-18Hz with one case of 50Hz (Sinclair *et al.*, 2014).

Variables are also not always clearly defined and having more consistency would ease comparison between research groups from different locations around the world. Researching universal implications, standardised techniques would be beneficial, or at least techniques should be similar enough for comparison.

2.4 COORDINATION AND MOVEMENT VARIABILITY

2.4.1 COORDINATION

Coordination refers to the cooperation of segments moving relative to each other including structures such as neurons, muscles, and joints (Bernstein, 1967; Heiderscheit, Hamill & Van Emmerik, 2002; Li *et al.*, 2016; Southard, 2014) Coordination also involves the spatial-temporal pattern of ordering these structures in relationship to each other (Seifert, Button & Davids, 2012) (Egan, Verheul & Savelsberg, 2007; Langhout *et al.*, 2015). Each segment is capable of moving independently, but work together with each other to form a functional synergy to complete desired tasks (Bernstein, 1967; Heiderscheit *et al.*, 2002), specifically, the relative movements between segments on the same limb (intra-segment coordination) or different limbs (inter-segment coordination), or between limbs segments and an object. A rugby kicker, for example, needs to fit together a movement pattern that would result in the optimal velocity of the foot at ball contact.

Similarly, in rugby kicking, the place kicker needs to develop high velocity at the distal segment. High end-point velocity could usually be achieved by a proximal-to-distal sequencing pattern (Davids *et al.*, 2000).

Coordination measures could improve the understanding of a gross motor, complex movement task such as place kicking. It provides insight into the movement patterns of joints and segments of the body relative to each other. It could also provide information on which joint or segment is the primary mover during different phases of a movement, called segment dominance (Needham, Naemi & Chockalingam, 2015). Methods used to quantify coordination in movement in research are explained in Section 2.3.3.

2.4.2 MOVEMENT VARIABILITY

In rugby, as reported in soccer instep kicking research, the kicker needs to control and coordinate multiple degrees of freedom with spatial and temporal constraints, having each limb at the right place at the right time with the right amount of force to produce the desired outcome (Davids *et al.*, 2000). This requires the involvement of the musculoskeletal system in order to recruit the appropriate muscle activity in the correct sequence to achieve an optimal velocity of the distal segment, in this case, the foot at ball contact (Davids *et al.*, 2000). However, even elite athletes are not able to perform a task without variability in their movement pattern (Bartlett, Wheat & Robins, 2007; Preatoni *et al.*, 2013). Every time a movement is executed, there will be small changes in the movement pattern, even if it is a well-trained and very familiar movement like writing a word. This is known as MV and was visually explained by Preatoni *et al.* (2013) as graphically depicted in Figure 5 below.

Figure 5: Example of variability in performing a familiar motor task such as writing
Source: Preatoni et al., 2013

In contrast with the traditional view of MV being detrimental to a control system, MV is associated in recent years with a system’s health, flexibility, and adaptability to environmental changes (Bartlett *et al.*, 2007; Glazier, Wheat, Pease & Bartlett, 2006; Preatoni *et al.*, 2013; Seifert *et al.*, 2012; Wheat & Glazier, 2006). The functional role of variability is that in order to perform a task, there is a range of possible movement patterns (solutions) and transitions between patterns. Movement variability is necessary for change in the coordination of the movement, such as transitioning from running to walking and back (Bartlett *et al.*, 2007; Cunningham, 2012). Quantifying MV provides insight into how an individual responds to environmental changes by for example responding to possible perturbations (Cunningham, 2012; Glazier *et al.*, 2006). In rugby place kicking, MV will allow the kicker to control multiple degrees of freedom and respond to changes in the environment and manage task constraints.

Bernstein (1967), the pioneer of the dynamic systems theory of motor control, proposed movement behaviour is a result of complex interactions. The dynamic systems theory implies that variability in movement could be functional, and should not always be seen as noise or error (Preatoni *et al.*, 2013). An investigation into the coordination and control it is proposed that movement output is a result of the complex interaction of subsystems of the body, environment, and a task (Newell, 1985). The challenge for the performer, for efficient task execution, is to control the magnitude degrees of freedom such as muscles, joints, and limb segments (Bernstein, 1967). Coordination of body segments is the process of converting the degrees of freedom to a controllable, efficient system (Davids *et al.*, 2000).

Outcome variability refers to the variability in the outcome of the movement (*what* has been achieved) such as ball speed or foot speed at ball contact, Ball direction of flight as well the final position of the ball crossing the posts. Execution variability is the variability of *how* a movement is achieved (including joint and segment angles and velocities) (Preatoni *et al.*, 2013). Execution variability is the primary focus for this research study.

Joint coupling and coordination, as well as inherent variation in coordination measures, are essential in performing a goal-directed activity such as rugby place kicking. For this reason, coordination has become a topic of interest in kicking research across football disciplines. (Cunningham, 2012; Wheat & Glazier, 2006). The methods used to quantify coordination and coordination variability are discussed in the following section.

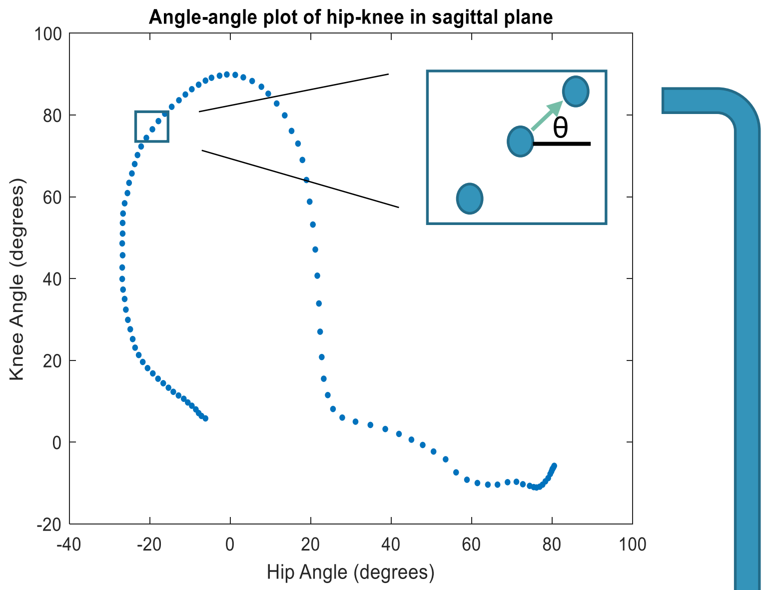
2.4.3 MEASUREMENT OF COORDINATION AND COORDINATION VARIABILITY

The movement of one segment or joint in the body is rarely isolated and affects the adjacent joints or segments. Angle-angle plots (cyclograms or relative motion plots) have been used to visually display intersegmental coordination (Stock, van Emmerik, Wilson & Preatoni, 2018). Hamill *et al*. (2000) described the angle-angle plot to define the proximal joint or segment on the horizontal axis, and the distal joint or segment on the vertical axis as graphically depicted in Figure 6 (Li *et al.*, 2016). The change of position in data points relative to the right horizontal is calculated (Heiderscheit *et al.*, 2002; Needham, Naemi & Chockalingam, 2014).

Vector coding was developed as a tool to quantify angle-angle plots and can provide information regarding inter-segmental coordination. Vector coding is a method for determining how two kinematic segments or joint variables interact with each other and is calculated by the angle between two adjacent data points relative to the right horizontal (Sparrow, Donovan, Van Emmerik & Barry, 1987). Two adapted vector coding methods were suggested for gait analysis – recently referred to by Stock *et al.* (2018) as the Heiderscheit Coordination Variability method

(Heiderscheit *et al.*, 2002) and the Tepavac Coordination Variability method (Tepavac & Field-Fote, 2001). Both methods involve quantification of the angle-angle plots. The Tepavac Coordination Variability method includes length and direction of the coupling vector (Tepavac & Field-Fote, 2001), whereas the Heiderscheit Coordination Variability method only includes vector direction in the equations (Heiderscheit *et al.*, 2002; Stock, van Emmerik, *et al.*, 2018). Vector coding has been used biomechanical analyses to investigate mainly different movements, but most research focus on walking and running (Chang, Van Emmerik & Hamill, 2008; Hafer & Boyer, 2017).

a)



b)

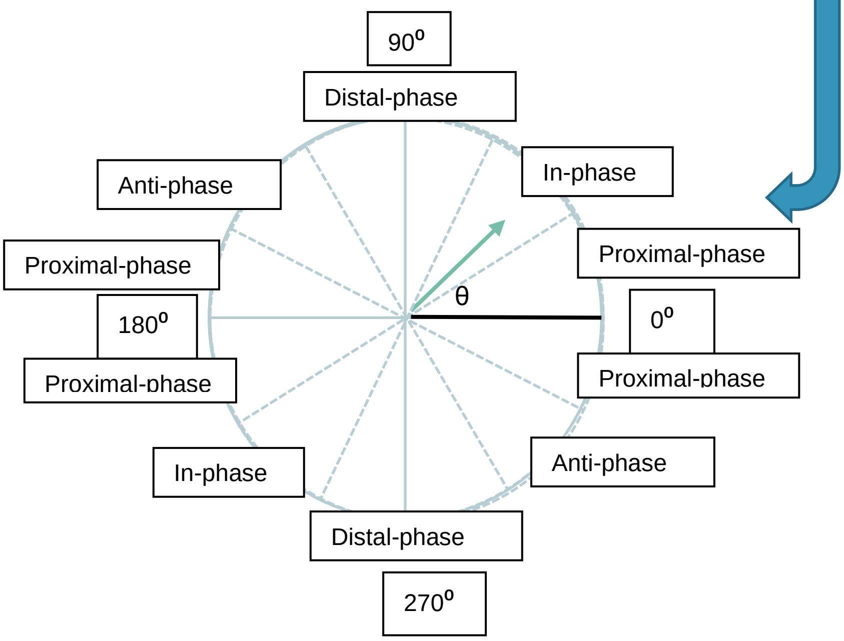


Figure 6: a) Coupling Angle calculation between datapoints on angle-angle plot. b) Coupling angle description of four unique coordination patterns
Source: Author, 2019

Table 5: Coupling angles classified into four unique coordination patterns each consisting of 45º

Coordination patterns	Degrees	Range	Description
In-phase	45º, 225º	22.5 ≤ θ < 67.5, 202.5 ≤ θ < 247.5	Segments rotating in the same direction
Anti-phase	135º, 315º	112.5 ≤ θ < 125.5, 292.5 ≤ θ < 337.5	Segments rotating in the opposite direction
Proximal phase	0º, 180º	0 ≤ θ < 22.5, 157.5 ≤ θ < 202.5, 337.5 ≤ θ < 360	Proximal segment rotation, no distal rotation
Distal phase	90º, 270º	67.5 ≤ θ < 112.5, 247.5 ≤ θ < 292.5	Distal segment rotation, no proximal rotation

CA can further be classified (or binned) into four unique coordination patterns (Chang *et al.*, 2008) as graphically depicted in Figure 6 (Li *et al.*, 2016) and described in Table 5. If, for example, you are investigating the coupling of the hip and the knee, a vertical vector would represent distal phase implying the knee dominating the movement, while a horizontal vector indicates proximal phase referring to the hip being the primary mover.

After calculating the coordination measures in a system, coordination variability can indicate variability in a movement control strategy (Cunningham, 2012), providing information on skill level, injury prevention, and motor learning (Stock, van Emmerik, *et al.*, 2018). Increased coordination variability has been linked to a decreased ability in goal-directed tasks (Bartlett *et al.*, 2007; Gosling, Needham & Chockalingam, 2017). Main methods for calculating for coordination variability found in research include: Coupling angle variability (CAV) and Bivariate area of ellipse method. CAV has been suggested as indicating the amount of variability in movement strategies (Cunningham, 2012; Heiderscheit *et al.*, 2002). CAV requires the use of circular statistics (Batschelet, 1981) to calculate the mean and standard deviation of the CA (Hamill, Haddad & McDermott, 2000) for a minimum of three trials (Cunningham, 2012). The CAV can be described as the circular mean and standard deviation of the CA values over the desired number of trials (Batschelet, 1981; Cunningham, 2012; Heiderscheit *et al.*, 2002; Stock, van Emmerik, *et al.*, 2018). A limitation has been identified with the CAV calculations where the use of circular statistics produce a statistical artefact leading to inflated variability with short vectors (Stock, van Emmerik, *et al.*, 2018).

Recently, the bivariate area of the ellipse method has been proposed to be more robust in determining true variability in coordination and is not susceptible to the statistical artefact as a result of the proximity of data points on angle-angle plots (Stock, van Emmerik, *et al.*, 2018). The approach entails forming an ellipse from the endpoint of coupling vectors at each time point, normalised to the origin. This method provides variability measure in length and direction of the coupling vectors (Stock, van Emmerik, *et al.*, 2018; Stock *et al.*, 2017). This research study makes use of the bivariate area of ellipse method in determining variability in segment coupling coordination.

2.4.4 COORDINATION AND VARIABILITY IN KICKING RESEARCH

Kicking is a crucial skill for the various football disciplines as it allows teams to score points. A kicker must be able to control the various degrees of freedom to execute an accurate kick. Intersegment- and joint coordination of the kicking leg is crucial for achieving optimal kicking foot velocity at ball contact in order to achieve considerable ball speed (Li *et al.*, 2016). In order to gain more information on the kicking mechanics contributing to high velocity and accurate kicking performance, coordination has been investigated. Coordination has been investigated using 2D sagittal plane evaluation as well as 3D motion capture. An approach of timing parameters can be followed (describing peaks and the time to peaks of variables such as maximum hip angle, maximum hip velocity, maximum knee angle, maximum knee velocity) or more information can be provided via angle-angle plots, vector coding, and variability calculations.

Li *et al*. (2016) investigated coordination soccer instep kicking using both cross-correlation and the vector coding technique in the sagittal plane using 2D video analysis. By means of the CA, it was reported during the backswing that the shank-phase (in this case, distal phase) is the dominant coordination pattern (Li *et al.*, 2016). Figure 7 graphically depicts the thigh and shank coordination patterns explained in a soccer kick. At the beginning of the backswing, an in-phase pattern is observed as the shank and thigh move backwards. Anti-phase occurs in the first part of the forward swing phase, increasing the stretch on the knee extensor muscles. Thereafter, the thigh and shank move in-phase as both segments rotate forward. The thigh then starts to decelerate with the shank accelerating forward and energy is transferred from the thigh to the shank. Just before ball contact, a shank-phase appears again as the thigh slows down further while the shank extension continues (Li *et al.*, 2016).

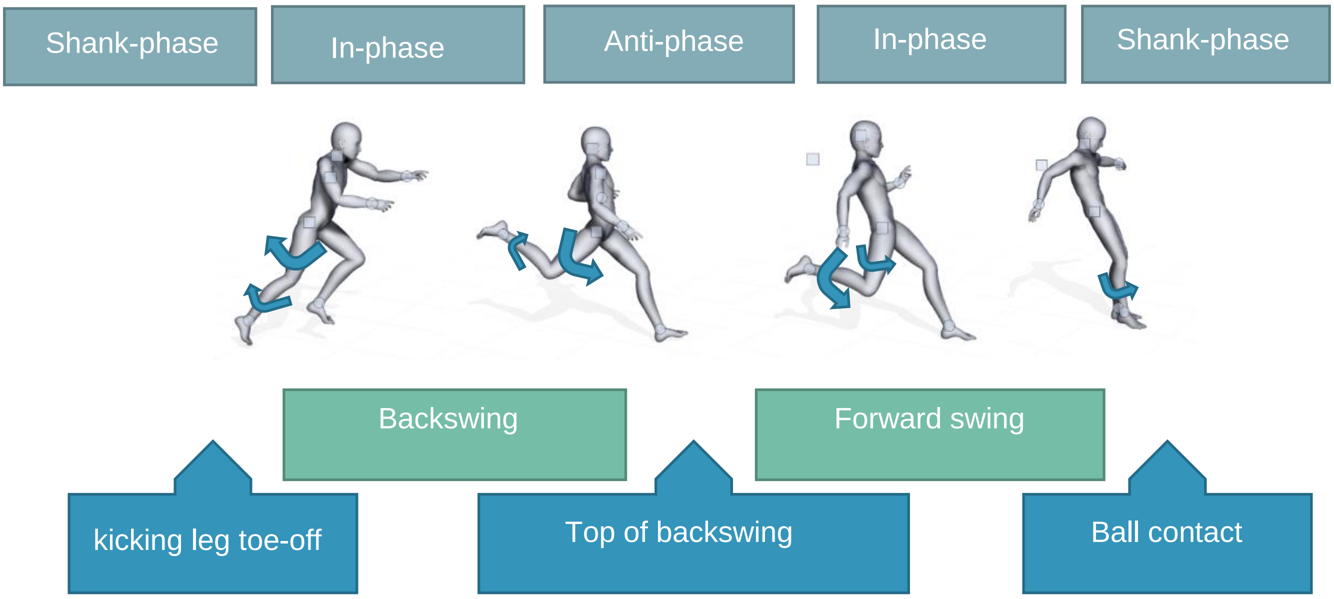


Figure 7: Example of kicking technique and the correlating coordination patterns of the shank and thigh
Source: Author, 2019

Research investigating the chip kick in soccer found that higher level kickers presented a stable hip with more rotation around the knee (Chow *et al.*, 2005; 2007; 2008). Research shows that skilled kickers display less variable movement patterns (low coefficient of variation) when kicking from different positions (Chow *et al.*, 2005). It was also reported that experienced kickers were able to vary their foot velocity based on task constraints (Chow *et al.*, 2005). Chow *et al.* (2008) reported that consistency improves with practice as intra-limb coordination becomes more stable.

In Australian football, the coordination patterns of the preferred- and non-preferred leg in drop punt kicks were investigated (Falloon *et al.*, 2010). When looking at discrete values, the ROM of the preferred leg pelvis and knee was more extensive than that of the non-preferred leg, but smaller for the hip, indicating a different strategy of motor control between the preferred and non-preferred leg. The angle-angle plots of the hip and pelvis indicated a change in movement pattern just before ball contact between the preferred and non-preferred kicking leg. It was theorised that the pelvis angular velocity of the preferred leg increased more than that of the non-preferred leg to generate more power at ball contact. Possibly, when performing kicks with the non-preferred leg, players could restrict the movement of their pelvis and knee ROM, limiting movement to the hip joint as it might be easier to control. This would be in line with Bernstein's (1967) degrees of freedom theory limiting movement in surrounding joints, allowing greater movement in a selected joint (Bernstein, 1967; Falloon *et al.*, 2010). The rationale for coupling a segment and a joint (pelvis and hip) was not provided in the study, and the appropriateness might be limited as the pelvis generally used as reference in hip angle calculations. A speculative rationale could be to account for upper body forward lean (as opposed to elevating thigh during hip flexion); in which case, the thorax segment would then be a more appropriate than the pelvis.

Other authors followed a kinetic chain analysis approach (Inoue, Nunome, Sterzing, Shinkai & Ikegami, 2012; Naito *et al.*, 2010; Nunome *et al.*, 2006). A kinetic chain analysis refers to the transfer of forces to the kicking leg. It was reported that the knee angular velocity is the most critical contributor to foot speed at ball contact. Kicking leg motion is also reportedly affected by gyroscopic angular acceleration in trunk rotation, centrifugal acceleration influence on kicking leg knee extension, and kicking leg Coriolis acceleration (Naito *et al.*, 2010). With the emphasis on generating high velocity at a distal point of a multi-linked system, a method used to determine direct- and indirect effects of joints torques contributing to distal endpoint speed was investigated using a rugby kicking movement (Koike, Ishikawa, Willmott & Bezodis, 2019). It was stated that although a whole-body approach is required, analysis of the kicking leg only is a good starting point (Koike *et al.*, 2019).

Led by the formation of the tension arc during maximal instep kicking, upper body segment interaction has also been investigated through a vector coding technique (Gosling *et al.*, 2017). During the backswing, the kicker winds up to form a tension arc involving hip extension, posterior pelvis rotation of the kicking side, anterior pelvic tilt, trunk extension/rotation, and non-kicking side shoulder extension (Langhout *et al.*, 2015; Naito *et al.*, 2010; Shan & Westerhoff, 2005). Gosling *et al.* (2017) focussed on pelvis thorax segment coupling and reported an in-phase coordination pattern between the thorax and the pelvis during the formation of the tension arc with thorax dominance. With release of the tension arc (during downswing), anti-phase is displayed. It was also stated that less variability in pelvis-thorax coupling and greater thorax tilt angle and ROM are associated with improved performance (Gosling *et al.*, 2017). It is, therefore, essential to include pelvis-thorax coupling measures in coordination investigations in addition to kicking limb mechanics.

Similarly, Egan *et al.* (2007) reported that upper body kinematics might be of importance in the coordination of a kicking movement, including the shoulder and arm of the non-kicking side (Egan *et al.*, 2007). Egan *et al.* (2007) found experienced participants to have a significantly higher speed of movement from the top of the backswing to ball contact.

2.4.5 TASK CONSTRAINTS

In rugby place kicking, there are various requirements such as accuracy and speed (achieving the correct distance) to perform an effective place kick. Some studies fall short by only instructing the participants to kick as hard as they can, ignoring the accuracy constraint. Evidence shows a trade-off between accuracy and distance; therefore, both constraints should be investigated in technique analysis studies (Atack, 2016).

By analysing 558 place kicks during the 2015 Rugby World Cup, it has been shown that task constraints (distance and angle from goal posts), as well as contextual constraints (time, score margin, and previous performance), have an influence on the accuracy of each kick (and other self-paced skills such as basketball or golf putting) (Pocock, Bezodis, Davids & North, 2017).

A heat map describing the influence of task constraints such as distance and direction on the outcome of place kick performance was developed (see Figure 8), indicating that the outcome of the kick may vary due to the field location of the kick (Pocock *et al.*, 2017).

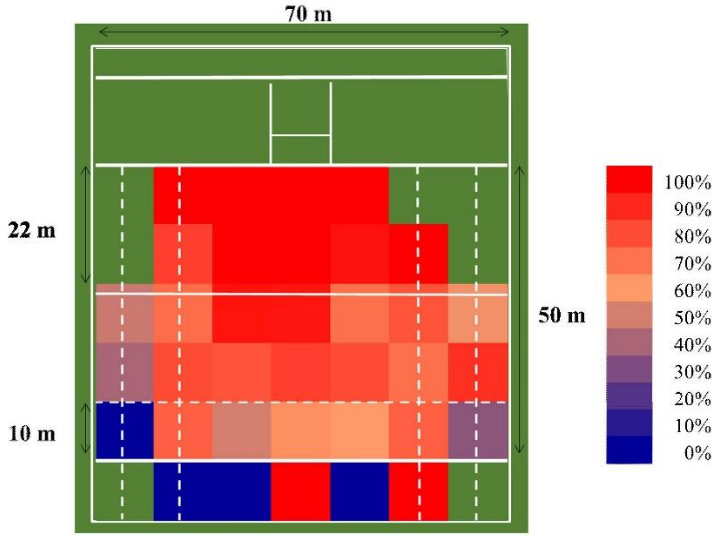


Figure 8: Position on the field and average kick percentages of place kicks in 2015 Rugby World Cup
Source: Pocock et al., 2017

Contextual constraints proved to have a significant influence on the success rate of the place kick. Kickers had a seven per cent better success percentage if they had a successful previous kick (77%) compared to kickers who missed their previous kick (70%). It was also reported that the highest average kicking success occurred during the first ten minutes of the match (80%), and the worst average kicking success occurred during the last ten minutes of the first half. Lastly, in the knockout rounds, the average kicking success was the worst when the kicker's team was behind with one to three points, with only a 50 per cent average kicking success (Pocock *et al.*, 2017).

Supporting the findings mentioned above, research shows that that ball speed decreases by 20 to 25 per cent from maximal values when an accuracy demand is placed on a kicker (Lees & Nolan, 2002). When investigating how practice influences coordination in soccer chip kicking, it was suggested that task constraints, as well as the constraints of the individual, determine the joint involvement and changes in degrees of freedom with practice (Chow *et al.*, 2008). It was stated that there is no universal pathway to establish the coordination and control of a skill with practice, as individual differences are found even with consistent task and structural constraints (Chow *et al.*, 2008).

2.5 SUMMARY

Research investigating the biomechanics of the place kick in rugby mainly uses a 3D movement analysis approach, focuses on individualised aspects, such as approach, support leg, kicking leg, torso and non-kicking side arm. Most studies have focussed on lower body mechanics, specifically of the kicking leg. Few studies had a full-body, multi-segment approach; however, it has been identified that torso and arm mechanics may play a significant role.

In general, the main movement characteristics involved in kicking research were described according to the placing of the support leg, pelvis rotation of the support leg, and kicking leg extension at the hip and flexion at the knee. The forward motion of the kicking leg is initiated by rotation of the kicking leg pelvis, and the kicking leg swings forward with flexion of the hip and knee. Thigh deceleration follows while the knee extends; the shank is accelerating to just before ball contact. The non-kicking side arm swings forward in reaction to the movement of the kicking leg. These basic characteristics are similar for kicking across different disciplines, with slight modifications based on task requirements.

Main findings from the research on the kinematics of rugby kicking include:

- During the approach, the length of the last step should be sufficient. This ensures that the kicking leg moves through a greater ROM, producing greater kicking foot velocity at ball contact.
- Norms have not defined the planting of the support leg, and although the literature found a natural planting foot position to be between lateral to the ball and behind the ball. It seems that by forcing the kicker to change his planting foot position, they can compensate.
- The kicking leg travel from the top of the backswing to ball contact. The thigh reaches a peak velocity first during the downswing, then starts to decelerate and, after that, the shank reaches a peak velocity just before ball contact.

- The pelvis should ideally be positioned to the dominant side of the goalposts, allowing the kicking leg hip to move through a greater ROM and reach optimal foot velocity at ball contact.
- A larger relative pelvis-to-torso angle will aid in kicker further but needs to be controlled as it may influence kicking accuracy.
- Aiding in the relative pelvis-to-torso rotation is the non-kicking side arm that contributes to performance as it stabilises the body in the mediolateral direction by opposing the action of the kicking leg.

Although the kinematics of the kicking movement pattern has received some attention in recent literature, little research has investigated segment interaction, and no research has focussed narrowly on coordination and coordination variability of rugby kicking.

Coordination refers to the organisation of joints and segments in the execution of movement tasks, in this case, goal-directed activity. Joint coupling and coordination are crucial in movement tasks. Coordination and coordination variability are essential in responding to change to order parameters in a system. CA can be calculated to quantify coordination. Knowledge about mechanisms underlying the kicking movement could aid in our understanding of multi-joint coordination. Quantifying coordination and coordination variability are important to understand a movement. The ability to adapt to different task constraints are beneficial in consistent performance in rugby kicking.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter provides information on the research methods used in the study. The chapter describes the research design, sample selected, equipment used, methods applied, and provides arguments as to why these methods were used. Data reduction and data analysis, as well as the limitations and ethical considerations relevant to this research study, are also discussed.

3.2 STUDY DESIGN

This research study followed a cross-sectional descriptive design with one testing session per kicker. The theoretical framework, an ecological approach, was used to understand key relationships between the performer, task, and environment (Handford, 2006).

3.3 RESEARCH PROCEDURES

All kicker volunteered to take part in the study and could terminate the testing without any consequence. The testing procedure and aim of the research were explained to each participant. In addition to signing the informed consent form, the players each completed a player history document adapted from World Rugby in order to determine their injury status (see Appendix B). Data collection took place on a sports field next to and using the equipment of the Central Analytical Facilities (CAF) Neuromechanics laboratory of Stellenbosch University. An employee of the CAF laboratory assisted with data processing as well. Demographical data were collected by using a standard scale and stadiometer. A bone calliper and measuring tape were used for anthropometric measurements. On the day of the testing, the researcher would log in to a live weather station less than five kilometres away and record the current weather.

3.4 PARTICIPANTS

Ten male university-level and semi-professional kickers volunteered to take part in the study. Convenience sampling was used to select the kickers from university- and surrounding rugby clubs. Kickers were included if they had at least four years' experience in place kicking and were injury free for at least one year. Potential kickers were excluded if they had any physical illness that would inhibit them from performing good quality place kicks.

3.5 DATA COLLECTION

After a self-selected warm-up of 10 – 15 minutes, the kicker was allowed to complete four to six familiarisation kicks. A standard weight and pressure size-5 rugby ball was provided to participants, but they were allowed to use their own kicking tee. The kicker was also allowed to do his own ball set-up and execute his preferred run up to ensure a natural kicking movement pattern. Each kicker completed a static- and dynamic calibration trial, as well as five trials at three distances from directly in front of the portable posts (22 m, 32 m, and 40 m) in randomised order, with at least three successful trials per condition. Five trials has been used in literature to represent the average of a condition (Atack *et al.*, 2014; Falloon *et al.*, 2010), in some research three trials per condition were executed (Baktash *et al.*, 2009; Shan & Westerhoff, 2005) In total about 15 to 20 trials were completed per subject, the researchers did not want fatigue to start to setting in. The 32 m distance is reported to be the average place kicking distance in international matches (Quarrie & Hopkins, 2015). The 22 m distance was chosen to represent an easy kick, and the 40 m distance presentments a kick at the end of their range. Distances were selected as a range where most professional kickers could convert the kick with above 80% accuracy (Pocock *et al.*, 2017), with the upper limit slightly reduced due to lower skill levels of kickers. The beginning and end of the range was selected to produce the greatest difference between conditions. The kicker was instructed to successfully convert the kick and could begin the kicking trial at his own pace.

Kinematic data were collected on an outdoor sports field (see Figure 9) using a ten-camera motion capture system (Vicon ™ Vantage V5, Oxford Metrics Ltd., Oxford, UK) – sampling at 300Hz, calibrated to the manufacturer's instructions with a capture volume of approximately 4 x 5 x 2 meter. Eight to ten camera motion capture systems have been used in rugby kicking literature (Atack *et al.*, 2014; Baktash *et al.*, 2009; Bezodis & Winter, 2014; Cockcroft & Van Den Heever, 2016; Sinclair *et al.*, 2017; Zhang *et al.*, 2012). The 3D motion capture systems were used as it provides accurate and comprehensive kinematic data, as discussed in Chapter Two. Multiple infrared cameras were set up to determine a capture volume (Figure 10). Two digital video cameras (Bonita 720c video cameras, 100Hz) were positioned behind and to the right of the kicker and was used to refer to if any anomalies were found in the trajectory data during data cleaning. Mobile posts were positioned on the field to simulate an actual kicking environment (Figure 11). Spherical markers were placed on the kicker on specific anatomical landmarks. The position of the markers is critical to ensure accurate data (Vicon, 2019). The marker placement is explained in the following section.

Figure 9: Image of data capture set-up on the field
Source: Author, 2019

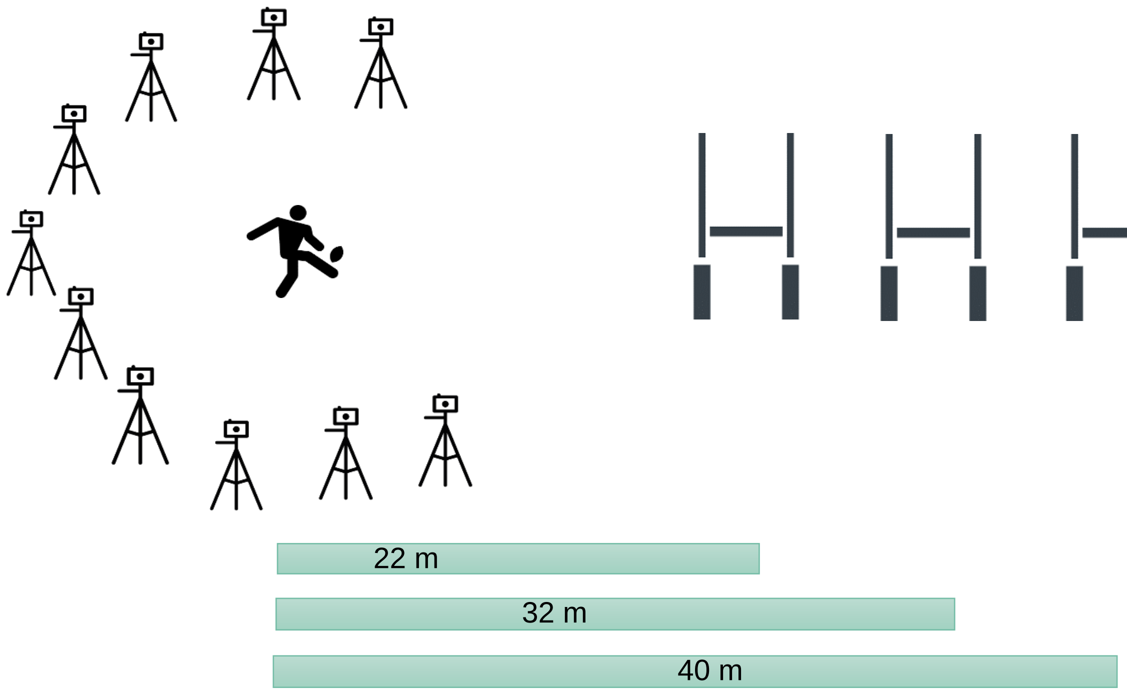


Figure 10: Diagram of the outdoor testing layout
Source: Author, 2019

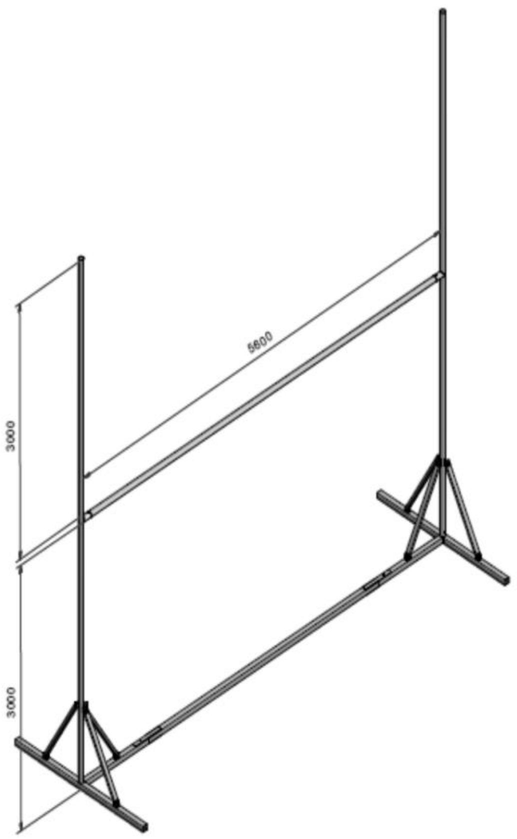


Figure 11: Dimensions of mobile kicking posts
Source: Daniel Lombard.

Spherical reflective markers were placed on anatomical landmarks of the kicker following the Plug-in-Gait model (Vicon, 2019) with the addition of a cluster of markers on the thigh and shank (see Figure 12 and Appendix C, Table C.1). Toe markers on the kicking foot were used for calibration but removed for the kicking trials. Four markers were placed on the ball and used to determine ball contact.

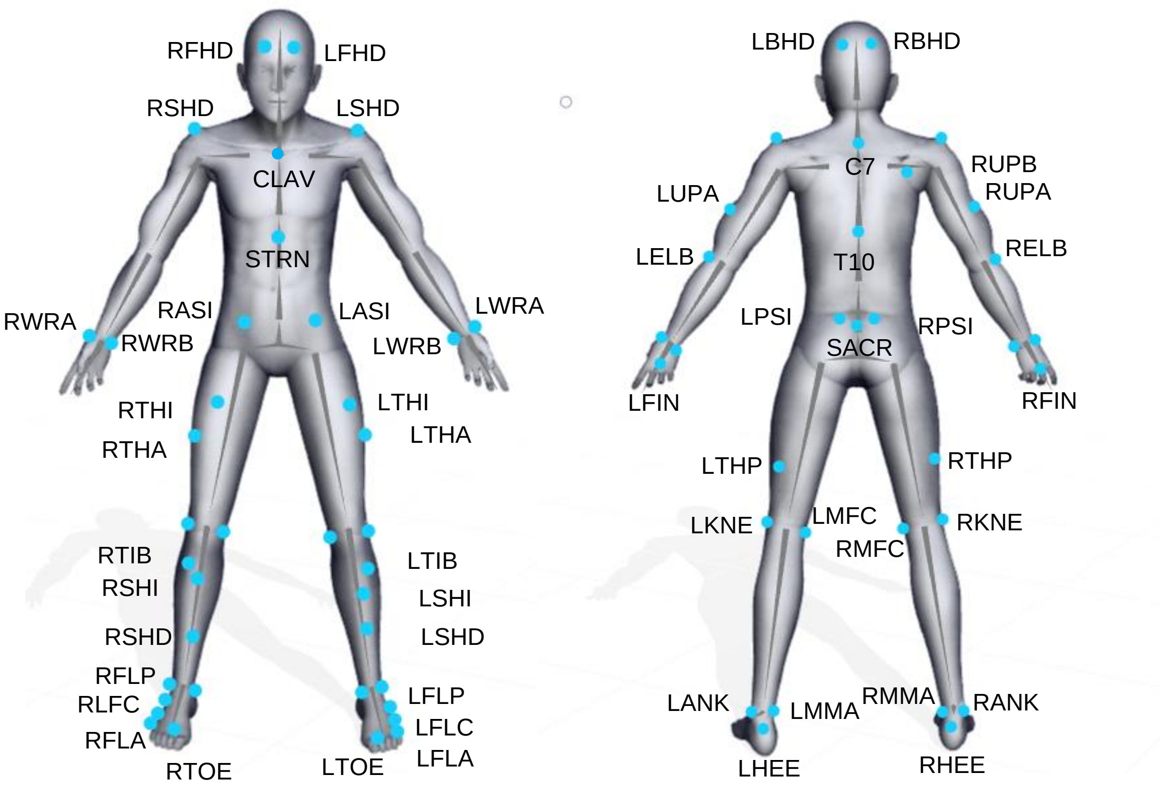


Figure 12: Visual representation of full marker model adapted from Vicon(2019)
Source: Author, 2019

3.6 DATA REDUCTION

The global coordinate system (Vicon, 2019) was defined as Y-axis: In the plane of the ground surface, with positive pointing into intended direction of ball travel; X-axis: In the plane of the ground surface, perpendicular to the direction of ball travel, with the positive to the right; Z-axis: Perpendicular to the ground surface, defining the vertical direction, with the positive pointing in an upward position.

5.3.1 MODELLING

For the model calibration, a standard static calibration (motorbike pose) was used and then the first kick was processed and use to run a functional skeleton calibration. The processing pipeline ran on the data include: reconstruction, labelling, gap filling, Dynamic Plug-in-Gait modelling, semi-automated event detection with manual correction. Data were then segmented and checked. Any corrections to the trajectories were implemented then and the modelling were repeated.

A modified Plug-in-Gait marker model set was used for the project. The right toe marker was filled using the remaining foot makers. Clusters were used to fill the tibia and thigh marker as required by the Plug-in-Gait model. Markers were filled by using the calibration trial to determine the position of the marker relative to the other markers on a segment. The marker can then be filled mathematically on a segment from the position of the other markers on the same segment, assuming the segment is rigid.

The subject model was reconstructed to form a 15-segment linked model, consisting of the head, thorax, left- and right humerus, radius, hand, pelvis, left- and right femur, tibia, and foot (Vicon, 2019). Kinematic variables of interest were defined and calculated as presented in Table 6 below (Vicon, 2019). Kinematic derivatives were calculated from the joint angle data for velocity measures.

Table 6: Description of kinematic variables collected from 3D motion analysis (Vicon, 2019)

Kinematic variable	Description
Thorax angle:	The absolute angle between the thorax and the coordinate system.
Thorax tilt	Calculated around the global transverse axis. A positive value indicates a forward tilt of the thorax.
Thorax obliquity	Measured in the plane of the thorax frontal axis and the global transverse axis (defined in the Z-axis). A positive value indicates that the opposite side of the thorax is lower.
Thorax rotation	Measured between sagittal axis of thorax and sagittal global axis.Positive value indicates internal rotation (opposite side in front)

Pelvis angle:	The absolute angle of the pelvis and the coordinate system. Pelvic tilt is measured around the transverse axis.
Pelvic tilt	Positive value indicates a posterior pelvic tilt.
Pelvic obliquity	Negative value indicates that the opposite side is lower.
Pelvic rotation	Negative value indicates external rotation (where the opposite side is in front)
Hip angle:	The relative angle between the pelvis and the thigh.
Hip flexion/extension	The angle between the sagittal thigh axis and the sagittal pelvis axis, where the positive flexion angle relates to the knee being in front of the body.
Hip abduction/adduction	The angle formed by the long axis of the thigh and the frontal axis of the pelvis. A positive value indicates adduction (inward movement) of the leg.
Hip rotation	The angle calculated between the sagittal axis of the thigh and the sagittal axis of the pelvis. A positive value indicates internal rotation of the thigh.
Knee angles	Measured between the shank and the thigh.
Knee flexion/extension	The relative angle between the thigh and the shank. Knee flexion is determined by the angle between the sagittal shank axis and the sagittal thigh axis. A positive value indicates knee flexion.
Knee valgus/varus	The long axis of the shank relative to the long axis of the thigh, in the frontal plane. A positive value indicates an outward bend of the knee (varus).
Knee rotation	Measured in the transverse plane, the sagittal axis of shank relative to sagittal axis of the knee. A positive value indicates internal rotation.
Ankle angle:	The relative angle between the shank and the foot. Calculated by the angle of the foot vector projected into the sagittal plane and sagittal axis of the shank. A positive value indicates dorsiflexion.
Ankle plantar-/dorsiflexion	Angle between the foot vector and the sagittal axis of the shank

5.3.2 FILTERING

Three-dimensional coordinates for the markers were reconstructed using Vicon Nexus software. Marker trajectories were smoothed using a fourth-order zero-phase Butterworth filter. Various filtering cut-off values used in kicking kinematics research with similar variables, were applied to the data and visually inspected over three subjects to determine effect on kinematic curves. The 18Hz (Atack, 2016) filter presented the desired results. Marker trajectories were filtered for the region of interest, from support leg toe off, through ball contact, to support leg leaving the ground after impact. Model outputs were not filtered, only marker trajectories to reduce high frequency noise. Subsequent data were processed using Matlab (Matlab 8, Mathworks inc., USA).

5.3.3 SEGMENTATION

The complete kicking trial was segmented into phases of interest. From the kicking leg initial toe-off (KLTO) to top of backswing (TOB) the phase was defined as the backswing, while the forward swing phase was defined as top of backswing to ball contact (see Figure 13).

Kicking events are defined as:

- KLTO: Kicking leg initial foot-off
- TOB: Top of backswing
- SLC: Supporting leg foot contact (next to kicking tee)
- BC: Ball contact
- SLTO: Supporting leg foot off

Kicking phases are defined as:

- Backswing KLTO to TOB
- Forward swing TOB to BC
- Follow-through BC onwards

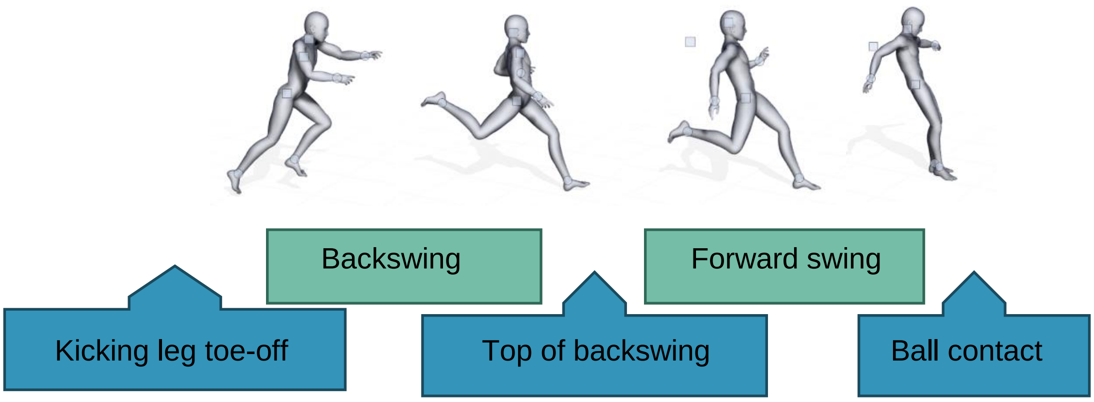


Figure 13: Events and phases of a rugby kick
Source: Author, 2019

Kicking leg toe off represents the first frame where the kicking foot is completely off the ground during the approach. The top of backswing is defined as minimal foot velocity of the kicking leg during the kicking leg toe-off to ball contact. It was decided to describe the forward swing from top of backswing to ball contact as opposed to from support leg contact to ball contact, as it would be more appropriate to describe the motion of the kicking leg. When assessing SL kinematics it might be appropriate to divide the kicking motion into a flight- and support phase, using events such as support leg contact for the start of the support phase (Inoue, Nunome, Sterzing, Shinkai & Ikegami, 2014). This is in contrast with analysing kicking leg motion when it might be more appropriate dividing the kicking leg motion into backswing and forward swing. The "top of backswing" measure can be used to indicate the initiation of the forward swing (Atack, 2016). Ball contact is defined by the first frame of movement of ball marker. Data were normalised to 100 data points for the backswing and forward swing respectively, for comparison across trials and individuals.

3.7 DATA ANALYSIS

Three groups were formed based on three kicking distances: 22m, 32m, and 40m. By comparing the differences between kicks of different intensities, insights can be gained on how kickers adjust their technique to achieve different tasks constraints (Nunome, Inoue, Watanabe, Iga & Akima, 2018). The mean of five kicks was used to represent each participant at a specific distance; thereafter, group means were calculated. The following table provide a list of variables selected for analysis as well as a description of the variable and the reason for including the variable (Table 7).

Table 7: List of variables selected for analysis as well as a description of the variable and the reason for including the variable

Variable/Parameter	Description	Reason for inclusion
Discrete measures		
Joint and segment angles at ball contact: **Ankle (X)** **Knee (X)** **Hip (X)** **Pelvis (Z)** **Thorax (Z)**	Joint angle extracted at the instance of ball contact.	Body position at ball contact provide the orientation of joints and segments at impact.
Range of motion: **Ankle (X)** **Knee (X)** **Hip (X)** **Pelvis (Z)** **Thorax (Z)**	Difference between maximal joint or segment angle and minimal angle for the entire kicking event (backswing and forward swing).	Joint and segment range of motion is greater for maximal compared to submaximal kicks. Kicking limb range of motion provide insight into the amount of force that can be applied to the kicking foot. Upper body range of motion are associated with tension arc development and release (Langhout *et al.*, 2017).
Peak velocity: **Knee extension (X)** **Hip flexion (X)**	Maximal velocity reached during the entire kicking event (backswing and forward swing).	Kicking leg knee flexion and hip extension velocity is associated with increased foot speed generation (Sinclair *et al.*, 2014; Zhang *et al.*, 2012).
Time to peak velocity: **Knee extension (X)** **Hip flexion (X)**	The time point of maximal velocity, expressed as a percentage of backswing or forward swing.	Timing of maximal hip velocity and maximal knee velocity to ball contact differ significantly between kickers of different skill levels (Egan *et al.*, 2007).
Foot speed at ball contact		Foot speed at ball contact is related to ball speed after impact (Ball, 2008; De Witt & Hinrichs, 2012).
Length of last step	Distance between the kicking side toe marker and support leg heel marker, normalised to subject height.	Length of last step provide indication of hip range of motion, associated with increased distance in kicking (Cockcroft & Van Den Heever, 2016).
Maximum approach velocity	Maximum linear velocity of centre of mass during approach (prior to kicking phase initialisation)	Identified as important factor for achieving greater distance kicks (Ball, 2008).
Support leg position (behind tee, lateral to tee)	Distance of the support foot behind the back of the tee and lateral distance from the most lateral point of the tee.	Elite kickers had a little variation in their support leg planting position, however it is unclear the influence of changing kicking distance (Cockcroft & Van Den Heever, 2016).
Foot progression angle	The average foot progression angle at the final 5% before contact.	Selected to provide an indication of foot-ball interaction.

Variable/Parameter	Description	Reason for inclusion
Continuous parameters		
Joint and segment angle measures: **Ankle (X)** **Knee (X,Y,Z)** **Hip (X,Y,Z)** **Pelvis (X,Y,Z)** **Thorax (X,Y,Z)**	Joint and segment angles for the backswing and forward swing	Joint orientation curves differ for kickers achieving different results (Atack *et al.*, 2019).
Joint velocity measures: **Knee (X)** **Hip (X)** **Pelvis (X,Y,Z)** **Thorax (X,Y,Z)**	Joint and segment angular velocities for the backswing and forward swing	Knee, hip and pelvis velocity identified to contribute to kicking foot velocity as a function of proximal-to-distal sequencing (Zhang *et al.*, 2012).
Coupling angle: **Knee-Ankle (X)** **Hip-Knee (X,Y,Z)** **Pelvis-Thorax (X,Y,Z)**	Measure of how two joints or segments move relative to each other.	Limited research using coupling angle in kicking research (Chow *et al.*, 2008; Li *et al.*, 2016), no research on how coupling angle differ for different kicking tasks.
Coordination variability: **Knee-Ankle (X)** **Hip-Knee (X,Y,Z)** **Pelvis-Thorax (X,Y,Z)**	Amount of variability present in the coordination measures.	Limited research on coordination variability in kicking research, although the importance of movement variability has been emphasised in biomechanical research (Stock, van Emmerik, *et al.*, 2018; Stock *et al.*, 2017).

Note: Brackets indicate direction; X: sagittal plane; Y: Frontal plane; Z: Transverse plane

3.7.1 DISCRETE VARIABLE COMPARISON

To determine statistically significant differences in discrete kinematic variables, for each participant, the mean of the five kicking trials was calculated. The group mean was calculated for each distance. An ANOVA comparison was made to determine statistical significance three groups described above. Effect size (Cohen's f) was calculated to determine the statistical significance between groups. Effect sizes were classified as: small f=0.10, moderate f=0.25, large f = 0.40 (Cohen, 1988; Grove & Cipher, 2016). Descriptive data were processed using the Statistical Package for Social Sciences software (SPSS) version 25 by the researcher.

3.7.2 CONTINUOUS VARIABLE COMPARISON

Statistical parametric mapping (SPM) is a method used to represent time-normalised one-dimensional trajectories of joint mechanics time-histories and significant differences in sections of time-histories (Pataky, 2012). Two rounds of SPM analysis were done in Matlab (Matlab 8, Mathworks inc., USA) by the researcher. The first round includes the pooled data of all the kicks, while the second round of data analysis include only successful trials. To determine differences in joint angle and velocity curves, a spm1d repeated measures ANOVA with a significance level of 0.05 was used. For post hoc analysis a two-tailed paired t-test was used (Pataky, 2012). SPM refers to the overall methodological approach; SPM {f} is the scalar trajectory variable. Critical threshold refers to the value of which the only alpha (5%) of smooth random curves would be expected to cross. A suprathreshold cluster is an area of the curve that exceeds the critical threshold. If the SMP{t} cross the critical threshold at any point, the null hypothesis is rejected (Pataky, 2012).

In the results, the post hoc test is more sensitive compared to the ANOVA test, as the SPM t-test used for comparison was not adjusted for multiple comparisons – thus p=0.05 for each of the t-tests. The SPM post hoc analysis with adjusting for multiple comparisons is not sensitive enough to display differences between groups in this study. The differences between the ANOVA results and the ANOVA post hoc results using SPM is a known issue where a separate smoothness assessment is used for each post hoc test (Pataky, 2019). The post hoc test results would be invalid as it assumes that the tests are independent (Pataky, 2019), where in the current study, it is not. In other rugby kicking research focussing on angle and angular velocity plots, the t-test method in SPM with an alpha level of 0.05 was also used to compare differences between three groups of interest (Atack *et al.*, 2016, 2017).

Methods used to quantify the difference in inter-joint and -segment coordination between 22 m, 32 m, and 40 m kicks, included vector coding (Needham *et al.*, 2014) in Matlab (Matlab 8, Mathworks inc., USA). Angle-angle diagrams of the hip-knee, knee-ankle, and pelvis-torso joints were created. From the angle-angle plots, vector coding was applied to quantify the coordination in the segment- and joint couplings, providing a CA. CA's were classified into four unique coordination patterns, namely 1) in-phase, 2) anti-phase, 3) proximal phase, and 4) distal phase. The percentage of time spent in each phase was calculated and represented in histograms (Chang *et al.*, 2008). Circular statistics were used to calculate the mean CA for each participant at each distance, as well as group means in Matlab (Matlab 8, Mathworks inc., USA).

Results will be discussed in Chapter Four concerning the sagittal-, frontal-, and transverse plane with reference to each event listed below (see Figure 14).

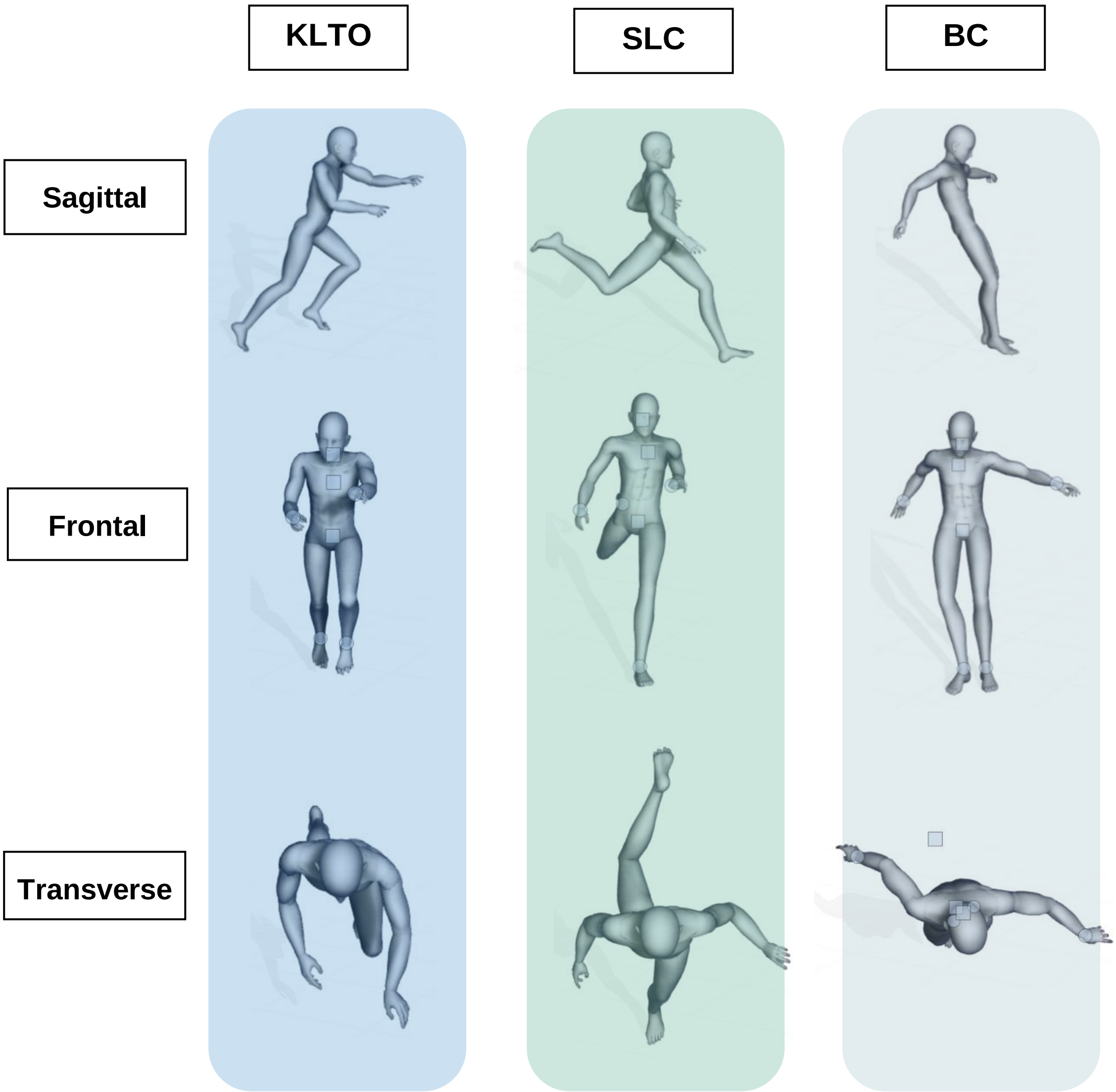


Figure 14: Description of planes and phases used in the following section
Source: Author, 2019
KLTO = kicking leg toe-off; SLC = support leg contact; BC = ball contact

3.7.3 CALCULATIONS FOR CA

For the CA analysis, only successful trials were used. The steps calculating CA are described below (Chang *et al.*, 2008; Cunningham, 2012; Hamill *et al.*, 2000; Needham *et al.*, 2014). The first step includes plotting angle-angle diagrams for joints or segments of interest. The proximal segment should be on the horizontal axis with the distal segment on the vertical axis. The following equation was used, where (i) refers to each instance during a normalised kicking phase, including backswing and forward swing. CA (γ_i) is calculated based on difference in proximal segment angles $(\theta_{P(i+1)} - \theta_{P(i)})$ and difference in distal segment angles $(\theta_{D(i+1)} - \theta_{D(i)})$.

$$\gamma_i = Atan\left(\frac{\theta_{D(i+1)} - \theta_{D(i)}}{\theta_{P(i+1)} - \theta_{P(i)}}\right).\frac{180}{\pi} \qquad \theta_{P(i+1)} - \theta_{P(i)} > 0$$

$$\gamma_i = Atan\left(\frac{\theta_{D(i+1)} - \theta_{D(i)}}{\theta_{P(i+1)} - \theta_{P(i)}}\right).\frac{180}{\pi} + 180 \qquad \theta_{P(i+1)} - \theta_{P(i)} < 0$$

The following conditions were applied:

$$\gamma_i = \begin{cases} \gamma_i = 90 & \theta_{P(i+1)} - \theta_{P(i)} = 0 \text{ and } \theta_{D(i+1)} - \theta_{D(i)} > 0 \\ \gamma_i = -90 & \theta_{P(i+1)} - \theta_{P(i)} = 0 \text{ and } \theta_{D(i+1)} - \theta_{D(i)} < 0 \\ \gamma_i = -180 & \theta_{P(i+1)} - \theta_{P(i)} < 0 \text{ and } \theta_{D(i+1)} - \theta_{D(i)} = 0 \\ \gamma_i = undefined & \theta_{P(i+1)} - \theta_{P(i)} = 0 \text{ and } \theta_{D(i+1)} - \theta_{D(i)} = 0 \end{cases}$$

CA (γ_i) was corrected to present a value between 0˚ and 360˚ (Chang *et al.*, 2008; Sparrow *et al.*, 1987).

$$\gamma_i = \begin{cases} \gamma_i + 360, \gamma_i < 0 \\ \gamma_i \qquad\quad, \gamma_i \geq 0 \end{cases}$$

3.7.4 VARIABILITY CALCULATIONS

Successful trials were used for the variability analysis. The variability calculations that were used within the ambit of this research study include area of ellipse method, a bivariate approach (Stock, van Emmerik, *et al.*, 2018). The method involves forming an ellipse around the end-point of the coupling vectors, providing a bivariate measure of variability in the direction and length of the vector. This method is more robust to changes in vector length (Stock, van Emmerik, *et al.*, 2018). The method is reported here in MATLAB code format:

The first step involves using the difference in velocity measures at each point of the kicking phase for the joints or segments of interest. Using velocity as the input measure is less susceptible to noise (Stock, Furlong, Wilson, van Emmerik & Preatoni, 2018). Covariate matrix is formed at each time point (t) for the movement phase of interest, with velocity used as input (ω):

$$C(t) = \text{cov}\,(\Delta\omega_1(t), \Delta\omega_2(t))$$

Eigenvalues of the covariate matrix:

$$[\sim, \lambda(t)] = \text{eig}\,(C(t))$$

Chi-squared scaling factor – the probability (p) that a given point would reside in the defined ellipse (set to 0.95):

$$k = \sqrt{-2 \bullet log_e(1-p)}$$

The magnitude of the two ellipse axes are altered according to the constant k:

$$X(t) = k \bullet \text{sqrt}(\text{svd}\,(\lambda(t))\,)$$

Area of the ellipse, representing a bivariate measure of coordination variability:

$$A(t) = \pi \bullet \text{prod}\,(X(t))$$

3.7.5 CLUSTER ANALYSIS

Only successful trials were used for cluster analysis. Values were extracted for the knee, hip and thorax in the sagittal plane at three forward swing events including, top of backswing, maximal knee flexion, and ball contact. Means were calculated for each individual and kicking distance. Kicking events were selected based on the ability to translate information to coaches and players. As opposed to time normalised data that can present significant flaws as a result of temporal dependency for example, not all the kickers will reach maximum knee flexion at the time exact time during the forward swing (Ball & Best, 2007).

To determine if different sagittal plane profiles existed at the three different kicking events in the sagittal plane, hierarchical cluster analysis was performed using SPSS (version 25) with squared Euclidean distance dissimilarity measure and between-group linage (Ball & Best, 2007; Milligan & Cooper, 1985). The number of clusters were selected based on using two stopping rules, step size and point-biserial correlation (Milligan & Cooper, 1985). Cluster validation was done by leave-one-out and replication method (Ball & Best, 2007). ANOVA comparisons were done to compare the variables at each kicking event between the clusters as well as to determine differences in foot speed at ball contact between clusters.

3.8 VALIDITY

This research study collected data on an outdoor field to ensure that the kicking environment represents the competitive situation as closely as possible. External validity represents the testing environment and should be controlled or accounted for as much as possible (wind speed, pitch conditions). Internal validity is related to the accuracy of data and can be influenced by measurement errors and bias (Atack, 2016). A 3D motion capturing system was used to collect kinematic data as it provides accurate data if marker placement is correct to ensure validity for a high intensity movement in multiple body planes.

3.9 ETHICAL CONSIDERATIONS

Ethical approval has been granted for the study “The analysis of rugby place kicking” by Dawie van den Heever and John Cockcroft in 2013 (reference number: N13/08/121). The ethical clearance has successfully been extended in 2017 and 2018 with amendments. Institutional permission was received from the director of high-performance sport at Stellenbosch University (Maties sport) to conduct this research study.

All kickers were invited to partake in the study voluntarily and could terminate the testing at any stage without any consequences. The participants completed an informed consent before data collection. They could keep the subject information sheet containing the contact information of the researchers. Data are kept confidential and anonymous.

CHAPTER FOUR: RESULTS

4.1 DESCRIPTIVE CHARACTERISTICS

Ten male rugby kickers took part in the study, with the sample characteristics summarised in Table 8. One kicker did not complete the full dataset and was excluded from further analysis. The average kicking success rate of all the trials during data collection was 72 per cent. Kicking success rate for each distance was 87 per cent, 71 per cent and 60 per cent for the 22 m, 32 m and 40 m kicks respectively, thereby decreasing in success rate with increase in distance. The unsuccessful 22 m and 32 m kicks were due to direction (achieved enough distance to pass over the crossbar), while the 40 m kicks were unsuccessful due to distance and direction. On the days testing took place, the temperature ranged between 19 and 25 degrees Celsius and the wind speed was below 15 kilometres per hour (light breeze).

Table 8: Characteristics of the sample used in the current study (n=9)

Descriptive Statistics		
	Mean	**SD**
Height (cm)	175.8	4.7
Weight (kg)	81.5	8.7
Age (years)	20.3	1.0

4.2 DISCRETE KINEMATICS

At ball contact the knee extension angle was 29º (8º), hip flexion 19º (13º), pelvis rotation -21º (10º), and thorax rotation -35º (11º) (Table 9). Maximal knee flexion in the current study was 101.º (8º). ROM in the current study was 43º (10º) for the hip and 73º (12º) for the knee, with no significant differences between groups (Table 10).

No significant difference in angular position of the kicking ankle, knee, and hip, as well as the pelvis and thorax at ball contact was reported, with change in kicking distance (Table 9). All the p-values for the angular positioning at support leg contact and ball contact were above 0.9, except for the kicking leg hip flexion/extension position at ball contact (p=0.87). The ROM during the forward swing phase of the kick had insignificant change from various kicking distances (Table 10), with p-values above 0.9, except for kicking leg knee flexion/extension ROM (p=0.83). The joint- and segment angle curves all displayed negligible to small effect size, except for hip flexion/extension at ball contact and ankle pantar-/dorsiflexion ROM with moderate effect scale.

Table 9: Angles of joints measured at ball contact (presented as mean and standard deviation)

	22 m		32 m		40 m		p	Effect size	Effect scale
	Mean	SD	Mean	SD	Mean	SD			
KL Ankle P/D (⁰) [a]	-37	9	-37	9	-38	9	.92	0.21	S
KL Knee F/E (⁰) [a]	22	10	21	8	22	8	.94	0.17	S
KL Hip F/E(⁰) [a]	21	13	19	14	18	13	.87	0.26	M
Pelvis I/E(⁰) [b]	-21	9	-22	10	-21	10	.99	0.08	N
Thorax I/E(⁰) [b]	-35	10	-35	10	-34	12	.97	0.11	S

[a] measured in sagittal plane
[b] measured in transverse plane
KL: Kicking leg
Ankle P/D (Plantar flexion/Dorsiflexion): Positive value indicating dorsiflexion
Knee F/E (Flexion/Extension): Positive value indicating knee flexion
Hip F/E (Flexion/Extension): Positive flexion angle relates to the knee being in front of the body
Pelvis I/E (Internal-/External rotation): Negative value indicating external rotation (where the opposite side is in front)
Thorax I/E (Internal-/External rotation): Positive value indicating internal rotation
Effect scale N: Negligible, S: Small, M: Moderate

Table 10*:* Range of motion of joint angles during the forward swing phase of the kick

	22 m		32 m		40 m		p	Effect size	Effect scale
	Mean	SD	Mean	SD	Mean	SD			
KL Ankle P/D (⁰) [a]	10	5	9	3	10	5	.90	0.26	M
KL Knee F/E (⁰) [a]	71	14	73	12	75	12	.82	0.16	S
KL Hip F/E(⁰) [a]	44	10	43	9	43	10	.96	0.13	S
Pelvis I/E(⁰) [b]	24	7	24	8	25	8	.93	0.19	S
Thorax I/E(⁰) [b]	6	4	6	3	6	4	.96	0.13	S

[a] measured in the sagittal plane.
[b] measured in transverse plane.
Ankle P/D (Plantar flexion/Dorsiflexion): Positive value indicating dorsiflexion
Knee F/E (Flexion/Extension): Positive value indicating knee flexion.
Hip F/E (Flexion/Extension): Positive flexion angle relates to the knee being in front of the body
Pelvis I/E (Internal-/External rotation): Negative value indicating external rotation (where the opposite side is in front)
Thorax I/E (Internal-/External rotation): Positive value indicating internal rotation
Effect scale S: Small, M: Moderate,

Peak angular hip flexion velocity and time to peak hip flexion velocity had a moderate effect size of f=0.31 and f=0.32, respectively with an increase in kicking distance. Peak knee extension velocity had a large effect size (f=0.67) (Table 11). Foot speed at ball contact indicated a large effect scale to increase with an increase in distance with f=1.24 (p=0.06) (Table 10).

Table 11: Angular velocities

	22 m		32 m		40 m		p	Effect size	Effect scale
	Mean	SD	Mean	SD	Mean	SD			
Peak KE velocity (deg/s)	-2092.3	214.6	-2170.8	196.5	-2215.8	178.0	.42	0.67	L
Time to peak KE velocity (%)	99.4	2.7	99.4	2.5	99.0	2.6	.92	0.21	M
Peak HF velocity (deg/s)	770.3	129.3	765.3	123.6	801.1	146.8	.83	0.31	M
Time to peak HF velocity (%)	41.4	13.7	40.4	12.0	37.8	11.2	.81	0.32	M
Foot Speed at BC (m/s)	22.2	0.9	22.8	1.0	23.3	0.8	.06	1.24	L

KE: knee extension: Positive value indicating knee flexion)
HF: hip flexion: Positive value indicating flexion measured in the sagittal plane
BC: Ball contact
SL: Support leg
Velocities calculated for the forward swing (top of backswing to ball contact).
Effect scale S: Small, M: Moderate, L: Large

Change in the distance from posts had a small effect on variables related to the approach, but with a trend towards an increase maximal approach velocity with moderate effect scale (p=0.49, f=0.36) with increase in distance (Table 12).

Table 12: Variables associated with the approach and planting of the support leg

	22 m		32 m		40 m		p	Effect size	Effect scale
	Mean	SD	Mean	SD	Mean	SD			
Length of last step (relative)	1.57	0.11	1.58	0.12	1.61	0.11	.77	0.36	M
Max Approach Velocity ($m.s^{-2}$)	3.7	0.3	3.8	0.4	3.9	0.4	.49	0.60	L
SL position behind tee (mm)	175.1	128.0	169.1	113.4	157.1	112.9	.95	0.17	S
SL position lateral to tee (mm)	378.5	72.3	381.3	74.6	388.5	73.0	.96	0.16	S

SL: Support leg
Length of the last step measured from toe marker at kicking leg toe-off to heel marker at support leg foot contact.
Effect scale S: Small, M: Moderate, L: Large

Foot progression angle at the final 5% before ball contact indicated no statistically significant difference between groups (p=0.94) with small effect size (Table 13). The foot stayed between 51 and 52 degrees of external rotation.

Table 13: Average foot progression angle during the final 5% of the kicking phase

	22 m		32 m		40 m		p	Effect size	Effect Scale
FPA (º)	-52	7	-51	7	-51	7	0.94	0.17	S

FPA: Foot Progression Angle
Effect scale S: Small

4.3 JOINT ANGLE CURVES

4.3.1 KICKING LEG ANKLE ANGLE

Ankle angles in the sagittal plane represent plantar flexion in the case of a negative value and dorsiflexion is represented by a positive value. During the backswing, the ankle started at about 20º of plantar flexion and moved to about 37º of plantar flexion towards the end of the backswing. For the forward swing, the ankle stayed in a relatively constant position of plantar flexion (see

Figure 15). The ankle joint displayed no significant difference between any of the three conditions through the whole backswing and forward swing of the kicking movement (see Figure 15). Similar results were seen for successful trials, represented in Figure 16.

Sagittal plane

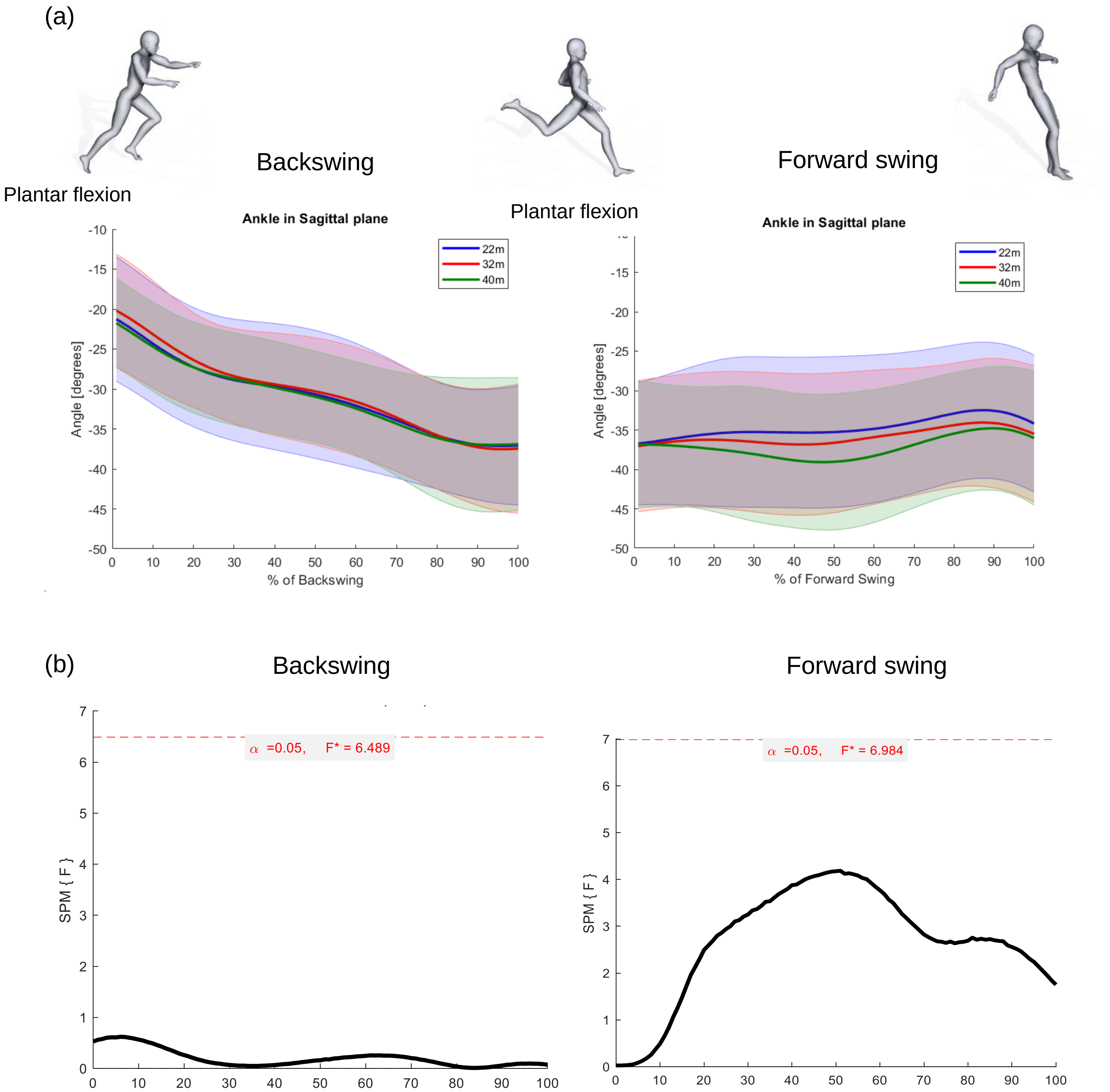


Figure 15: a) Mean trajectories for ankle angles in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 6.489 (backswing) and 6.964 (forward swing) was not exceeded.

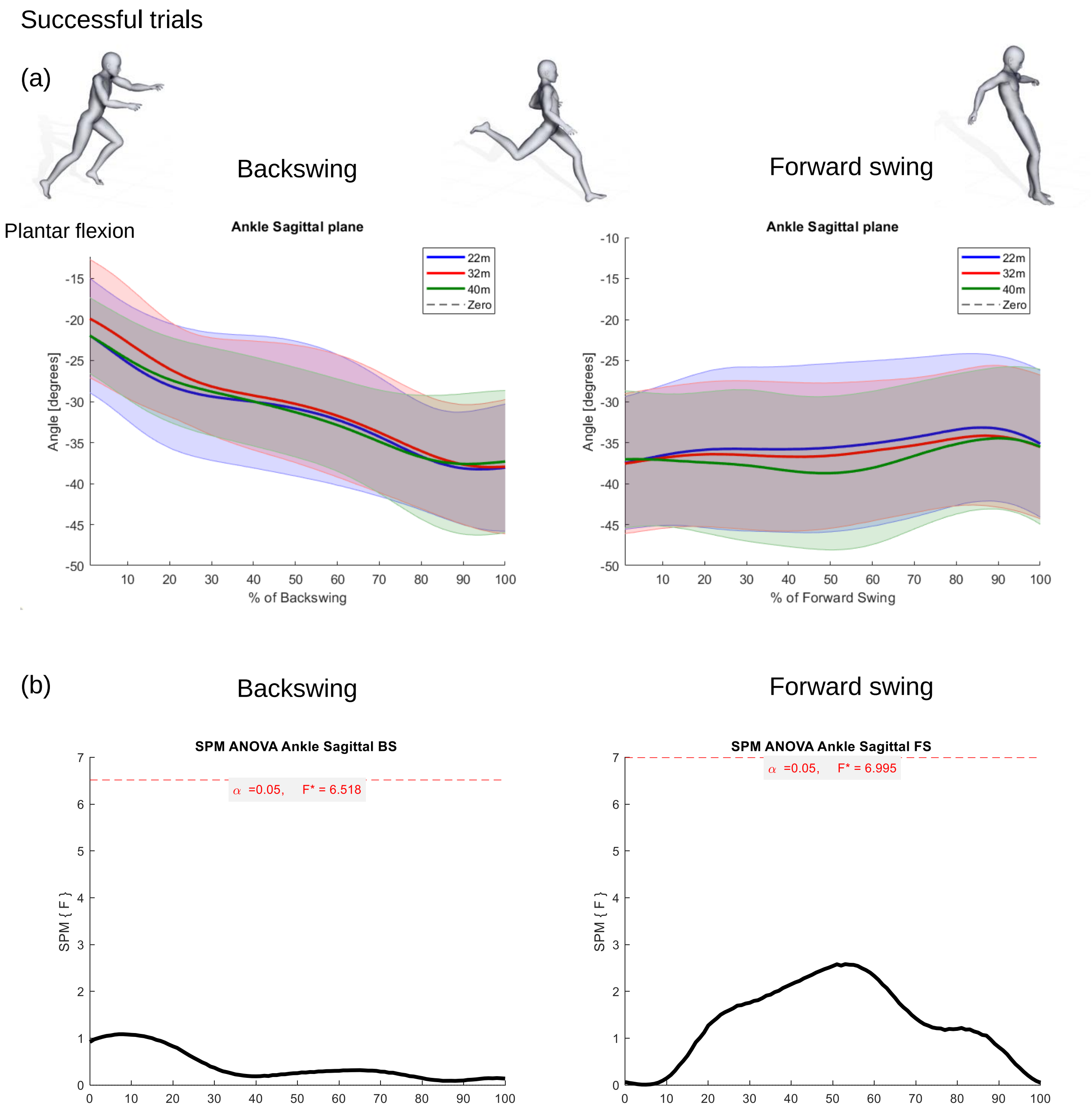


Figure 16: a) Mean trajectories for ankle angles in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 6.518 (backswing) and 6.995 (forward swing) was not exceeded.

4.3.2 KICKING LEG KNEE ANGLE

Knee sagittal plane motion indicated flexion and extension, with positive indicating knee flexion. Frontal plane motion represents knee valgus and varus with positive indicating varus (outward bend of the knee). In the transverse plane, internal and external rotation is seen, where positive indicating internal knee rotation.

The knee starts in an extended position at kicking leg toe-off and moves towards a state of flexion as it approaches the top of the backswing. During the forward swing, the knee flexion continues to ~100º at 40 – 50 per cent of the forward swing. Thereafter, rapid knee extension takes place towards ball contact. For the knee joint in the sagittal plane, no difference was found in the joint angle for the backswing; however, a significant difference was found for the first 70 per cent of the forward swing (Figure 17). The post hoc test revealed significantly more knee flexion for the 40 m kicks when compared to the 22 m and 32 m kicks, respectively (Figure 18). However, no difference was reported between the 32 m and 22 m kicks. Less than five degrees of knee angle change in the frontal plane was observed during the backswing and forward swing (Figure 19). In the transverse plane, the knee moves through a total of ~10º of knee rotation across the entire backswing and forward swing combined (Figure 20). No differences were found in the joint orientation plots in the frontal (Figure 19) and transverse plane (Figure 20),indicating no difference between the groups. Successful trials only represented in Figure 22 to Figure 24, displaying similar movement patterns.

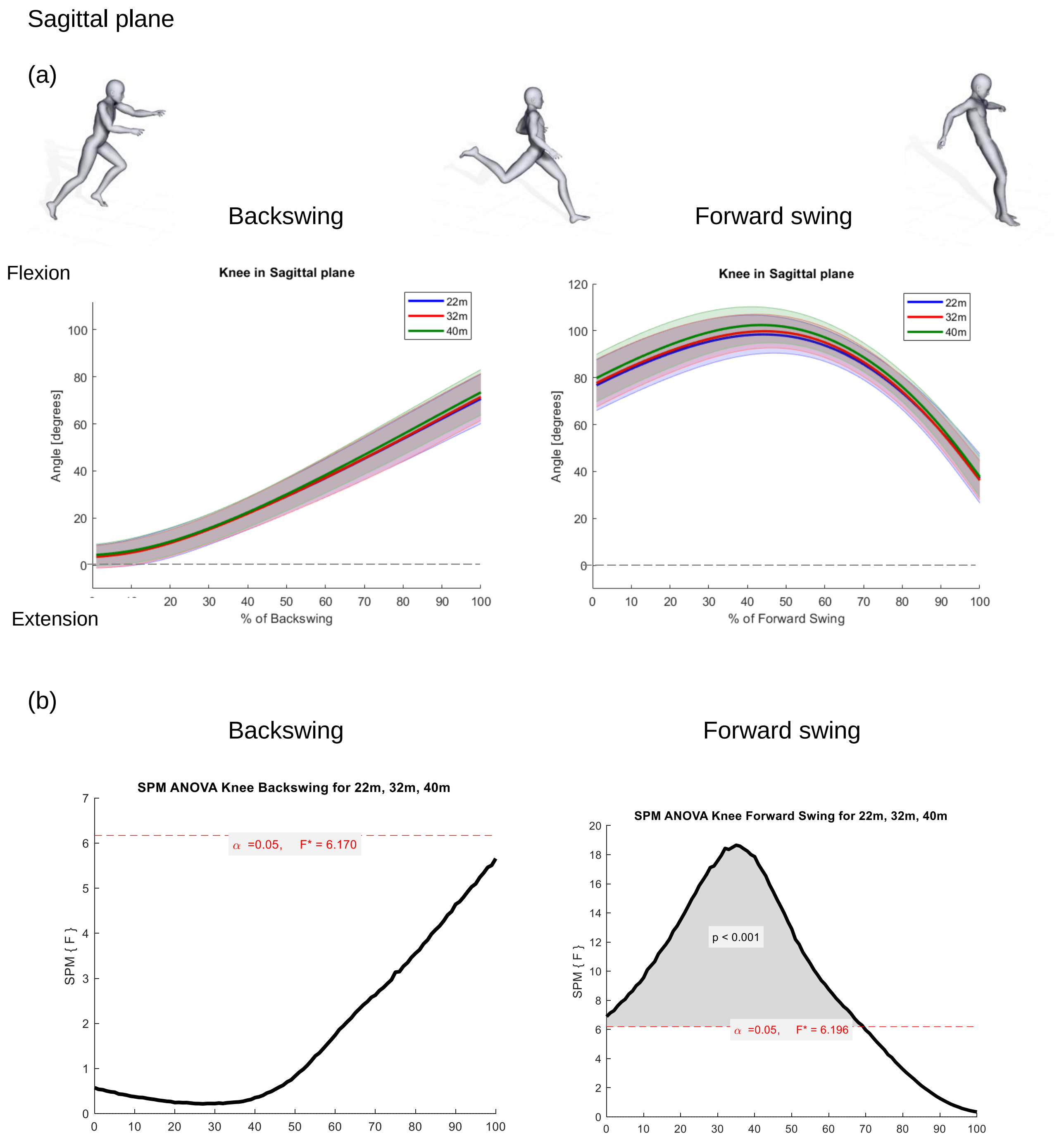
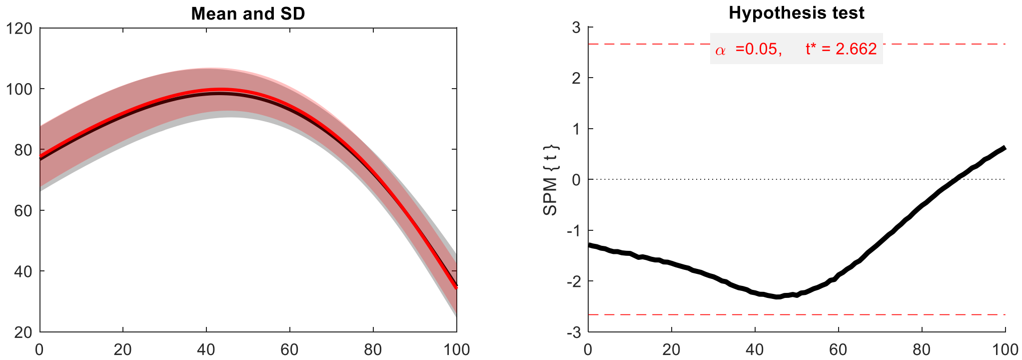


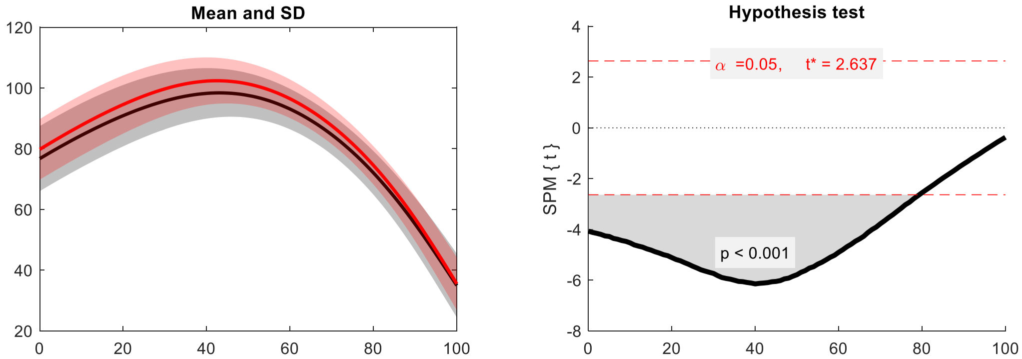
Figure 17: a) Mean trajectories for knee angles in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 6.170 (backswing) was not exceeded. The critical threshold of 6.196 (forward swing) was exceeded for the first 70% of the forward swing with a supra-threshold cluster probability of $p<0.001$, indicating a significant difference between groups.

Post hoc test

(a) 22 – 32



(b) 22 – 40



(c) 32 – 40

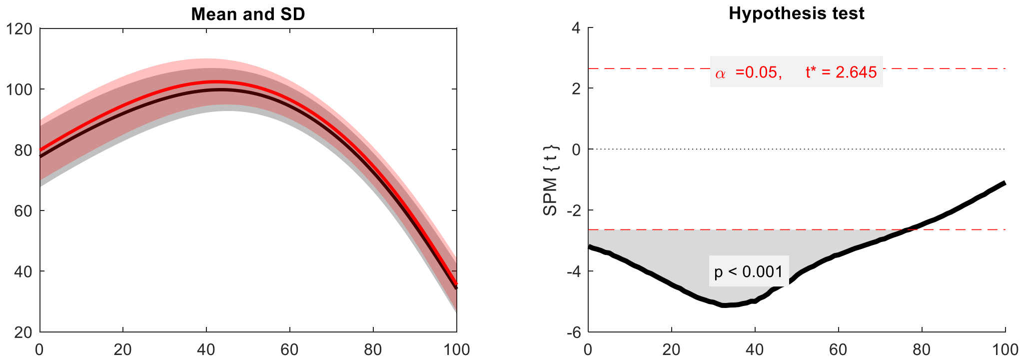


Figure 18: a) Statistical inference curves indicating no difference between 32m and 22m kicks. b) A significant difference between 40m and 22m kicks from the beginning to time point 80%. c). A significant difference between 40m and 32m kicks from the start to time point 80%.

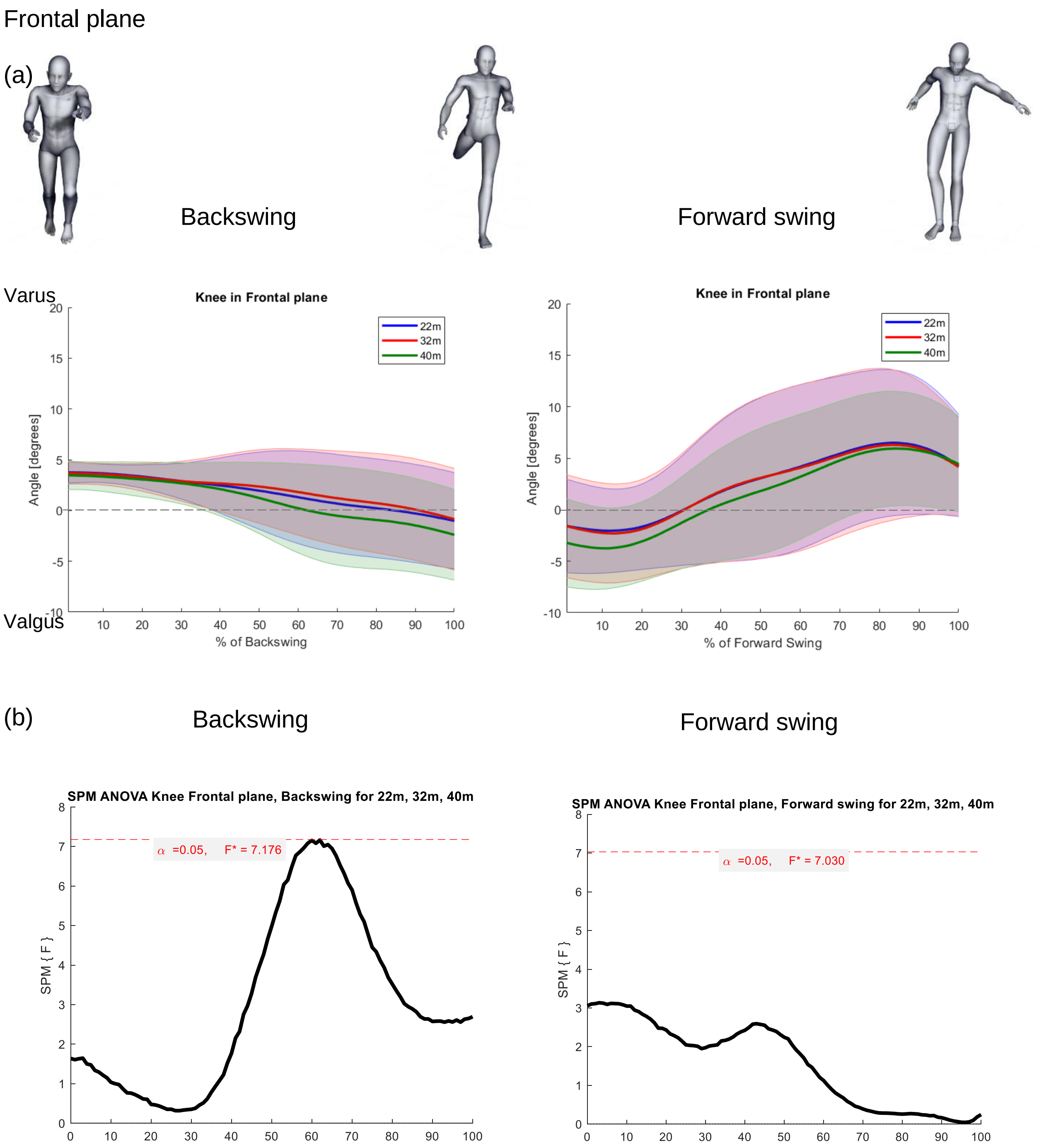


Figure 19: a) Mean trajectories for knee angles in frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.176 (backswing) and 7.030 (forward swing) was not exceeded.

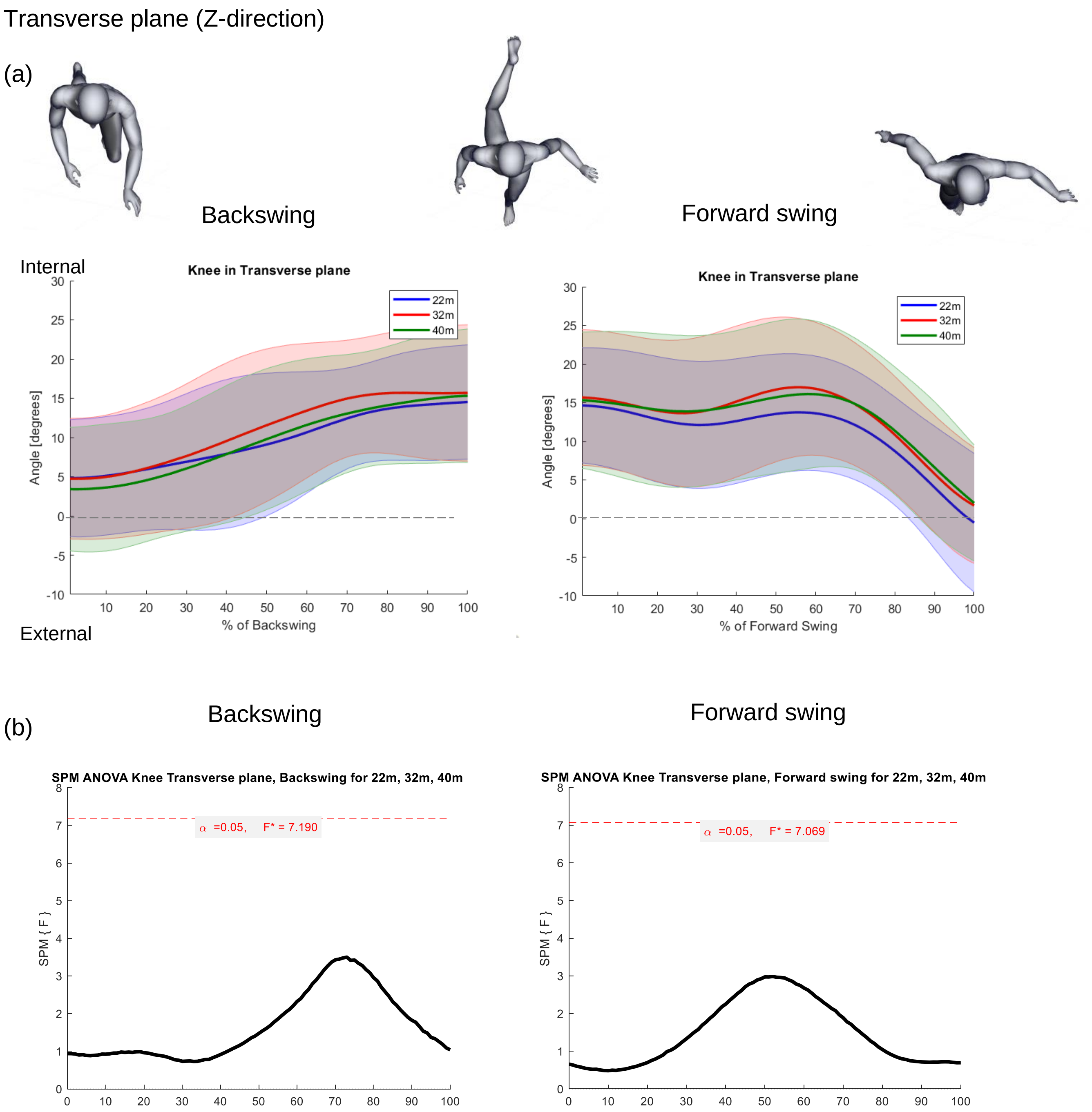


Figure 20: a) Mean trajectories for knee angles in transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.190 (backswing) and 7.069 (forward swing) was not exceeded.

Successful trials

Sagittal plane

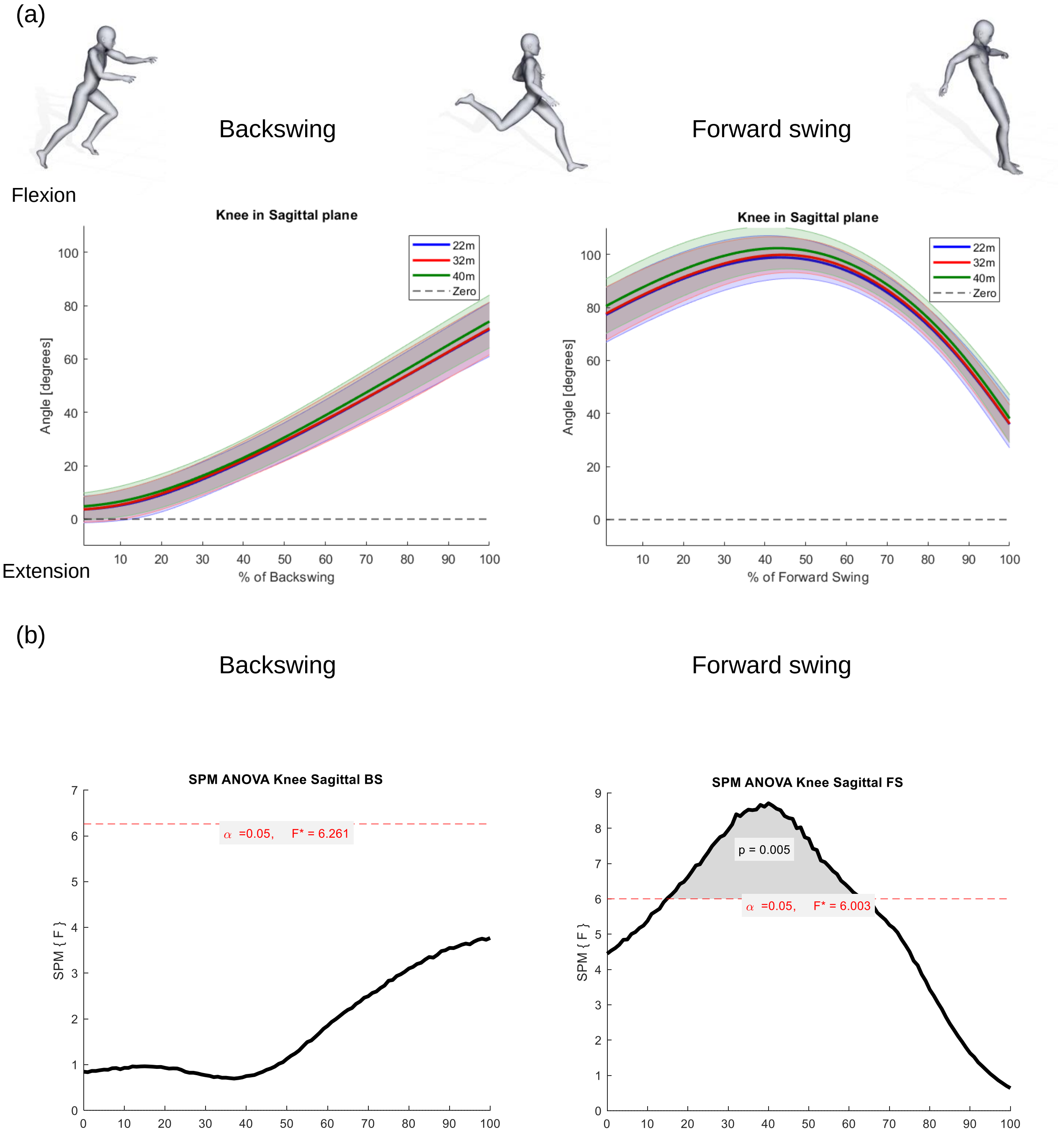
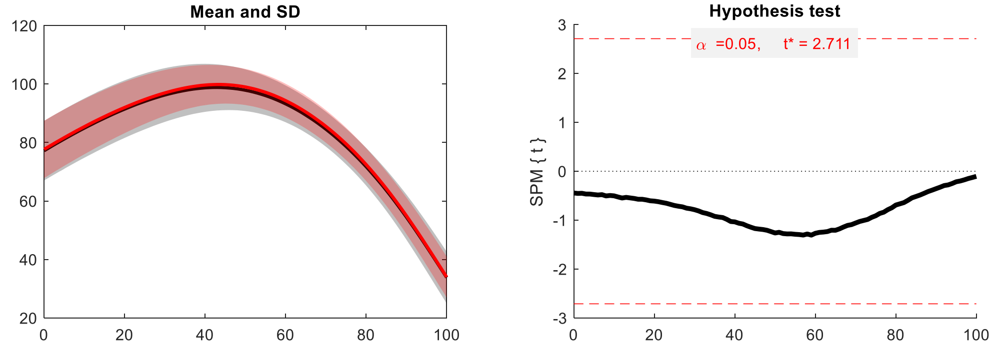


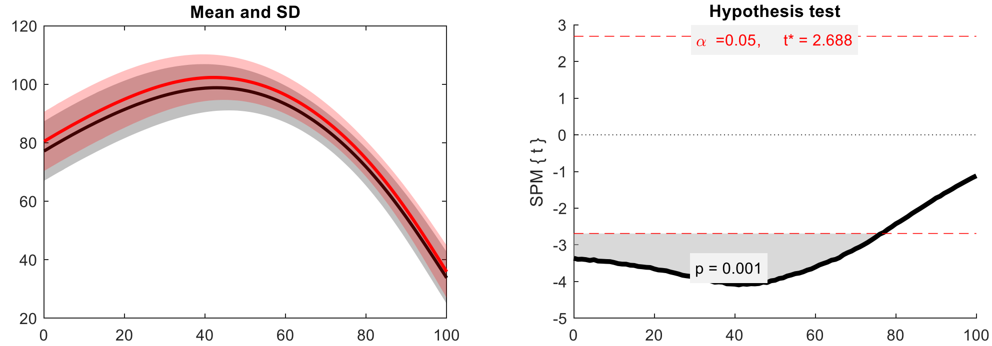
Figure 21: a) Mean trajectories for knee angles in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 6.261 (backswing) was not exceeded. The critical threshold of 6.003 (forward swing) was exceeded for the first 70% of the forward swing with a supra-threshold cluster probability of p<0.005, indicating a significant difference between groups

Post hoc test

(a) 22 – 32



(b) 22 – 40



(c) 32 – 40

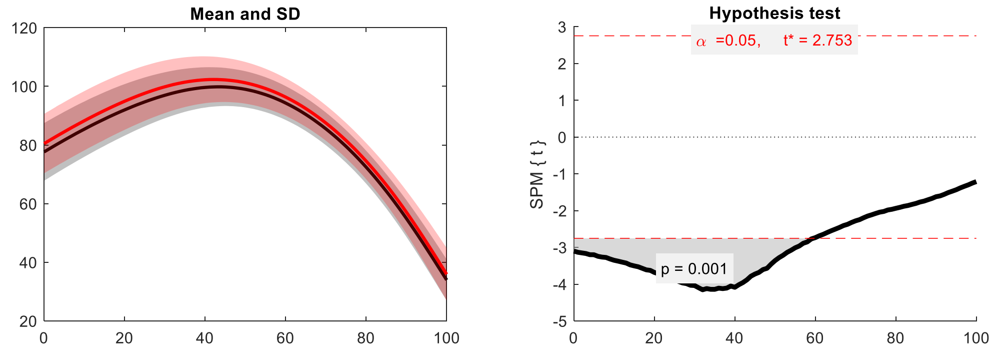


Figure 22: a) Statistical inference curves indicating no difference between 32m and 22m kicks. b) A significant difference between 40m and 22m kicks from the beginning to time point 80%. c) A significant difference between 40m and 32m kicks from the start to time point 45%.

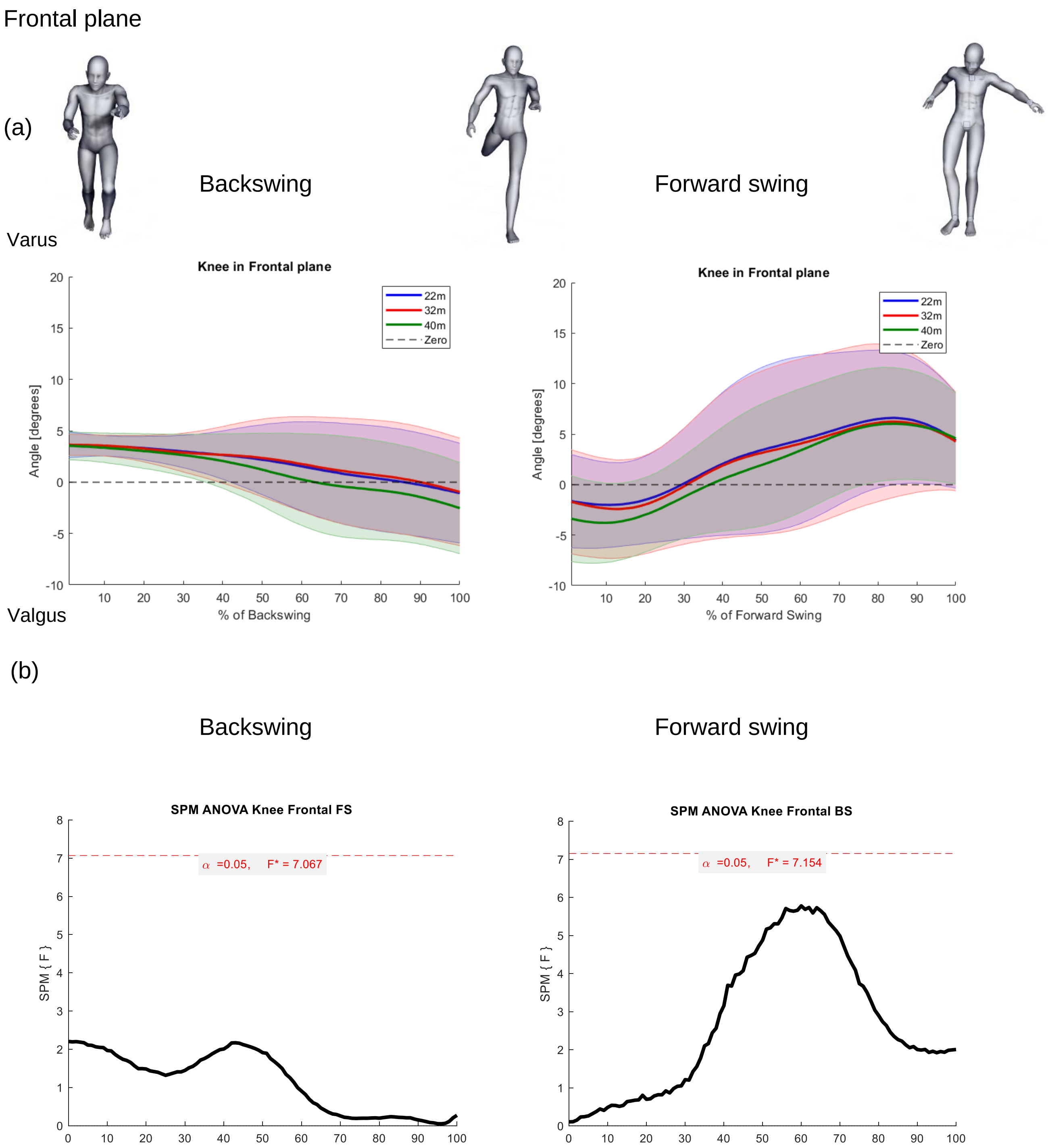


Figure 23: a) Mean trajectories for knee angles in frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.067 (backswing) and 7.154 (forward swing) was not exceeded.

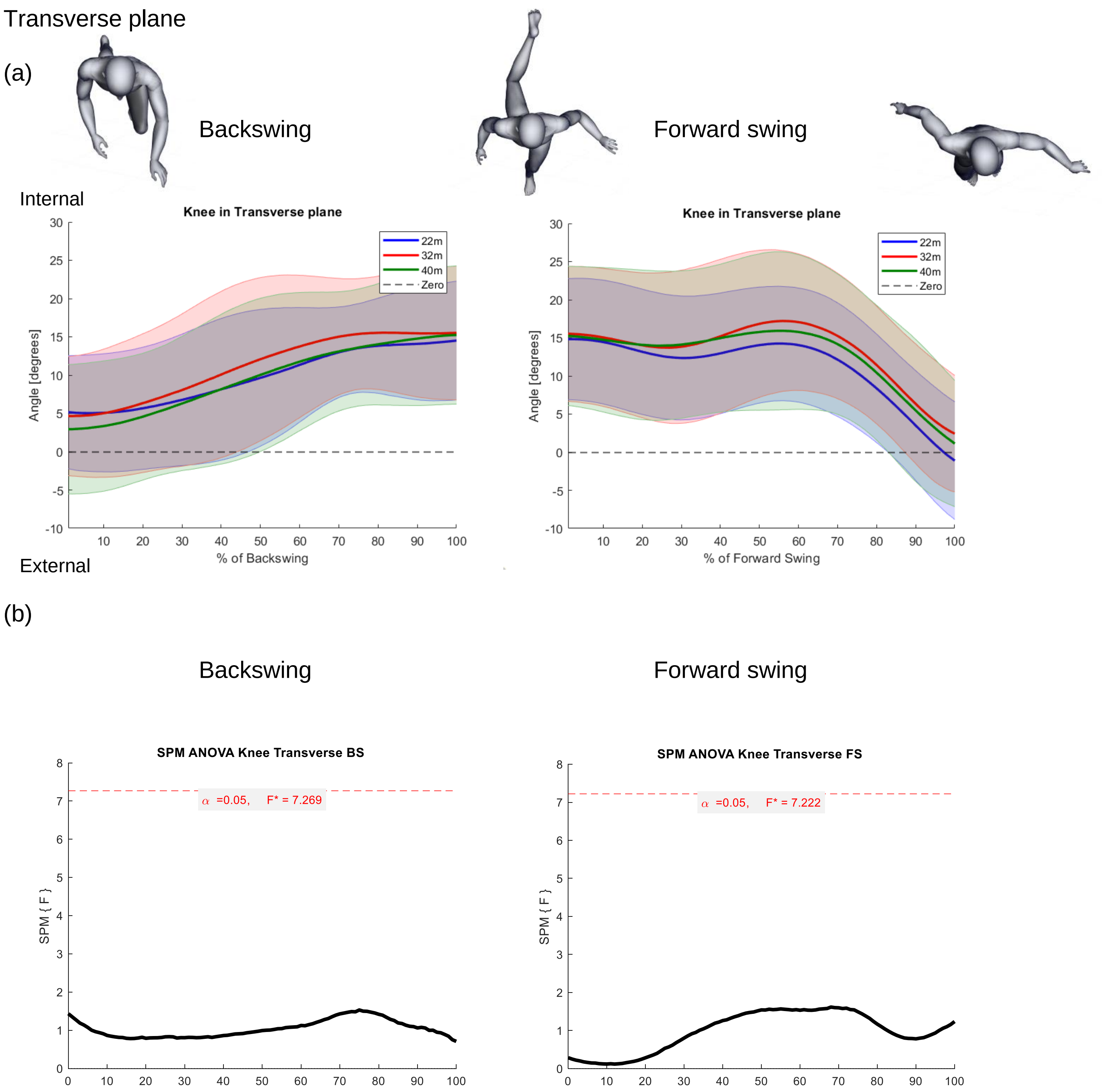


Figure 24: a) Mean trajectories for knee angles in transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.269 (backswing) and 7.222 (forward swing) was not exceeded.

4.3.3 KICKING LEG HIP ANGLE

Hip angle in the sagittal plane represents flexion and extension of the hip. A positive flexion angle relates to the knee being in front of the body. Frontal plane motion indicates hip abduction and adduction, where a positive value indicates adduction (inward rotation) of the leg. Hip rotation is seen in the transverse plane, here a positive value indicates internal hip rotation.

In the sagittal plane, the hip starts at ~12º of extension, and during the backswing moves to a maximum of ~25º at about 80 per cent to 90 per cent of the backswing. Thereafter, the hip moves into flexion and continues to flex to a maximum of ~20º at the end of the forward swing, before ball contact. During the backswing from 35 per cent to 75 per cent, the hip angle in the sagittal plane displayed a significant difference between groups (Figure 25), with more hip extension angle during the 40 m kicks compared to 22 m and 32m kicks, respectively (Figure 26). No difference was found between the 32 m and 22 m kicks. The frontal plane hip joint angles stayed between approximately 10º to 30º of abduction for the entire kicking movement and displayed no difference between groups (Figure 27). In the transverse plane, the hip external rotation stayed between 7º and 5º for the entire backswing. During the forward swing, the hip rotated from ~5º external rotation to ~15º internal rotation at ball contact. The only significant difference between groups was noted from 40 per cent to 65 per cent in the backswing (Figure 28). The post hoc test (Figure 29) indicated more external hip rotation in the 40 m kicks compared to the 32 m and 22 m kicks, respectively. In all three directions (X, Y, and Z) no differences were observed in the forward swing phase between groups. Similar findings reported for successful trials (Figure 30 to Figure 32), however no difference between groups reported for the transverse plane (Figure 33).

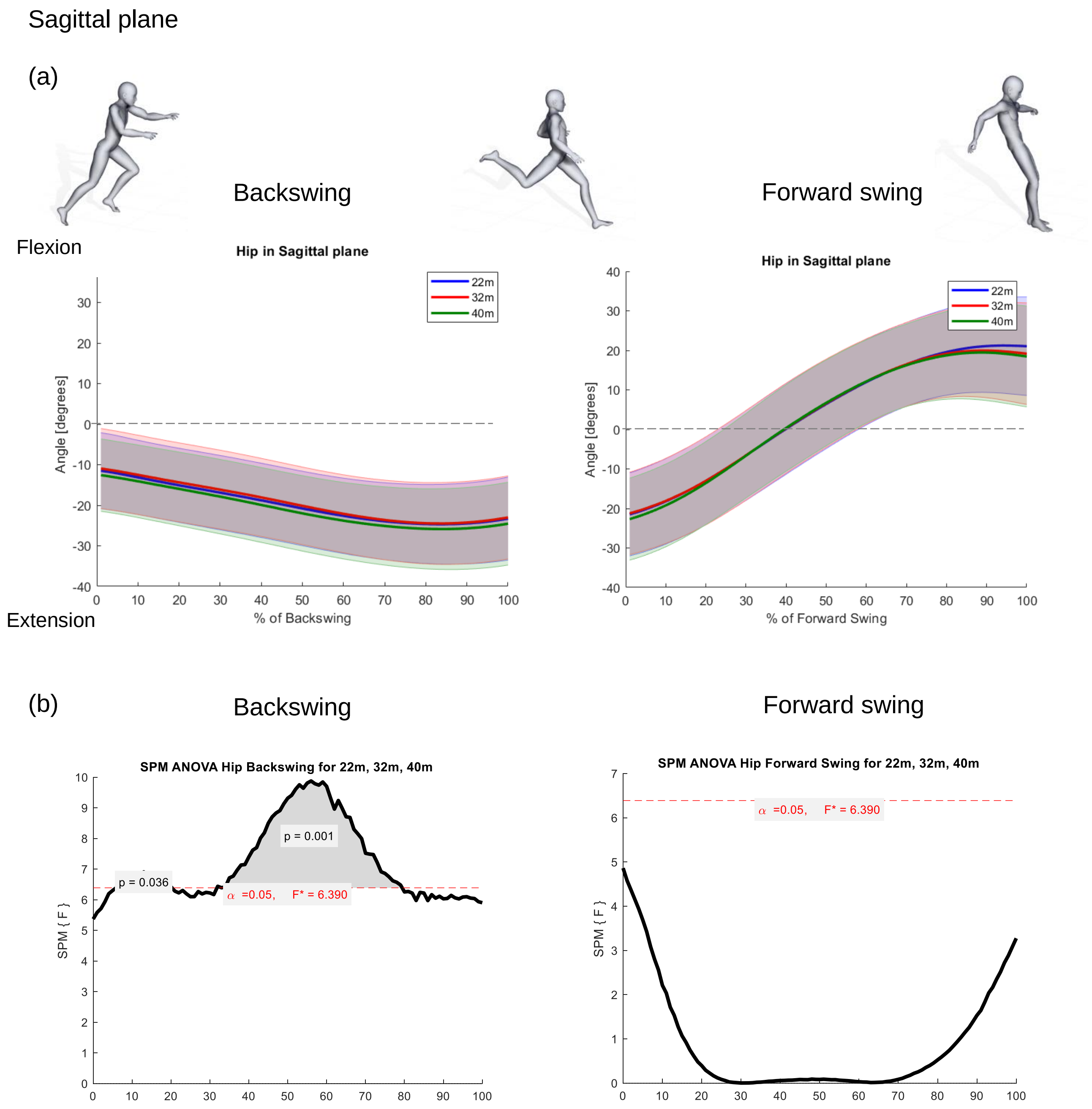
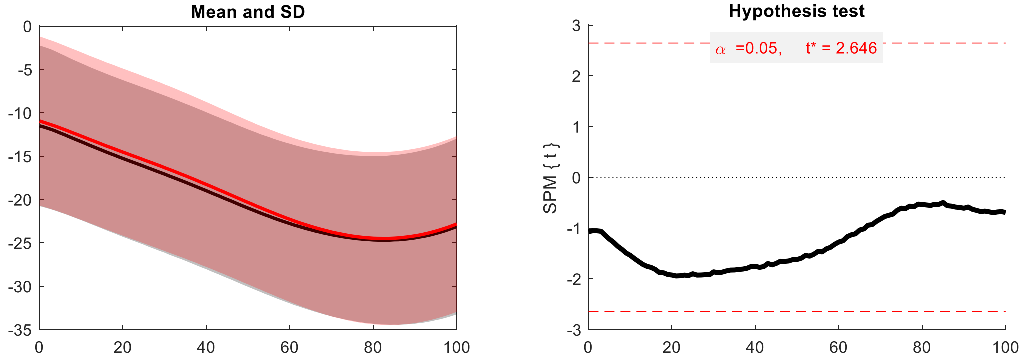


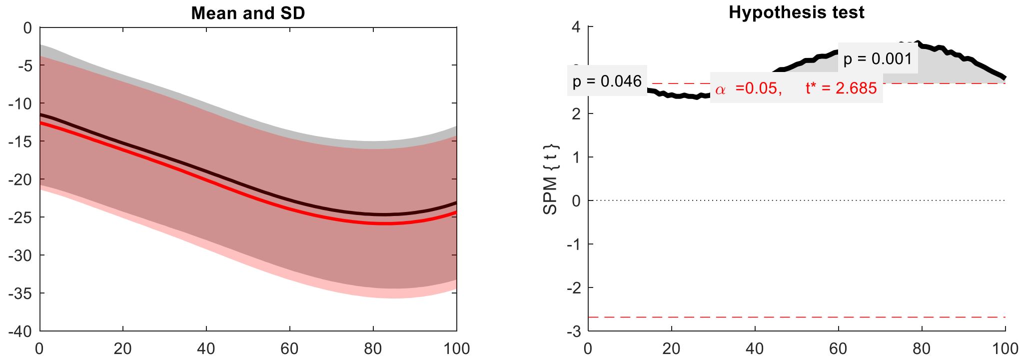
Figure 25: a) Mean trajectories for hip angles in the sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 6.390 (forward swing) was not exceeded. The critical threshold of 6.390 (backswing) was exceeded at time point 10% with a supra-threshold cluster probability of p=0.036, and again at time point 35% to 75%, with a supra-threshold cluster probability of p=0.001, indicating a significant difference between groups.

Post hoc test

(a) 22 – 32



(b) 22 – 40



(c) 32 – 40

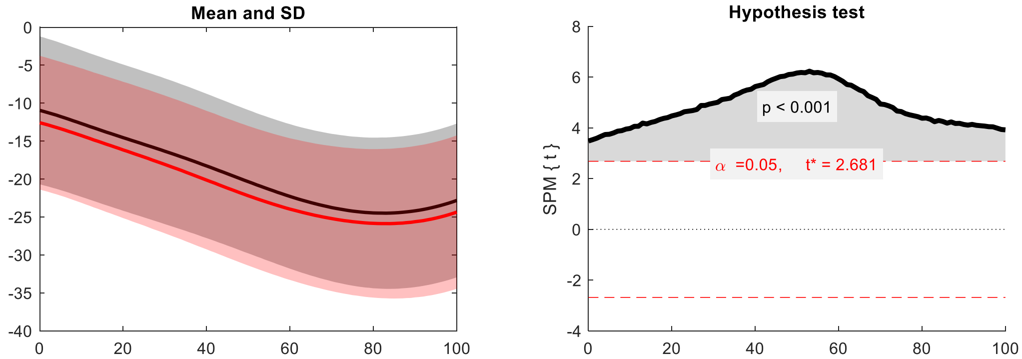


Figure 26: a) Statistical inference curves indicating no difference between 32 m and 22 m kicks. b) A significant difference between the 22 m and 40 m kicks for the first 5%, as well as the final 60%. c) A significant difference between the 32 m and 40 m kicks for the entire backswing.

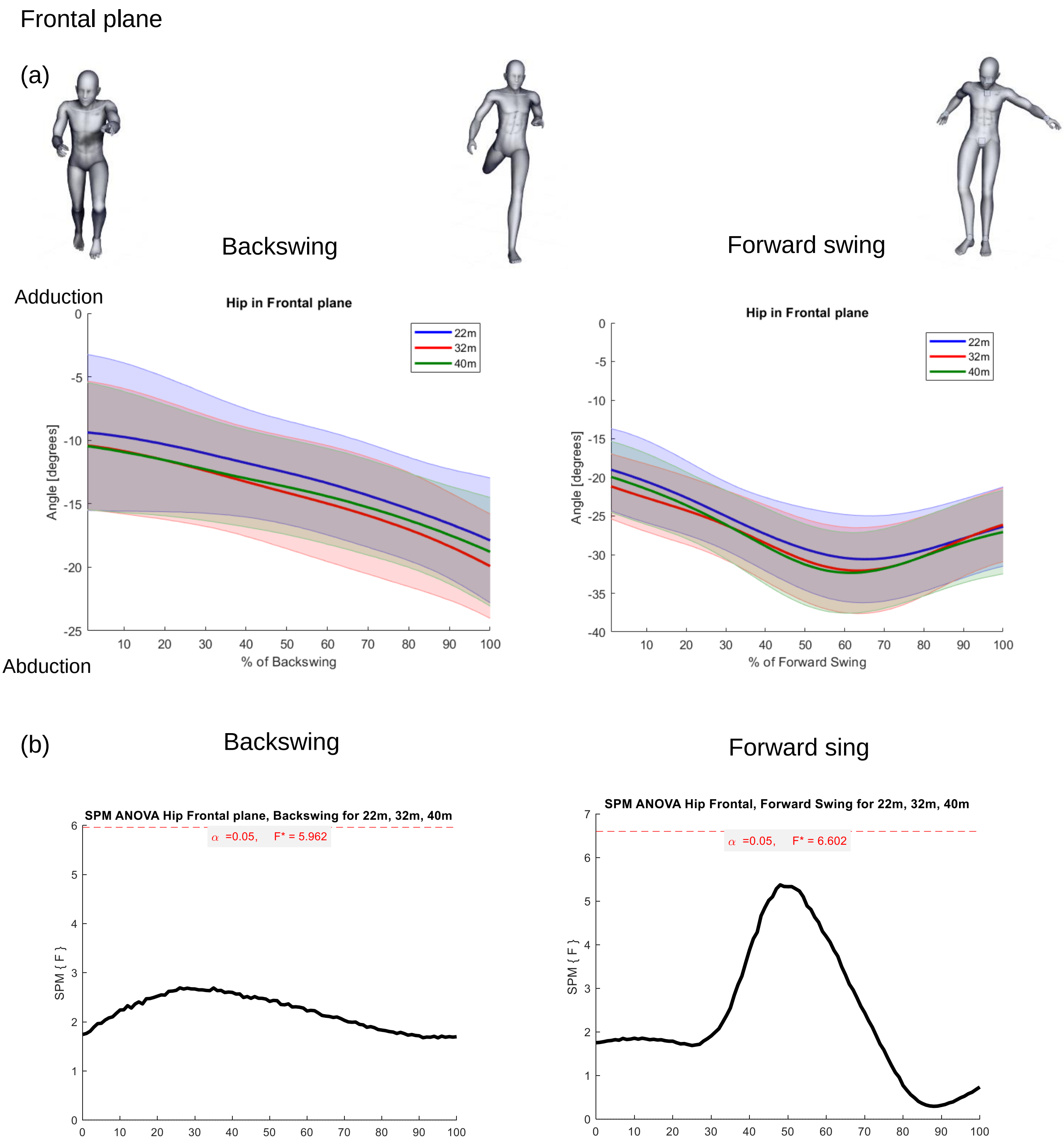


Figure 27: a) Mean trajectories for hip angles in frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 5.962 (backswing) and 6.602 (forward swing) was not exceeded.

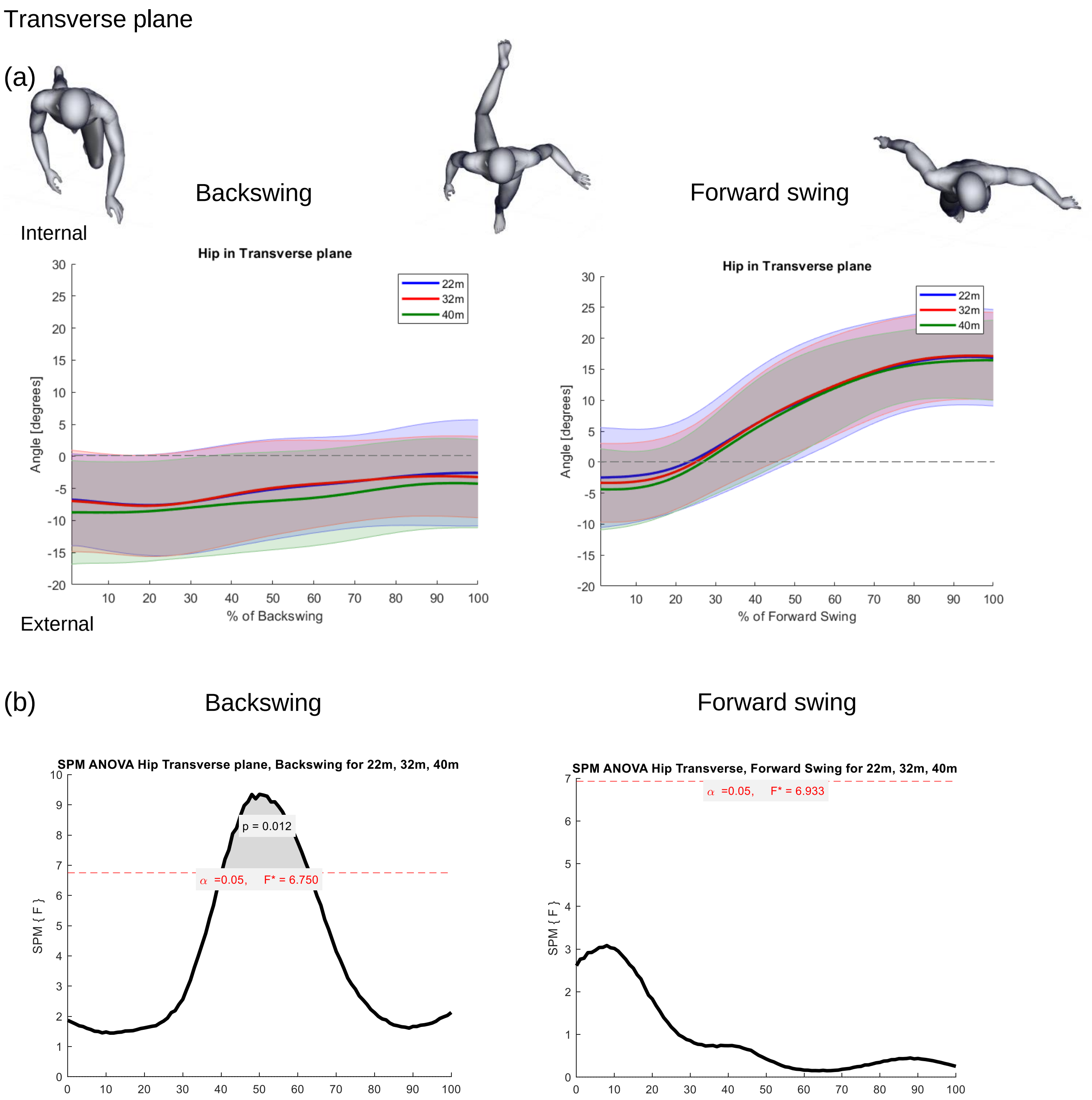
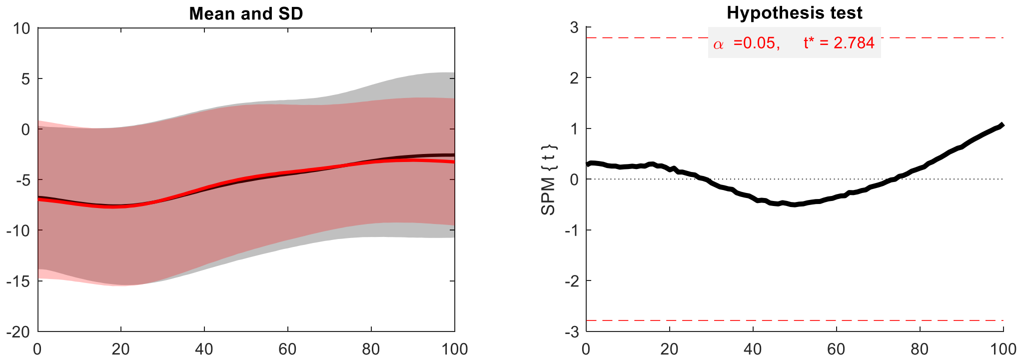


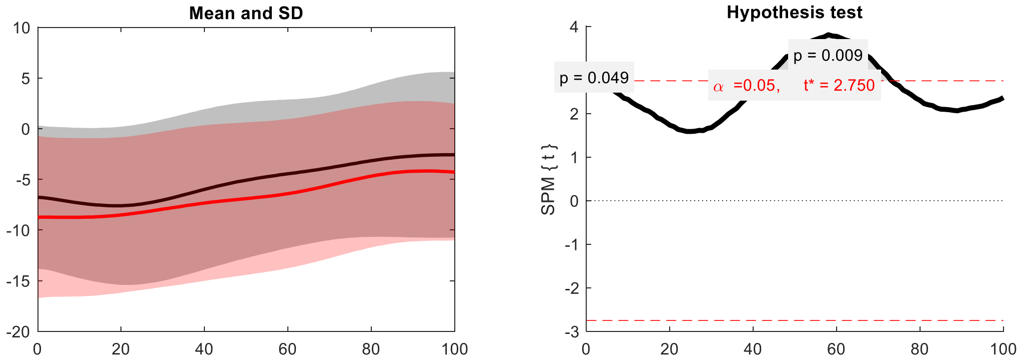
Figure 28: a) Mean trajectories for hip angles in transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 6.933 (forward swing) was not exceeded. The critical threshold of 6.750 (backswing) was exceeded from time point 40% to 65%, with a supra-threshold cluster probability of p=0.012, indicating a significant difference between groups.

Post hoc test

(a) 22 – 32



(b) 22 – 40



(c) 32 – 40

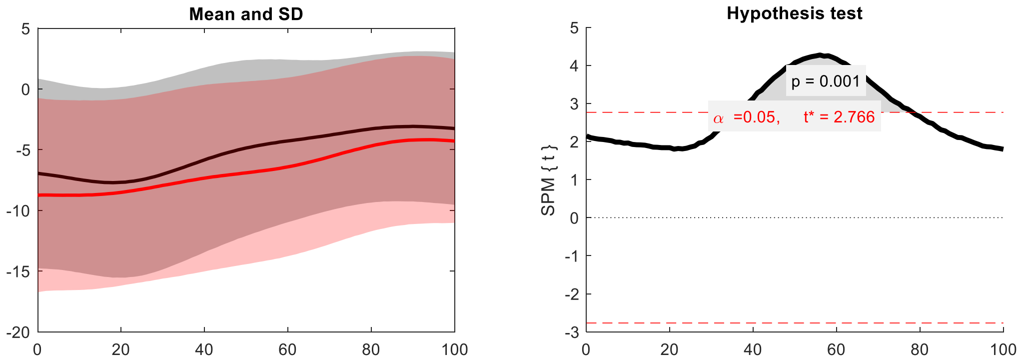


Figure 29: a) Statistical inference curves indicating no difference between the 22 m and 32 m kicks. b) A difference between the 22 m and 40 m kicks from time point 50% to 70%. c) A difference between the 32 m and 40 m kicks from time point 40% to 80%.

Successful trials

Sagittal plane

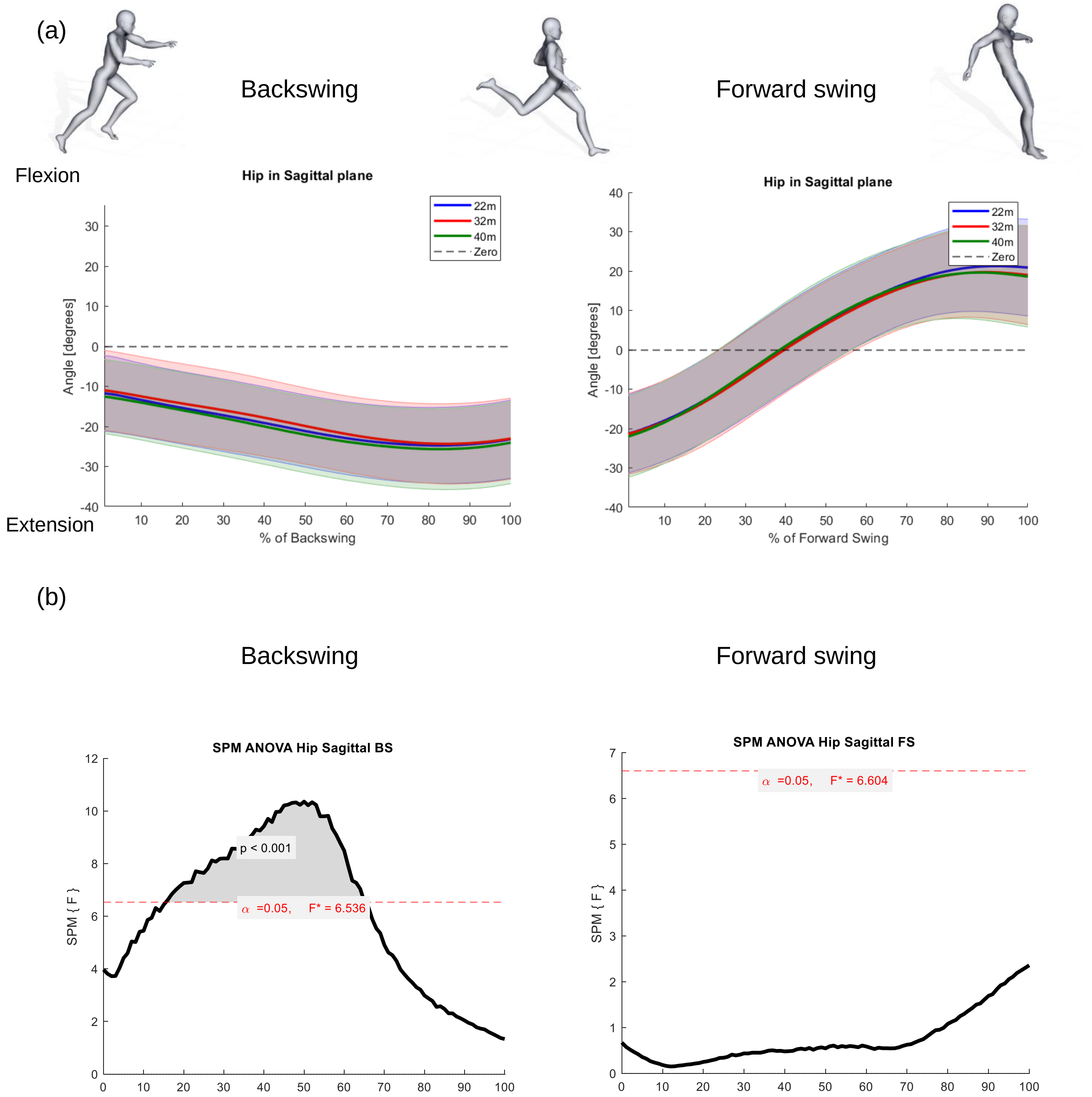
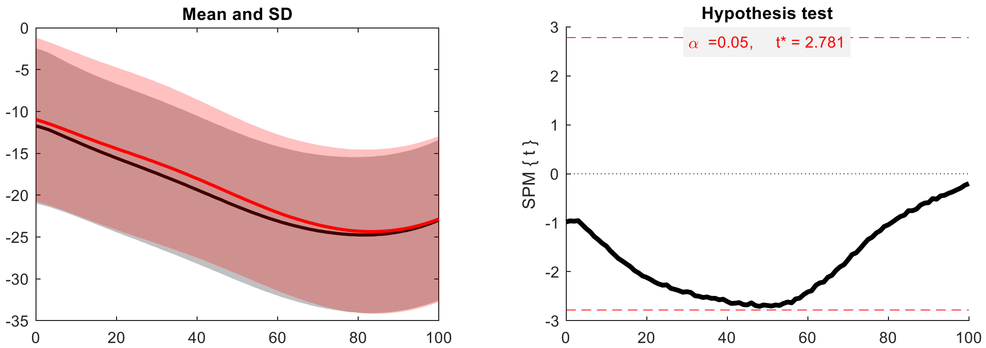


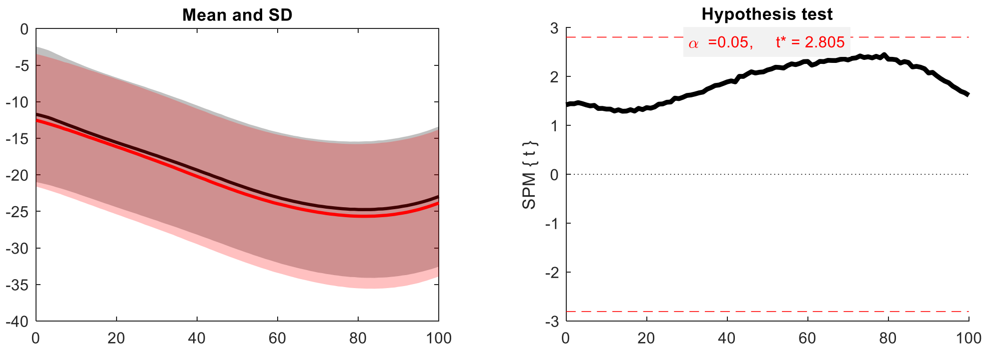
Figure 30: a) Mean trajectories for hip angles in the sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 6.604 (forward swing) was not exceeded. The critical threshold of 6.536 (backswing) was exceeded at time point 15% to 70%with a supra-threshold cluster probability of p<0.001, indicating a significant difference between groups.

Post hoc test

(a) 22 – 32



(b) 22 – 40



(c) 32 – 40

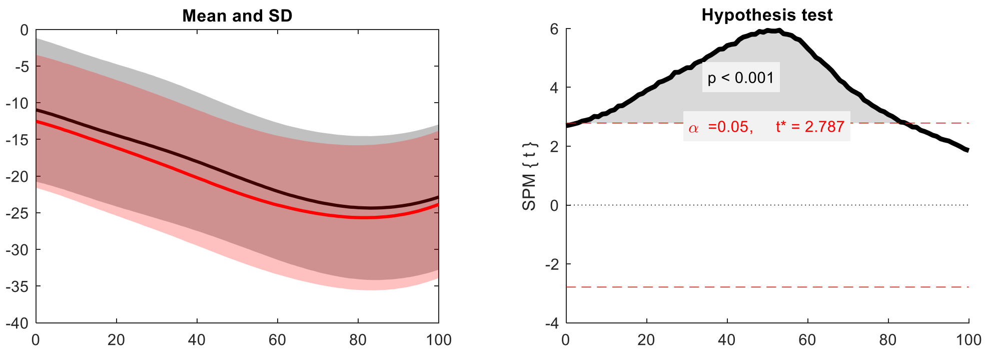


Figure 31: a) Statistical inference curves indicating no difference between 32 m and 22 m kicks. b) No significant difference between the 22 m and 40 m kicks. c) A significant difference between the 32 m and 40 m kicks for the first 80% of the backswing.

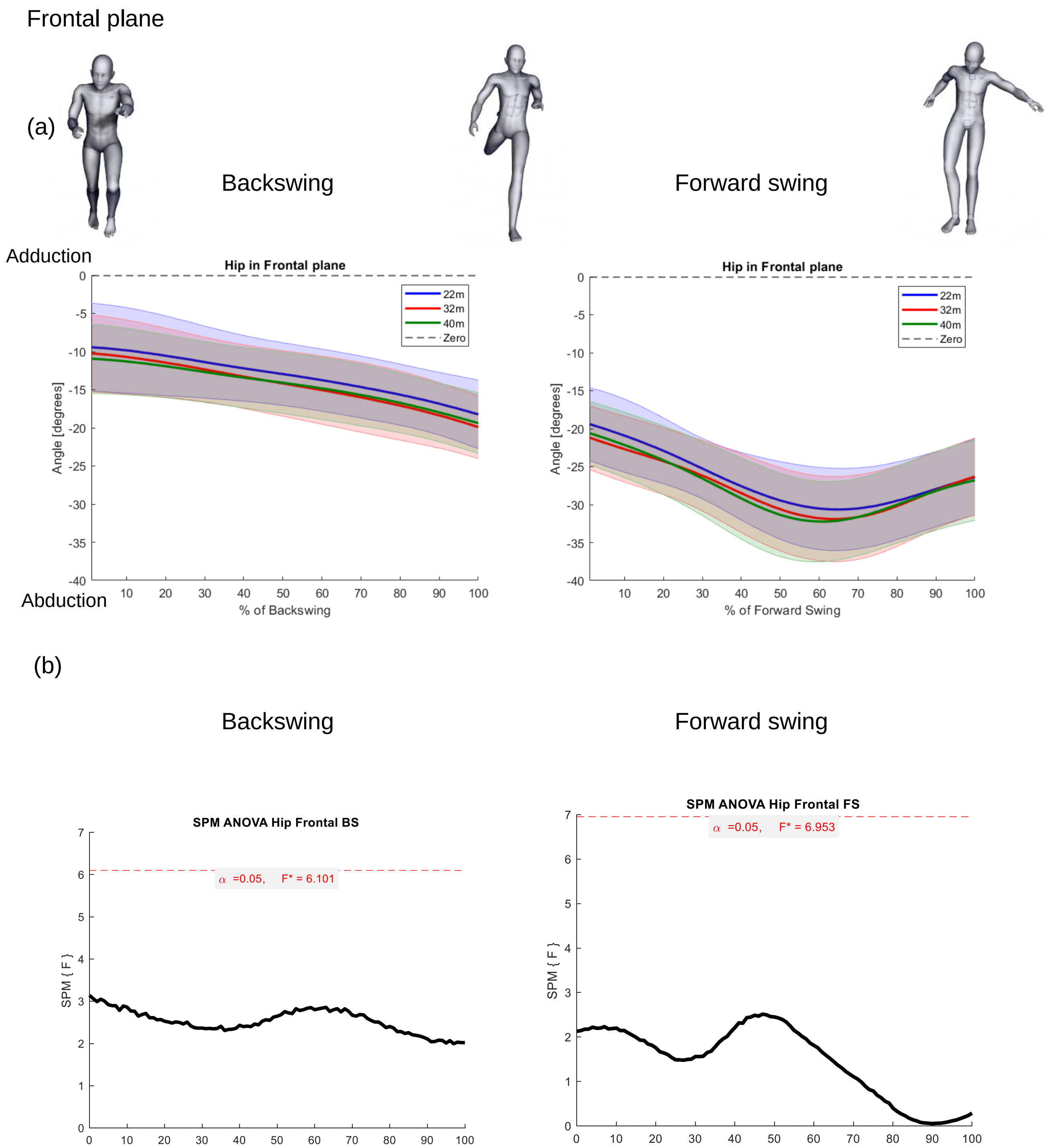


Figure 32: a) Mean trajectories for hip angles in frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 6.101 (backswing) and 6.953 (forward swing) was not exceeded.

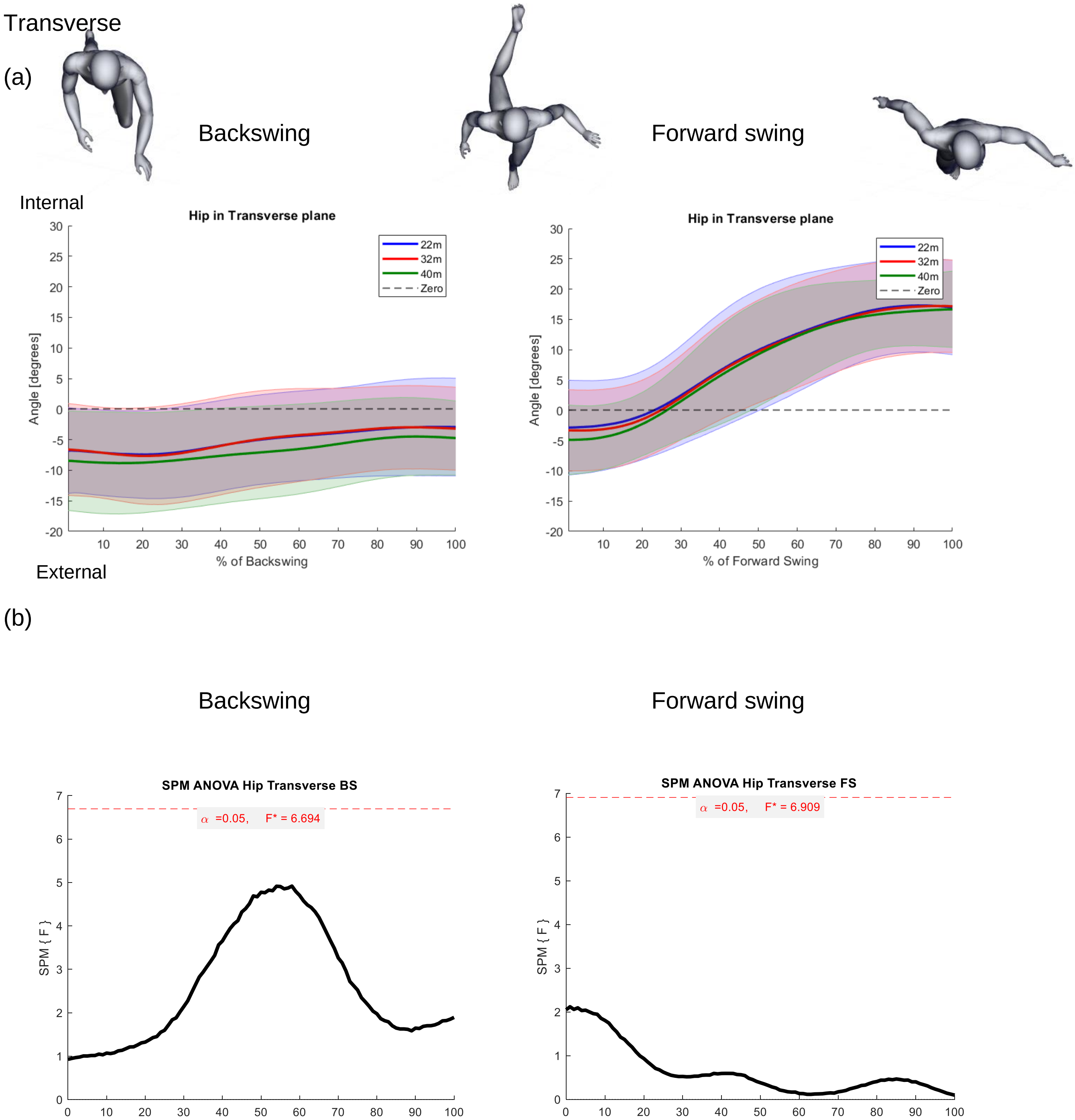


Figure 33: a) Mean trajectories for hip angles in transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 6.694 (backswing) and 6.909 (forward swing) was not exceeded.

4.3.4 PELVIS ANGLE

The pelvis segment angles are relative to the laboratory reference system. The pelvis angle in the sagittal plane describes pelvic tilt, with positive indicating a posterior pelvis tilt. In the frontal plane pelvic obliquity is described, with negative indicating the opposite side is lower. Pelvic rotation is presented in the transverse plane, where a negative value indicates external rotation, with the opposite side in front.

In the sagittal plane, the pelvis stayed in an posterior tilted position (~27º to ~20º) during the backswing, while the position of the pelvis during the forward swing moves from ~20º posterior tilt to ~10º anterior tilt (Figure 34). In the frontal plane, the pelvic obliquity moves from ~12º (non-kicking side lower) to 5º (kicking side lower) during the backswing, while the forward swing consists of pelvic obliquity from ~5º to ~15º (kicking side lower) (Figure 35). In the transverse plane, during the backswing, the pelvis starts at ~50º external rotation and stayed relatively constant during the backswing while during the forward swing external rotation is decrease to ~25º of external rotation at ball contact (Figure 36).

The pelvis angles displayed no difference for the backswing or the forward swing in the sagittal- and frontal plane (see Figure 34 and Figure 35). In the transverse plane, during the first 50% of the backswing, a significant difference is evident between groups (Figure 36). The post hoc test (Figure 37) shows that the 22 m kick displayed less external rotation relative to the posts of the pelvis compared to the 32 m and 40 m kicks. The 32 m kicks also had less external rotation compared to the 40 m kicks, but only in the first part of the kick. For the successful trials the sagittal- and frontal plane are the same as the pooled data (Figure 38 and Figure 39), but the transverse plane no difference between the groups, unlike the pooled data (Figure 40).

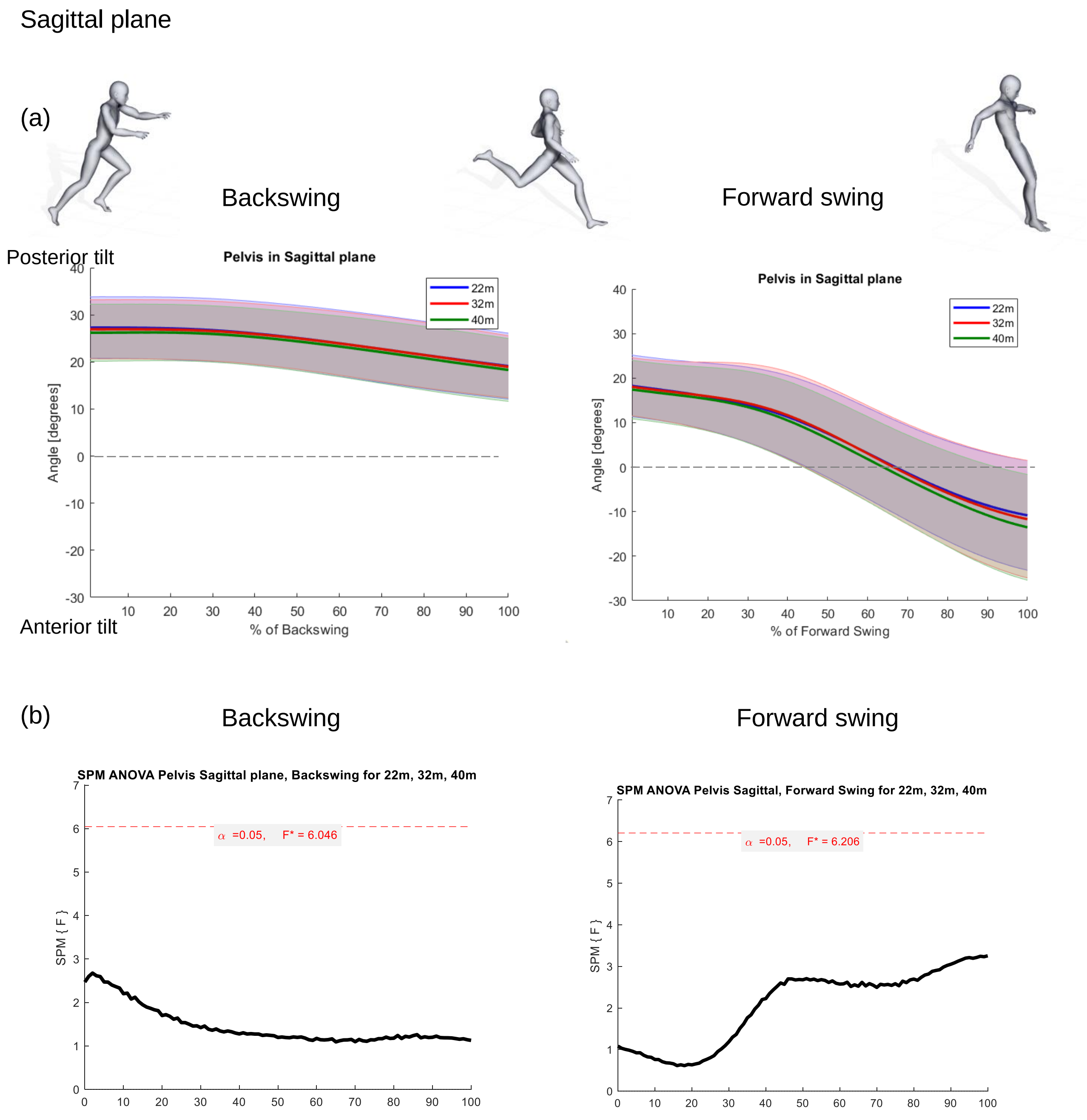


Figure 34: a) Mean trajectories for pelvis angles in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 6.206 (backswing) and 6.043 (forward swing) was not exceeded.

Frontal plane

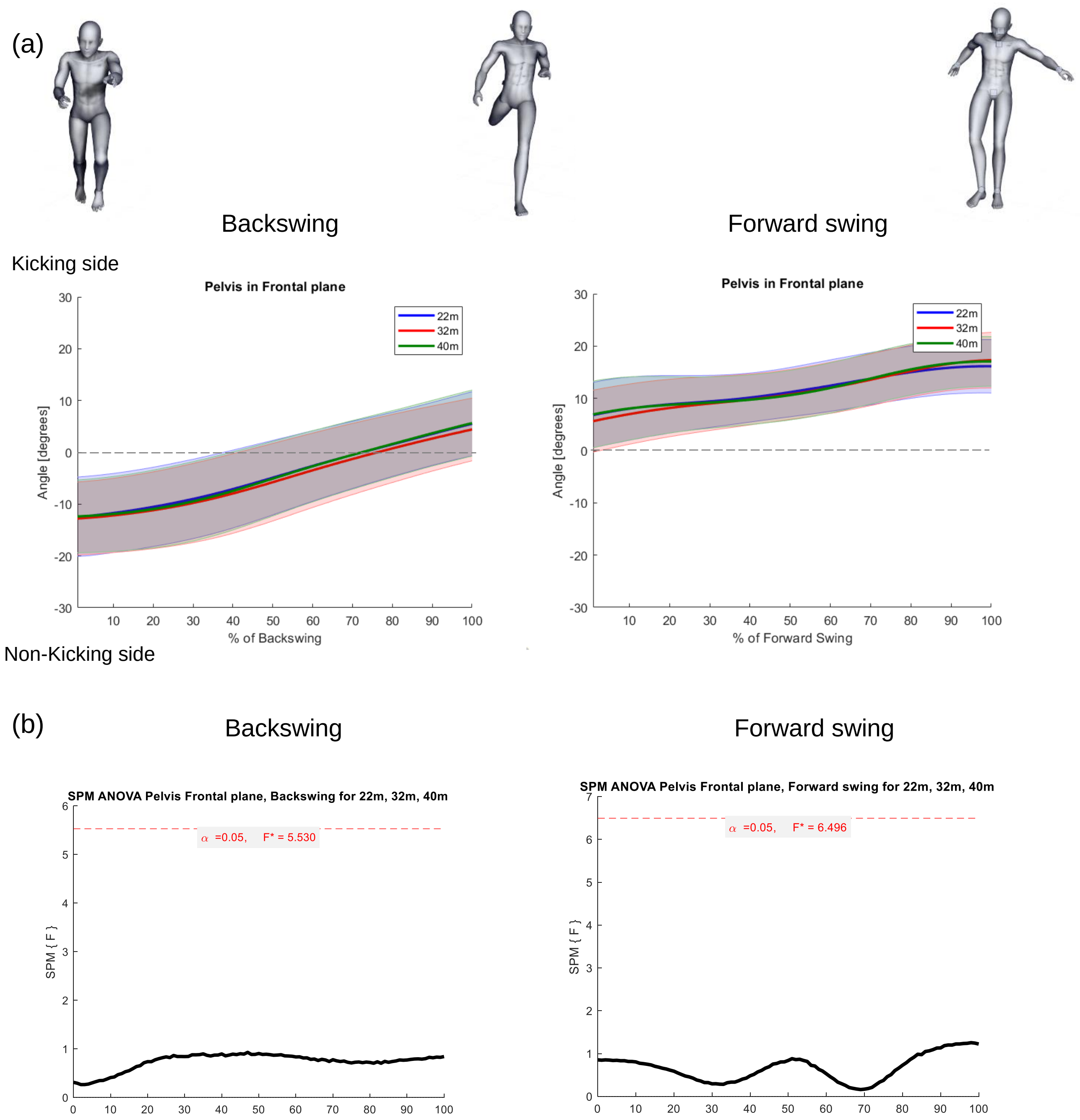


Figure 35: a) Mean trajectories for pelvis angles in frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 5.530 (backswing) and 6.496 (forward swing) was not exceeded.

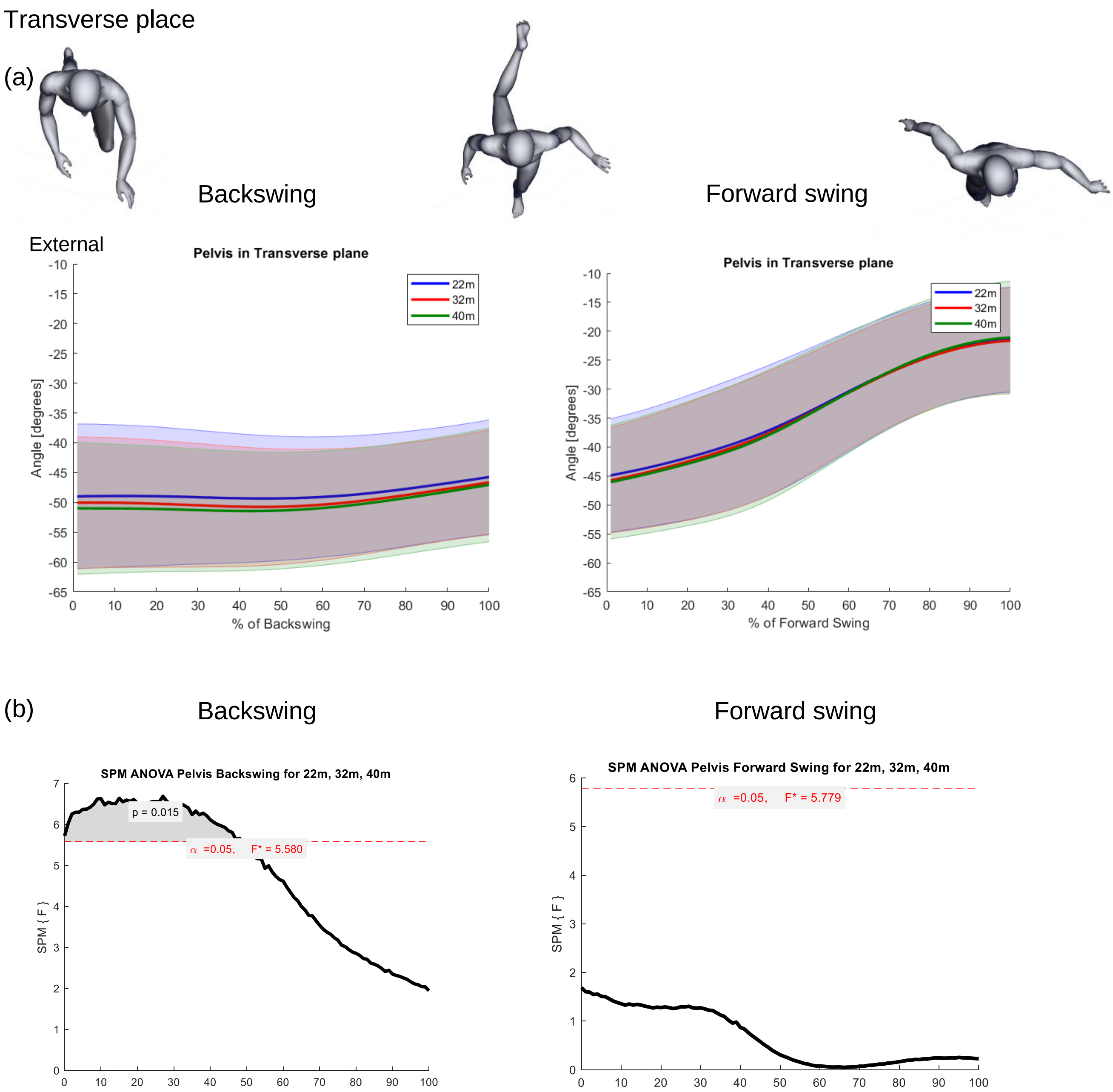
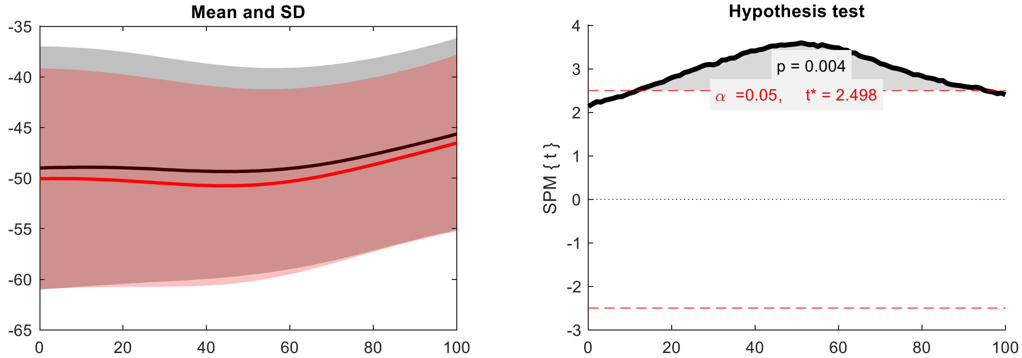


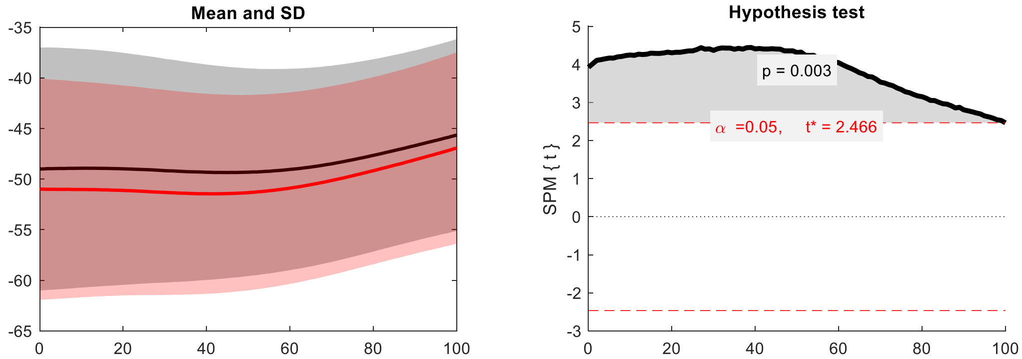
Figure 36: a) Mean trajectories for pelvis angles in transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 5.779 (forward swing) was not exceeded. The critical threshold of 5.580 (backswing) was exceeded for the *first* part until time point 50% with a supra-threshold cluster probability of p=0.015, indicating a significant difference between groups.

Post hoc test

(a) 22 – 32



(b) 22 – 40



(c) 32 – 40

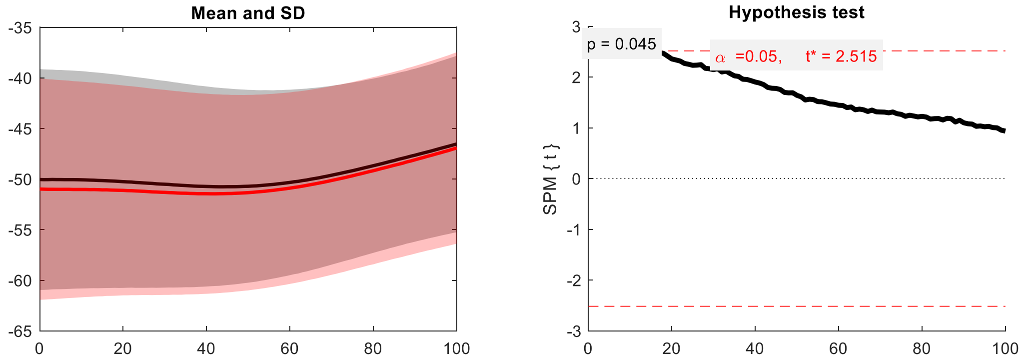


Figure 37: a) Statistical inference curves indicating a significant difference between the 22 m and 32 m kicks for the entire backswing. b) A significant difference between 22 m and 40m kicks for the entire backswing. c) A significant difference between the 32 m and 40 m kicks form the start to time point 10%.

Successful trials

Sagittal plane

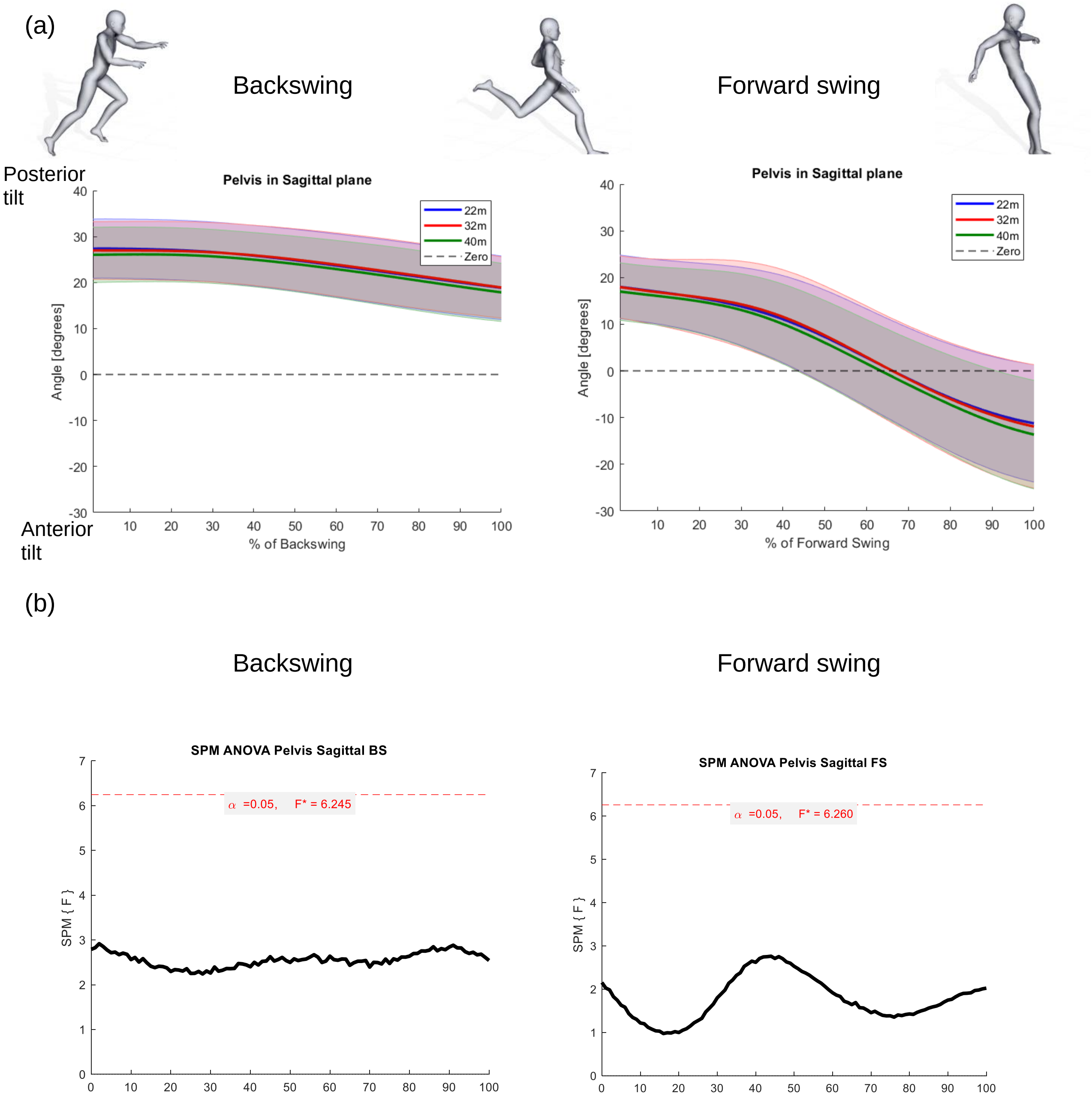


Figure 38: a) Mean trajectories for pelvis angles in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 6.245 (backswing) and 6.260 (forward swing) was not exceeded.

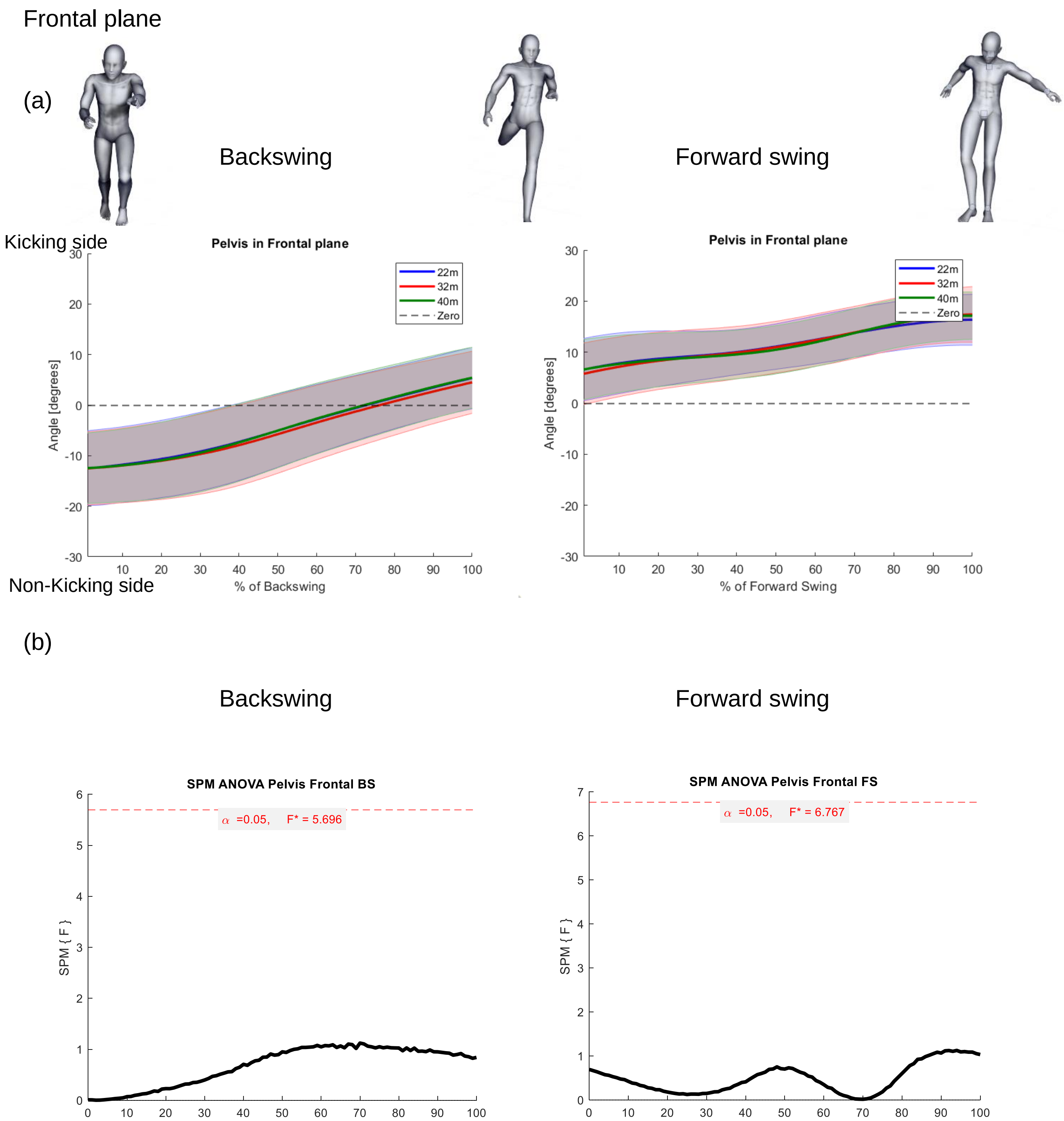


Figure 39: a) Mean trajectories for pelvis angles in frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 5.696 (backswing) and 6.767 (forward swing) was not exceeded.

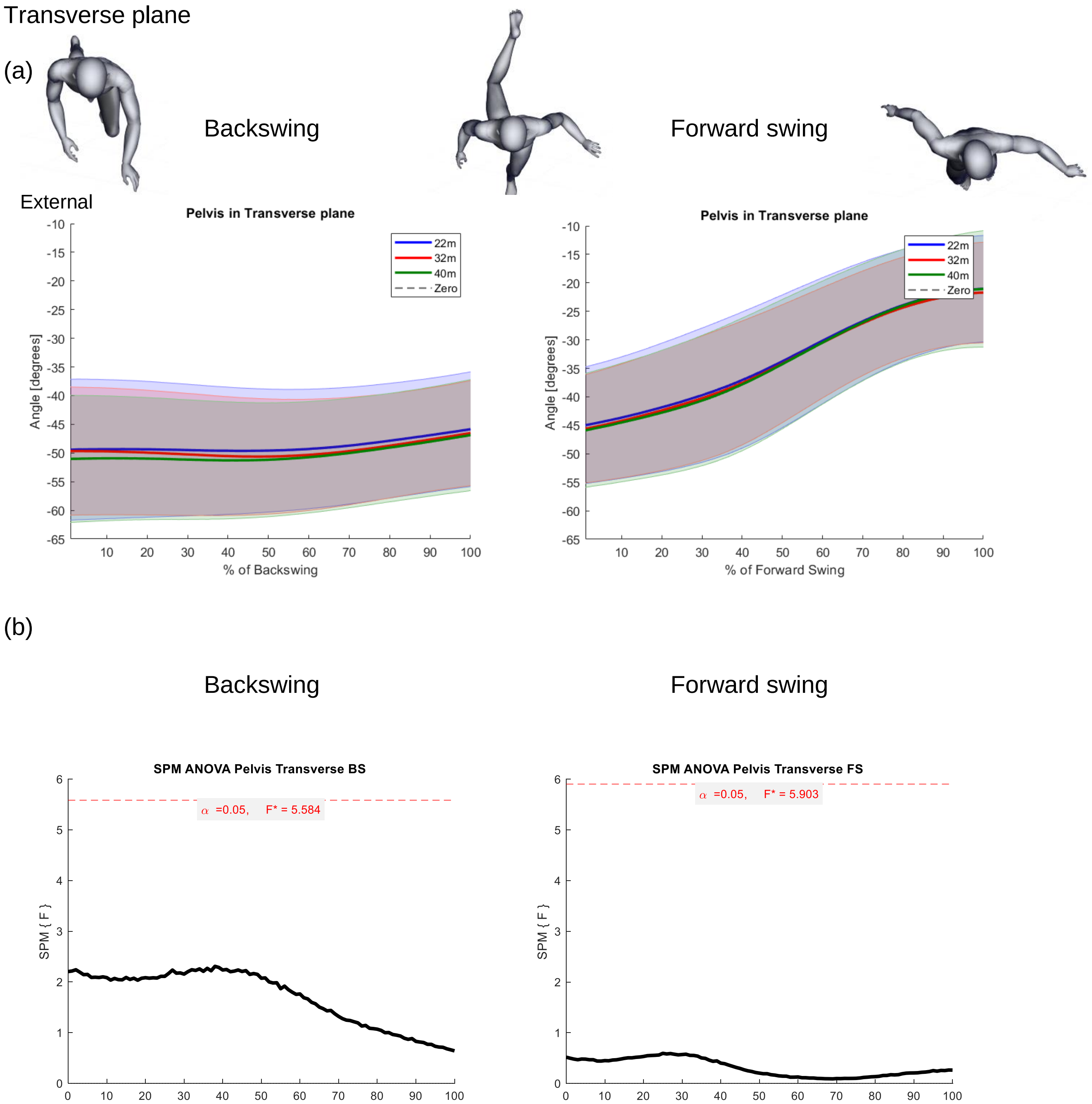


Figure 40: a) Mean trajectories for pelvis angles in transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 4.584 (backswing) and 5.903 (forward swing) was not exceeded.

4.3.5 THORAX ANGLE

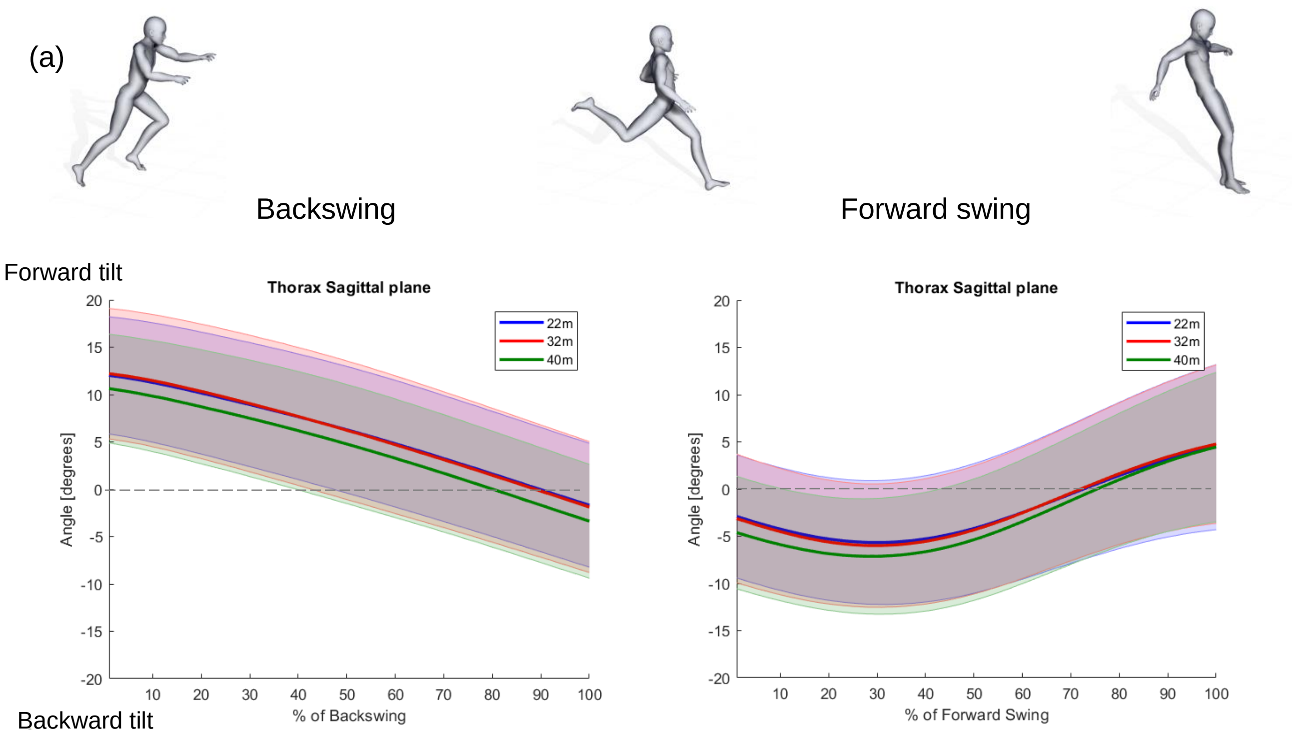
Thorax segment angles are referred to the laboratory reference system. In the sagittal plane a positive thorax angle indicates a forward tilt of the thorax. The frontal plane represents thorax obliquity, where a positive value indicates the opposite side of the thorax is lower. In the transverse plane thoracic rotation is seen. A negative value indicates external thoracic rotation, where the kicking side of the thorax is in front.

The thorax starts at ~10º forward lean and moves to ~5º backward lean and then from ~5º backward lean to 5º of forward lean during the backswing and forward swing, respectively (see Figure 41). Thorax obliquity moves from ~15º to ~5º with the kicking side lower during the backswing, and in the forward swing it moves back to ~15º (Figure 42). In the transverse plane, during the backswing, the thorax moves from ~40º of external rotation to ~35º external rotation, while during the forward swing the thorax position stays relatively constant at ~35º external rotation (see Figure 43).

In the sagittal- and frontal plane, the thorax angle displayed no difference during the backswing and the forward swing (see Figure Figure 41 and Figure 42). In the transverse plane, significant differences were found for the first 45 per cent of the backswing (Figure 43). The post hoc test identified relative to the posts, significantly less external rotation between the 22 m and the 32 m kicks, the 22 m and the 40 m kicks, but only a minimally decreased external rotation in the first five per cent of the backswing between 32 m and 40 m kicks (Figure 44). During the analysis of the successful trials a difference between the groups were found for the sagittal plane motion (Figure 45 to Figure 47), however, similar results were seen for the frontal- and transverse planes (Figure 48 to Figure 50Figure 49), compared to the pooled trials.

Sagittal plane

(a)



(b)

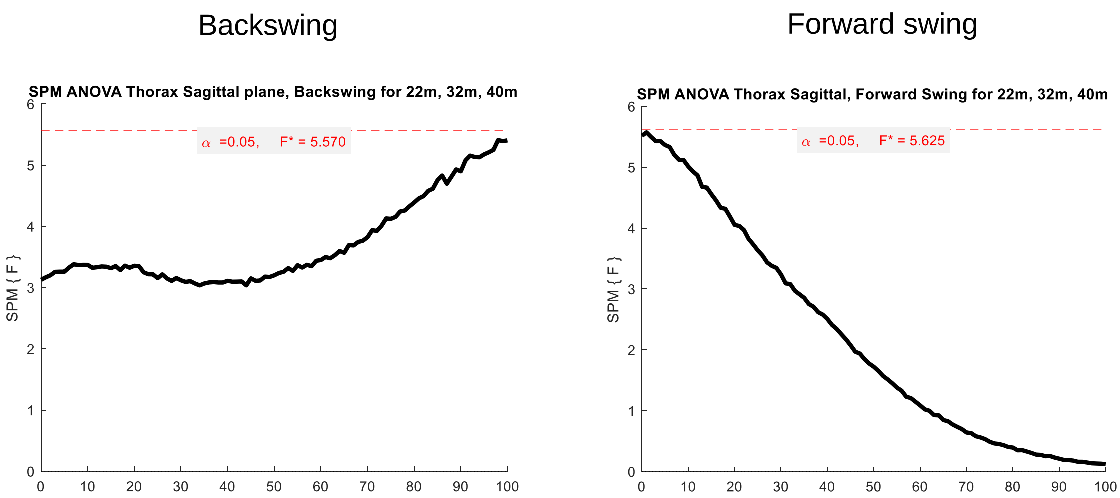


Figure 41: a) Mean trajectories for thorax angles in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 5.570 (backswing) and 5.625 (forward swing) was not exceeded.

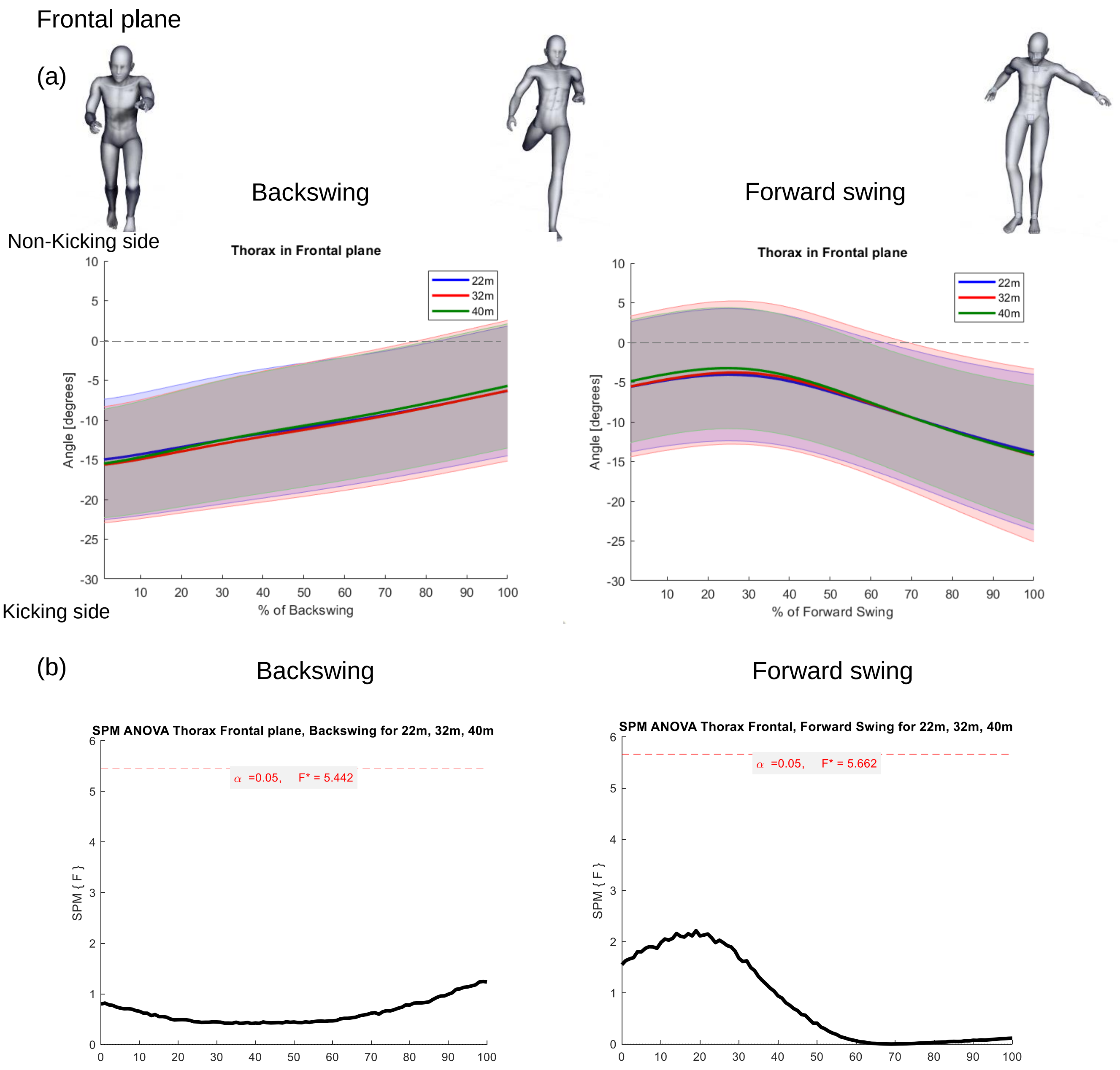


Figure 42: a) Mean trajectories for thorax angles in frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 5.662 (backswing) and 5.442 (forward swing) was not exceeded.

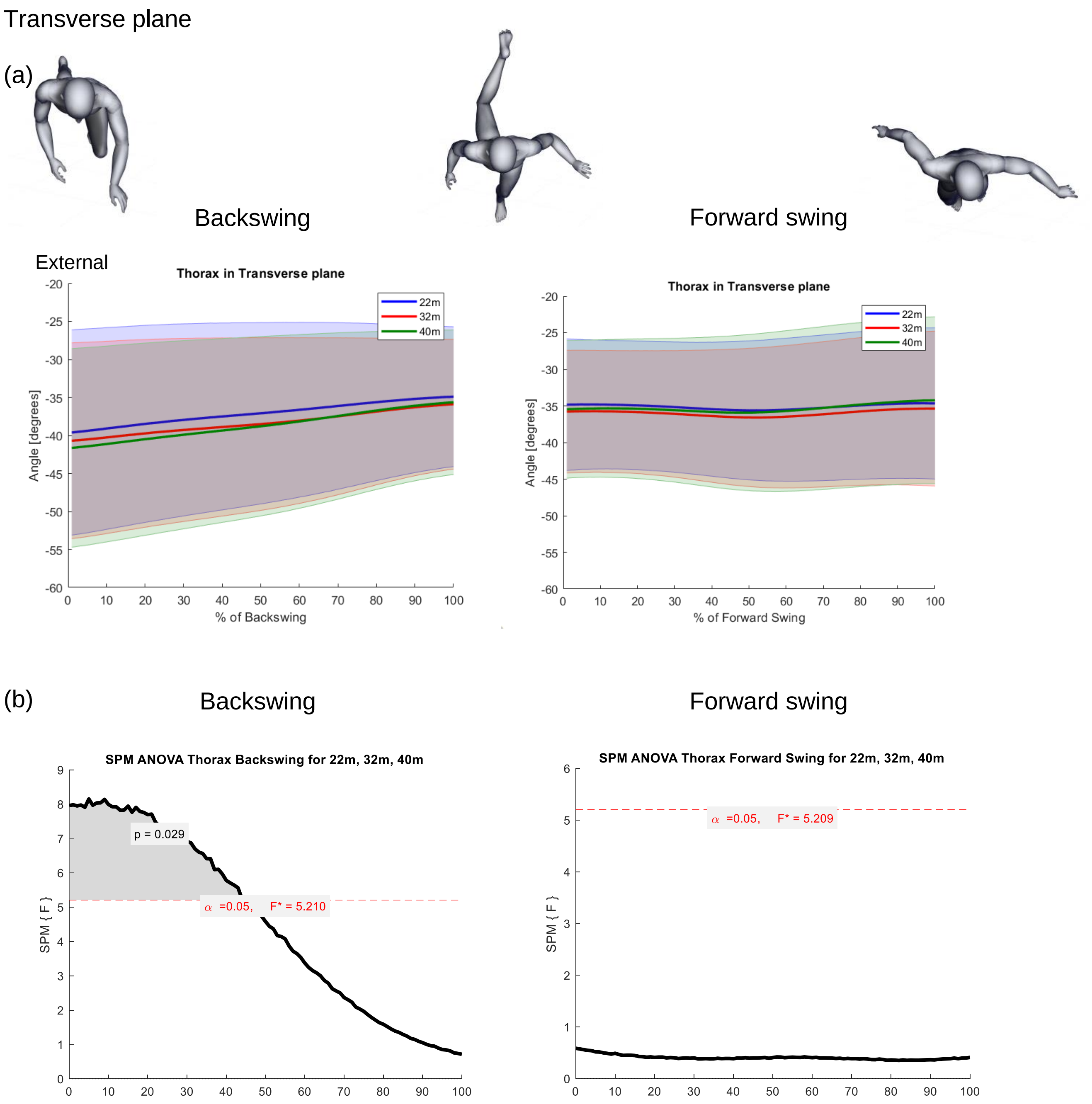
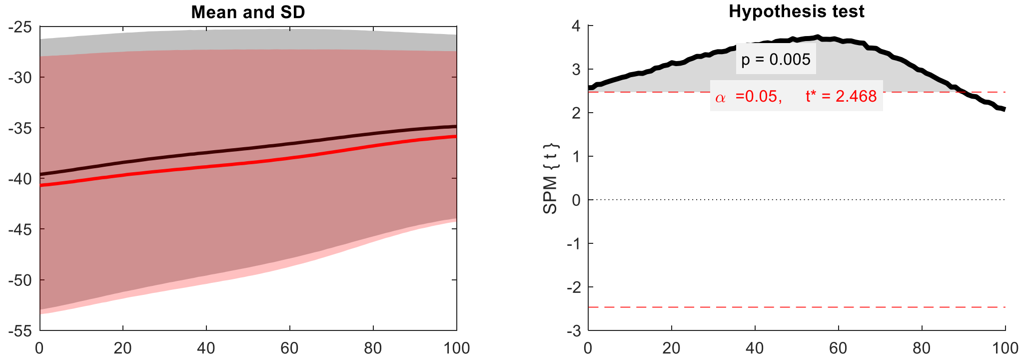


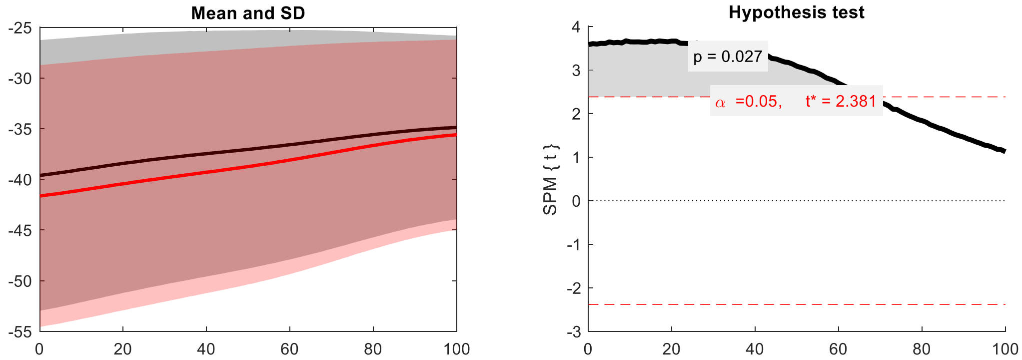
Figure 43: a) Mean trajectories for thorax angles in transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 5.209 (forward swing) was not exceeded. The critical threshold of 5.120 (backswing) was exceeded for time point 0% to 45%, with a supra-threshold cluster probability of p=0.029, indicating a significant difference between groups.

Post hoc test

(a) 22 – 32



(b) 22 – 40



(c) 32 – 40

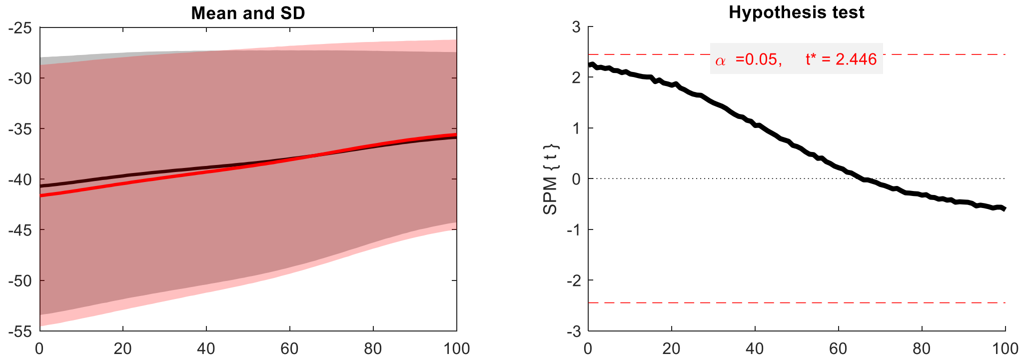


Figure 44: a) Statistical inference curves indicating a difference between the 22 m and 32 m kicks for the first 90% of backswing. b) A difference between the 22 m and 40 m kicks from the start to time point 60%. c) No difference between the 32 m and 40 m kicks.

Successful trials

Sagittal plane

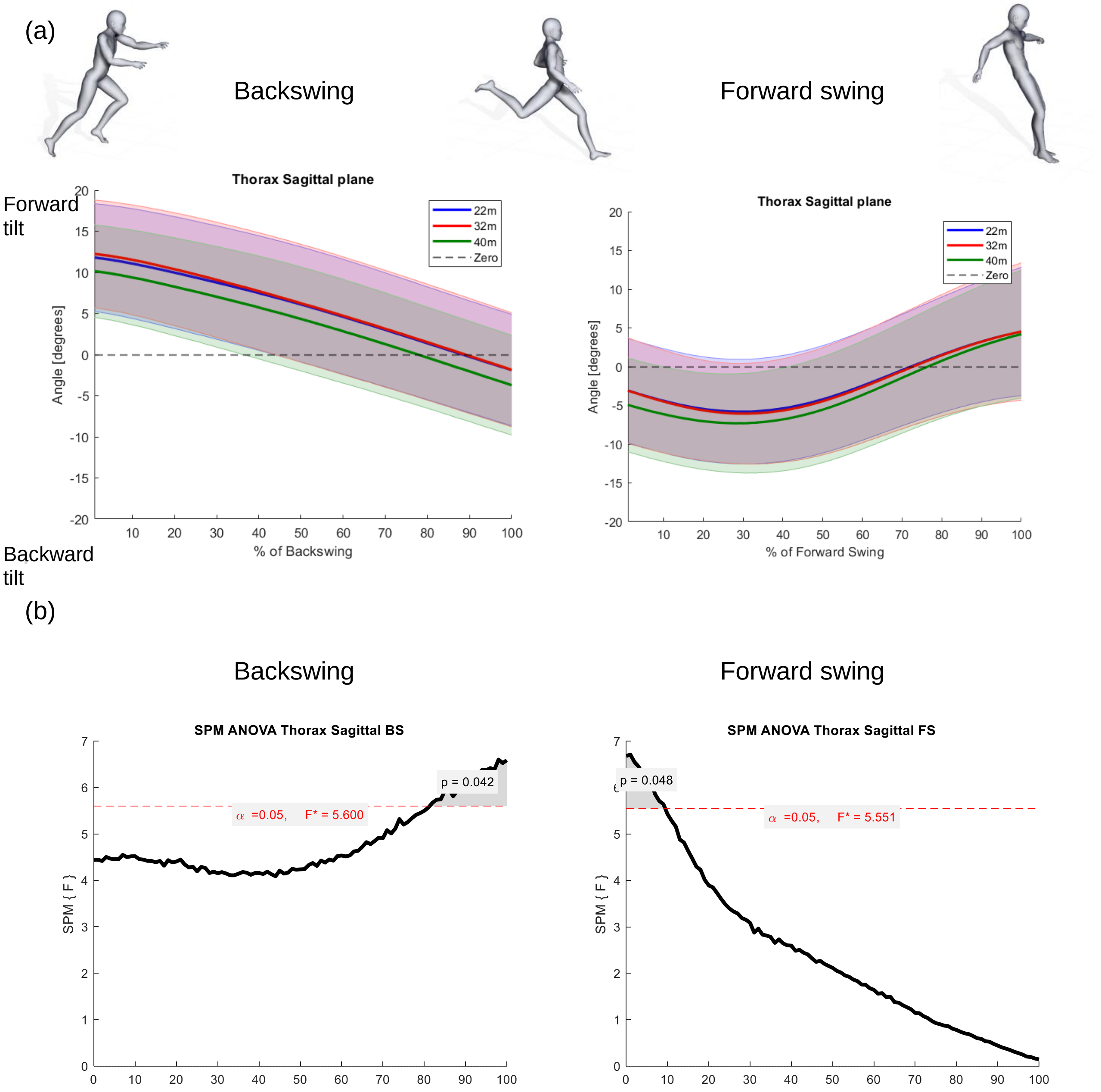
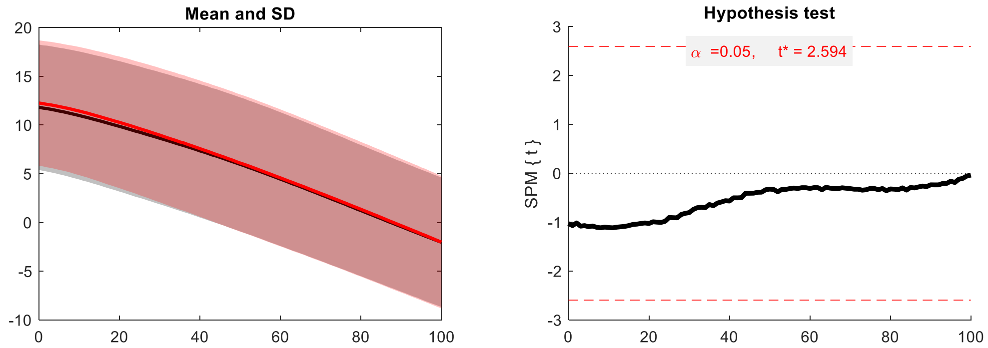


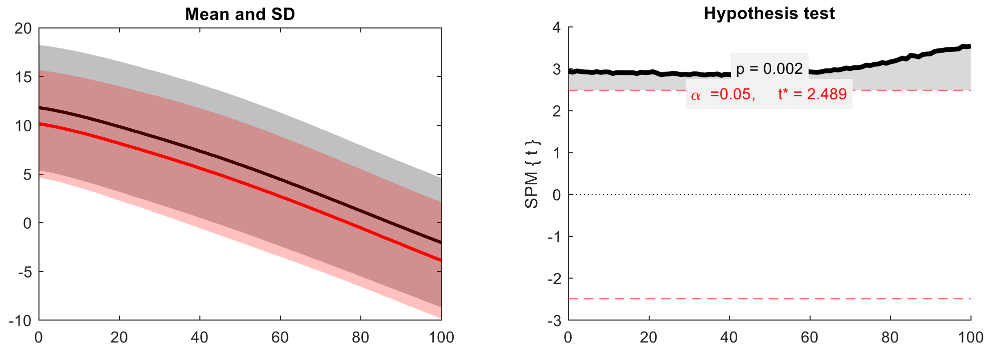
Figure 45: a) Mean trajectories for thorax angles in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 5.600 (backswing) was exceeded for final 10% of backswing, with a supra-threshold cluster probability of p=0.049, and 5.551 (forward swing) was exceeded for the first 10% of forward swing, with a supra-threshold cluster probability of p=0.029, indicating a significant difference between groups.

Post hoc test (backswing)

(a) 22 – 32



(b) 22 – 40



(c) 32 – 40

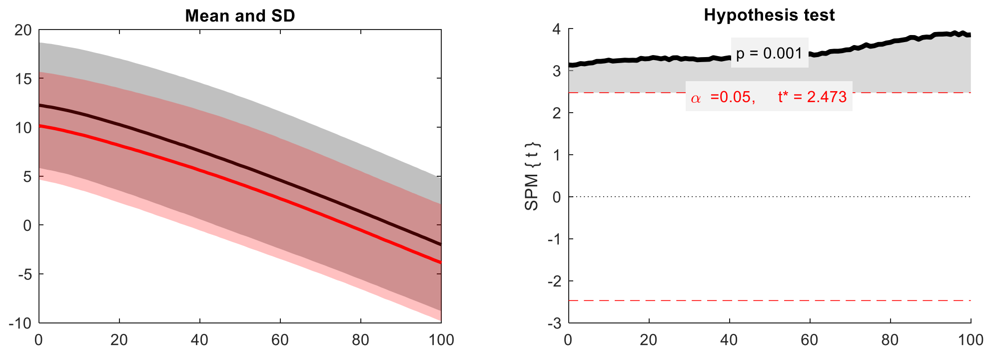
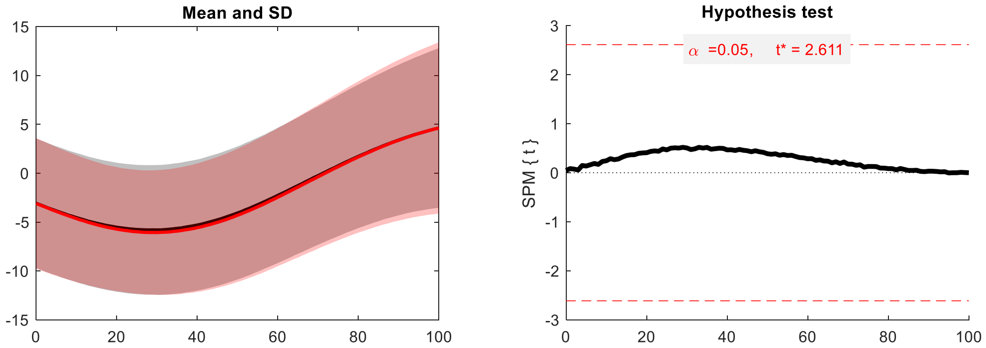


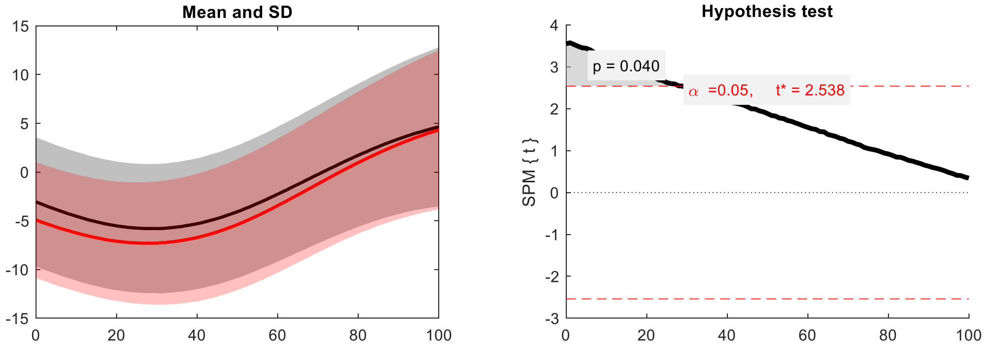
Figure 46: a) Statistical inference curves indicating no difference between the 22 m and 32 m kicks for the entire backswing. b) A difference between the 22 m and 40 m kicks for the entire backswing. c) A difference between the 32 m and 40 m kicks for the entire backswing.

Post hoc test (forward swing)

(a) 22 – 32



(b) 22 – 40



(c) 32 – 40

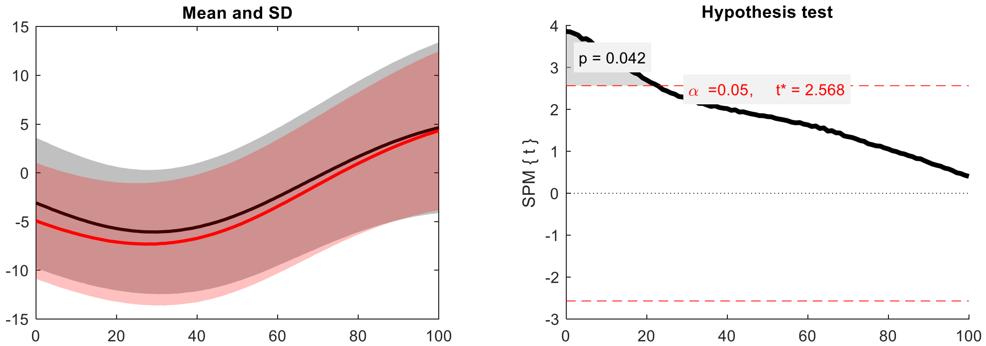


Figure 47: a) Statistical inference curves indicating no difference between the 22 m and 32 m kicks for the entire backswing. b) A difference between the 22 m and 40 m kicks for the initial 25% for forward swing. c) A difference between the 32 m and 40 m kicks for the initial 20% of forward swing.

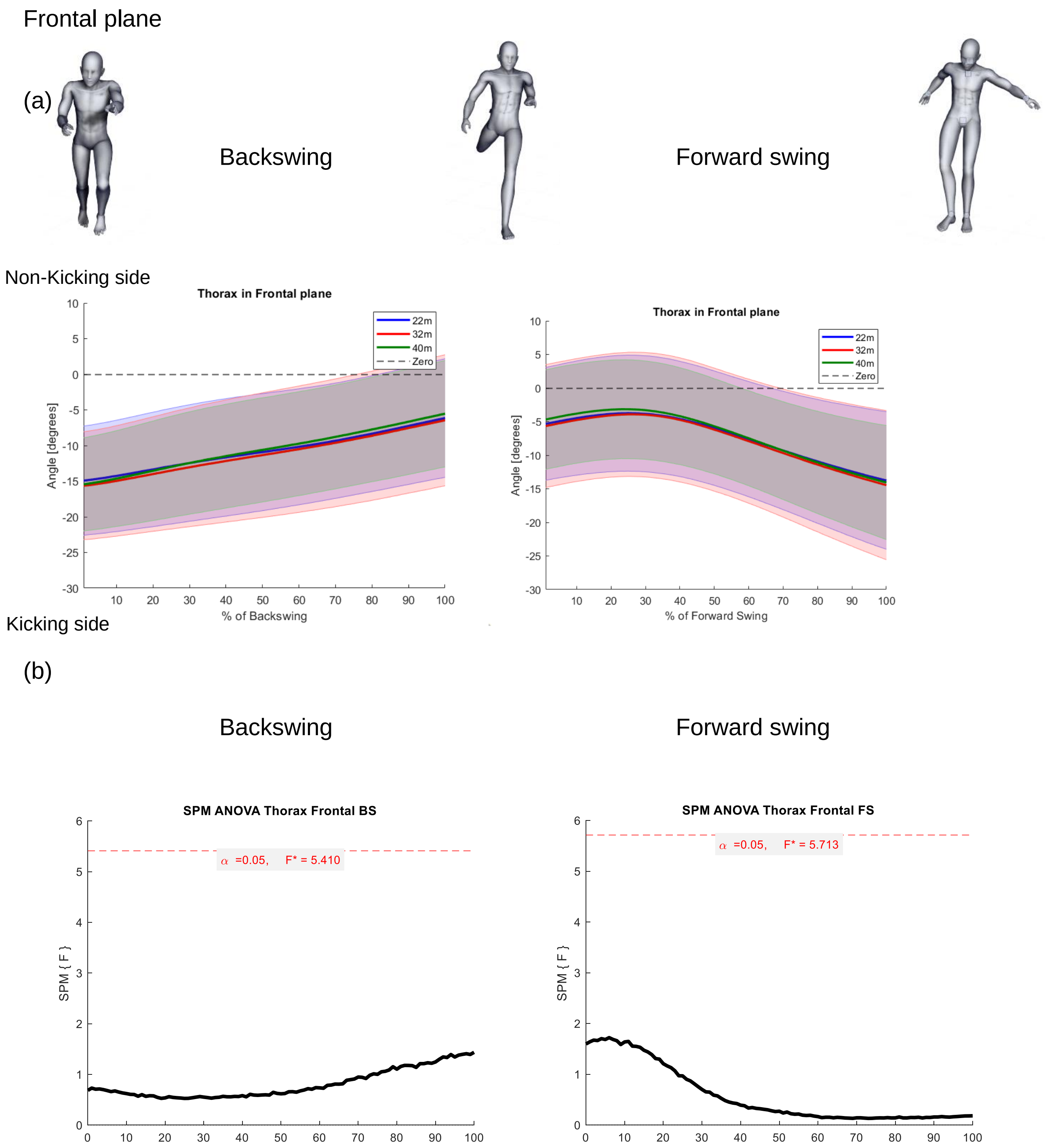


Figure 48: a) Mean trajectories for thorax angles in frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 5.410 (backswing) and 5.713 (forward swing) was not exceeded.

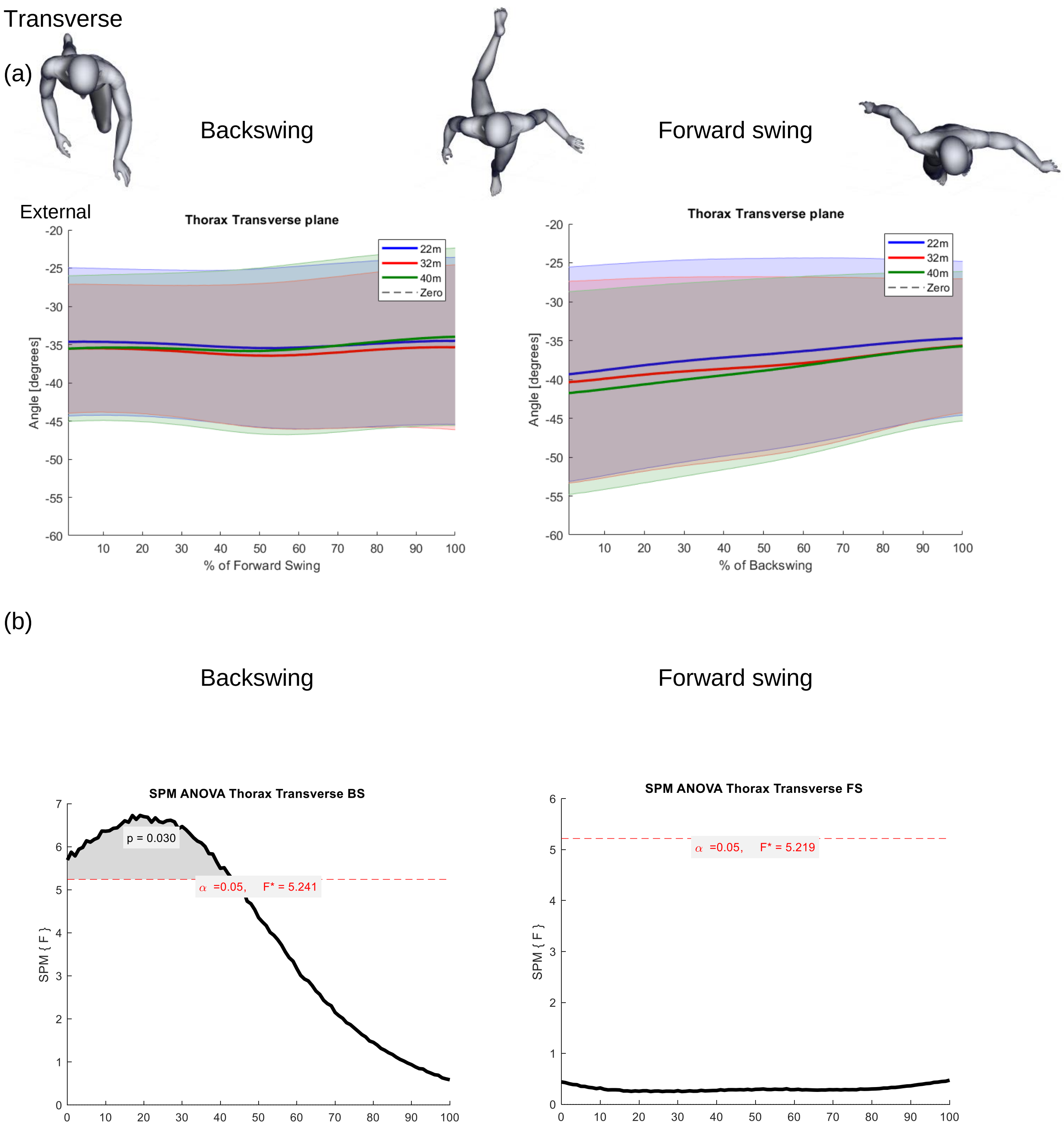


Figure 49: a) Mean trajectories for thorax angles in transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 5.219 (forward swing) was not exceeded. The critical threshold of 5.241 (backswing) was exceeded for time point 0% to 45%, with a supra-threshold cluster probability of p=0.030, indicating a significant difference between groups.

Post hoc test

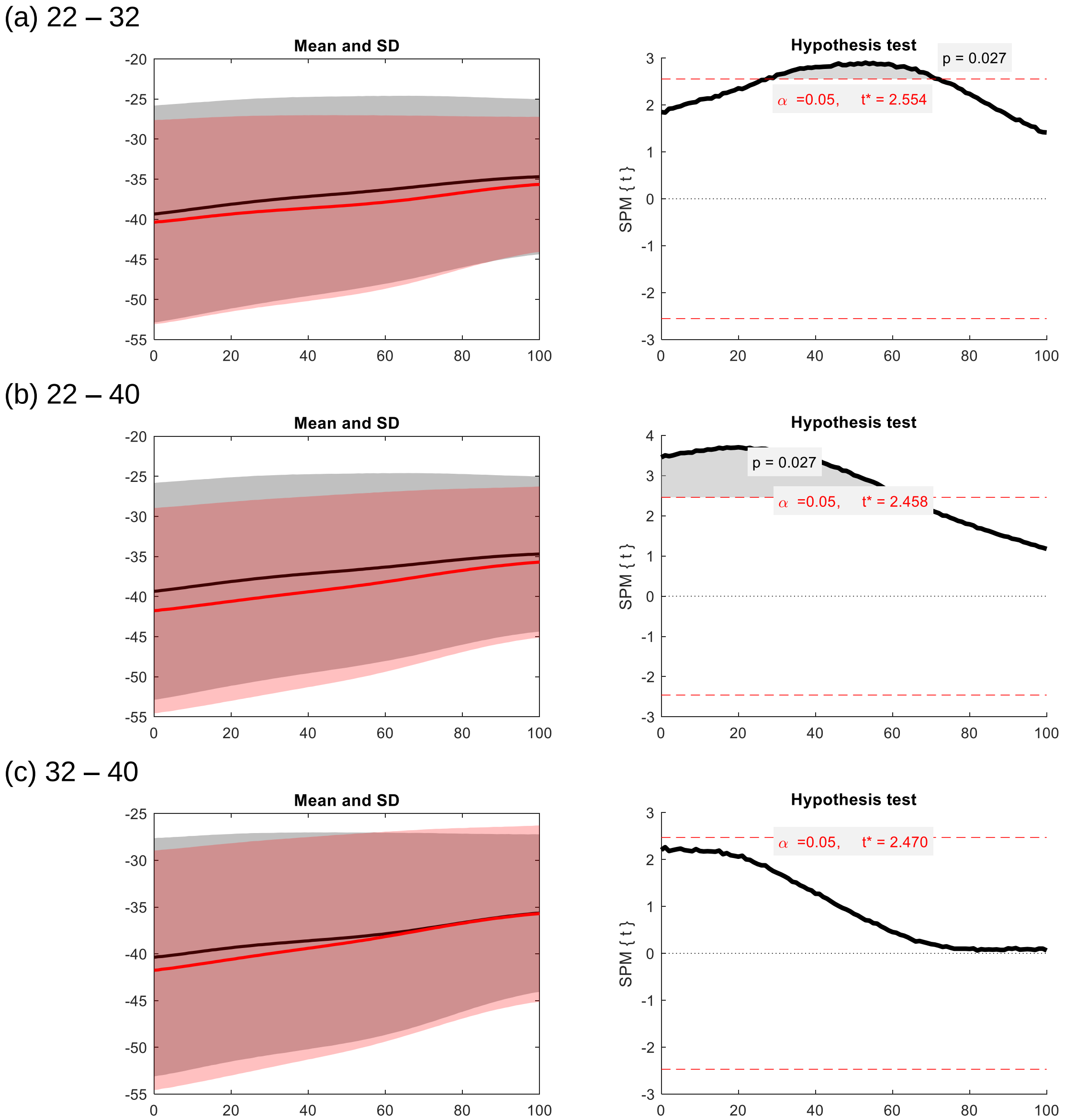


Figure 50: a) Statistical inference curves indicating a difference between the 22 m and 32 m kicks from 30% to 50% of backswing. b) A difference between the 22 m and 40 m kicks from the start to time point 60%.c) No difference between the 32 m and 40 m kicks.

4.4 JOINT AND SEGMENT VELOCITY CURVES

4.4.1 KICKING LEG KNEE VELOCITY

During the backswing, the knee had a positive flexion velocity change from ~200 to ~800 degrees per second (deg/s) (see Figure 51) from beginning to end of backswing. The kicking leg knee of the 40 m kicks had a higher velocity at the end of the backswing compared to the 32 m and 22 m kicks. No difference was noted between the 32 m and 22 m kicks (see Figure 52). During the forward swing, there was still flexion (positive velocity) for the first part of the forward swing. At around 40 per cent of forward swing, the knee started to extend rapidly as it approached ball contact (Figure 53). Significantly higher knee extension velocity was found for the final 20 per cent of the forward swing for the 40 m and 32 m kicks, compared to the 22 m kicks (Figure 53). Similar results seen with successful kicks only (Figure 54 and Figure 55).

Sagittal plane

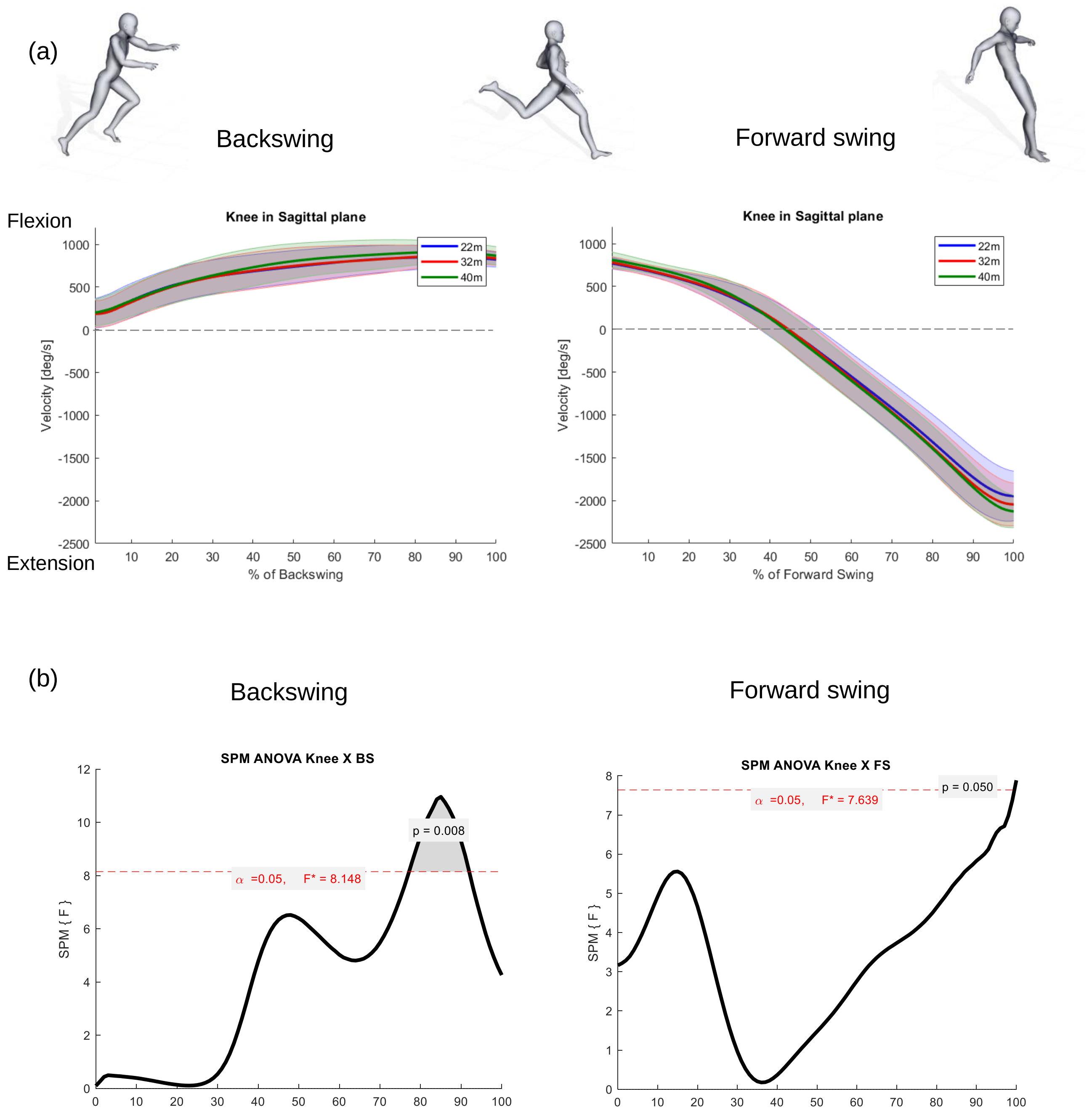
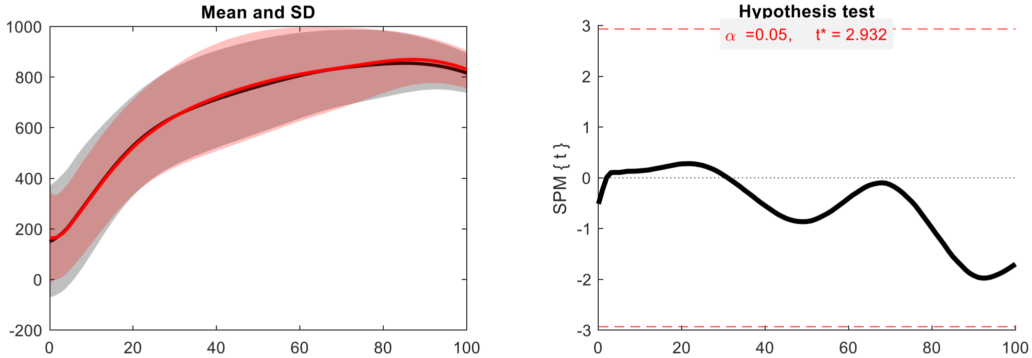


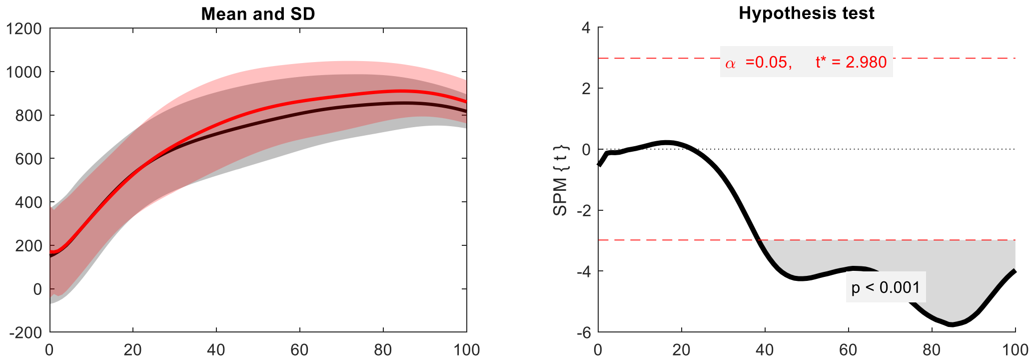
Figure 51: a) Mean trajectories for knee flexion/extension velocities in the sagittal plane for kicking at three different distances from the posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 8.148 (backswing) was exceeded from time point 75% to 95%, with a supra-threshold cluster probability of p=0.008, indicating a significant difference between groups. The critical threshold of 7.639 (forward swing) was exceeded at time point 85%, with a supra-cluster probability of p=0.050, indicating a significant difference between groups.

Post hoc test – Backswing

(a) 22 – 32



(b) 22 – 40



(c) 32 – 40

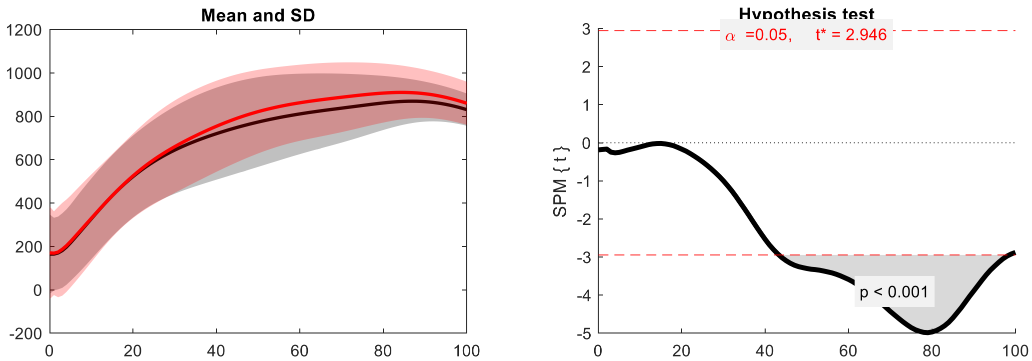
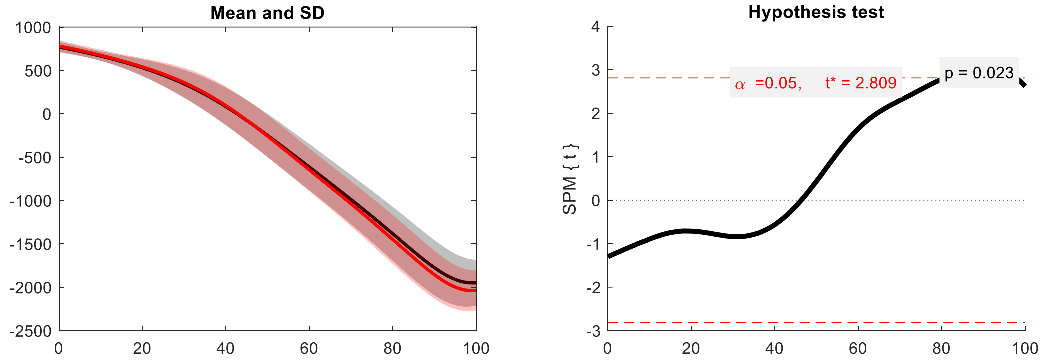


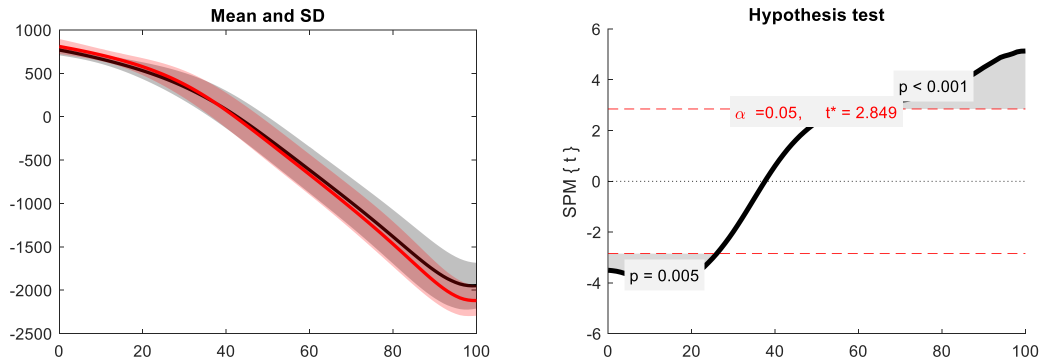
Figure 52: a) Statistical inference curves indicating no difference in kicking between 32 m and 22 m kicks. b) A significant difference between 40 m and 22 m kicks from time point 40% onwards. c) A significant difference between 40 m and 32 m kicks from time point 40% onwards.

Post hoc – Forward swing

(a) 22 – 32



(b) 22 – 40



(c) 32 – 40

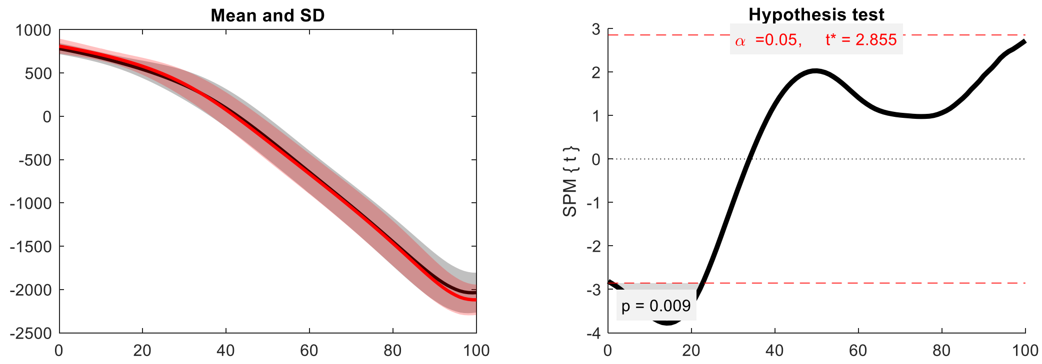


Figure 53: a) Statistical inference curves indicating a significant difference between 22 m and 32 m kicks from time point 90% onwards. b) A significant difference between 22 m and 40 m kicks *from* time point 60% onwards. c) A significant difference between 40m and 32 m kicks from the time point 0% to 20%.

Susscessful trials

Sagittal plane

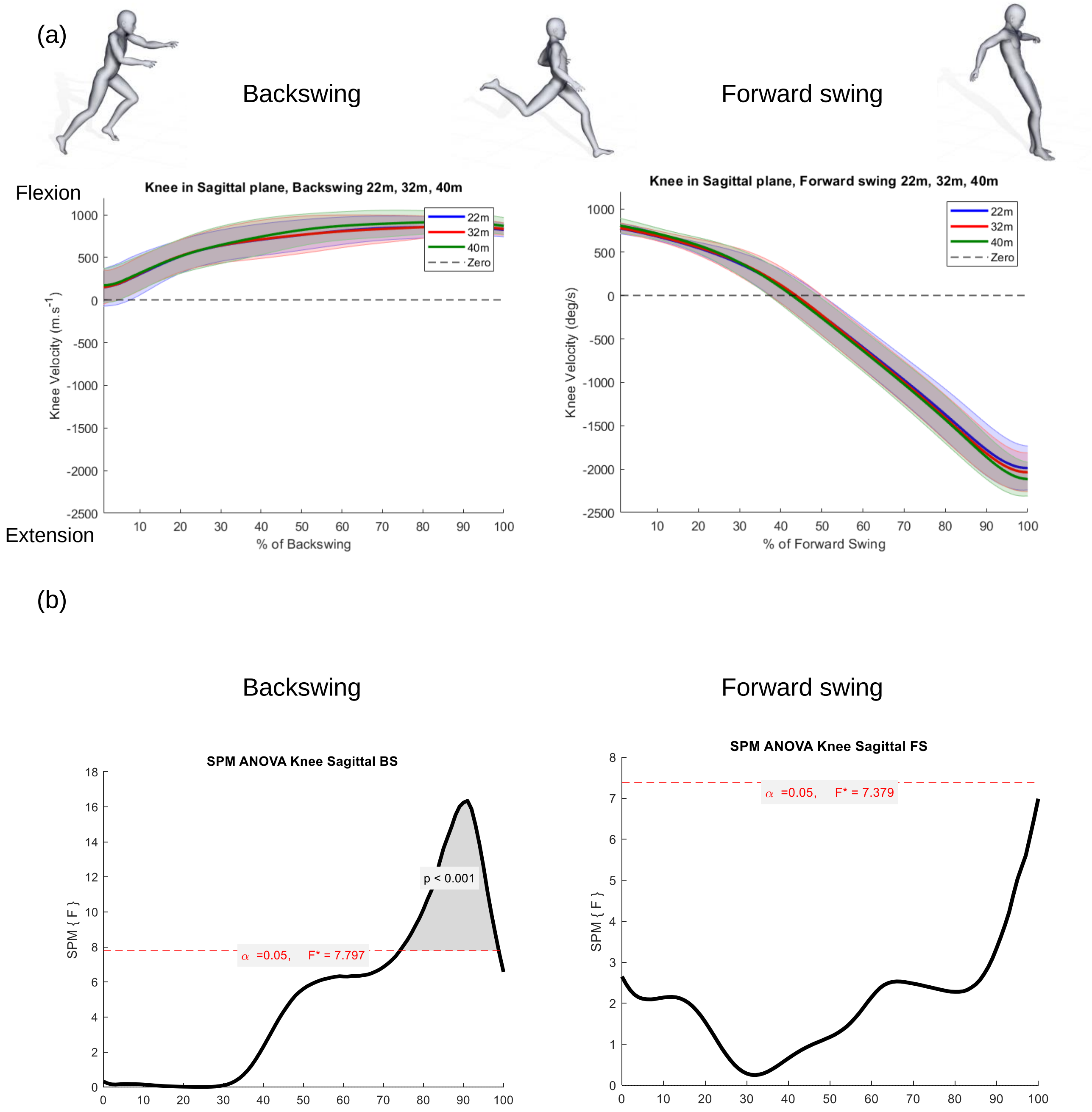


Figure 54: a) Mean trajectories for knee flexion/extension velocities in the sagittal plane for kicking at three different distances from the posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.797 (backswing) was exceeded from time point 75% to 95%, with a supra-threshold cluster probability of p<0.001, indicating a significant difference between groups. The critical threshold of 7.379 (forward swing) was not exceeded.

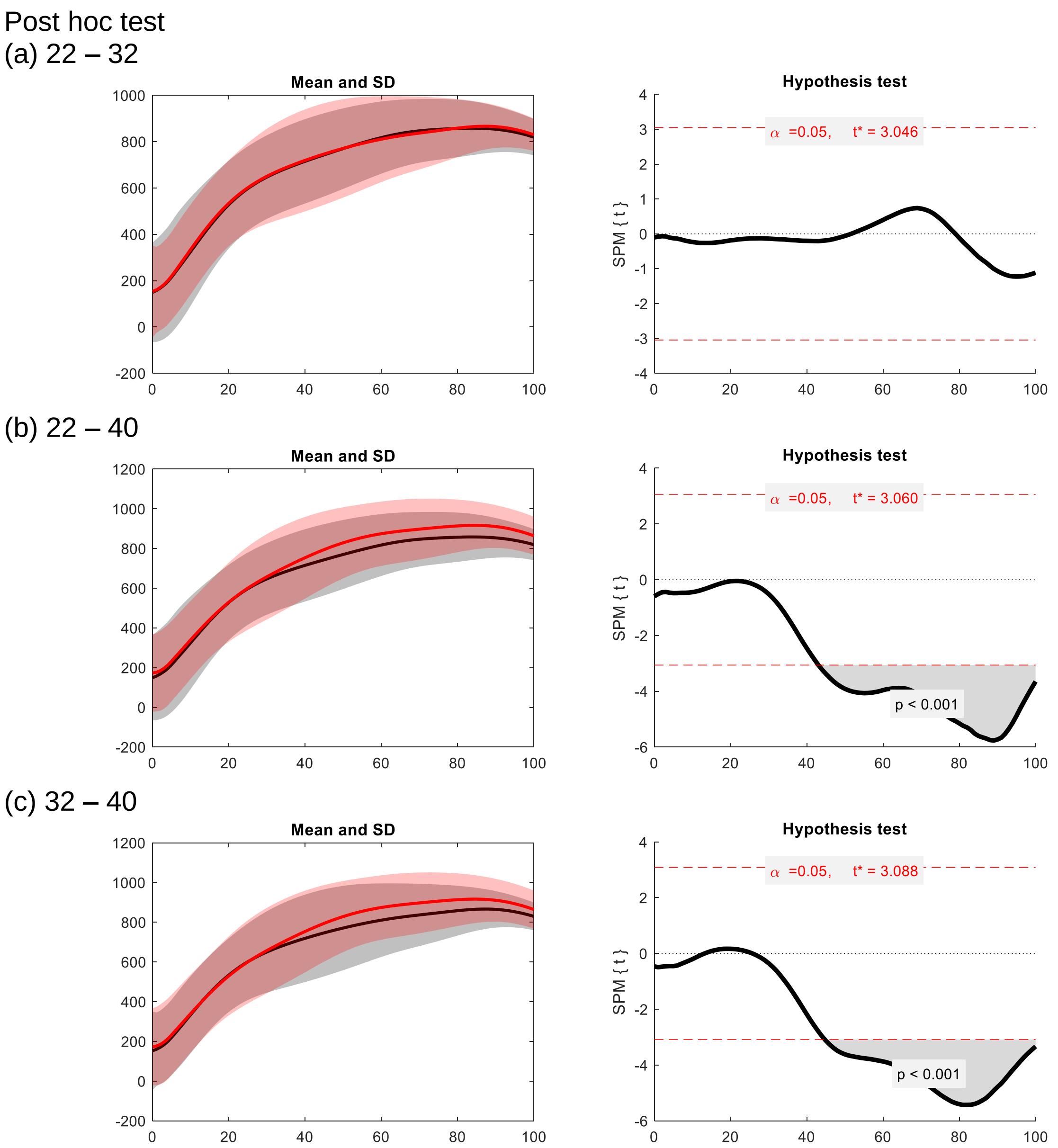


Figure 55: a) Statistical inference curves indicating no difference in kicking between 32 m and 22 m kicks. b) A significant difference between 40 m and 22 m kicks from time point 40% onwards. c) A significant difference between 40 m and 32 m kicks from time point 40% onwards.

4.4.2 KICKING LEG HIP VELOCITY

During the first part of the backswing, hip flexion velocity was ~180 deg/s. At around 80 per cent of the backswing, zero (0) velocity was reached, and hip extension started (see Figure 56). Hip extension velocity continued during the forward swing and reached a peak at about 30% of forward swing. Hip extension velocity stayed positive to time point 90 per cent of the forward swing (Figure 56) In the sagittal plane, no significant difference was seen between groups for the entire backswing and forward swing. When analysing the successful trials only, only a small area of difference between groups are seen during the forward swing (Figure 57 and Figure 58).

Sagittal plane

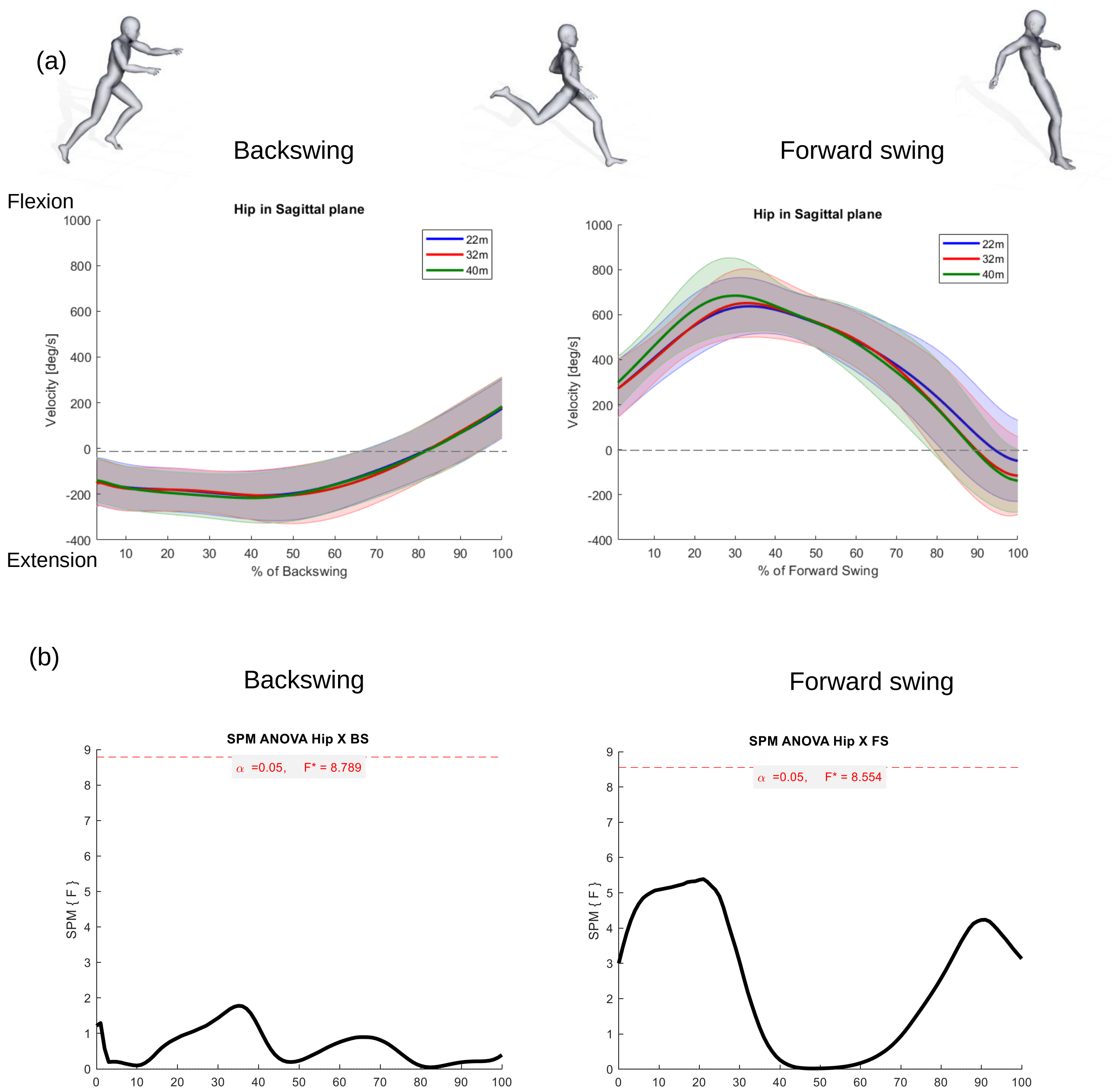


Figure 56: a) Mean trajectories for hip flexion/extension velocities in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 8.789 (backswing) and 8.554 (forward swing) was not exceeded.

Successful trials

Sagittal plane

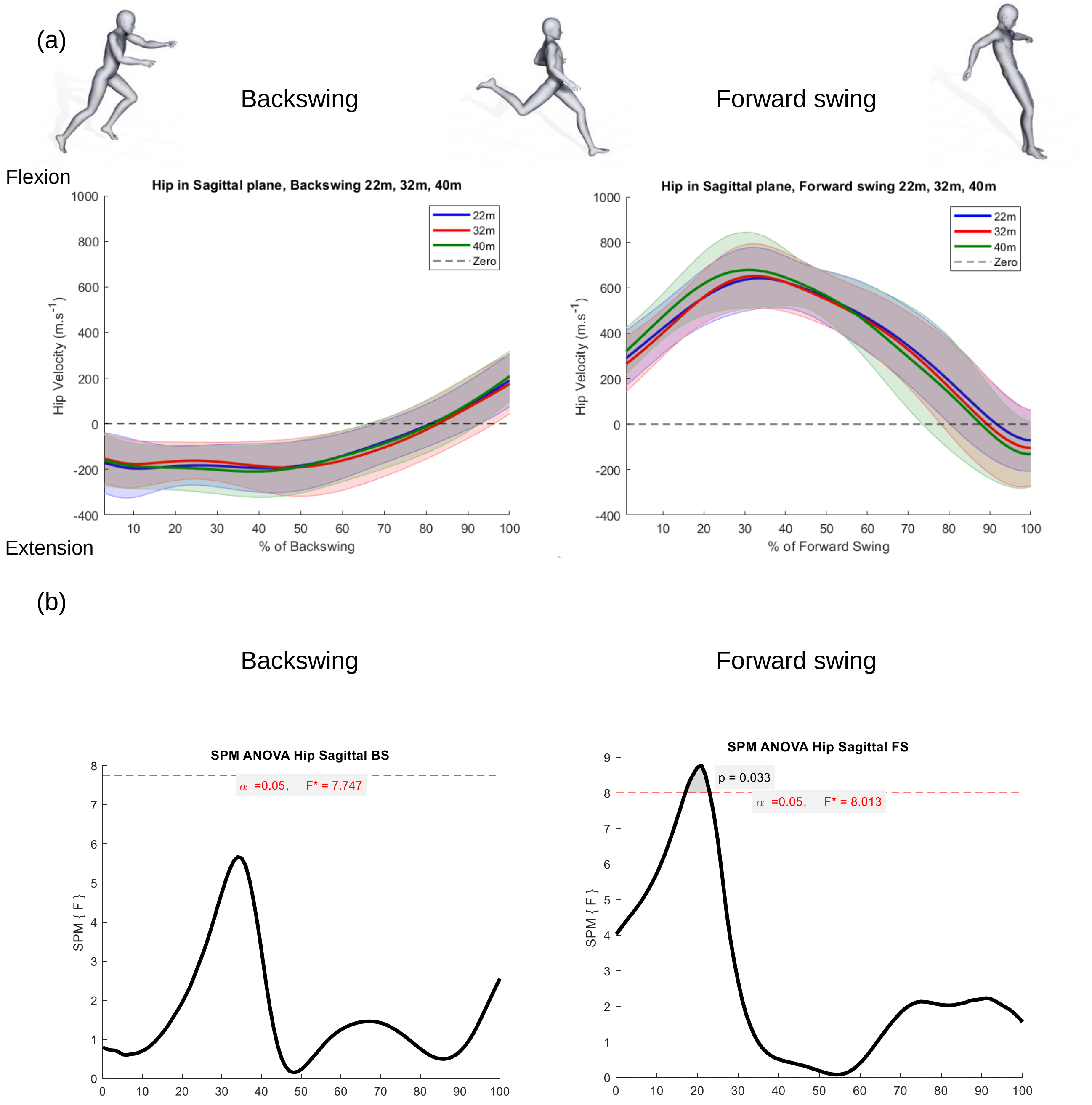
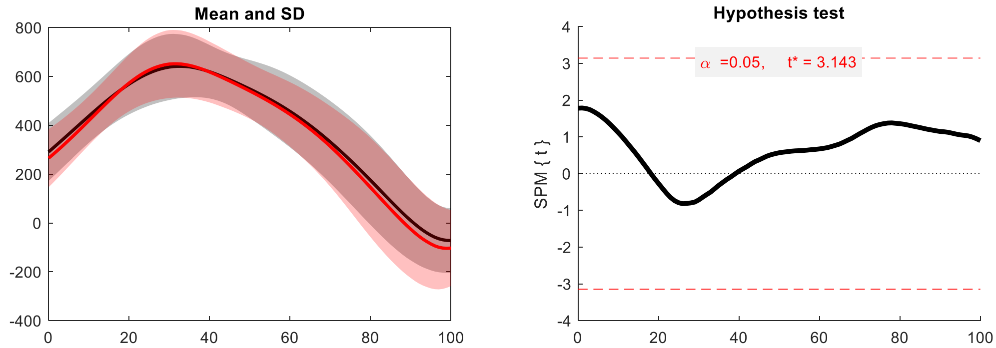


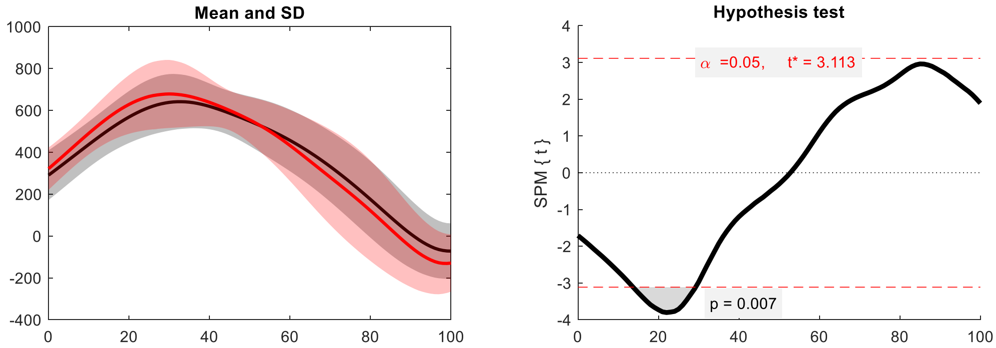
Figure 57: a) Mean trajectories for hip flexion/extension velocities in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 8.747 (backswing) was not exceeded and 8.013 (forward swing) was exceeded from time point 10% to 20%, with a supra-threshold cluster probability of p=0.033, indicating a significant difference between groups.

Post hoc test

(a) 22 – 32



(b) 22 – 40



(c) 32 – 40

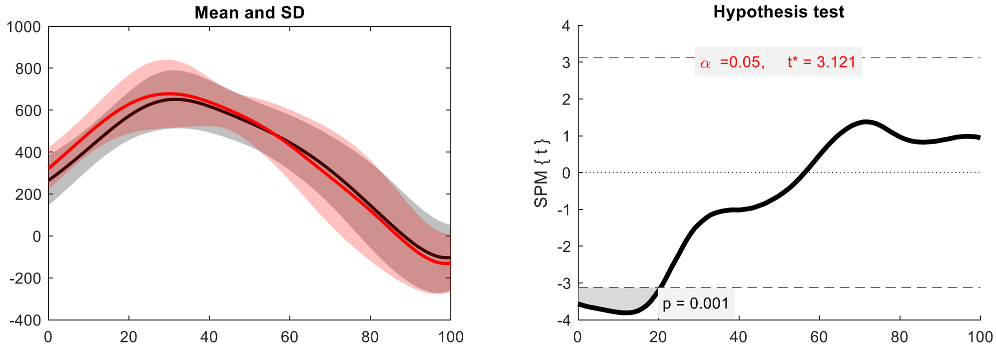


Figure 58: a) Statistical inference curves indicating no difference in kicking between 32 m and 22 m kicks. b) A significant difference between 40 m and 22 m kicks from time point 15% to 25%. c) A significant difference between 40 m and 32 m kicks from time point 0% to 20%.

4.4.3 PELVIS VELOCITY

The pelvis had a negative velocity in the sagittal plane, for the entire backswing and forward swing with a maximum of about 420 deg/s posterior pelvic tilt velocity about 60 per cent of the forward swing (Figure 59). In the frontal plane, the pelvis had a positive velocity for pelvic obliquity (kicking side lower) for the entire backswing and forward swing (Figure 60). The transverse plane indicated mostly internal pelvic rotation. During the backswing the pelvis stayed in internal rotation velocity until approximately 55 per cent of the forward swing where a peak was reached (~300 deg/s). Pelvic internal rotation decelerates for the remainder of the forward swing (Figure 61).

In the sagittal-, frontal-, and transverse plane for the entire backswing and forward swing, no significant differences were seen between groups (Figure 59 – Figure 61). In the frontal plane, there seemed to be a trend towards higher peak velocity in pelvic obliquity for 60 per cent to 80 per cent of the forward swing in the 40 m kicks compared to the 22 m kicks. However, the large standard deviation in groups made it difficult to see statistically significant results (Figure 60). Similarly, in the transverse plane, no statistically significant difference was seen between groups; however, a trend was noted for 40 per cent to 60 per cent of the forward swing where greater internal rotation velocity correlates with kicking from a greater distance (Figure 61). Similar findings were reported by successful trial only for sagittal- and transverse plane (Figure 62 and Figure 65), however the frontal plane indicated a small area of difference between groups (Figure 63 and Figure 64).

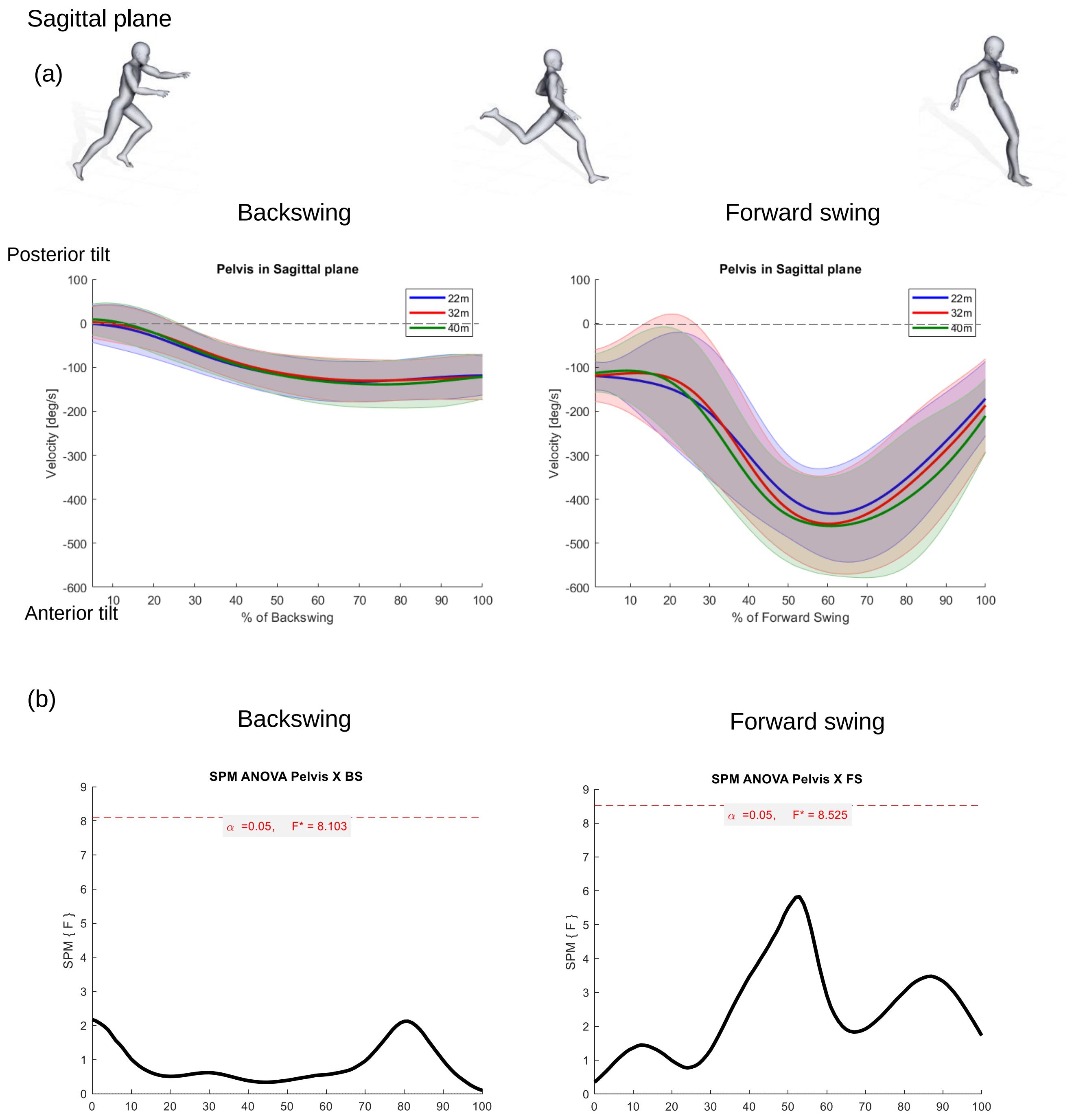


Figure 59: a) Mean trajectories for pelvis tilt velocities in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 8.103 (backswing) and 8.525 (forward swing) was not exceeded.

Frontal plane

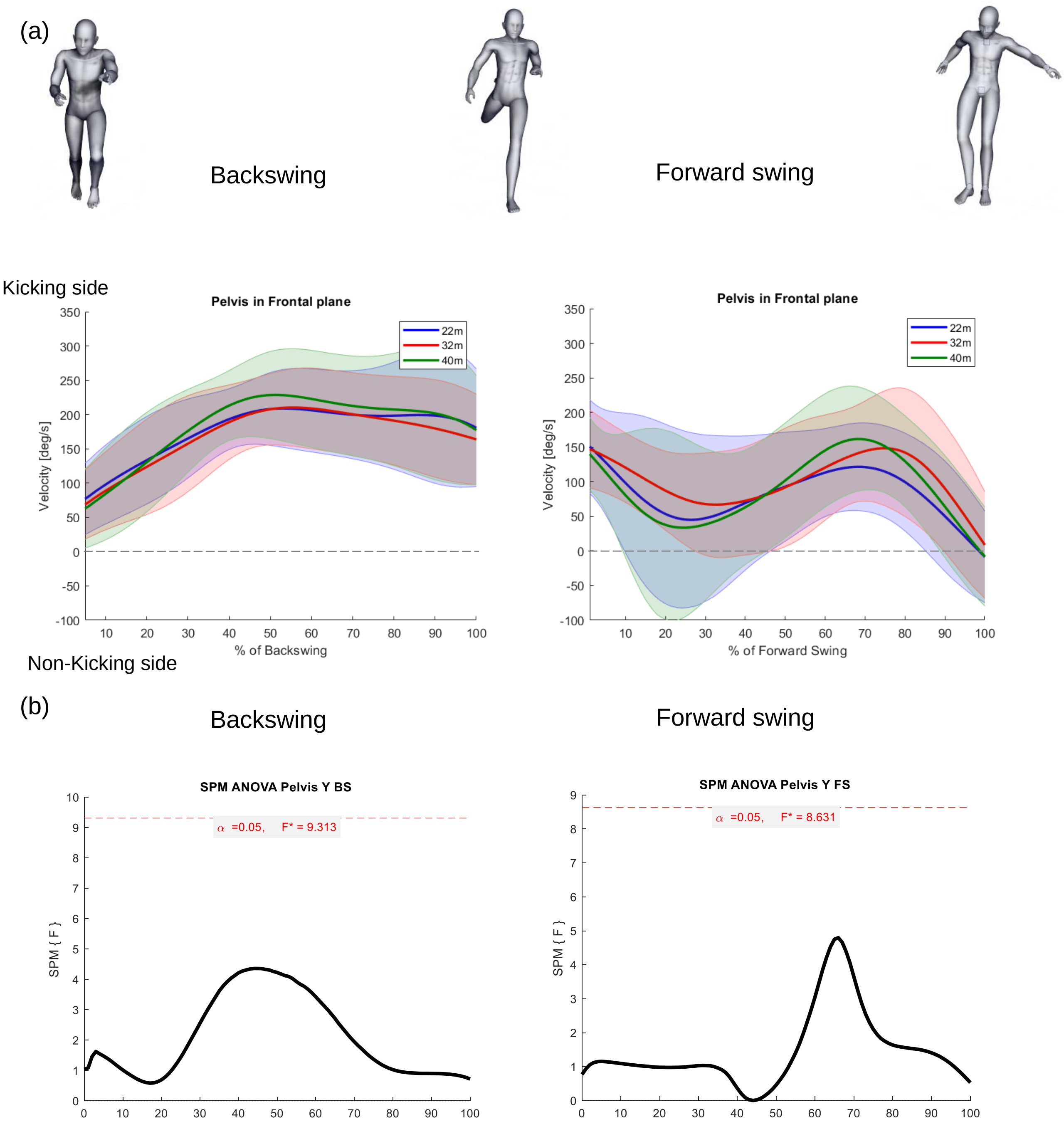


Figure 60: a) Mean trajectories for pelvis obliquity velocities in frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 9.313 (backswing) and 8.631 (forward swing) was not exceeded.

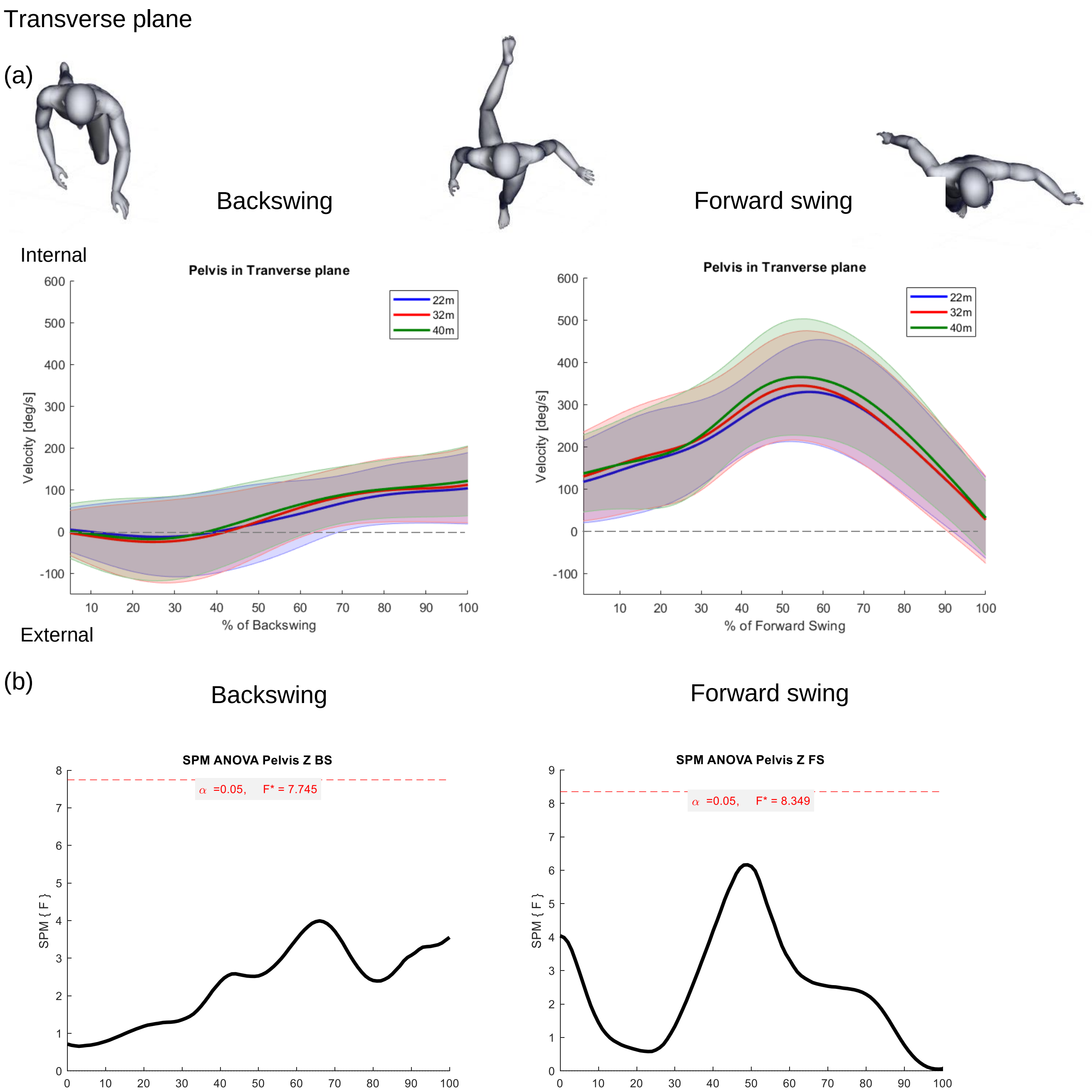
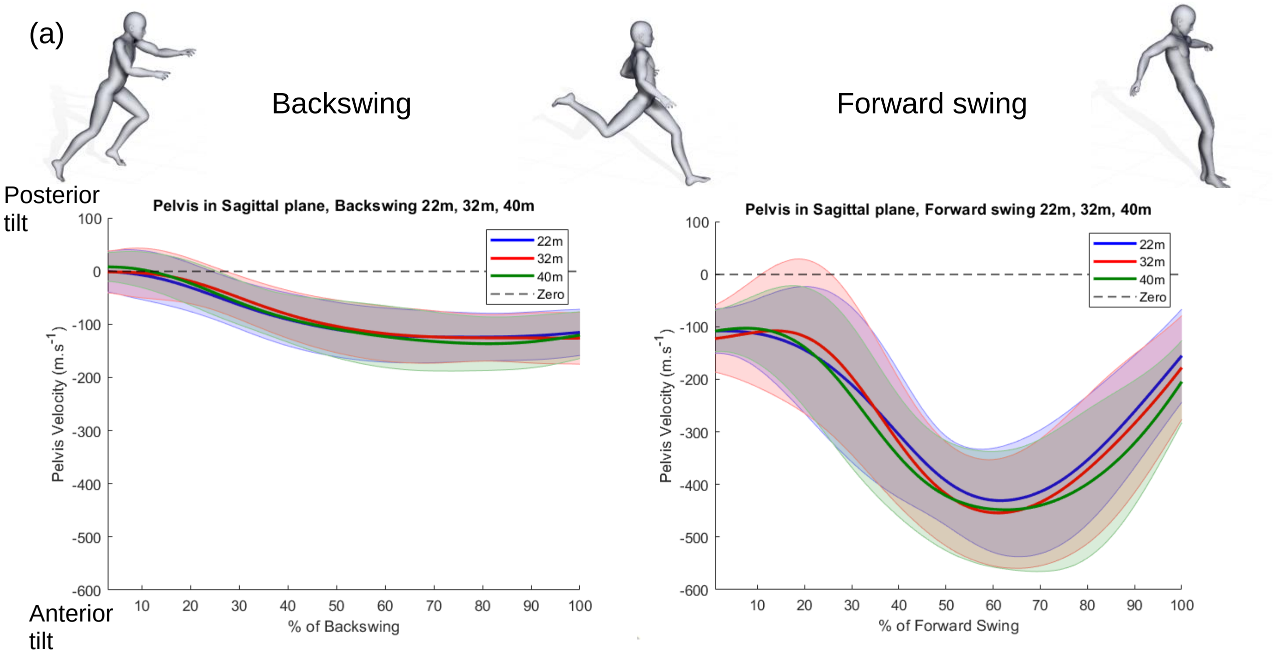


Figure 61: a) Mean trajectories for pelvis rotation velocities in transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.745 (backswing) and 8.349 (forward swing) was not exceeded.

Successful trials

Sagittal plane

(a)



(b)

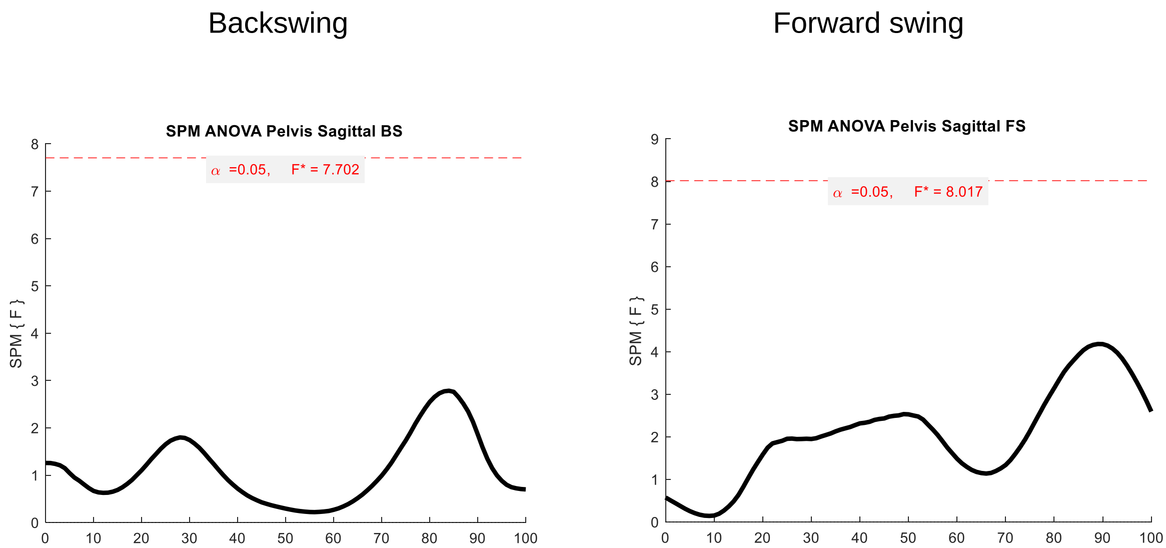


Figure 62: a) Mean trajectories for pelvis tilt velocities in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.702 (backswing) and 8.071 (forward swing) was not exceeded.

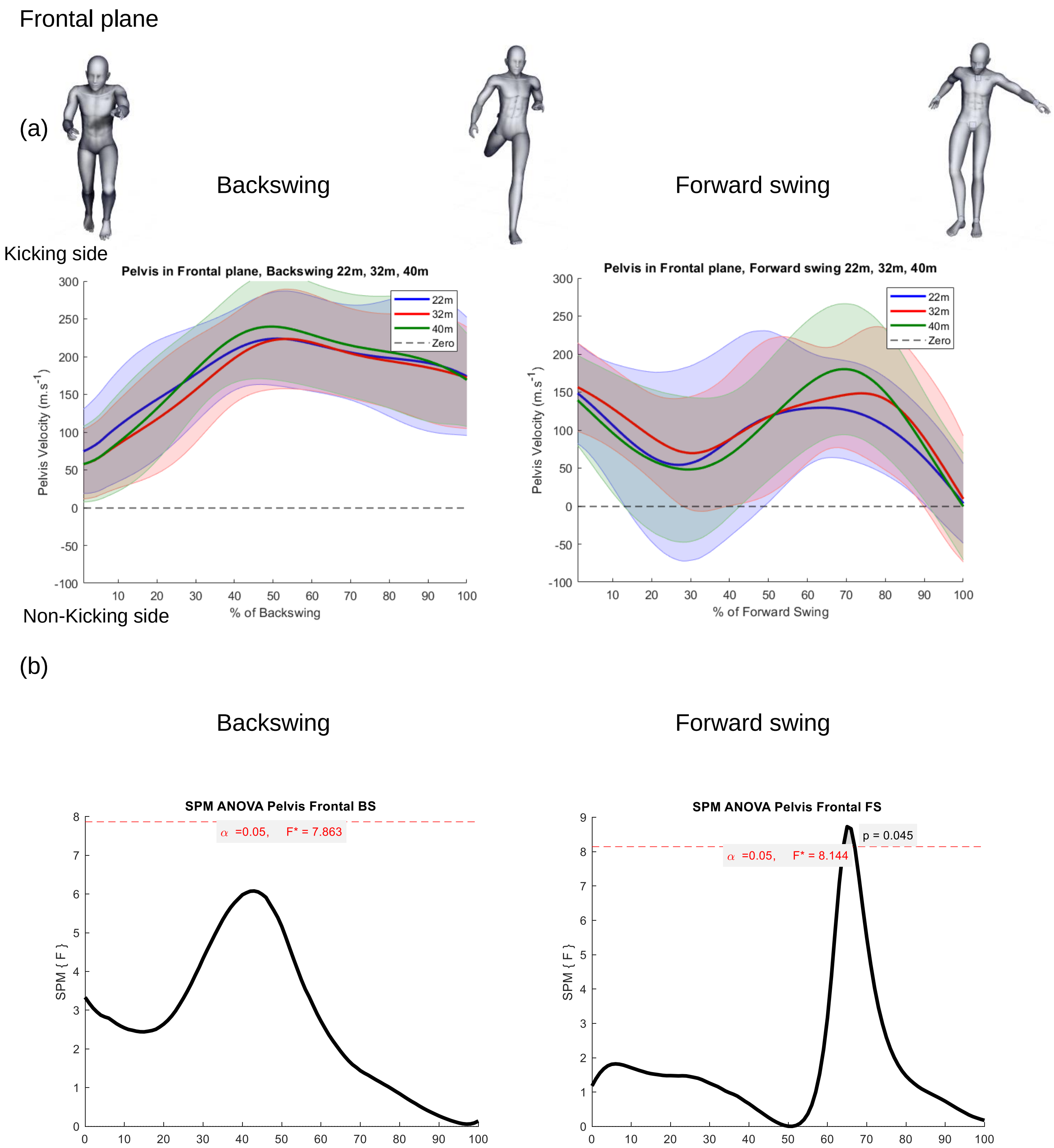
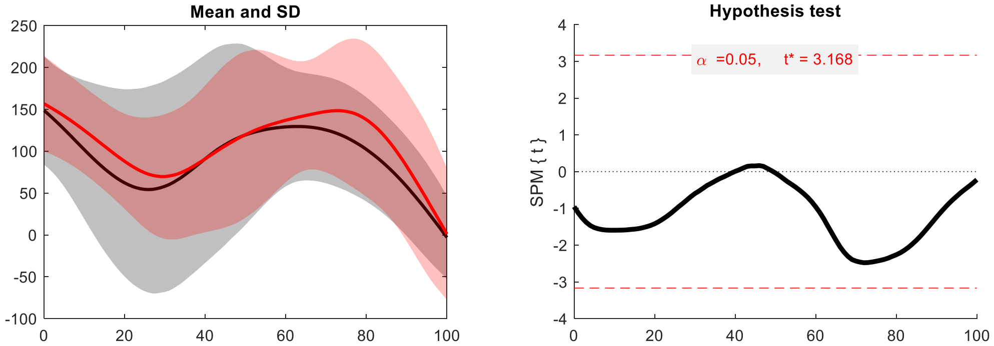
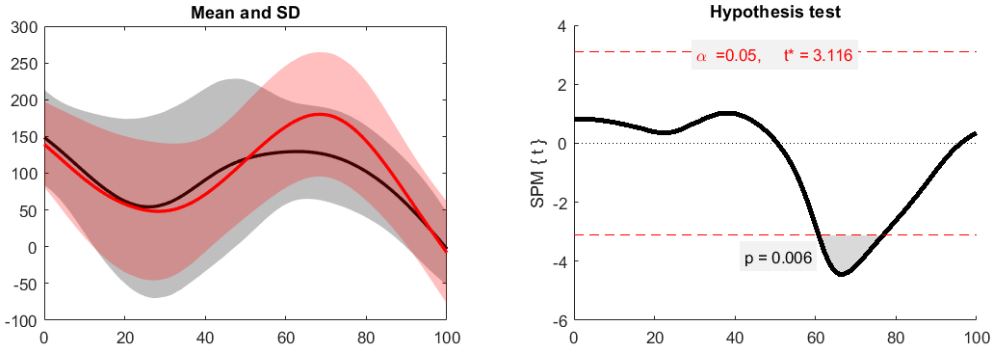


Figure 63: a) Mean trajectories for pelvis obliquity velocities in frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.863 (backswing) was not exceeded and 8.631 (forward swing) was exceeded at time point 60% to 70%, with a supra-threshold cluster probability of p=0.045, indicating a significant difference between groups.

Post hoc test
(a) 22 – 32



(b) 22 – 40



(c) 32 – 40

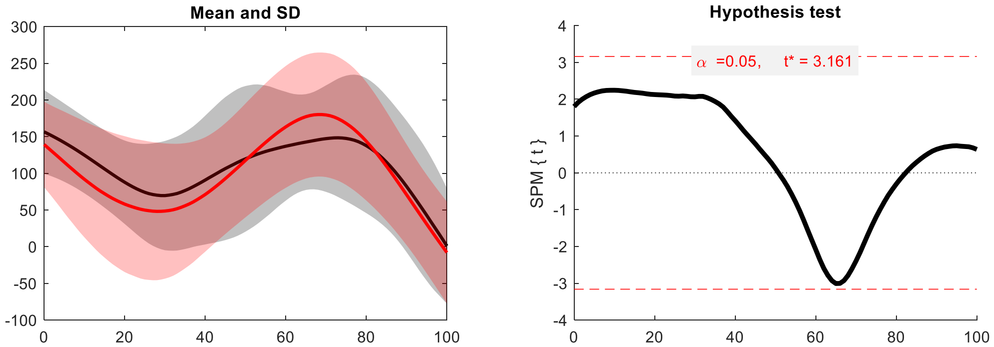


Figure 64: a) Statistical inference curves indicating no difference in kicking between 32 m and 22 m kicks. b) A significant difference between 40 m and 22 m kicks from time point 60% to 70%. c) No difference between 40 m and 32 m kicks.

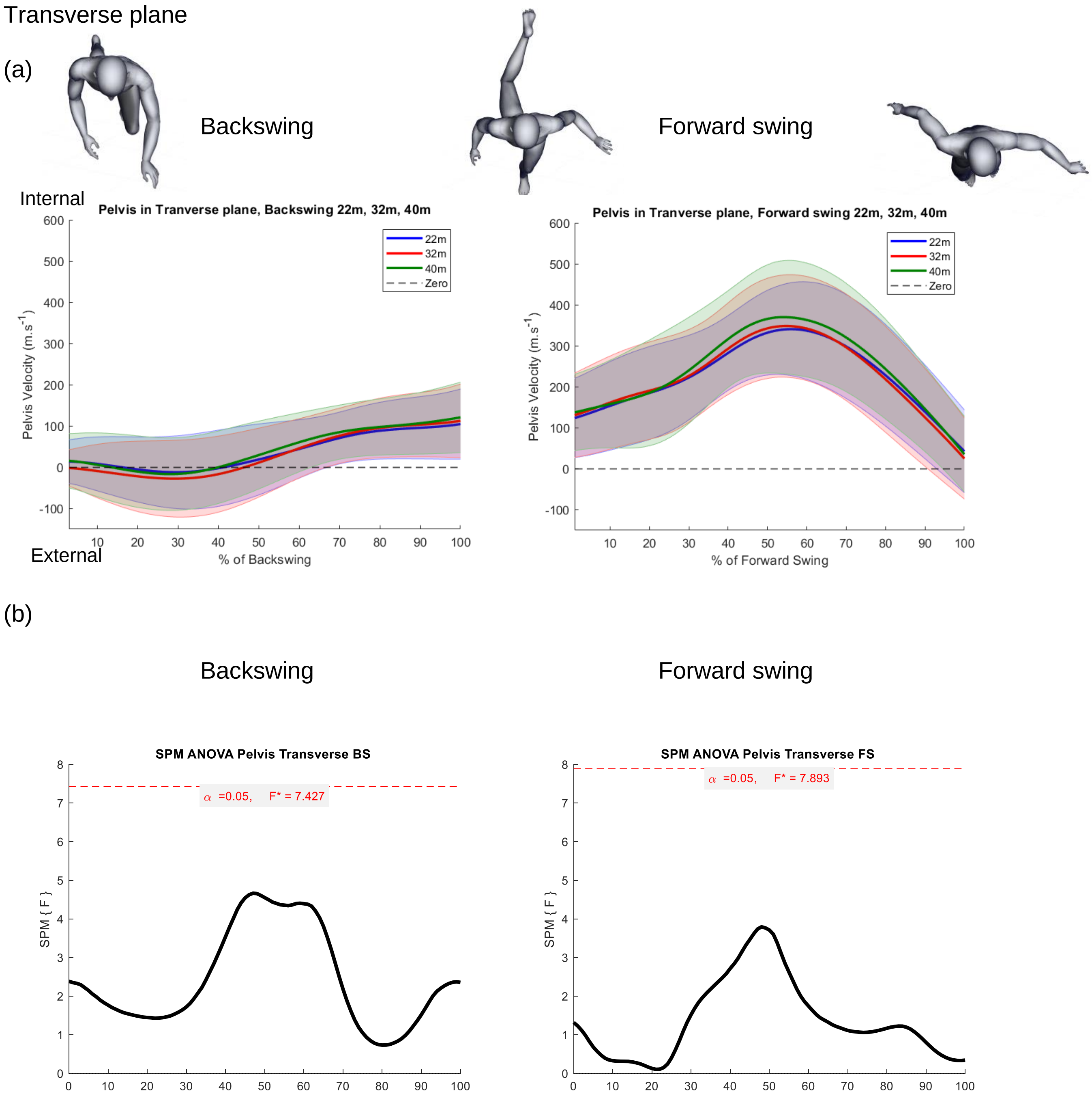


Figure 65: a) Mean trajectories for pelvis rotation velocities in transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.427 (backswing) and 7.893 (forward swing) was not exceeded.

4.4.4 THORAX VELOCITY

In the sagittal plane, the thorax velocity started at about 80 deg/s of backward tilt at the beginning of the backswing and moved to a maximum of ~170 deg/s of backward tilt velocity at the end of the backswing (the final 30% of the backswing). The thorax backward tilt decelerated to 0 velocity at about 30 per cent. Thereafter, forward tilt velocity increased to ~200 deg/s until 70 per cent of forward swing (see Figure 66). In the sagittal plane, no difference was seen between groups during the backswing. However, from 55 per cent to 85 per cent of the forward swing, a significant difference was seen between groups (Figure 66), with significantly greater forward tilt velocity during the 40 m kicks compared to the 32 m and 22 m kicks (Figure 67).

In the frontal plane, the thorax started with a positive obliquity velocity of 80 deg/s and fluctuated between 60 deg/s and 120 deg/s for the entire backswing (kicking side lower). During the forward swing, the thorax decelerated rapidly to 0 velocity at about 30 per cent. Thoracic obliquity velocity increased (with non-kicking side lower) to a peak at 50 per cent to 60 per cent of the forward swing (Figure 68). In the frontal plane, from 15 per cent to 30 per cent of the backswing a significant difference was seen between groups (Figure 68), with the 40 m kicks displaying significantly higher thoracic obliquity velocity compared to the 22 m and 32 m kicks (Figure 69).

The thoracic rotation, in the transverse plane, started at 50 deg/s internal rotation and stayed consistent for most of the backswing, slowly decelerating towards the end of the backswing. Thoracic rotation started with about 0 velocity in the forward swing. Rotation velocity displayed slight external rotation velocity and then internal rotation velocity to about 50 per cent and then external velocity again closer to ball contact (Figure 70). No difference in the transverse plane for the entire backswing and forward swing (Figure 70) was noted. Successful trials only indicated no difference between groups in the sagittal plane (Figure 71). Similar frontal- and transverse plane results were seen (Figure 72, Figure 73 and Figure 74),

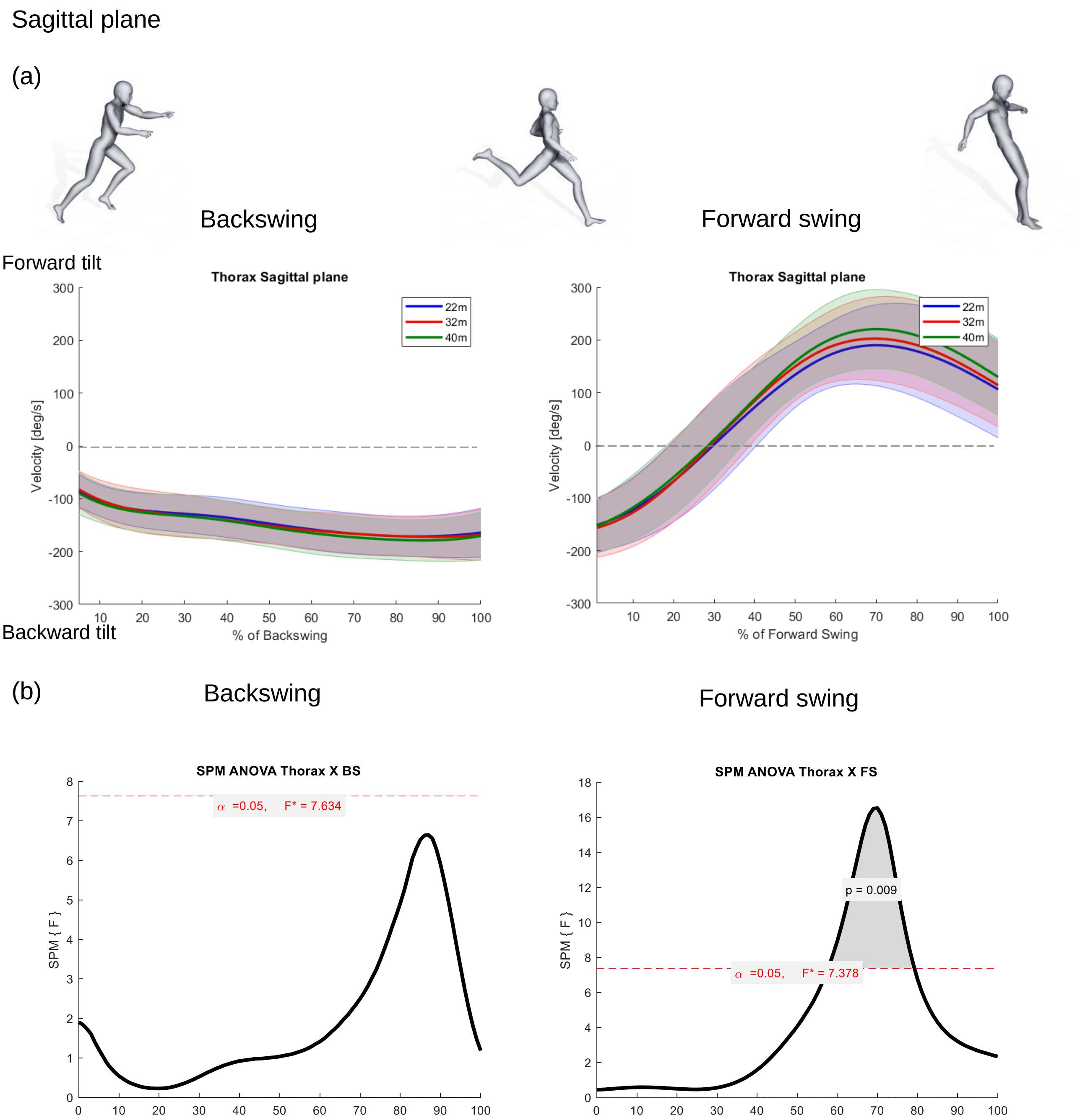
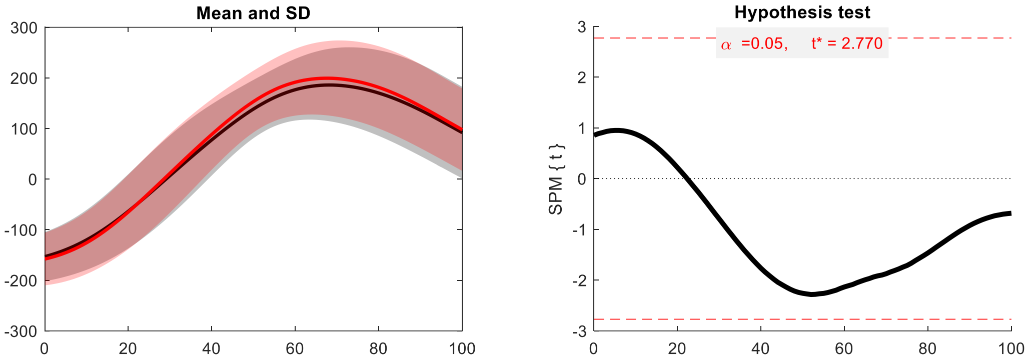


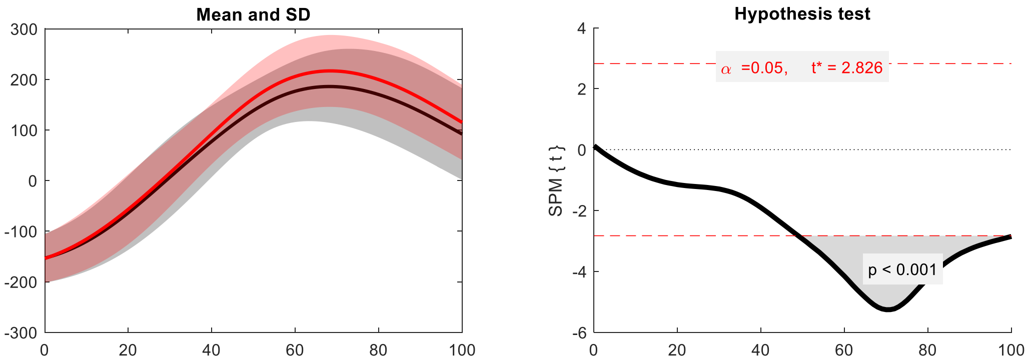
Figure 66: a) Mean trajectories for thorax flexion/extension velocities in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.7634 (backswing) was not exceeded. The critical threshold of 7.378 (forward swing) was exceeded at timepoint 55% to 85% with a supra-cluster probability of p=0.009, indicating a significant difference between groups.

Post hoc test

(a) 22– 32



(b) 22 – 40



(c) 40 – 32

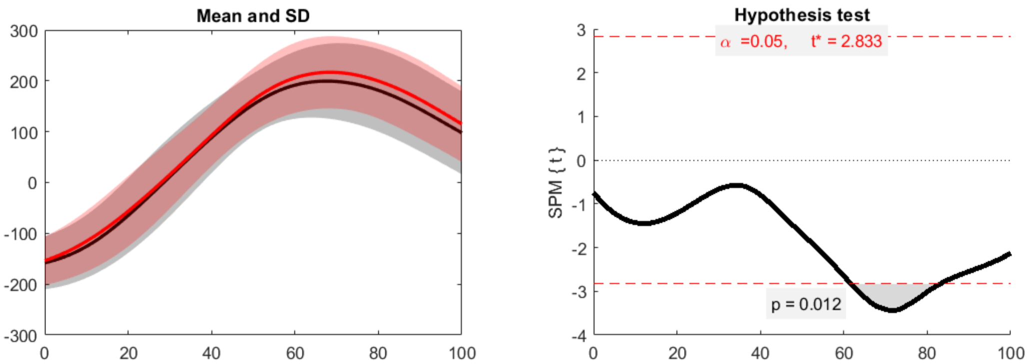


Figure 67: a) Statistical inference curves indicating no difference between 32 m and 22 m kicks. b) A significant difference between 40 m and 22 m kicks from time point 40% onwards. c) A significant difference between 40 m and 32 m kicks from time point 60% to 80%.

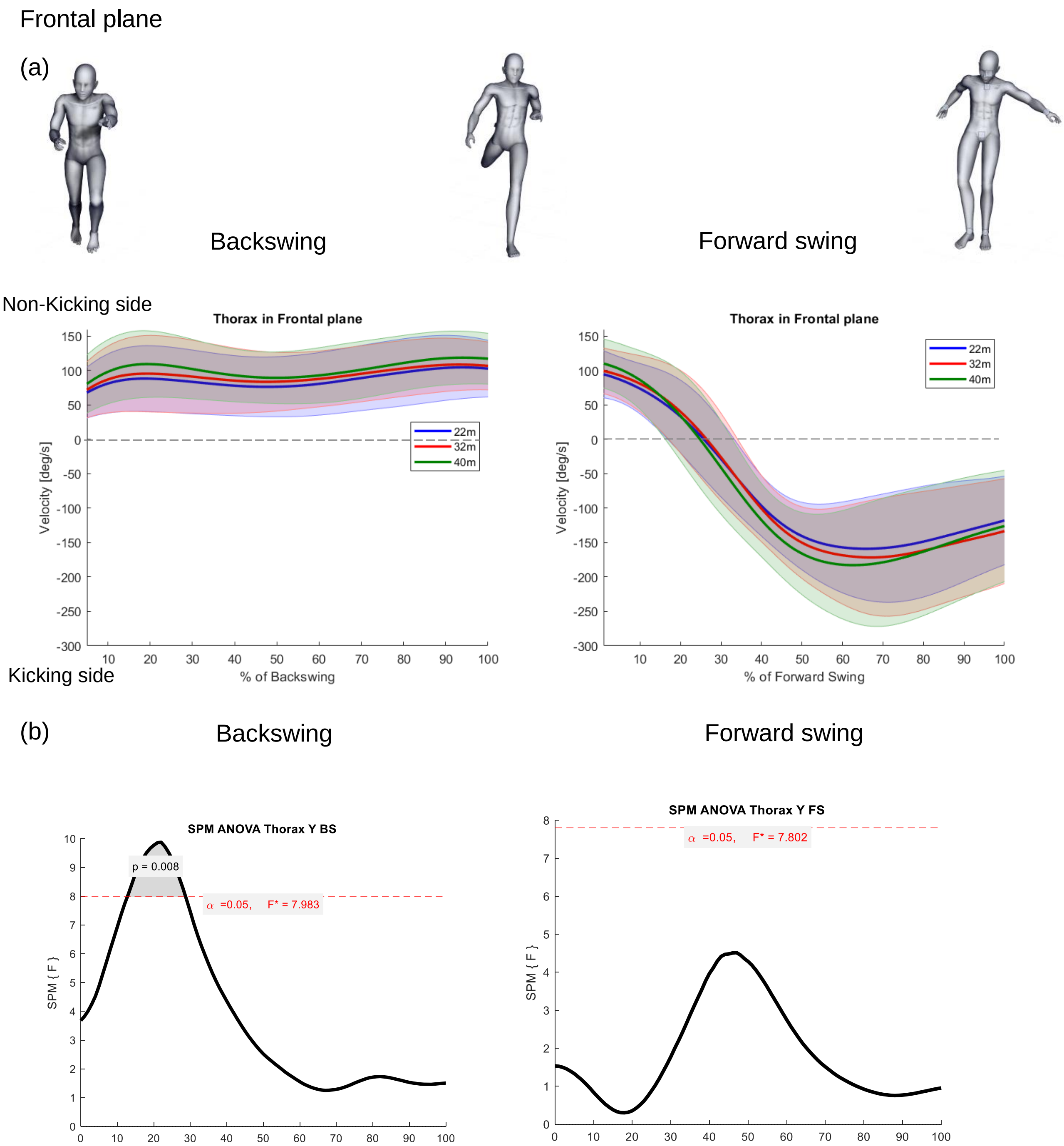
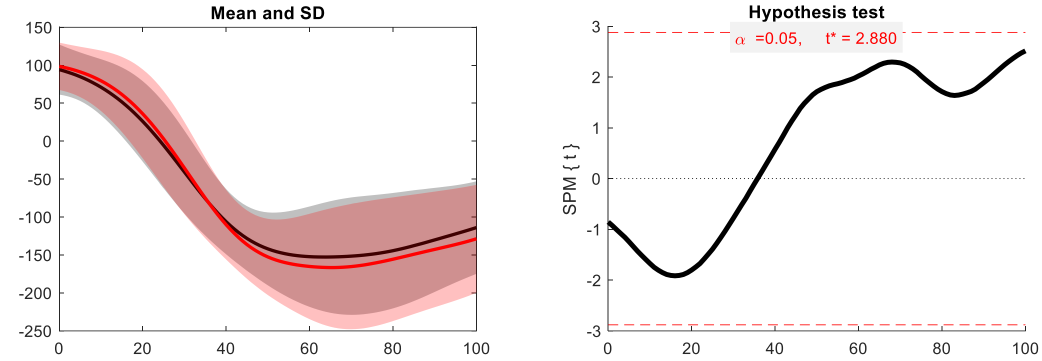


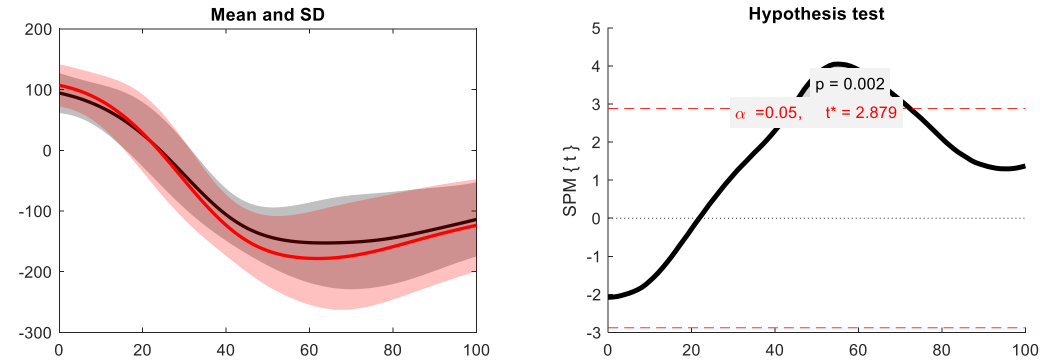
Figure 68: a) Mean trajectories for thorax lateral flexion velocities in frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.983 (backswing) was exceeded at time point 15% to 30% with a supra-cluster probability of p=0.008, indicating a difference between groups. The critical threshold of 7.802 (forward swing) was not exceeded.

Post hoc test

(a) 22 – 32



(b) 22 – 40



(c) 32– 40

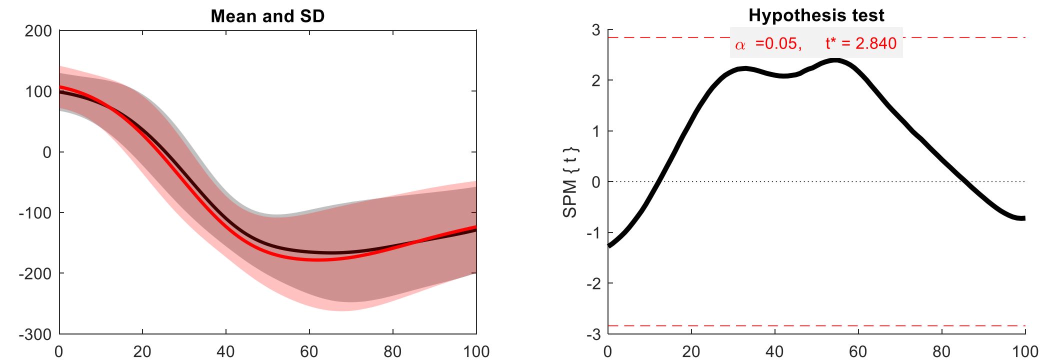


Figure 69: a) Statistical inference curves indicating no difference between 32 m and 22 m kicks. b) A significant difference between 40 m and 22 m kicks from time point 5% to 60%. c) A significant difference between 40 m and 32 m kicks from time point 5% to 30%.

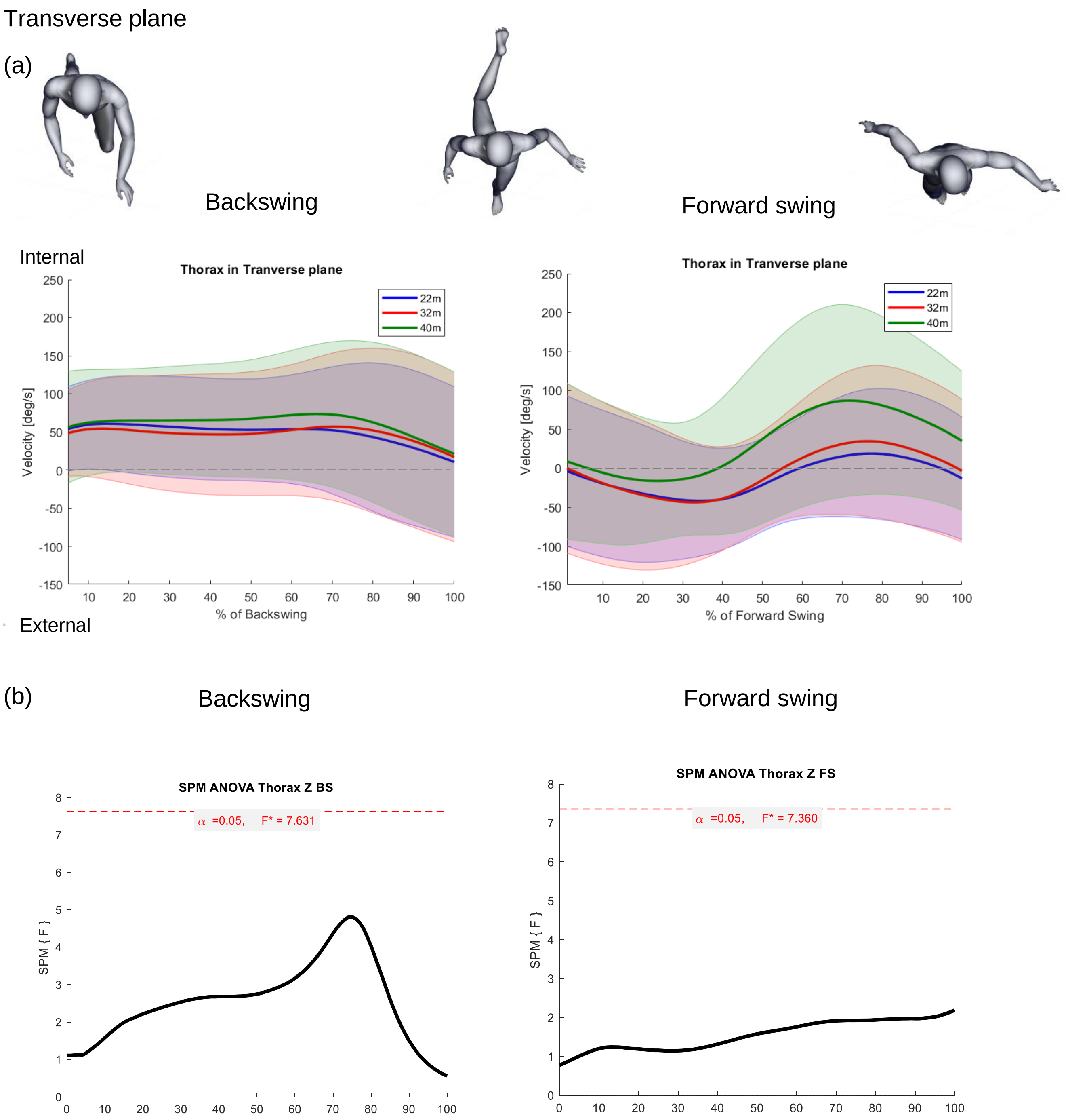
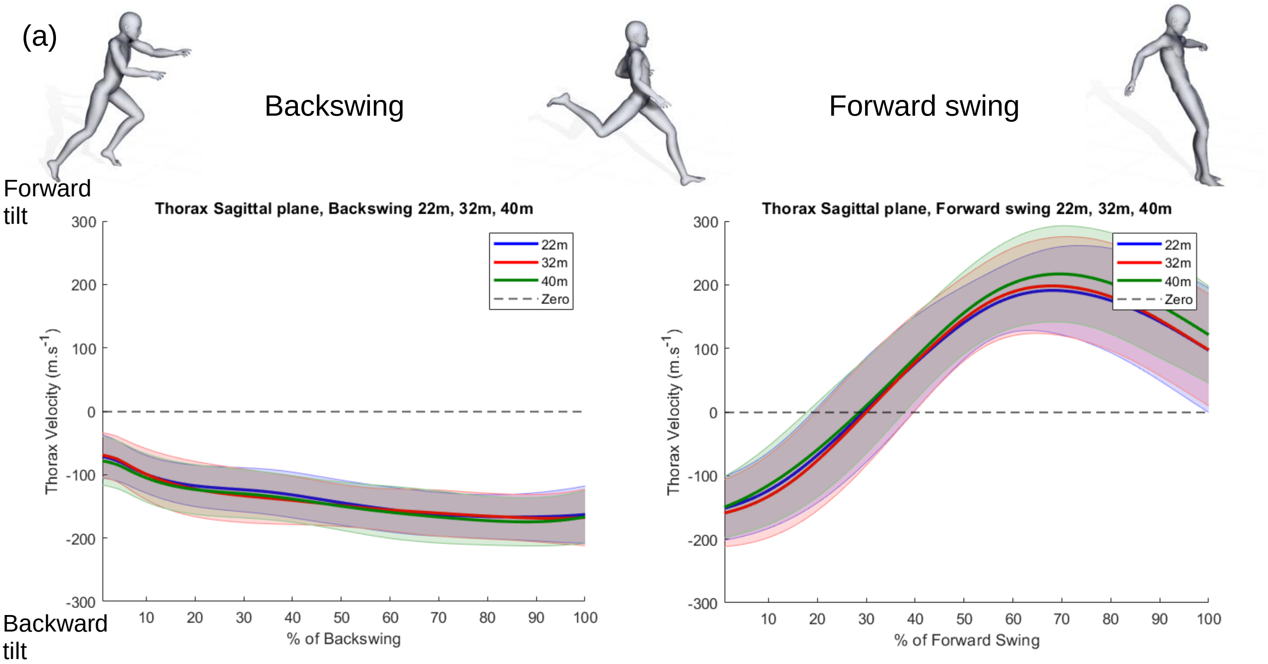


Figure 70: a) Mean trajectories for thorax rotation velocities in transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.631 (backswing) and 7.360 (forward swing) was not exceeded.

Successful trials

Sagittal plane

(a)



(b)

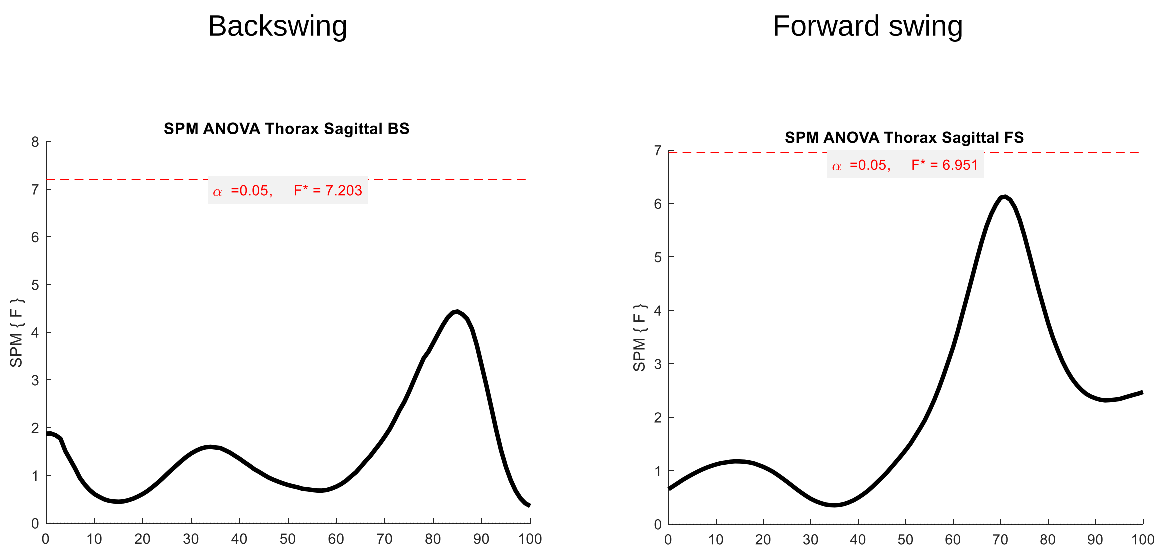


Figure 71: a) Mean trajectories for thorax flexion/extension velocities in sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.7634 (backswing) and 6.951 (forward swing) was not exceeded.

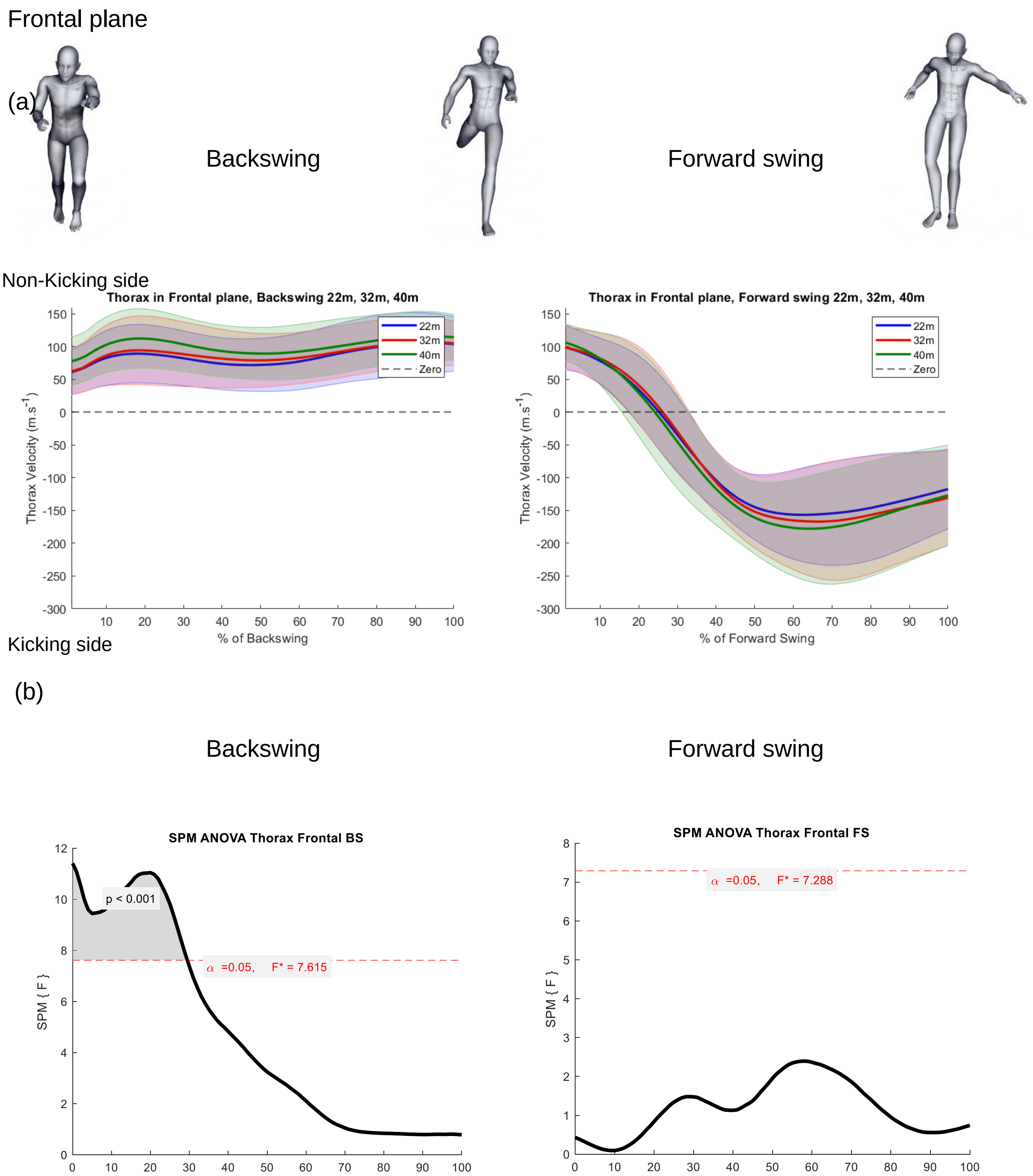


Figure 72: a) Mean trajectories for thorax lateral flexion velocities in frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.615 (backswing) was exceeded for the initial 30% of backswing with a supra-cluster probability of p<0.001, indicating a difference between groups. The critical threshold of 7.288 (forward swing) was not exceeded.

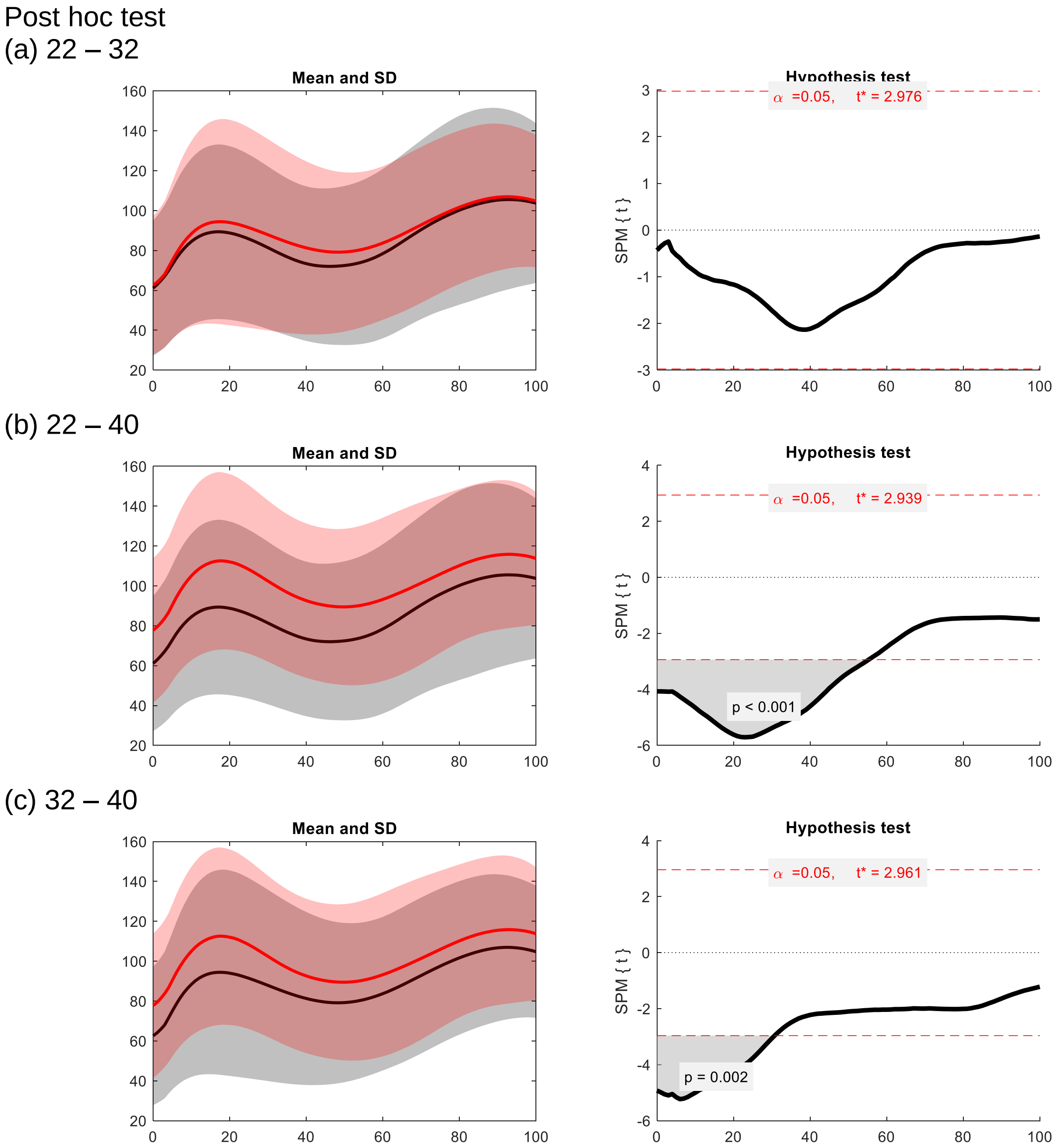


Figure 73: a) Statistical inference curves indicating no difference between 32 m and 22 m kicks. b) A significant difference between 40 m and 22 m kicks from time point 0% to 50%. c) A significant difference between 40 m and 32 m kicks from time point 0% to 30%.

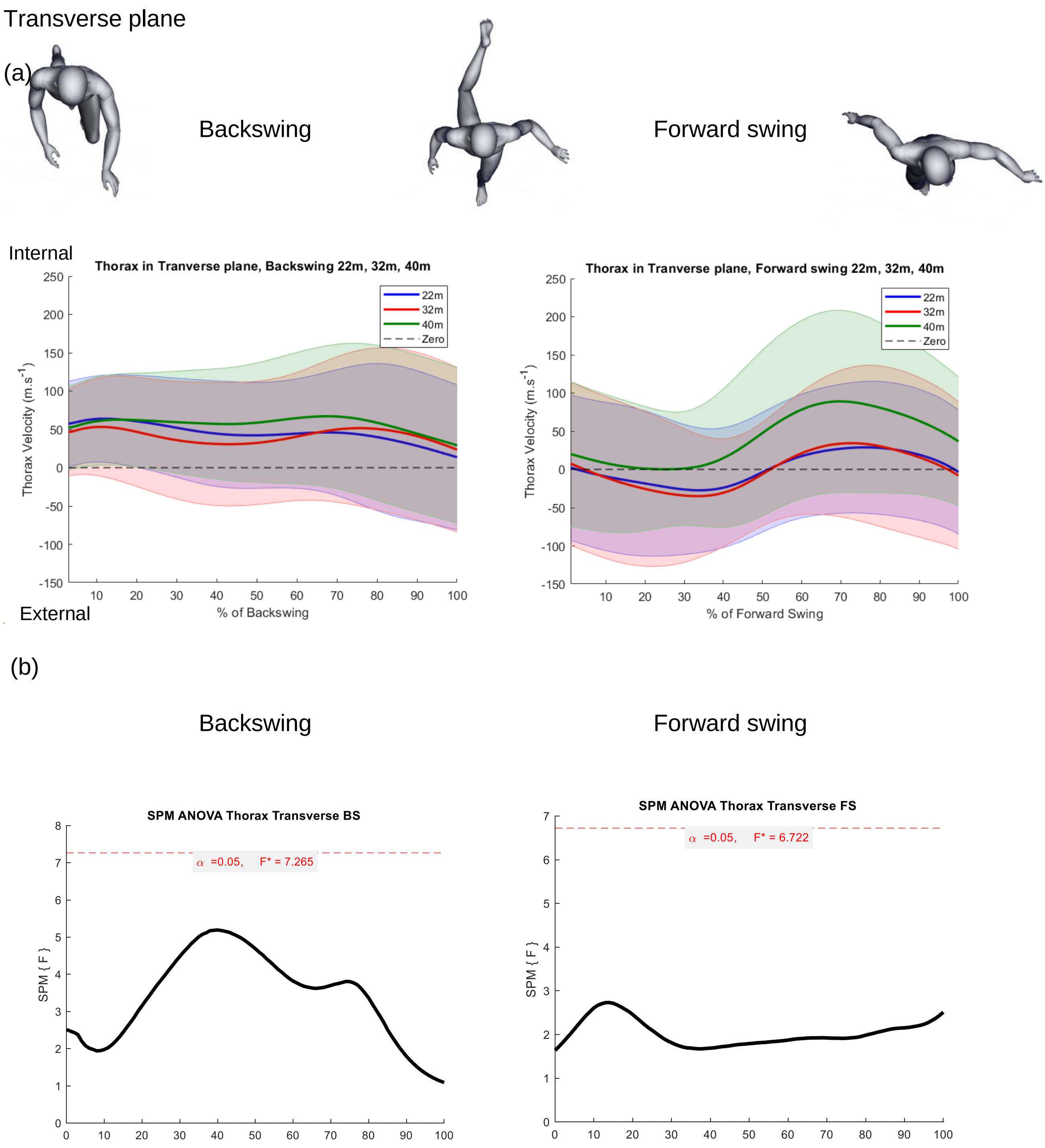


Figure 74: a) Mean trajectories for thorax rotation velocities in transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 7.265 (backswing) and 6.722 (forward swing) was not exceeded.

4.5 JOINT AND SEGMENT COUPLINGS

The third objective was to compare segment couplings between place kicks at 22 m, 32 m, and 40 m from the posts. Histograms were used to group the joint and segment kinematics into the following coordination patterns:

- Anti: Anti-phase
- Dist: Distal phase
- In: In-phase
- Prox: Proximal phase

The coordination graphs in the following section can be interpreted by referring to the legend (Figure 75).

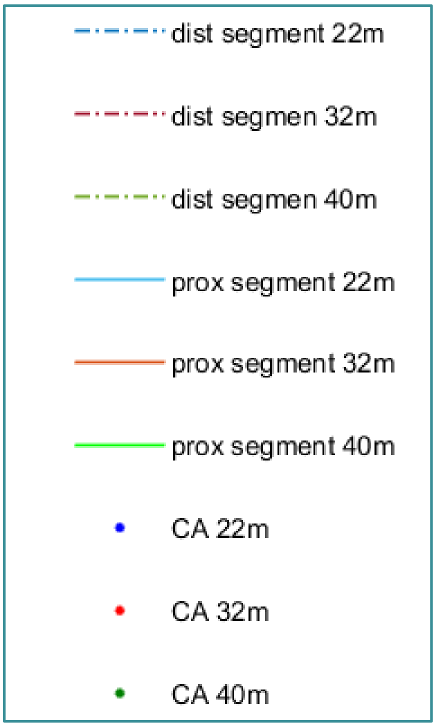


Figure 75: Legend to CA graphs in text

4.5.1 HIP-KNEE

In this section, the distal phase and proximal phase refer to the knee dominant phase and hip dominant phase, respectively.

Sagittal plane

During the backswing the hip-knee coupling indicated anti-phase, then transitioned into knee-phase for most of the backswing as the knee is the primary mover. During the backswing, most time was spent in the knee phase (80%) and the remainder in the anti-phase (20%). During the forward swing, the coupling moves from knee- to in- to hip-phase, it moves through anti-phase and then stays in knee-phase for the remainder of the forward swing. most time was spent in the knee phase (~35%) followed by the in-phase (~30%), anti-phase (~18%), and hip phase (~15%) (see Figure 76). No difference was seen between groups. Successful trials represented in Figure Figure 79, reporting similar movement patterns.

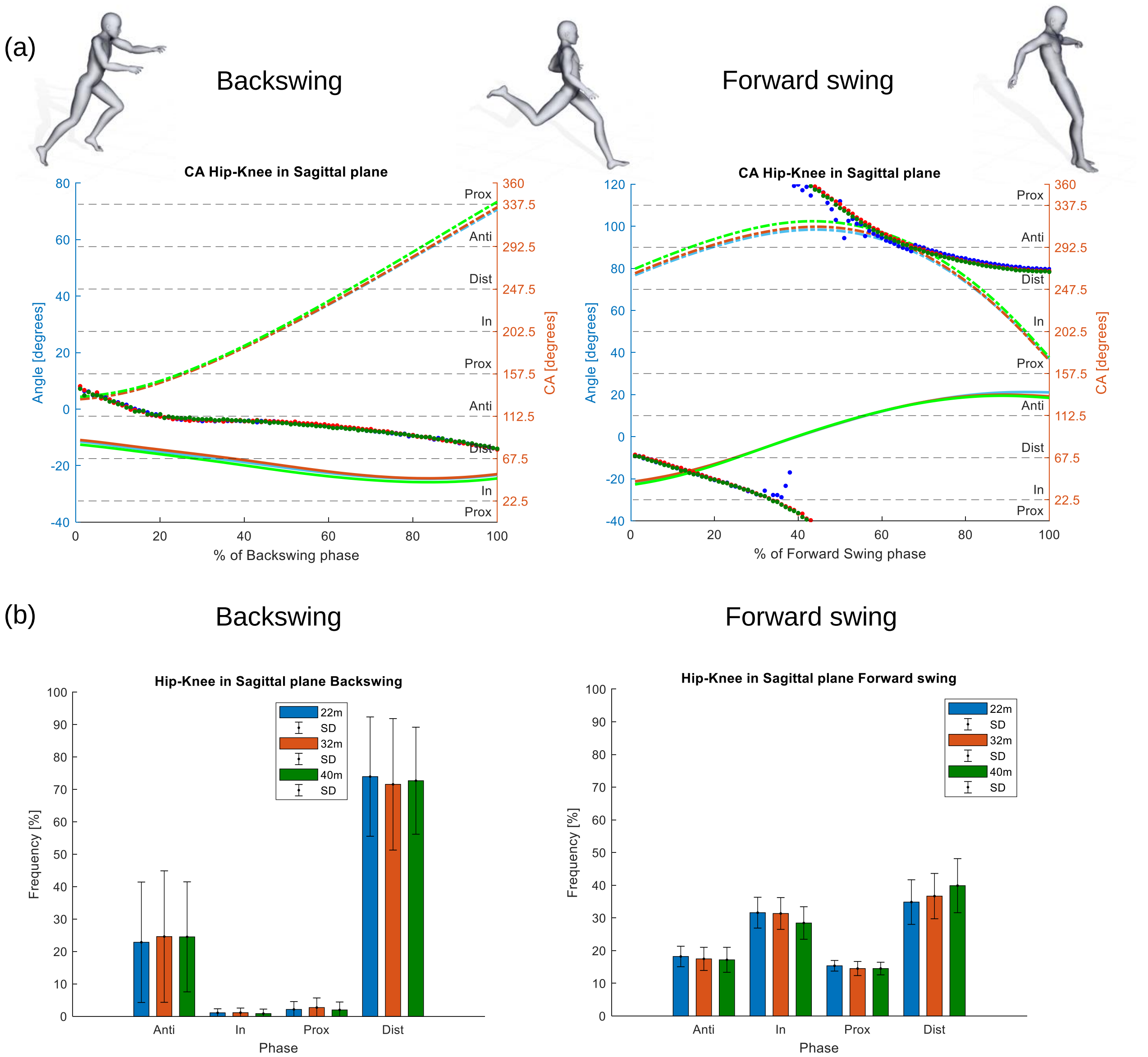


Figure 76: a) Mean CA of hip-knee in sagittal plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for hip-knee in sagittal plane during the backswing and forward swing of the kicking movement.

Frontal plane

During the backswing, most time was spent in the in-phase with hip (proximal) dominancy. During the forward swing, the coupling moves from hip-phase to anti-phase, through knee-, in- and hip-phase to end at anti-phase just prior to ball contact. In the forward swing, most time was spent in the hip phase (~35%) followed by the anti-phase and in-phase (~10%) (see Figure 77). Similar values were reported for the three groups. Figure 80 represents the same movement pattern as the pooled data.

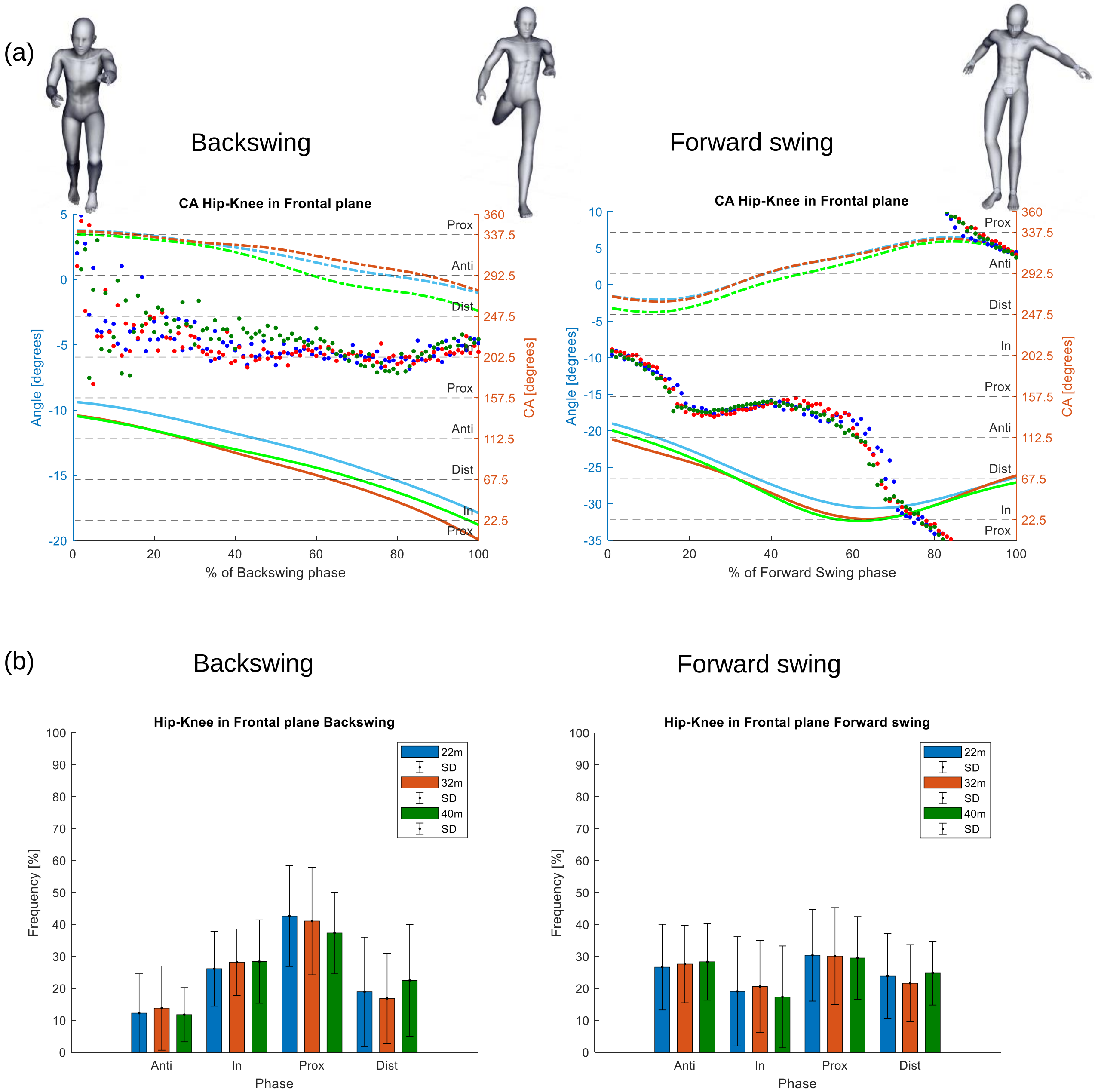


Figure 77: a) Mean *CA* of hip-knee in frontal plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for hip-knee in frontal plane during the backswing and forward swing of the kicking movement.

Transverse plane

Backswing presented with coordination pattern switching knee-phase, in-phase and back to knee-phase. The knee phase was the dominant coordination pattern during the backswing. During the forward swing anti-phase was seen followed by hip-phase and back to anti-phase with knee-phase right at the end. The hip phase was the dominant coordination pattern followed by the anti-phase and knee-phase (see Figure 78). Similar trends were found between all three groups. Figure 81 Shows the movement pattern for the successful trials only.

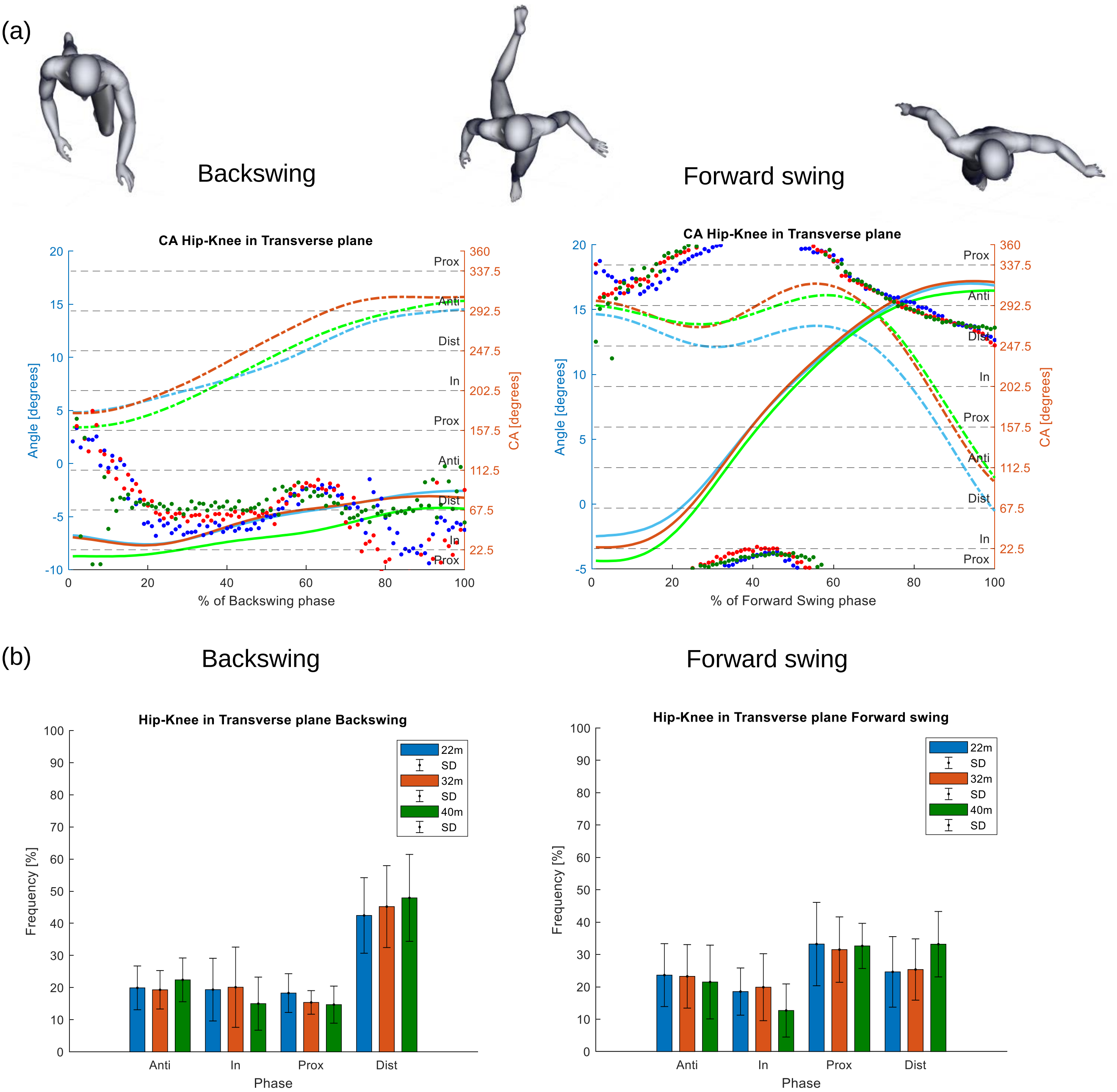


Figure 78: a) Mean *CA* of hip-knee in transverse plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for hip-knee in transverse plane during the backswing and forward swing of the kicking movement.

Successful trials

Sagittal plane

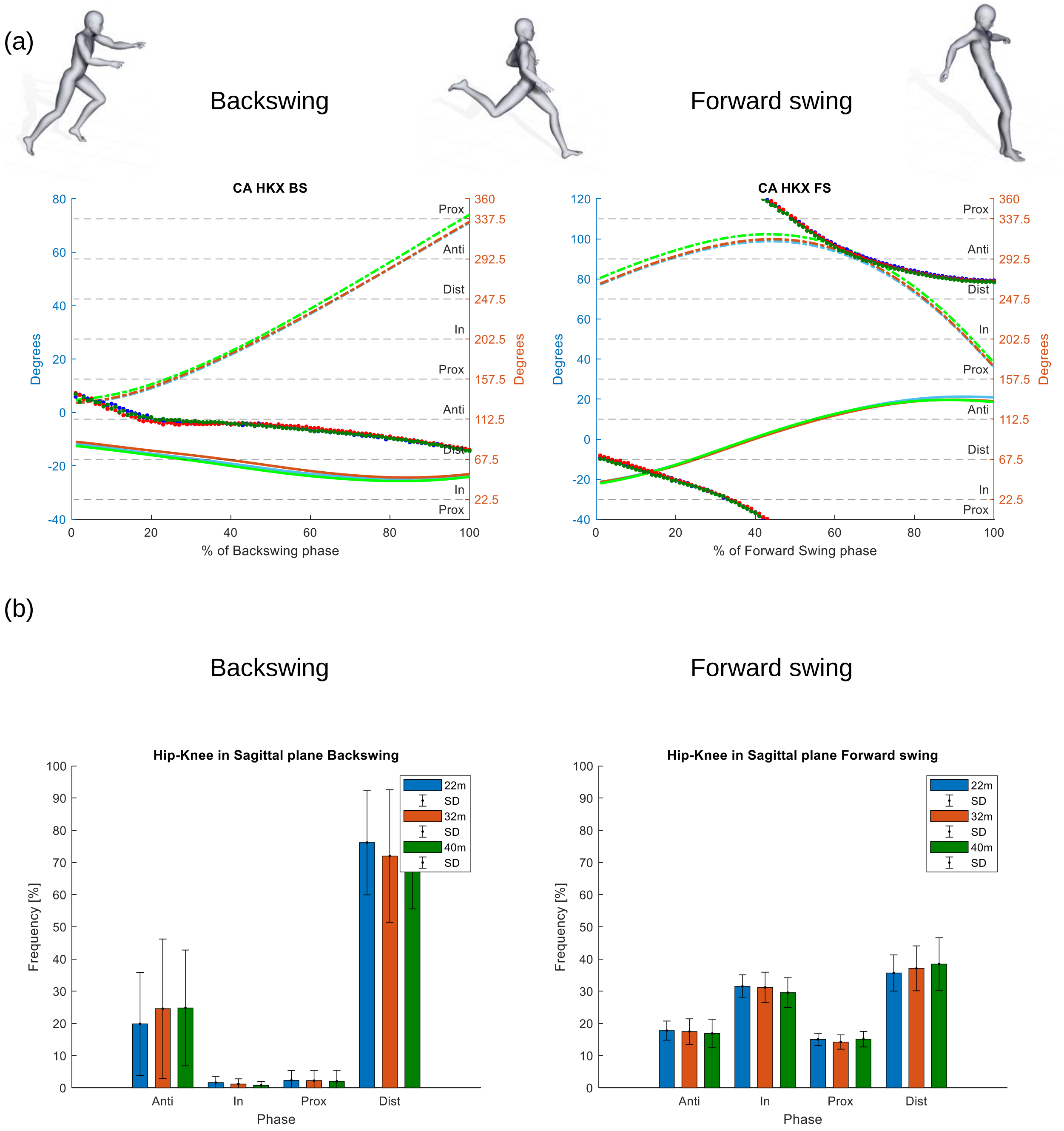


Figure 79: a) Mean CA of hip-knee in sagittal plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for hip-knee in sagittal plane during the backswing and forward swing of the kicking movement.

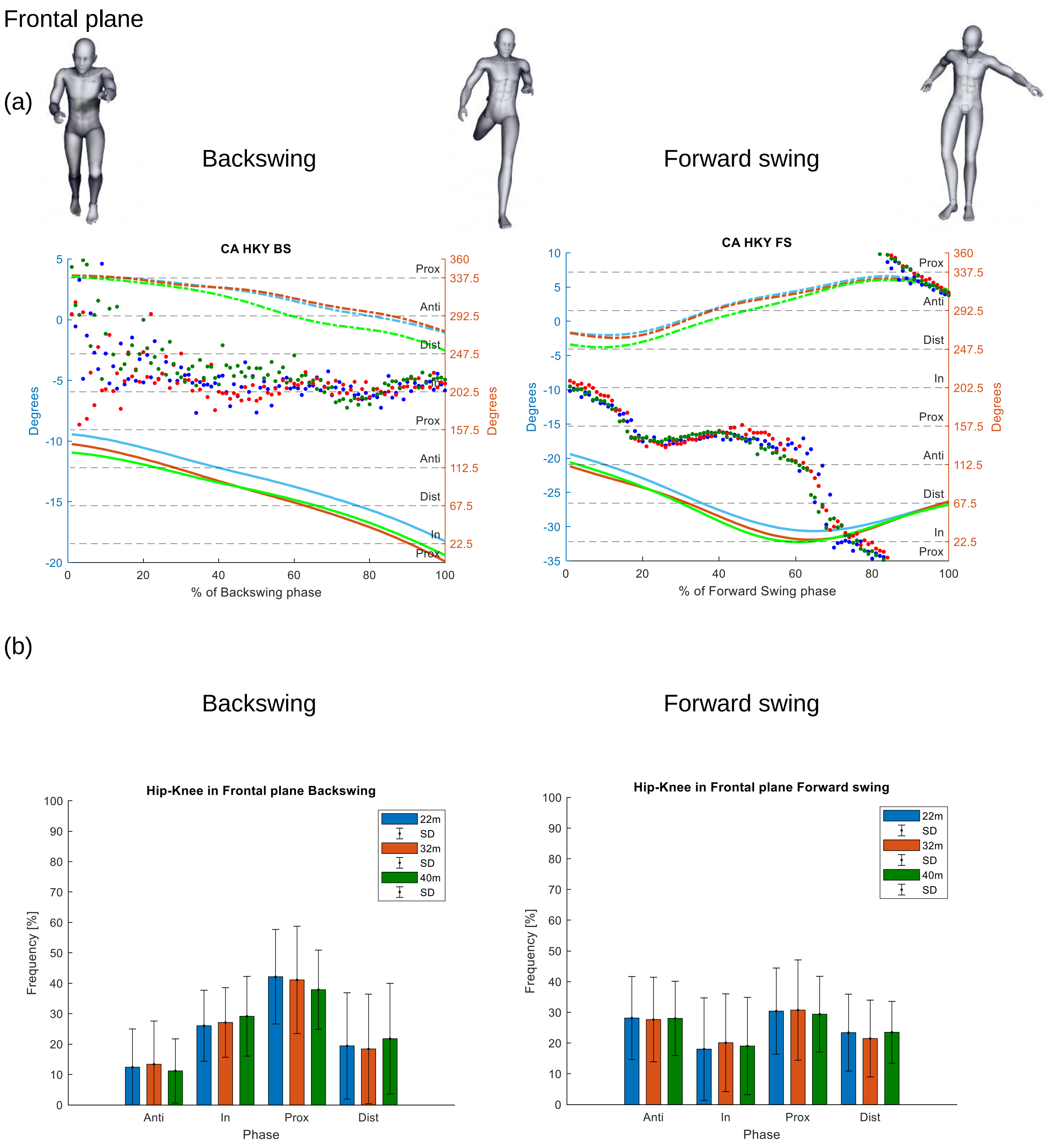


Figure 80: a) Mean *CA* of hip-knee in frontal plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for hip-knee in frontal plane during the backswing and forward swing of the kicking movement.

Transverse plane

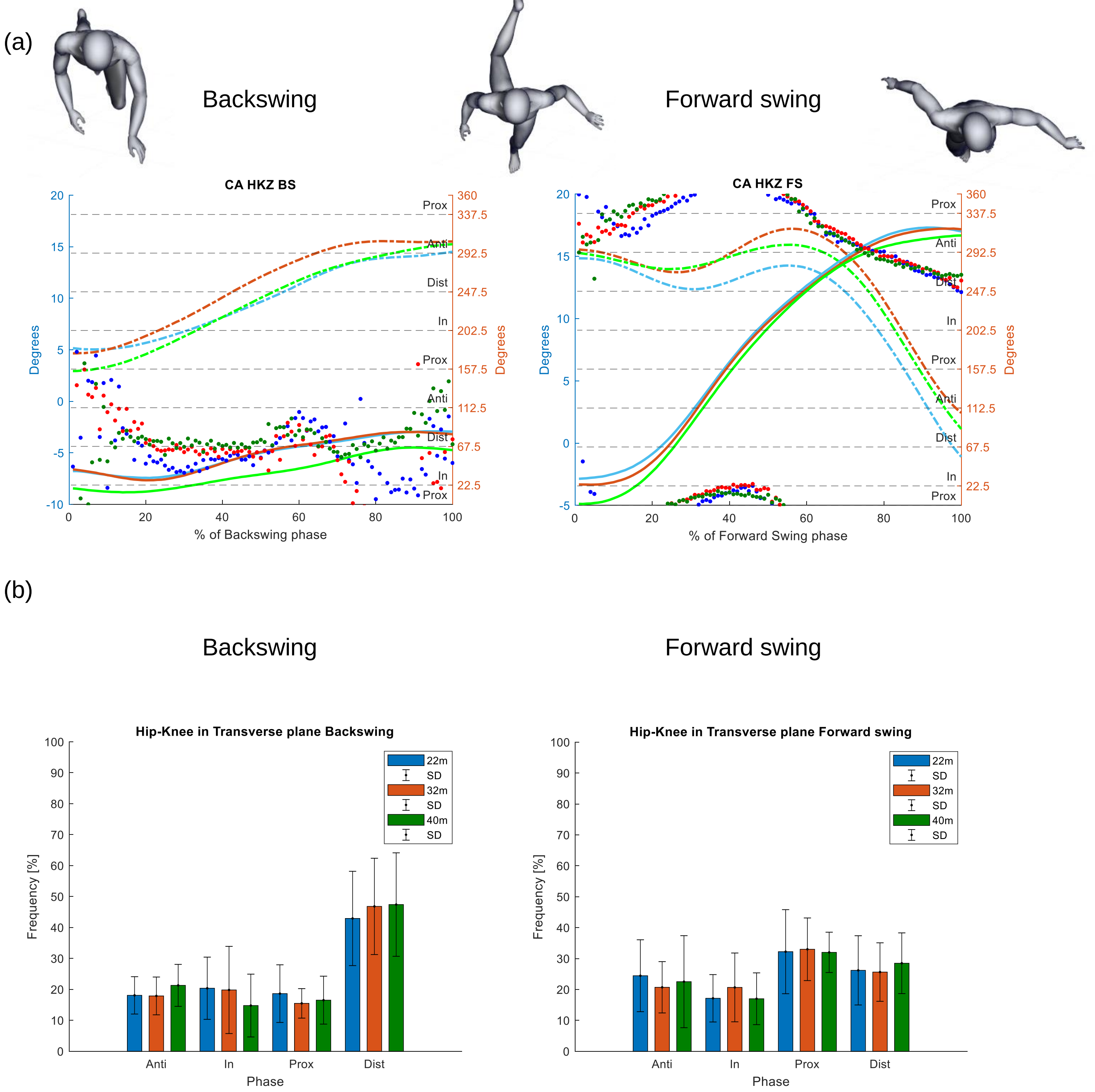


Figure 81: a) Mean *CA* of hip-knee in transverse plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for hip-knee in transverse plane during the backswing and forward swing of the kicking movement.

4.5.2 PELVIS-THORAX

In this section distal-phase indicate pelvis dominancy, while proximal refers to thorax dominancy.

Sagittal plane

During the backswing, coupling moves from thorax dominancy to in-phase. Most time was spent in the in-phase (~75%) followed by the thorax phase (~20%). During the forward swing, in-phase occurred first then moving into distal- and anti-phase. The pelvis phase and anti-phase was dominant, followed by the in-phase which was present in the beginning of the forward swing (see Figure 82). Similar trends were seen for all three groups. Successful trials represented in Figure 85.

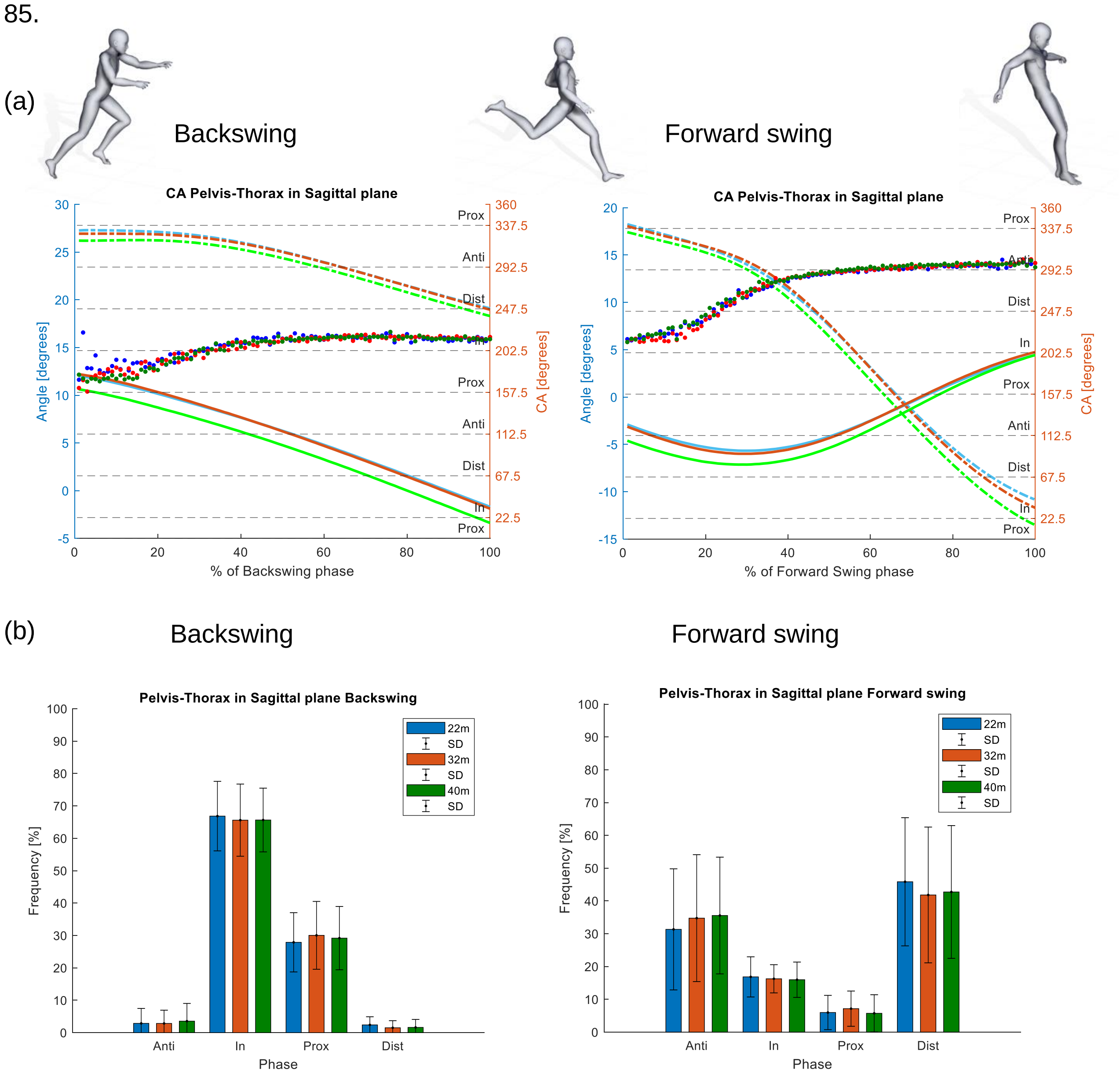


Figure 82: a) Mean *CA* of pelvis-thorax in sagittal plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for pelvis-thorax in sagittal plane during the backswing and forward swing of the kicking movement.

Frontal plane

During the backswing, coupling moves between in-phase and pelvis-phase. Most time was spent in the in-phase (~60%) and pelvis phase (~35%). During the forward swing, coupling moves from in-phase to pelvis-phase to anti-phase thereafter moving into thorax-phase just prior to ball contact. The anti-phase was the most dominant (~40%) followed by the thorax phase (~30%), while the in-phase and pelvis phase represented the least dominance (~15 to 18% each) (see Figure 83). No apparent differences between groups. Figure 86 represents the successful trials.

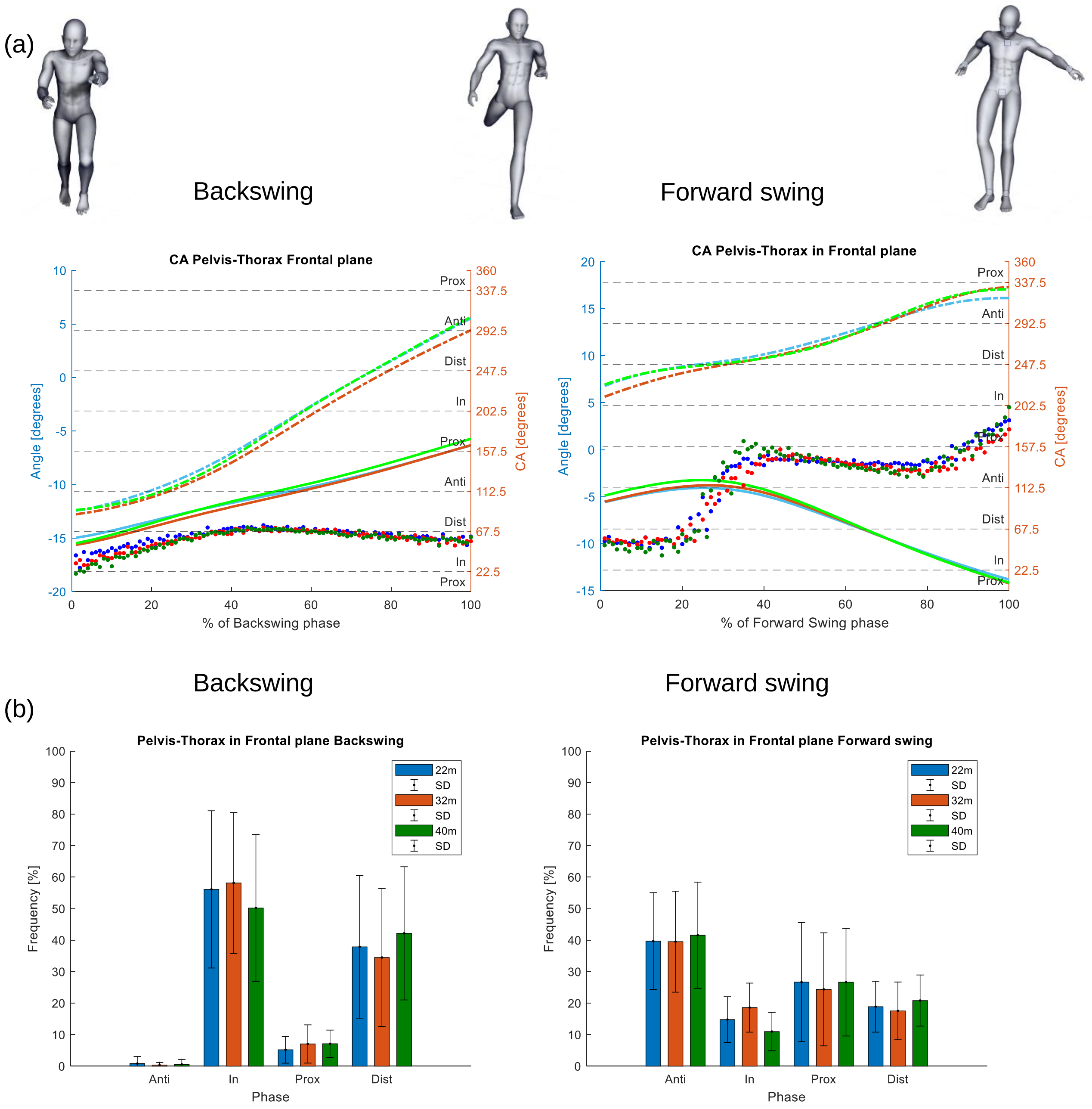
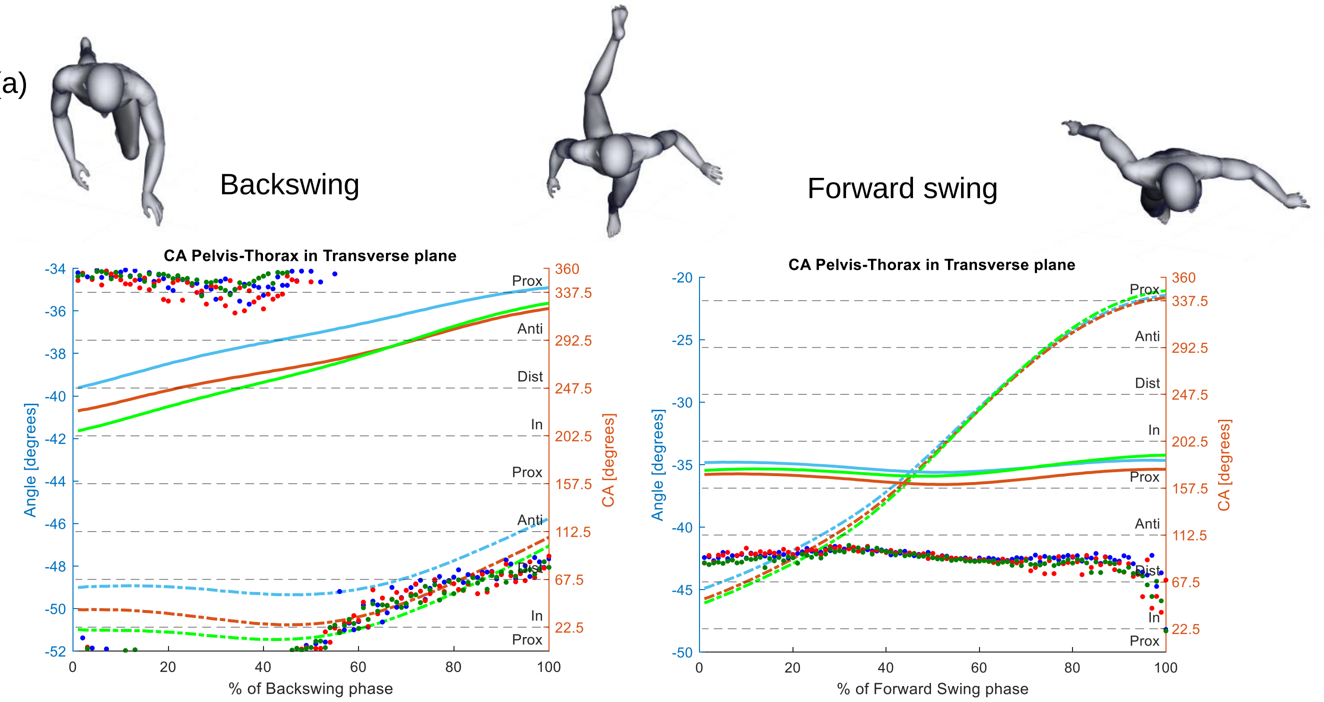


Figure 83: a) Mean CA of pelvis-thorax in frontal plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for pelvis-thorax in frontal plane during the backswing and forward swing of the kicking movement.

Transverse plane

During the backswing, coupling moves from thorax-phase and anti-phase to in-phase and pelvis-phase. Most time was spent in the thorax phase and the in-phase, followed by pelvis phase, and anti-phase. During the forward swing, the pelvis phase was the dominant coordination pattern (see Figure 84). No group differences were seen. Successful trials only represented in Figure 87.

(a)



(b)

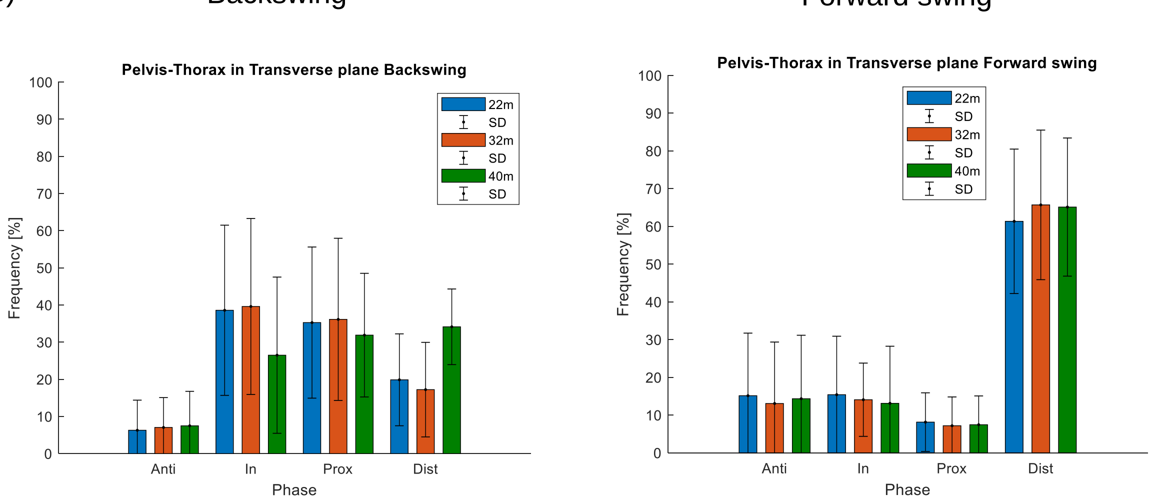
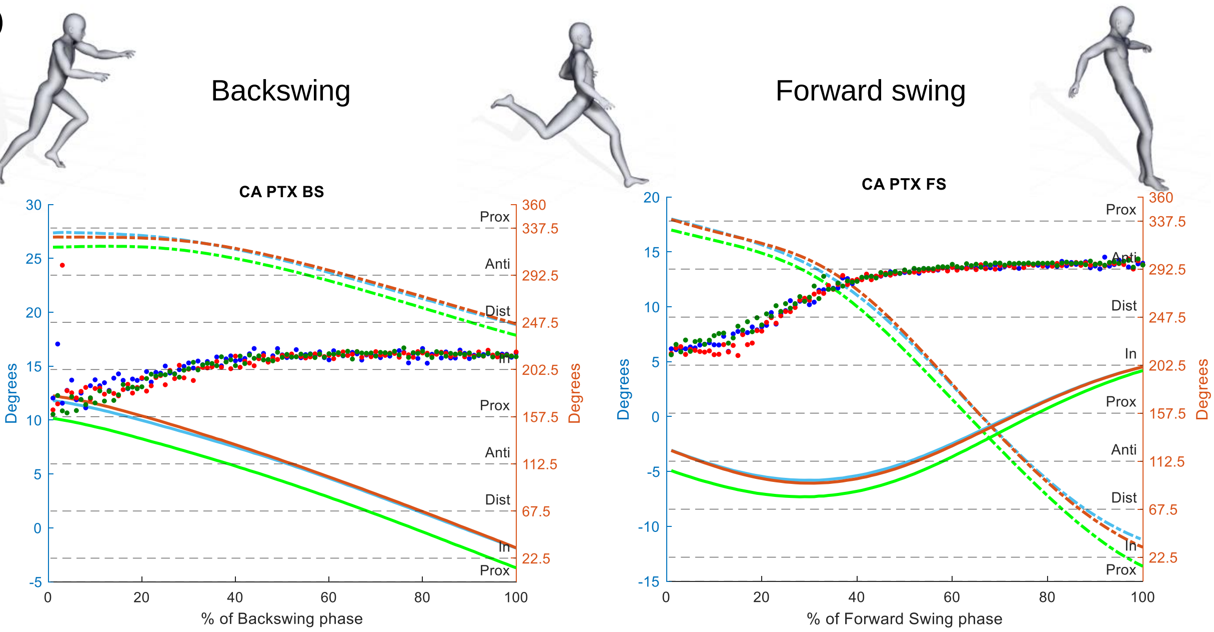


Figure 84: a) Mean CA of pelvis-thorax in transverse plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for pelvis-thorax in transverse plane during the backswing and forward swing of the kicking movement.

Successful trials

Sagittal plane

(a)



(b)

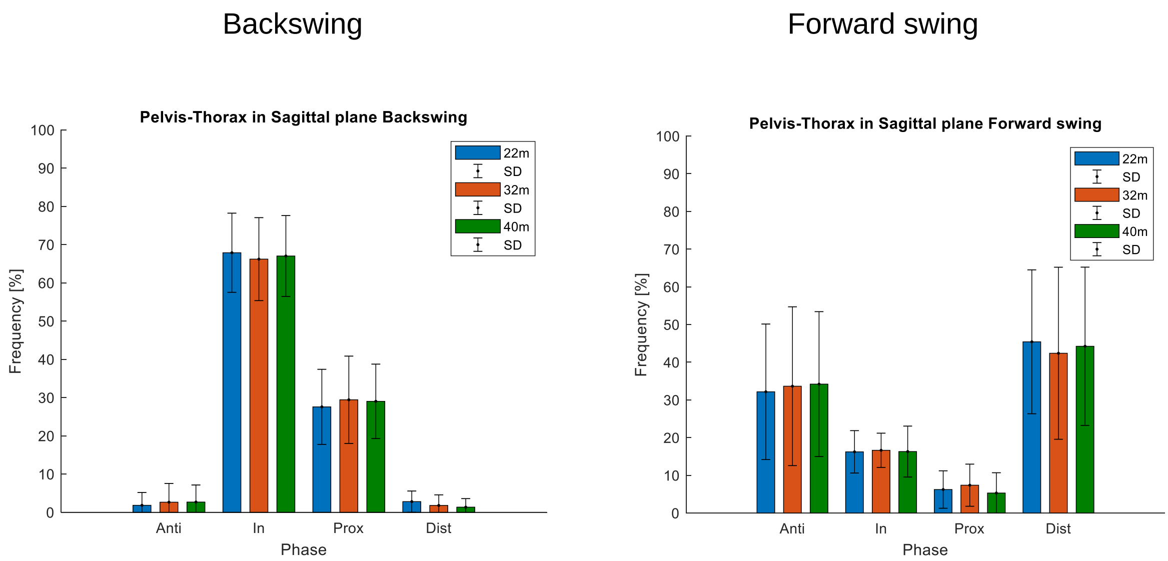


Figure 85: a) Mean *CA* of pelvis-thorax in sagittal plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for pelvis-thorax in sagittal plane during the backswing and forward swing of the kicking movement.

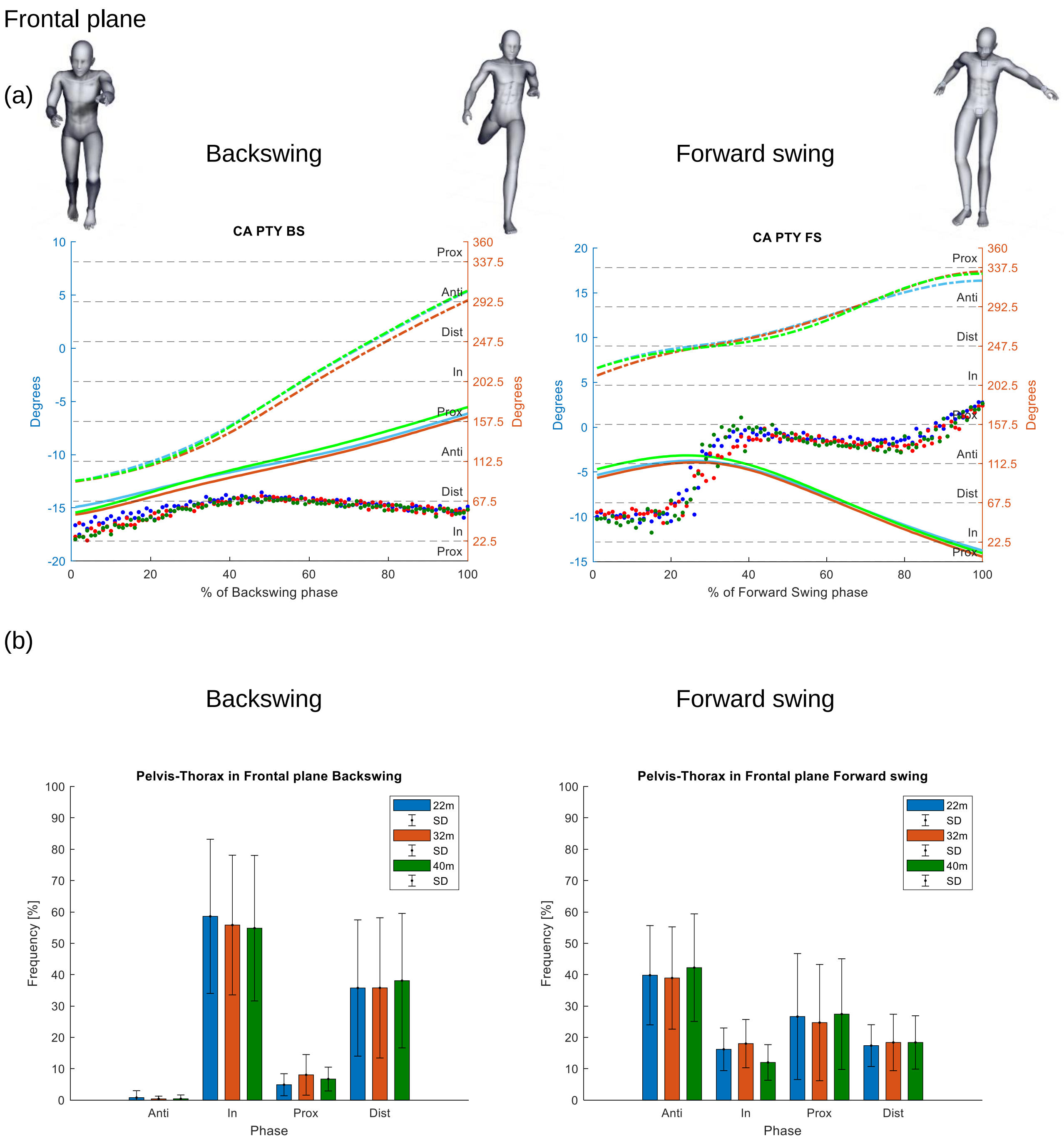


Figure 86: a) Mean CA of pelvis-thorax in frontal plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for pelvis-thorax in frontal plane during the backswing and forward swing of the kicking movement.

Transverse plane

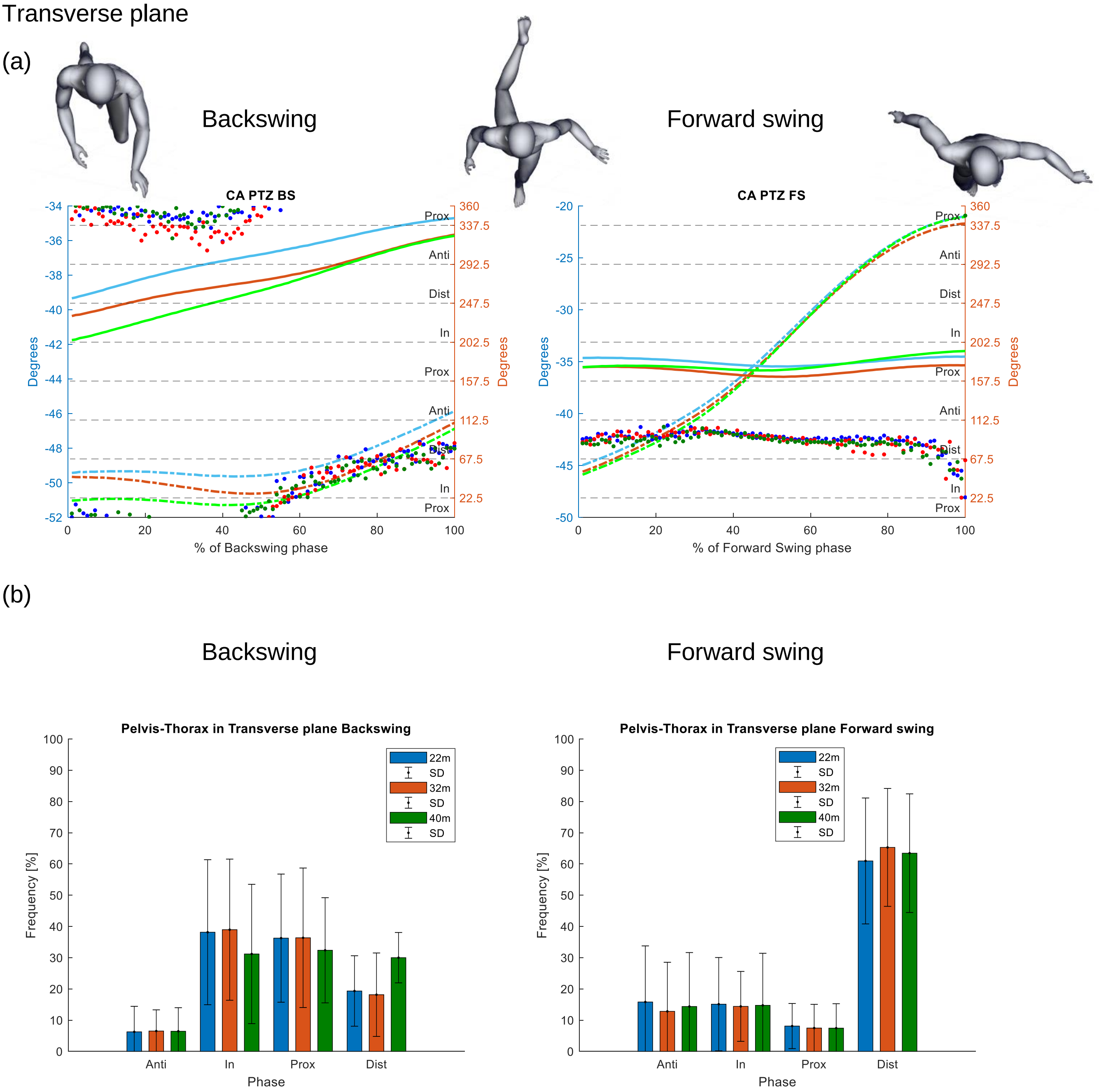


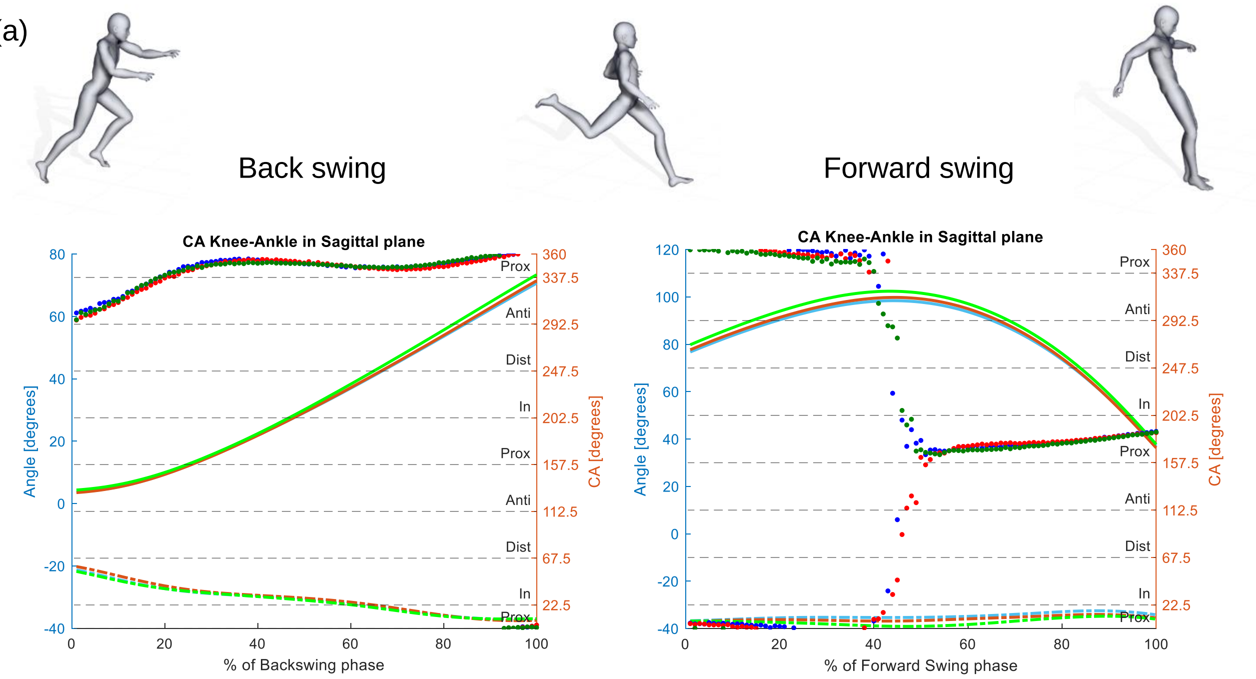
Figure 87: a) Mean CA of pelvis-thorax in transverse plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for pelvis-thorax in transverse plane during the backswing and forward swing of the kicking movement.

4.5.3 KNEE-ANKLE

Sagittal plane

The anti-phase was observed for the first part of the backswing; after that, it stayed in the knee-phase for the majority of the backswing. For the forward swing, the knee-phase was the dominant coordination pattern. No difference was found between groups (see Figure 88). Figure 89 provides the coordination patterns for the successful trials.

(a)



(b)

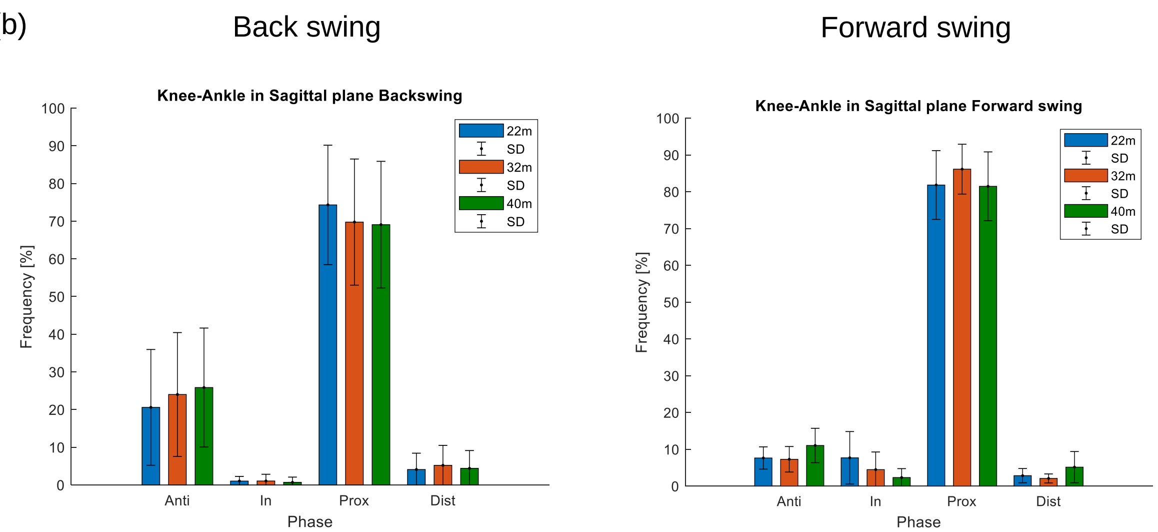
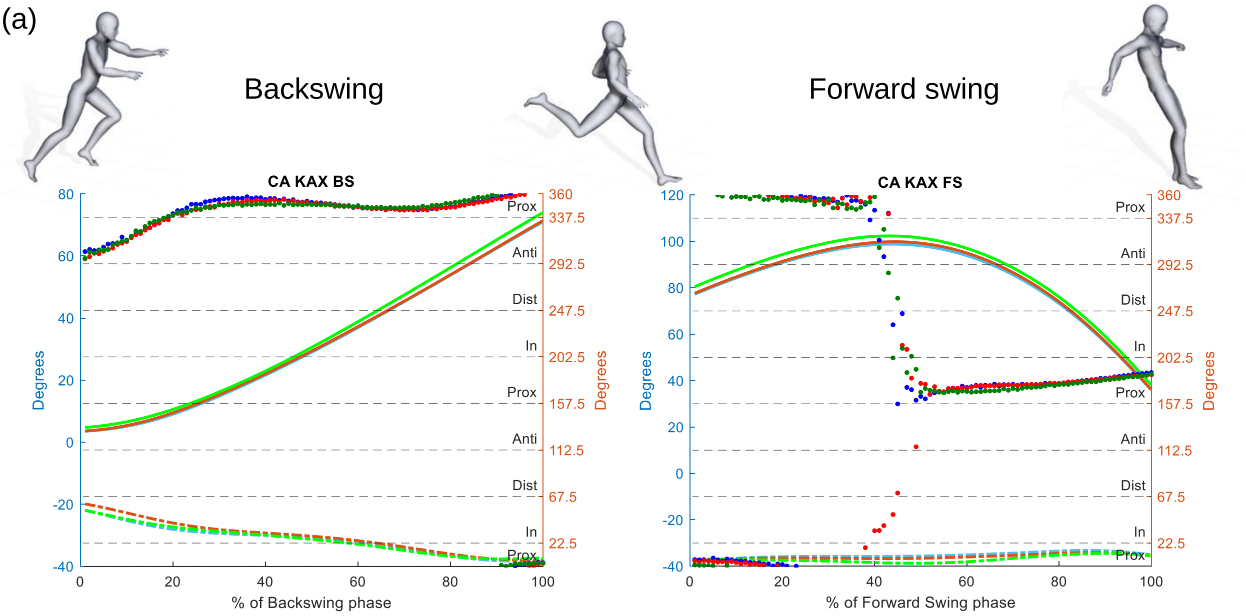


Figure 88: a) Mean *CA* of knee-ankle in sagittal plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for knee-ankle in sagittal plane during the backswing and forward swing of the kicking movement.

Successful trials

Sagittal plane

(a)



(b)

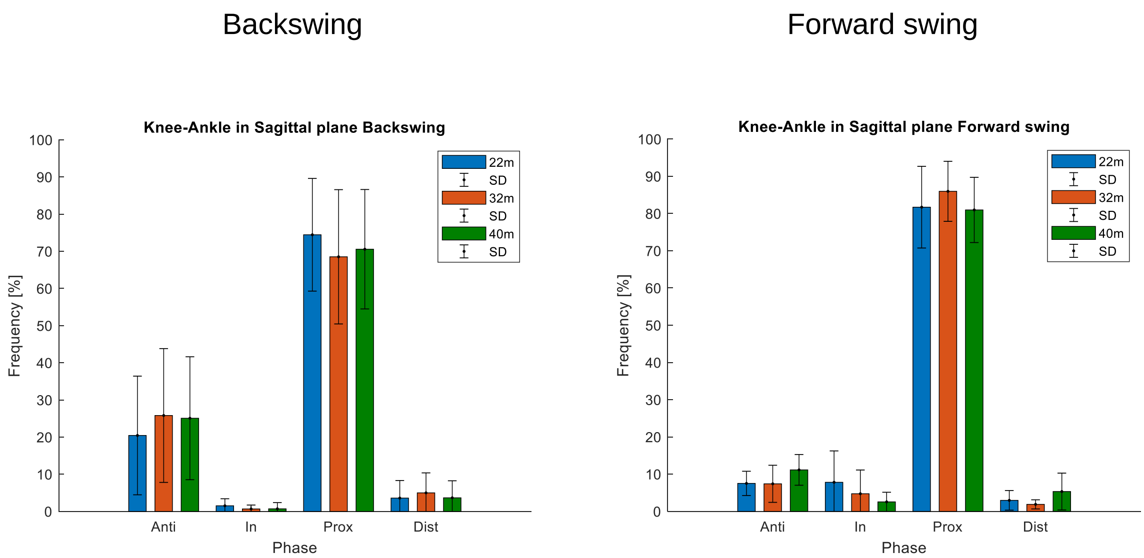


Figure 89: a) Mean *CA* of knee-ankle in sagittal plane for backswing and forward swing for 22 m, 32 m, and 40 m kicks. b) Histogram of time spent in each coupling phase for knee-ankle in sagittal plane during the backswing and forward swing of the kicking movement.

4.6 COORDINATION VARIABILITY

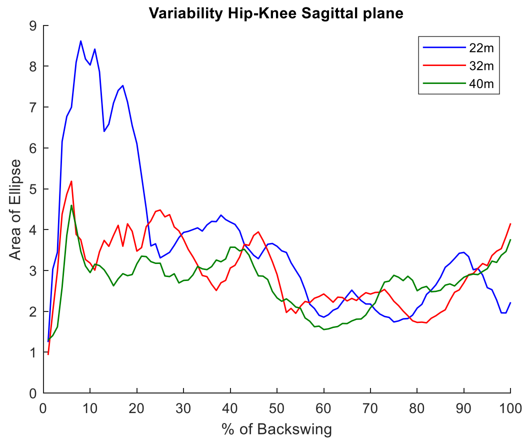
The fourth objective was to compare coordination variability in place kicks at 22 m, 32 m, and 40 m from the posts.

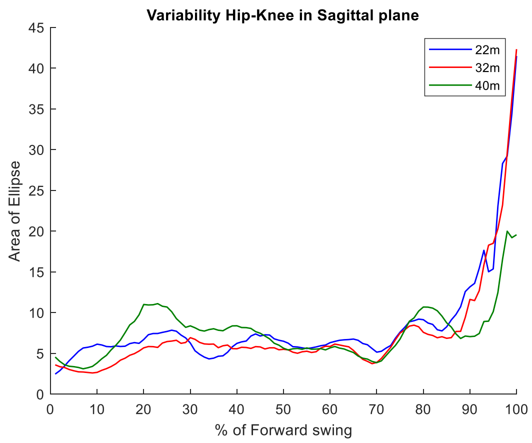
4.6.1 HIP-KNEE

For the hip-knee coupling, movement in the sagittal plane showed no significant difference between kickers for kicking from different distances from the posts (Figure 90), with the successful trials represented in Figure 91.

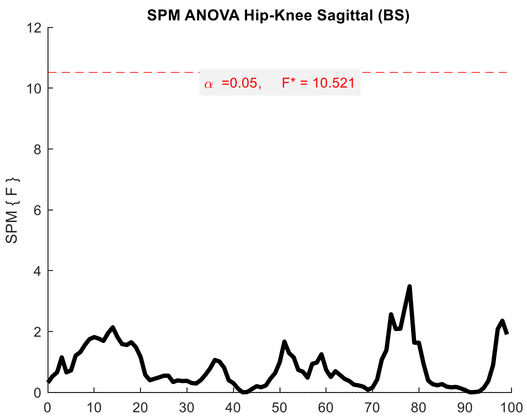
Sagittal plane

(a) Backswing Forward swing





(b) Backswing Forward swing



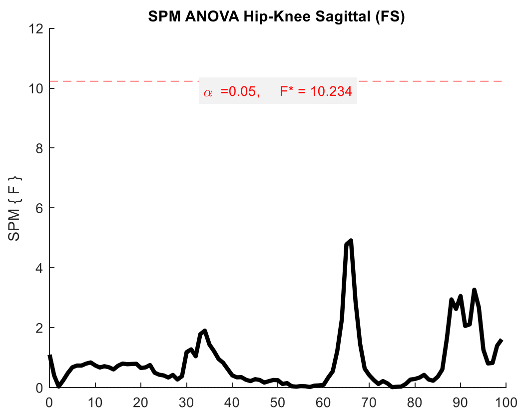


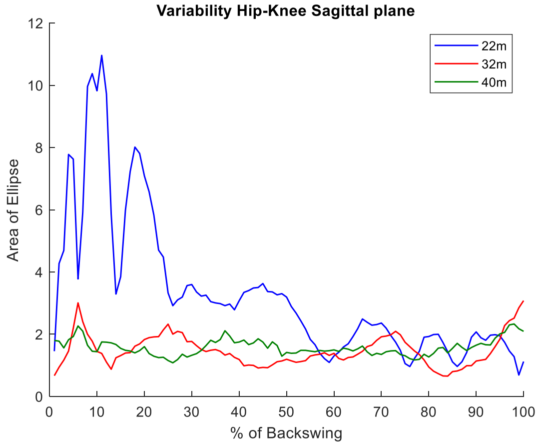
Figure 90: a) Variability curve for the hip-knee coupling in the sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 10.521 (backswing) and 10.234 (forward swing) was not exceeded.

Successful trials

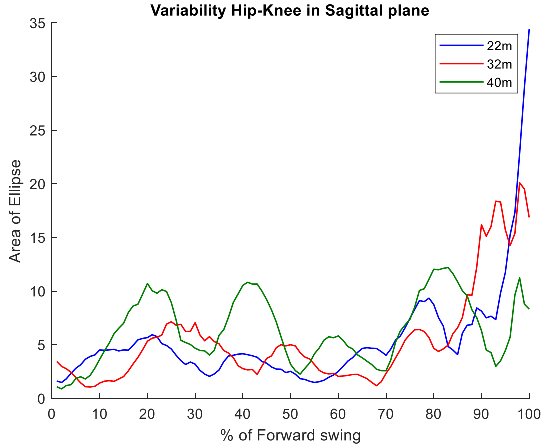
Sagittal plane

(a)

Backswing

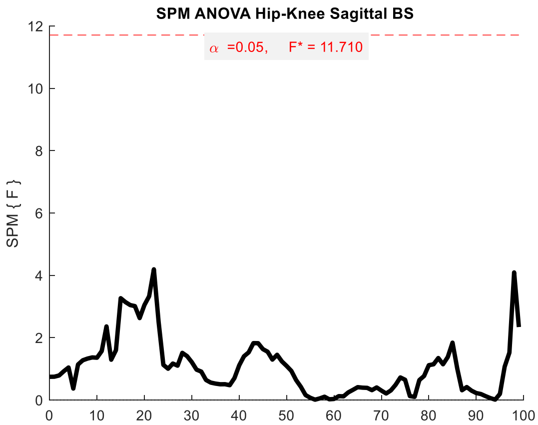


Forward swing



(b)

Backswing



Forward swing

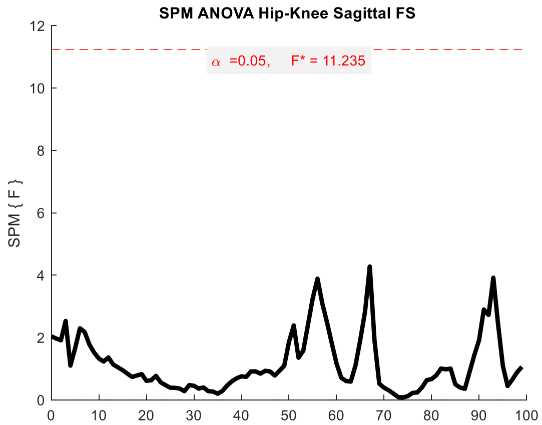


Figure 91: a) Variability curve for the hip-knee coupling in the sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 11.710 (backswing) and 11.235 (forward swing) was not exceeded.

4.6.2 PELVIS-THORAX

For the pelvis-thorax coupling, movement in the sagittal-, frontal-, and transverse plane showed no significant difference between kickers for kicking from different distances from the posts for pooled data (Figure 92 to Figure 94) and successful trials (Figure 95 to Figure 97).

Sagittal plane

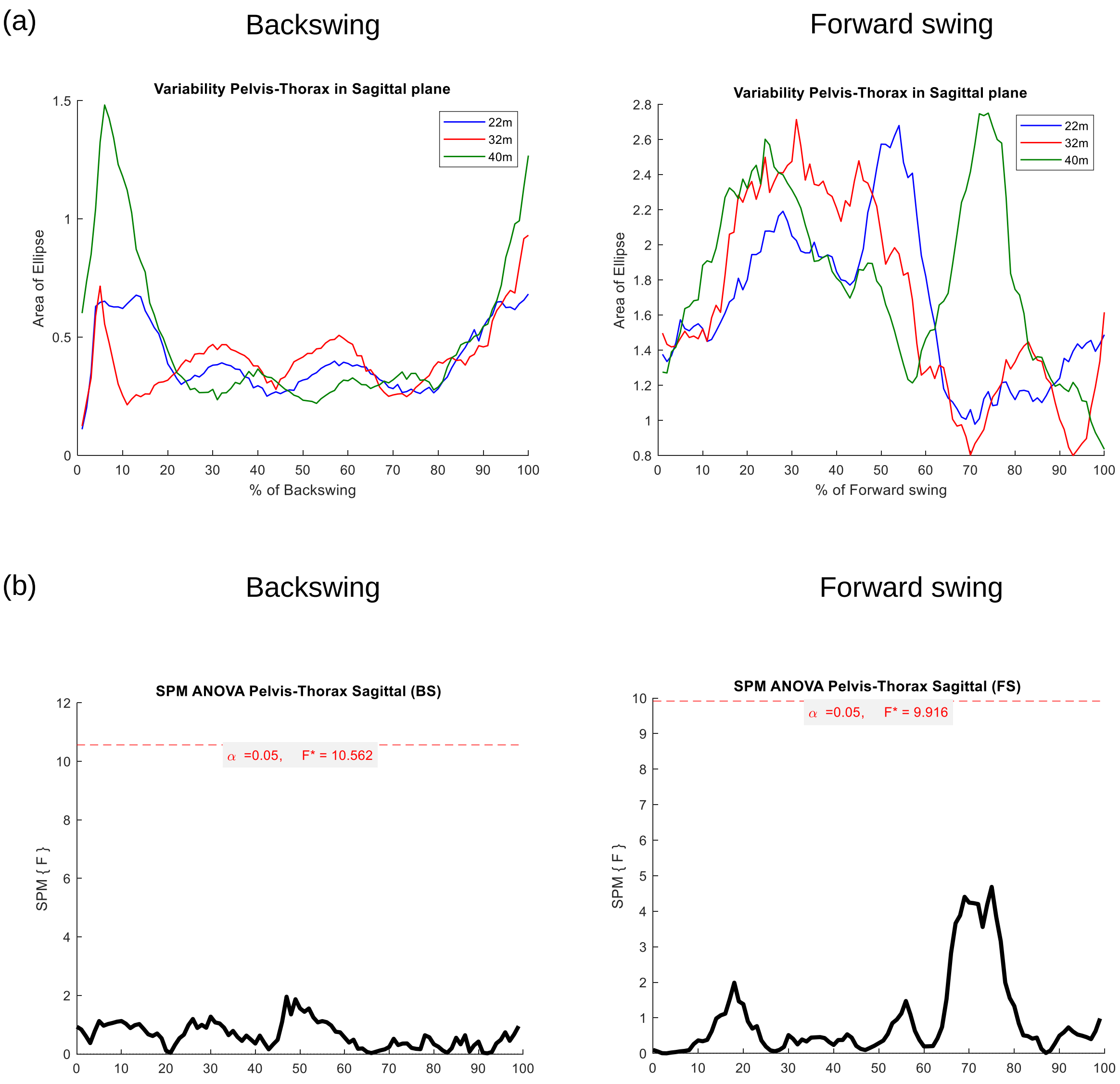
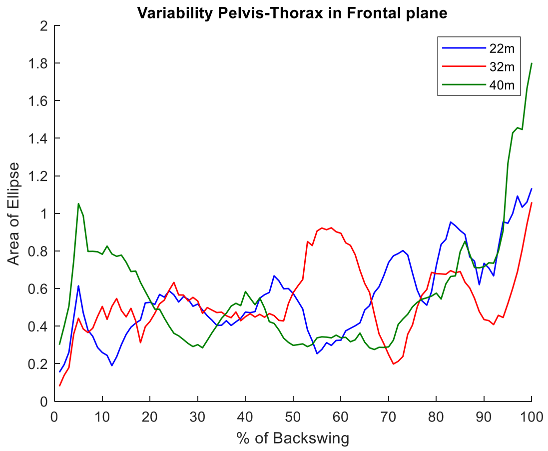
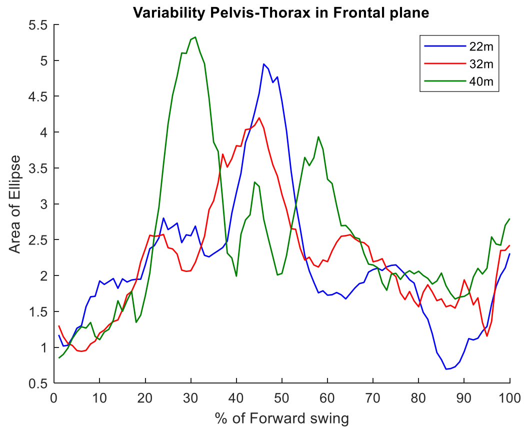


Figure 92: a) Variability curve for the pelvis-thorax coupling in the sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 10.562 (backswing) and 9.916 (forward swing) was not exceeded.

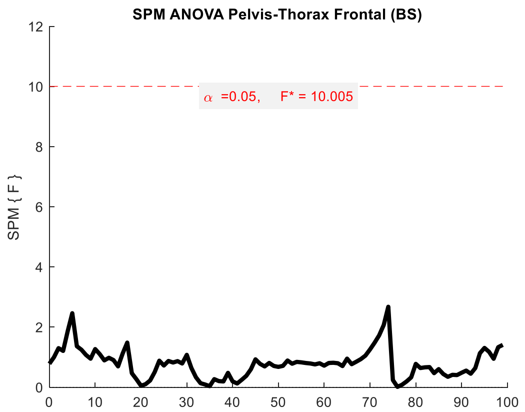
Frontal plane

(a) Backswing | Forward swing





(b) Backswing | Forward swing



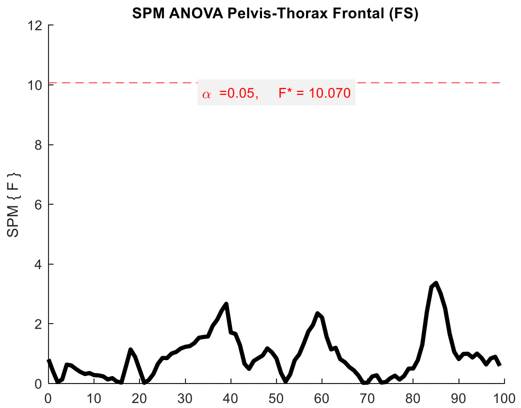
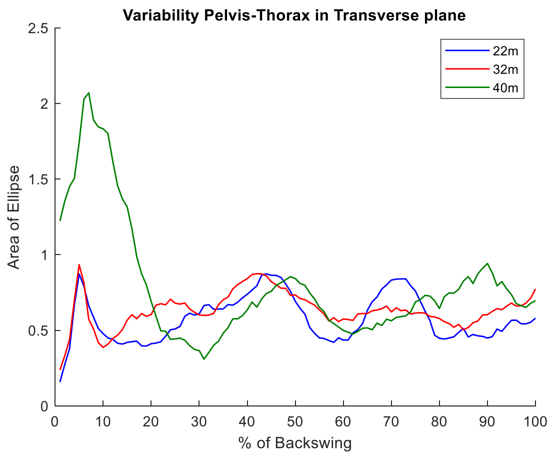
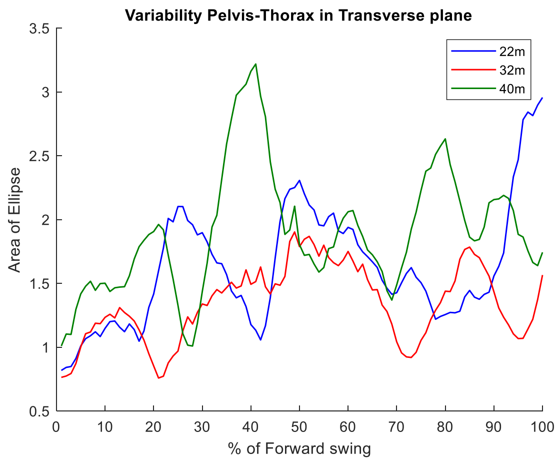


Figure 93: a) Variability curve for the pelvis-thorax coupling in the frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 10.005 (backswing) and 10.070 (forward swing) was not exceeded.

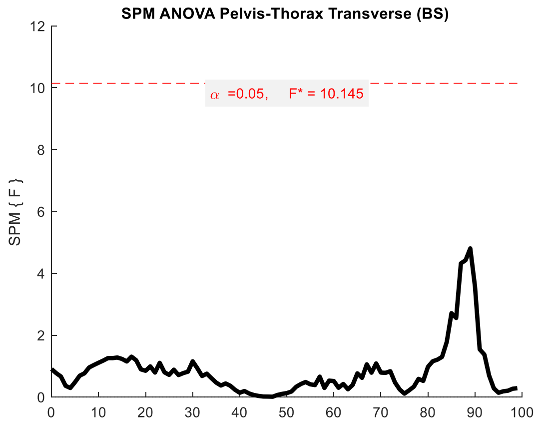
Transverse plane

(a) Backswing | Forward swing





(b) Backswing | Forward swing



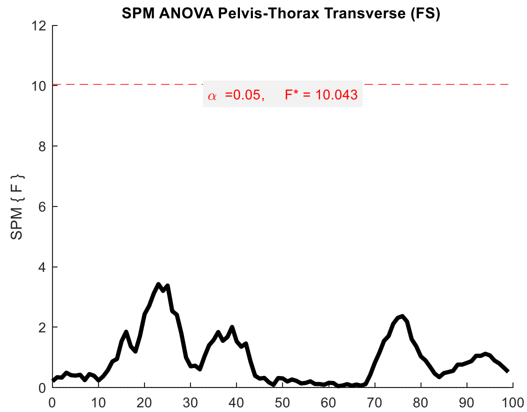


Figure 94: a) Variability curve for the pelvis-thorax coupling in the transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 10.145 (backswing) and 10.043 (forward swing) was not exceeded.

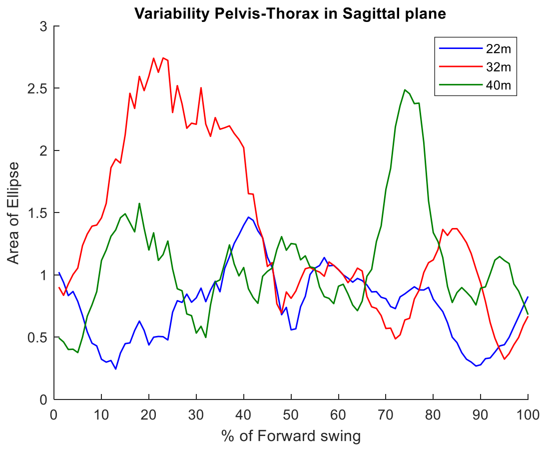
Successful trials

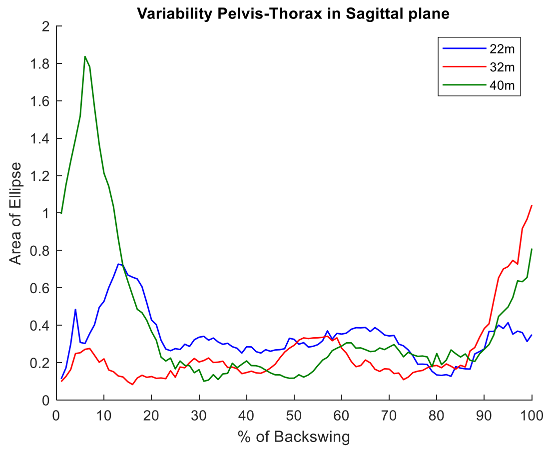
Sagittal plane

(a)

Backswing

Forward swing

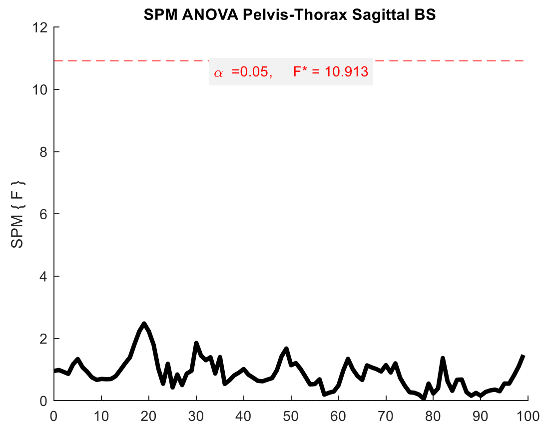




(b)

Backswing

Forward swing



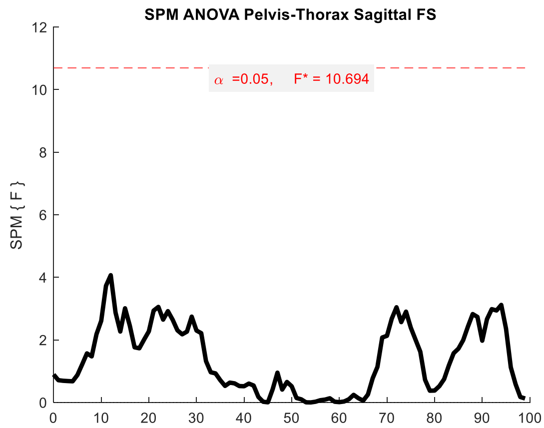
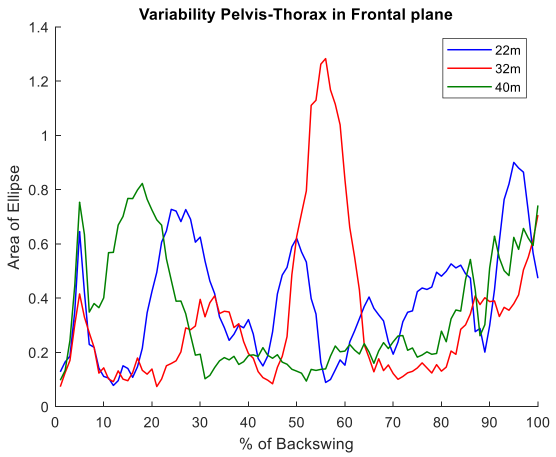


Figure 95: a) Variability curve for the pelvis-thorax coupling in the sagittal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 10.913 (backswing) and 10.694 (forward swing) was not exceeded.

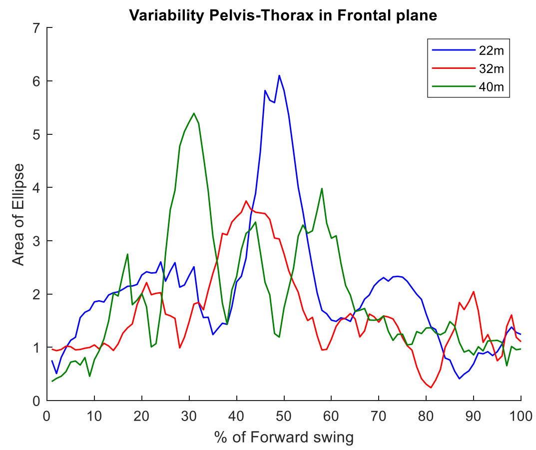
Frontal plane

(a)

Backswing

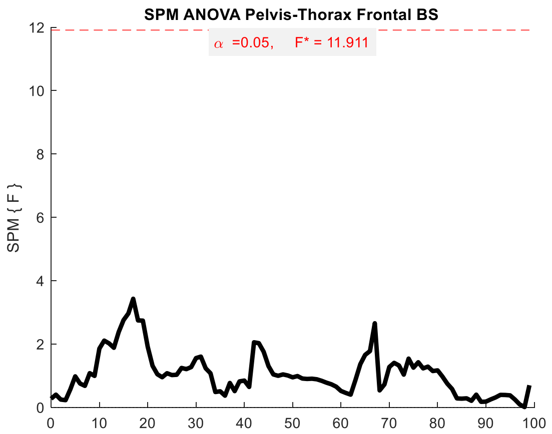


Forward swing



(b)

Backswing



Forward swing

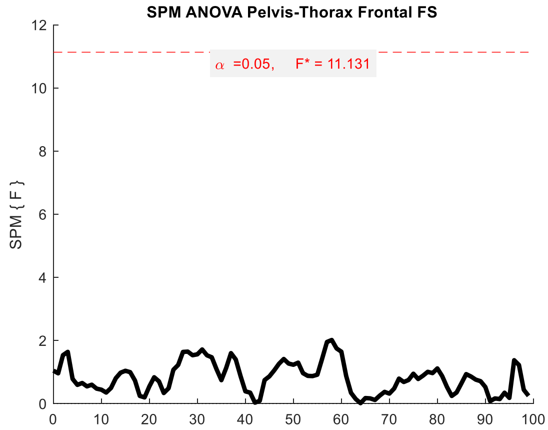
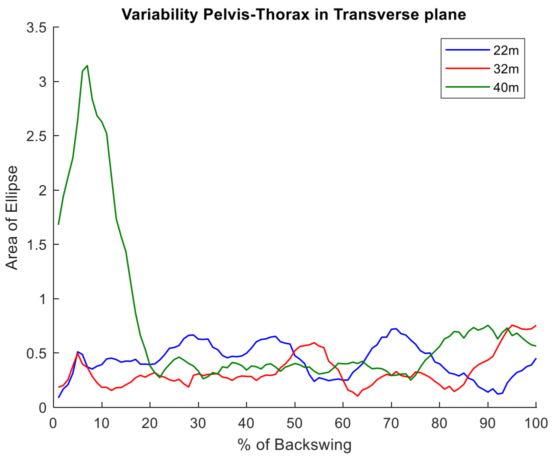


Figure 96: a) Variability curve for the pelvis-thorax coupling in the frontal plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 11.911 (backswing) and 11.131 (forward swing) was not exceeded.

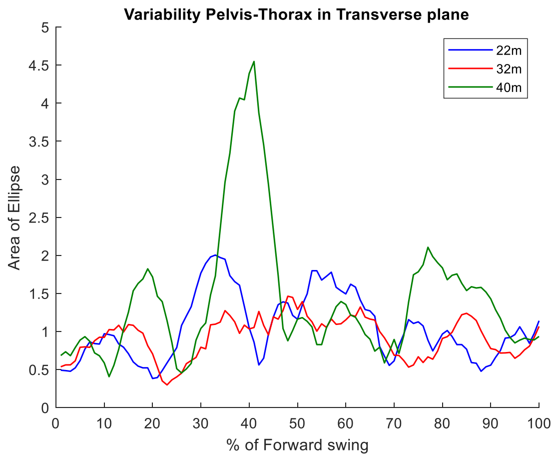
Transverse plane

(a)

Backswing

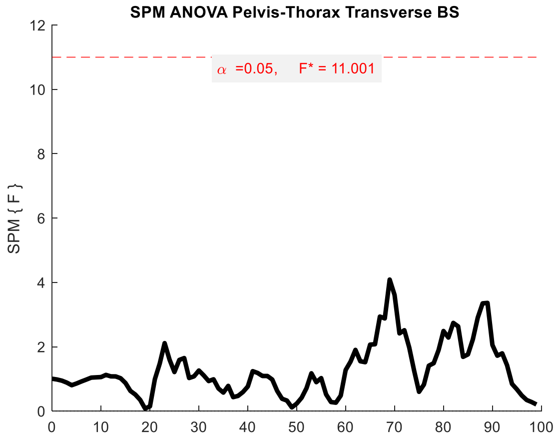


Forward swing



(b)

Backswing



Forward swing

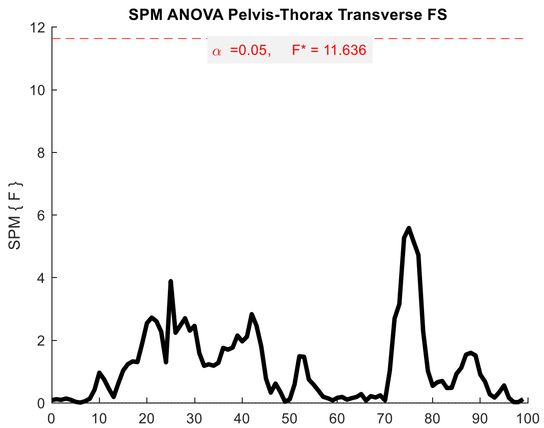


Figure 97: a) Variability curve for the pelvis-thorax coupling in the transverse plane for kicking at three different distances from posts during the backswing and forward swing. b) Repeated measures ANOVA test statistic SPM{F}. The critical threshold of 11.001 (backswing) and 11.636 (forward swing) was not exceeded.

4.7 CLUSTER ANALYSIS

From the hierarchical cluster analysis, a dendrogram was produced (Figure 98), with a two-cluster, three-cluster and five-cluster solutions presents the largest steps. Two to six cluster solutions were analysed with point-biserial correlation and the three-cluster solutions proved to be optimal consisting of one large cluster (cluster two, 18 cases, 6 kickers), and two smaller clusters (cluster one, 6 cases, 2 kickers; cluster three, 3 cases, 1 kicker) The three-cluster solution proved to be robust as both validation methods indicated excellent results (both replication and leave-one-out method presented with 100% of cases successfully reclassified).

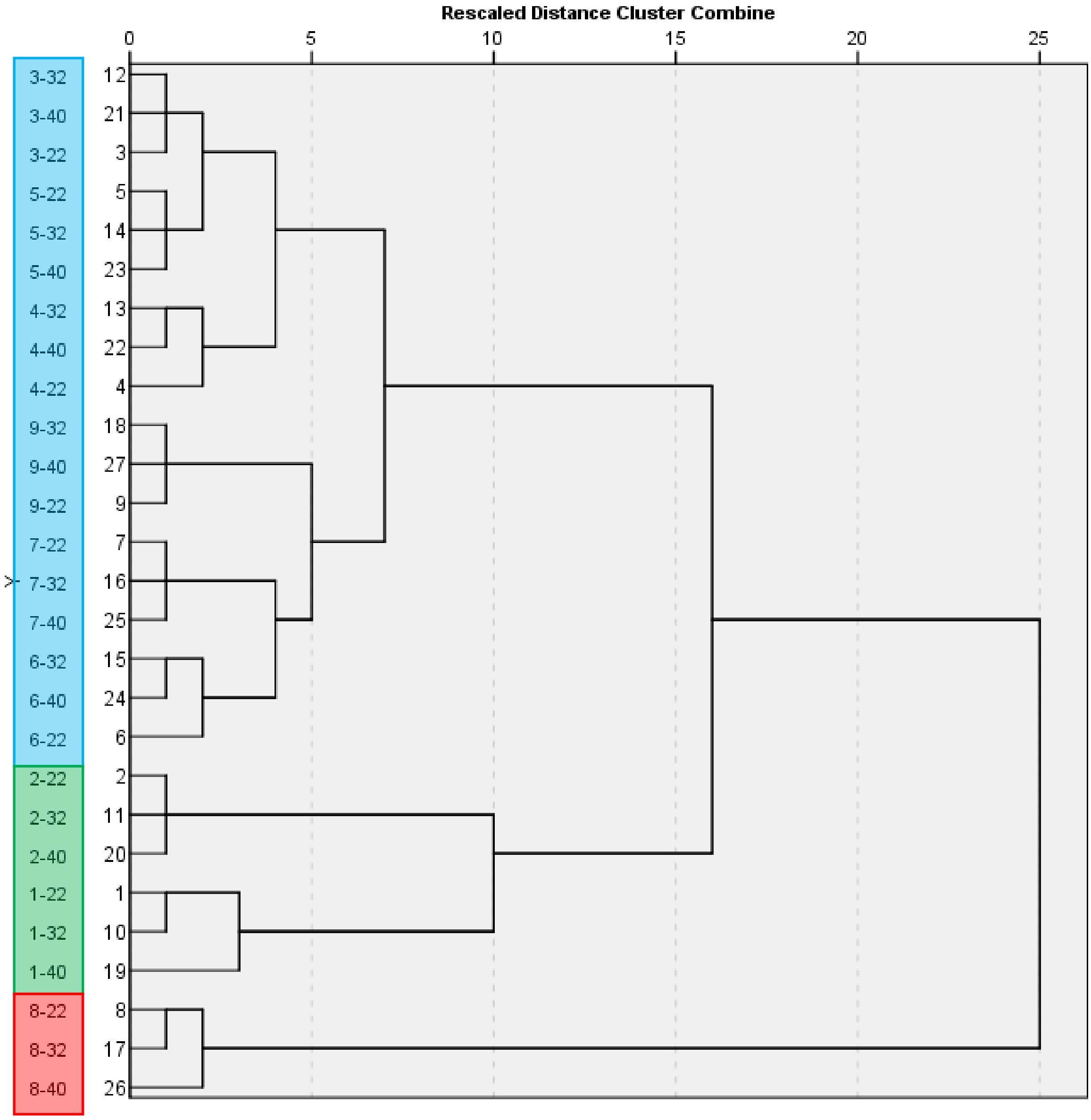


Figure 98: Dendrogram of cluster analysis using average linkage (between groups), with kicker number and kicking distance listed at the left. Green = Cluster one, Blue = Cluster two, Red = Cluster three.

One-way ANOVA indicated significant differences between clusters at p<0.05 for the hip (Figure 100) and thorax angle (Figure 101) at all forward swing events as well as the knee angle (Figure 99) at maximal knee flexion and the top of backswing, but no differences were seen in knee angle at ball contact.

Figure 99: Mean knee angle at swing events for three different clusters, TOB = knee top of backswing, MAXKF = maximal knee flexion, BC = ball contact.
⋆ Indicates statistically significant difference p<0.01

Figure 100: Mean hip angle at swing events for three different clusters, TOB = knee top of backswing, MAXKF = maximal knee flexion, BC = ball contact.
⋆ Indicates statistically significant difference p<0.01

Figure 101: Mean thorax angle at swing events for three different clusters, TOB = knee top of backswing, MAXKF = maximal knee flexion, BC = ball contact.
⋆ Indicates statistically significant difference p<0.01

One-way ANOVA indicated no significant differences between clusters for foot speed at ball contact (Table 14).

Table 14: Group mean and standard deviation of foot speed at ball contact for the three clusters

	Cluster One		Cluster Two		Cluster Three		ANOVA		
	Mean	SD	Mean	SD	Mean	SD	p	Effect size	Effect scale
Foot speed at BC (m/s)	22.3	0.8	22.9	1.1	22.7	1.0	0.45	0.65	L

Note: BC: ball contact
Effect scale L: Large

CHAPTER 5: DISCUSSION

5.1 INTRODUCTION

Place kicking has been identified as a crucial skill in the success of a rugby team. Place kicking has received some attention in research, and various variables have been identified as indicators for success; however, timing and intersegmental coordination have not been investigated in depth in rugby research. It is also unclear how a kicker manipulates their movement pattern when asked to kick at different distances from the posts.

The aim of this study was to investigate the characteristics of place kicking technique by comparing differences in the kicking technique when a kicker is instructed to kick at different distances. Differences were investigated in terms of discrete kinematic- and timing variables, continuous joint angle and velocity curves, CA, as well as coordination variability.

Based on the results of this research study, the hypothesis that there will be no significant difference in discrete kinematic variables between place kicks at 22 m, 32 m, and 40 m from the posts was accepted. However, the hypothesis that there will be no significant difference in continuous kinematic variables between place kicks at 22 m, 32 m, and 40 m from the posts was rejected.

Intersegmental coordination can objectively be investigated and quantified by means of vector coding (Li *et al.*, 2016). Studies describing the motion of the kicking leg reported on a linked-segment system. Forces acting on each segment include active muscle activity, gravitational acceleration, as well as the motion of the adjacent segments and segments further up the kinetic chain. This linked-segment system needs to be considered when describing the control of the fast motion of the kicking leg (Bezodis *et al.*, 2014). This research study is the first study that reports on movement patterns and inter-segment coordination using angle-angle plots and vector coding in rugby place kicking. The investigation included CAs of the knee-ankle-, hip-knee- and pelvis-thorax segments. It was hypothesized that there would be no significant difference in segment couplings between place kicks at 22m, 32m, and 40m, but this hypothesis was rejected.

The discussion will follow the following sequence. Firstly, the approach will be discussed in terms of length of the last step, position of planting foot and approach velocity. The approach has an impact on variables that related to increasing kicking distance. Secondly, a discussion is presented of the lower body kinematics and coupling, followed by the upper body. Coordination variability is discussed and finally an investigation into the individualised approach is presented.

5.2 APPROACH

The length of last step and planting of the support leg showed no difference between groups (three distances) in the current study, corresponding to literature indicating little variability in a group of elite kickers in the placement of the support leg next to the tee (Cockcroft & Van Den Heever, 2016). Cockcroft and Van Den Heever (2016) reported the planting of the support leg to be 33 cm (3 cm) lateral to the tee and 3 cm (7 cm) behind the tee in elite kickers compared to the current study of 38 cm (7 cm) lateral to the tee and 18 cm (13 cm) behind the tee. The current sample seems to plant their support leg further behind the ball compared to the sample of elite kickers. The laboratory-based environment and incorrect footwear used in the study of elite kickers might affect the validity of the support leg planting results. The length of the last step in the current research study was, on average, 1.59 m (0.11 m) and did not change significantly with an increase in distance. The length of the final step is consistent with a previous study on elite kickers (Cockcroft & Van Den Heever, 2016) reporting 1.53 m (0.12 m) for elite rugby kickers. The length of the last step has been identified as an important aspect of the kicking technique. As a result of a greater length of the last step, the hip is placed in an extended position, allowing a large ROM for speed generation (Ball, 2008; Cockcroft & Van Den Heever, 2016; Lees, 2002). Comparing the length of the last step in the current study with stationary kicking in soccer shows that the step length in the soccer kicks were relatively short (maximal instep kicking 0.72 m - 0.81

m; submaximal kicks 0.53 m - 0.55 m) (Lees & Nolan, 2002) compared to the rugby kicks. The researcher acknowledges that instep kicking in soccer occurs over shorter distances than the majority of rugby place kicks and therefore the approach characteristics of soccer instep kicking might not be comparable to rugby place kicking.

The maximal approach velocity had a large effect size (f=0.60), increasing with greater distance from posts. Increasing the approach velocity could have contributed to kicking foot velocity at ball contact in attempt to achieve longer ball flight time. Approach velocity increased without the kicker adding steps to their approach, indicating more explosive steps as the kicker advances towards to ball. It is evident that the length of the final step of the approach did not change, neither the position of the planting of the support leg relative to the ball for the different kicking distances. However, the approach velocity is increased for the long-range kicks indicating increased linear velocity of the body when closing in at the ball. The linear velocity could then be transferred into increased angular velocities of joints and finally increased foot speed at ball contact. In Australian football, it was reported that increased approach speed is a significant predictor of foot speed, and concluded that kickers should be coached to increase approach velocity for distance kicking (Ball, 2008).

5.3 ANGUALR VELOCITY AND JOINT ANGLE MEASURES

This research project had a foot speed at ball contact of between 22.2 (0.9) m/s and 23.3 (0.8) m/s. Literature reports the foot speed at ball contact to be between 15.1 m/s and 18.0 m/s for rugby (Atack *et al.*, 2017; Zhang *et al.*, 2012), to 14 m/s for young Australian football kickers (Blair *et al.*, 2017) and 22.4 (0.7) m/s for punt kicking in Australian football (Ball., 2013). When soccer kickers are asked to kick maximally, the foot speed at ball contact ranges from 14.87 (1.38) m/s (De Witt & Hinrichs 2012) to 23.8 m/s (Dörge, Bullandersen, Sørensen & Simonsen, 2010; Nunome, Lake, Georgakis & Stergioulas, 2006). The foot speed at ball contact is within the range reported in rugby literature, but slower than Australian football and soccer research. Both soccer and Australian league football studies reported on maximal kicks, where in the current study the kickers might not have produced a maximal kick in order to successfully pass over the crossbar. A possible explanation could be that in kicking in Australian football is drop punt kicking, and not place kicking, and is likely a different movement pattern and not comparable to rugby place kicking. Filtering methods used in the current study might affect the results around ball contact, potentially lowering the values.

Foot speed at ball contact in the current study displayed a large effect size (f=0.84) with higher speeds at the long range kicks and the lowest speed reported for the 22 m kicks. This indicates the kickers made an effort to increase the horizontal distance of the ball travel. The difference in task constraints (demands placed on the kicker) could have been sufficient to produce increase in foot speed, which should in turn increase the ball speed and distance achieved. A strong association has been described in literature linking foot speed to ball speed (Nunome, Lake, *et al.*, 2006; De Witt & Hinrichs, 2012) and to kicking distance (Ball, 2008). These findings lead to the question – how did the kickers alter their technique to achieve greater foot speed for the long-range kicks? Investigation into lower- and upper body kinematics might provide the answer.

For the kinematic curves, the results were grouped in phases from kicking leg toe-off to top of backswing, indicating the backswing. Thereafter, the forward swing took place and terminated at ball contact. For the backswing and forward swing, results are presented for the sagittal plane, frontal plane. Lower body and upper body kinematics were discussed separately in the following section.

5.3.1 LOWER BODY

5.3.1.1 KICKING LEG ANKLE KINEMATICS

The kicking leg ankle moves into plantar flexion during the backswing and remains in a relatively constant plantar-flexed position for the entire forward swing. Similarly, research into the kicking leg kinematics indicated that the ankle is in plantar flexion for the majority of the movement (Atack *et al.*, 2014). Foot progression angle indicated between 50 and 52 degrees of external rotation of the foot just prior to ball contact. The foot is in a plantar flexed externally rotated position at ball contact.

5.3.1.2 KICKING LEG KNEE KINEMATICS

The knee undergoes flexion during the backswing and continues to flex during the forward swing. Maximal knee flexion of 101.0º (7.5º) occurred at around 40 per cent to 50 per cent of the forward swing, then rapidly extended as it approached ball contact. Corresponding to the findings of the current study, previous literature reports on knee flexion during the backswing, continuing to roughly 50% of the forward swing, followed by rapid knee extension (Atack *et al.*, 2014).

Knee flexion/extension ROM was 72.9º (12.4º) for the knee, with no significant differences between groups. Higher knee flexion/extension ROM is found in soccer instep kicking research with a ROM of 80º (10º) to 108º (8º) (Shan & Westerhoff, 2005). Other soccer kicking of a stationary ball found knee a ROM of 64.7º (13.1º) for less experienced kickers and 74.2º (12.6º) for experienced kickers (Egan *et al.*, 2007) was found. Compared to the current study more maximal knee flexion was found in young Australian football players (12-year-olds), reaching an average of 123º (Blair, Grant, Robertson & Ball, 2017). This might indicate that young players are more flexible. The results of the current study was more in line with rugby place kickers at university level reporting peak knee flexion angle of 103.2º (7.5º) (Sinclair *et al.*, 2014). It is plausible that it takes skill and conditioning to kick with a large instep and big ROM in an accurate manner.

The knee was not fully locked at maximal knee extension at ball contact but was in 21.7º (8.3º) flexion for kicking from various distances (22 m, 32 m, and 40 m) at the posts. A knee angle at ball contact of 32.1º (13.6º) has been reported in other research investigating rugby kicking in a university level sample (Sinclair *et al.*, 2014). Kicking leg knee angle at ball contact can be slightly flexed in attempt to control the foot-ball interaction. It should also be considered that the values reported around ball contact in the current study might be slightly lower compared to other studies as a result of filtering through ball contact, which can be a limitation in the current study.

When assessing the knee angle curves, the 32 m- and 22 m kicks displayed no statistically significant difference. These kicks were likely submaximal kicks as the kickers were able to achieve the distance, therefore, the same movement pattern was executed. However, the 40 m kicks (representing a long-range kick) had significantly greater knee flexion for the first 70 per cent of the forward swing. The knee stayed more flexed for longer during the forward swing for the 40 m kicks compared to the 22 m and 32 m kicks. Kickers were possibly trying to add more knee flexion range for increased angular velocity. Increased knee flexion produces greater pre-stretch in the thigh muscles potentially leading to greater foot speed at ball contact due to the stretch-shortening cycle. However, for the last bit of the forward swing, the knee angle in the sagittal plane was consistent across all three distances. Likely, at the end of the forward swing, the knee was moving towards an extended position, and kickers ensured the natural knee position before ball contact. The increased knee angle for the 40 m kicks increase the distance through which the foot is moved during the forward swing, allowing more work as force can be applied over a greater distance (work = force x distance) resulting in greater foot velocity.

As expected, little movement of the knee in the frontal plane was found with an overall movement of less than 8º, which is in line with research reporting that the kicking leg should ideally have minimal movement in the mediolateral direction (Bezodis *et al.*, 2007). The transverse plane knee angle also displayed a ROM of about 10º, slightly lower than findings in soccer research reporting a knee rotation ROM of 22º (4º) to 12º (3º) (Shan & Westerhoff, 2005). The investigation by Shan and Westerhof *et al.* (2005) had less leg markers compared to the current research study. The influence of the soft-tissue artifact such as muscle or skin movement can be a source of measurement error with the Plug-in-Gait marker set, especially with high amounts of knee flexion and rapid extension. Proximal placement of lateral thigh markers has been shown to reduce the amount of soft-tissue artifact (Cockcroft, Louw & Baker, 2016). It is also crucial to ensure correct marker placement to avoid misalignment and increased measurement error (Cockcroft *et al.*, 2016).

Peak kicking leg knee extension angular velocity increase with greater distance kicked for the forward swing near ball contact. The 22 m kicks had the lowest, while the 40 m greatest knee extension velocity. The kicking leg knee extension has been identified as the most critical factor influencing the foot velocity at ball contact (De Witt & Hinrichs, 2012) to achieve greater ball speed, and therefore kicking distance (Sinclair *et al.*, 2014). In the current study, an increased knee angle in the sagittal plane at the beginning of the forward swing could allow for the increased angular velocity at the end of the forward swing.

Maximal knee extension velocity in the current study was 2159 (196) deg/s, which is higher than results from a sample of 20 university-level kickers, where knee velocity at ball contact of 1768 (207.33) deg/s was reported (Sinclair *et al.*, 2014). Higher knee extension velocities in the current study might be as a result of the total distance travelled of the ball. Sinclair *et al.* (2014), instructed the participants to kick into a net eight meters away from the kicker in a laboratory, affecting the ecological validity of the study. A strength of the current study may lie in the simulation of a true kicking environment. Similar findings (and in some cases lower values) are seen in shank peak angular velocity is soccer kicking with 1610 to 2258 deg/s (Nunome, Ikegami, *et al.*, 2006; Nunome *et al.*, 2018). Zhang *et al*., (2012) emphasised the importance of rapid knee extension as the knee flexion/extension velocity was the main contributor to foot speed at ball contact. Other studies confirmed that knee extension velocity is the main contributor to foot velocity at ball contact (Sinclair *et al.*, 2014).

In addition to knee extension velocity, foot velocity at ball contact is influenced by the motion of the proximal segments. However, at the instance of ball contact, the contribution of the proximal segments has been reported to be negligible. Time-histories indicated that proximal segment provides a substantial contribution to foot speed. (Atack *et al.*, 2014; Bezodis & Winter, 2014; Zhang *et al.*, 2012). Therefore, the hip, pelvis and thorax mechanics were also investigated in this research study.

5.3.1.3 KICKING LEG HIP KINEMATICS

In the frontal plane, abduction of the hip stayed between 10º and 30º for the entire backswing and forward swing phase. Transverse plane hip motion also stayed constant between 5º and 7º of external rotation during the backswing. The hip then rotated to 15º internal rotation during the forward swing.

In the sagittal plane, the hip was more extended for the most part of the backswing during the 40 m kicks, compared to the 22 m and 32 m kicks, but the hip angles were very similar for the forward swing. It is likely that the thigh motion is the same for all the kicks, while the trunk is leaning more backward during the backswing for the 40 m kicks, tilting the pelvis in such a way to produce hip extension. The larger hip extension values in the backswing may indicate more hip involvement for maximal kicks during the backswing. It could be a power strategy in attempt to achieve a greater backswing, creating a larger ROM and thereby greater resultant foot velocity. The findings support the theory of improving the tension arc formation and pre-stretch in muscles for long-range kicks. In adult professional soccer club players kicking at maximal and submaximal intensities, increased hip extension during the backswing is reported, which points to an improved tension arc, as well as an increased pre-stretch for the stretch-shortening cycle and energy storage (Langhout *et al.*, 2017). These statements are supported by Australian football research, suggesting that the hip might be a major area of force generation in maximal kicking (Dichiera, Webster, Kuilboer, Morris, Bach & Feller, 2006).

Similar to sagittal plane hip motion, the current research study found a difference in the hip angle in the transverse plane for the 40 m kicks compared to the 32 m and 22 m kicks during the backswing. The X-factor stretch refers to the difference between the thorax and pelvis rotation angles (Chu, Sell & Lephart, 2010; Green *et al.*, 2016). Greater X-factor angle indicated greater difference between two segments. Greater hip external rotation during the backswing might relate to the X-factor stretch, as the thorax is likely more externally rotated (with the kicking side in front, thorax facing towards the right of the posts) and this is affecting the hip angle through changes in the pelvic orientation. However, the significant difference in the hip rotation was not sustained for the entire backswing.

The increased hip extension and external rotation during the backswing aid in tension arc formation, creating a pre-stretch across body, which aids generating kicking foot velocity at ball contact, by means of the stretch-shortening cycle. However, it has been reported that while tension arc parameters correlate positively with kicking distance, kicking accuracy might decrease (Atack *et al.*, 2017; Green *et al.*, 2016). The current study supports previous finding by showing that the kicking success rate in this research study decreased by 12 per cent for the long range kicks (40 m), compared to the 32 m kicks, and 23 per cent compared to the 22 m kicks. In the frontal plane a trend was observed towards less hip abduction for the 22 m kicks compared to the 32 m and 40 m kicks, possibly related to the focus on accuracy. Less hip abduction might indicate kickers placing a focus on accuracy for the short-range kicks. However, more research is needed to confirm these findings.

Absolute peak hip velocity in the current study was 782 (133) deg/s, with no significant difference between kicking distances. Peak hip velocity results are in the range reported in literature 499.36 (118.18) deg/s to 1048.5 (86.0) deg/s (Nunome, Ikegami, *et al.*, 2006; Nunome *et al.*, 2018; Sinclair *et al.*, 2014). When analysing the angular velocity curve, a trend towards increased hip flexion velocity early in the forward swing suggests a hip strategy might be used for the 40 m kicks. Increased hip extension angle for the 40 m kicks, provides the potential for greater hip flexion velocity as it moves over a greater range of motion. More force provided over a greater distance will increase the work done and in turn transfer to increased foot velocity with the summation of speed method (Putnam, 1993). Zero velocity of the hip and pelvis at ball contact is reported in the literature, indicating that a stable position aids in the control of movement for desired ball contact (Langhout *et al.*, 2015; Lees *et al.*, 2010; Shan & Westerhoff, 2005). Similarly, the current study found the hip in the sagittal plane and the pelvis in the frontal and transverse plane, to have a velocity near zero at ball contact.

In this research study, the knee displayed some significant differences in flexion/extension velocity measures when kicking at different distances from the posts. In soccer literature, more significant differences were seen when a kicker was asked to kick at different intensities. A possible explanation would be that rugby kickers are coached to keep their kicking movement pattern as consistent as possible (Linthorne & Stokes, 2014), whereas in soccer, the kicker needs to rely heavily on controlling the ball and, will be required to kick at various distances during a match. It could also be speculated that the 40 m kicks were not challenging enough to represent a maximal kick, and possibly if the kickers were asked to kick at 50 m from the posts, bigger differences would be seen.

In order to achieve greater foot speed for the long-range kicks, greater knee flexion, hip extension and hip external rotation is present in the lower body kinematics. These factors relate to a larger kicking leg ROM as well as improved tension arc formation translating into increased foot velocity at 40 m kicks.

After describing the knee and hip variables in isolation, it is also of importance to discuss the hip-knee interaction. In Australian football, greater knee ROM at the preferred leg was reported compared to the non-preferred leg, whereas the non-preferred leg had a greater hip ROM compared to the preferred leg (Falloon *et al.*, 2010). These findings indicate different strategies used and could be related to a knee-dominant and a hip-dominant strategy reported in rugby kicking research (Atack *et al.*, 2019; Ball, 2008). No individual differences were investigated in the current study, therefore, no separation of data based on a knee-dominant and hip-dominant movement pattern was considered. The current sample could consist of a variety of kicking techniques. Possibly, in future research, individual differences could be accounted for.

A proximal-to-distal sequencing pattern is reported where the movement starts at the proximal segment, segments then interact and transfer momentum to the kicking foot (Putnam, 1993).The hip reaches a peak velocity first, then knee peak velocity is reached just before ball contact to increase the foot speed at ball contact. By increasing the velocity of the proximal segments, distal endpoint velocity should increase (De Witt & Hinrichs, 2012). In the current study, peak hip flexion velocity occurs at 40 per cent of the forward swing, while peak knee extension velocity occurs just before ball contact (99 per cent of the forward swing). Hip extension velocity occurring prior to peak knee extension velocity indicates the proximal-to-distal sequencing pattern frequently reported on in literature (Atack *et al.*, 2014; Bezodis & Winter, 2014; Naito *et al.*, 2010; Nunome *et al.*, 2018; Putnam, 1993; Southard, 2014; Zhang *et al.*, 2012). The current findings are consistent with previous research, rapid thigh forward rotation followed by rapid shank forward rotation points to a prominent proximal-to-distal sequence (Atack *et al.*, 2014; Bezodis & Winter, 2014; Naito *et al.*, 2010; Nunome *et al.*, 2018; Putnam, 1993; Southard, 2014; Zhang *et al.*, 2012).

During the forward swing, the hip flexion velocity reaches a peak first at 40 per cent, followed by pelvic rotation peak at 52 per cent, then peak pelvic tilt velocity at 62 per cent. Thereafter the thoracic tilt and thoracic rotation reaches a peak at 70 per cent and 75 per cent respectively. Knee extension velocity is the final segment to reach a peak, just before ball contact (99 per cent of forward swing). This indicates the hip being the initial moving segment providing energy transfer to the lower body segments in order for optimal foot speed at ball contact. It is likely that the movement of the upper body segments balance the momentum from the lower limbs. Similarly in previous rugby kicking research it was suggested that upper body and kicking limb segments interact to maintain whole-body momentum (Bezodis *et al.*, 2007).

5.3.1.4 HIP-KNEE COUPLING

In the sagittal plane, during the backswing, the hip-knee coupling started in the anti-phase for 20 per cent of the time, then moved to the knee phase for the remaining 80 per cent of the backswing. The knee was the primary mover as it moved through a large ROM than the hip. Hip flexion occurred throughout the entire forward swing, however, knee flexion was still present for the initial part of the forward swing. Therefore, the in-phase was reported for the first 50 per cent of the forward swing, as both the joint flexion angles grow more positive. Peak knee flexion was then reached, and extension commenced. The anti-phase was present as the knee is extending and hip angle is flexing. The coupling angle moved from anti-phase to the knee phase for the final 20 per cent, indicating the final rapid knee extension before ball contact. The finding of the current study is consistent with previous research in segment coordination in soccer kicking (Li *et al.*, 2016).

The distal- and in-phase present in the final part of the backswing and beginning of the forward swing may have contributed to the increased stretch of the knee extension muscles, aiding in the stretch-shortening cycle (Li *et al.*, 2016; Shan & Westerhoff, 2005). Here, hip flexion and knee flexion takes place. Thereafter tension arc is released during the forward swing with rapid knee extension forming a whip-like motion of the kicking limb which is supported by the knee phase reported.

In soccer kicking, a faster leg swing produces a higher ball velocity when kicking with the preferred leg compared to the non-preferred (Nunome, Ikegami, *et al.*, 2006). However, differences were attributed to muscle force, with no significant changes in the inter-segmental movement pattern. The researchers speculated that a well-coordinated movement pattern was seen for both the preferred and non-preferred leg. The sample used was highly trained club players with a mean age of 16.8 years. The sample used within the ambit of this research study displayed similar coordination trends for kicking at different intensities, thereby indicating a well-trained pattern. Task constraints could have been perceived by the kickers to be fairly similar, where increasing the kicking distance even more, could possibly produce more differences. The researcher did not collect information from the kickers in the current study to verify their perceptions relating from the kicks from different distances.

5.3.1.5 KNEE-ANKLE COUPLING

In the sagittal plane, for knee-ankle coupling, the anti-phase was present for the first part of the backswing. After that, it stayed in the proximal phase for the remainder of the backswing. During the forward swing, the proximal phase was the dominant coordination pattern where the knee was the primary mover while the ankle stayed in a relatively plantar flexed position. These findings are supported by Atack *et al*. (2014), reporting the ankle staying in plantar flexion for an extended time during the kicking phase(Atack *et al.*, 2014). The ankle being locked in plantarflexion provides a stable position for foot-ball interaction. No difference existed in knee-ankle coupling between groups.

5.3.2 UPPER BODY

For the upper body segments, angles are defined relative to the "global coordinate system" in this research study. It is important to consider that the angle of the approach will have an influence on the position of the segments at the beginning of the backswing. The pelvis and thorax angle in the transverse plane are described relative to the posts (the target) in the following discussion.

5.3.2.1 PELVIS KINEMATICS

Pelvis anterior- and posterior tilt, as well as pelvic obliquity, displayed less movement for the entire backswing and forward swing across all three distances compared to the thorax motion. It could be necessary to maintain a stable pelvis to ensure kicking accuracy but was not investigated in this study. These findings are contradicting with findings in soccer kickers, reporting a substantial increase in the pelvis posterior rotation for the final part of the forward swing in maximal kicks compared to submaximal kicks (Langhout *et al.*, 2017). Soccer kicking might not be comparable to rugby kicking, as previously mentioned. It is possible that soccer kickers position their bodies differently relative their feet allowing them to apply side- or top spin to the ball to manipulate flight path of the ball.

In the transverse plane, more pelvis rotation was found during the backswing, with greater distances from the posts. Relative to the target, the pelvis angle for the 32 m kicks was more externally rotated than the 22 m kicks. The pelvis rotation angle for the 40 m kicks was more externally rotated than the 32 m kicks, and the 40 m kicks were mostly more externally rotated compared to the 22 m kicks. More significant pelvis rotation at the initiation of the backswing could indicate a different approach angle utilised by the kickers. More pelvis rotation might be an attempt to increase the ROM for the kicking limb to increase foot velocity at ball contact. A greater pelvis rotation could represent a greater tension arc and shoulder-hip separation involvement. According to previous research studies, a higher tension arc or pelvis-thorax angle correlates positively to foot speed but negatively to accuracy (Atack *et al.*, 2017; Green *et al.*, 2016; Padulo, Granatelli, Rustcello & D'Ottavio, 2013) These findings align with this research study as the kicking success rate decreased with greater distances from the posts. There was no difference in the pelvis rotation between all the distances during the forward swing of the kick in the current study.

Pelvis- and thorax orientation in the transverse plane were investigated by Atack *et al.* (2016, 2017) who found a smaller pelvis rotation angle for the forward swing in kickers falling short compared to longer range kickers. It was speculated that a less external pelvic rotation angle is related to limited force generation. In the current study, no difference was seen in the forward swing, only during the backswing for kicking at different distances from the posts. With increase in kicking distance, the results of the current study indicate that the angular positioning of the pelvis and thorax differ during the backswing but stay consistent during the forward swing.

Differences in pelvis rotation angle translated into higher peak pelvic rotation velocity seen for the 40 m kicks. Increased pelvic rotation velocity can contribute to increased foot speed at ball contact in combination with increased knee extension and hip flexion for the 40 m kicks. Pelvis rotation velocity might also negatively affect the kicking accuracy by influencing the total body transverse plane momentum, if not countered by the non-kicking side arm (Bezodis *et al.*, 2007).

5.3.2.2 THORAX KINEMATICS

The thorax angle in the transverse plane was measured relative to the posts and should be considered when interpreting results. During the backswing and forward swing, the thorax stayed constant in external rotation in the transverse plane, at around 40º to 35º (towards the non-kicking side). Thoracic rotation angle in this research study was within 10º of other rugby kicking research reporting an average of 45º of external thoracic rotation at ball contact with a similar population to the current study indicating a more open stance (Green *et al.*, 2016).

The thorax started in a 12º degrees forward lean in the sagittal plane and moved to 5º of backward lean at the end of the backswing. During the forward swing, the thorax moved to 5º of forward flexion at ball contact. The sagittal plane thorax tilt at ball contact of 18.8º to 27.9º has been reported in literature to be the desired range in soccer kicking (Gosling *et al.*, 2017; Lees & Nolan, 2002), which is significantly higher than that of the current population. It was proposed that decreased values could lead to less power generation with tension arc release, thereby decreasing the mechanical efficiency during kicking (Gosling *et al.*, 2017). A possible explanation can be the difference in distance from the target, as well as the desired ball trajectory angle. In rugby kicking, the ball has to move over the crossbar at a minimum of 3.4 m from the ground. With kicking in soccer, the goal box is, at its highest point, 2.4 m from the ground affecting the projection angle of the ball. In the current study a trend is seen towards a more upright thorax positioning during the forward swing which could affect the hip flexion and pelvic tilt angles. Place kickers presenting with increased forward lean for the close-range kicks could suggest a focus on accuracy, while during the longer-range kickers might try to produce a greater X-factor stretch and improved tension arc.

Sagittal plane trunk motion likely needs to balance the shift in the kicking leg mass, therefore with faster foot speeds, greater knee extension angular velocity and kicking leg mass, similar trends should be reflected in trunk motion. However, in the current study, differences in pelvis- and thorax angles individually in the transverse plane at the initiation of the backswing, did not translate into increased angular velocity of either the pelvis- or thorax segments. Green *et al.* (2016) reported that trunk and pelvis rotation correlates positively with the distance of the kick, but negatively with kick accuracy. In the current study, greater pelvis- and thorax rotation were present for kicks further away from the posts. Similarly, a decrease in the overall kicking success rate was reported with an increase in distance from the posts, confirming the trade-off between accuracy and distance (Andersen & Dörge, 2011; Green *et al.*, 2016; Kellis & Katis, 2007).

Pelvis and torso mechanics have been identified as an important factor that is used by longer range kickers compared to short range kickers (Atack *et al.*, 2017). The current study did not differentiate between different types of kickers, and it is speculated that although different trunk mechanics exist between individuals. It is evident that, regardless of the types of kickers in the current study, the kickers did not change their technique when asked to perform long- or short-range kicks. In the study of Atack *et al*. (2017), it was reported that kickers missing the posts to the left, presented with increased relative pelvis-thorax angle for the majority of the forward swing. It was then suggested that although the tension arc parameters might be beneficial to increasing foot speed and in turn ball speed to achieve greater kicking distance, the accuracy of the kick might be negatively affected (Atack *et al.*, 2017). In another research paper it was reported that the greater tension arc formation at the top of backswing, for wide kickers, is due to a more front-on thorax, with the same pelvis orientation. This increase in pelvis-thorax angle creates a stretch across the body and when released during the forward swing would contribute to increased kicking foot velocity as a result of the stretch-shortening cycle. The pelvis and thorax segment motions differ compared to the results presented by Atack *et al*. (2017), possibly due to the selection of a larger sample with a range of skill levels, compared to the current study consisting of a smaller uniform sample. Results of the current may also differ based on the laboratory-based environment in the study of Atack *et al.* (2017), where kickers might adapt their technique compared to a field-based environment used in the current study,

5.3.2.3 PELVIS-THORAX COUPLING

The importance of including pelvis and thorax kinematics when analysing kicking performance is highlighted in recent work. The pelvis-thorax coupling and as well as thorax rotation plays an important role in producing high-quality kicks and are mainly related to tension arc formation (Gosling *et al.*, 2017). In the current study, the pelvis moves less than the thorax in the transverse plane, for the first 50 per cent of the backswing, leading to a thorax dominant coordination pattern. During the second 50 per cent of the backswing, both the pelvis and thorax rotated in the same direction. The coordination moved from thorax dominancy to in-phase, and from in-phase to pelvis dominancy at the end of the backswing. Pelvis dominancy then prevails for the majority of the forward swing. These findings suggest that the pelvis and thorax play a role in tension arc formation, increasing the stretch across the body. During tension arc release however, the pelvis is the main mover, while the thorax is more stable. Similarly, in the sagittal plane, the pelvis and thorax are both moving into backward tilt, for the backswing, creating an in-phase pattern, which contributes to tension arc formation. During the backswing, in the sagittal plane, the pelvis stayed relatively constant and started to decrease at about 30 per cent. The thorax angle decreased for the entire backswing. This resulted in a thorax dominant movement pattern up to 30 per cent of the backswing. Thereafter, the in-phase was noted as the pelvis and thorax segments moved in the same direction. During the forward swing, the pelvis becomes the main mover with rapid anterior tilt, prevalent in the pelvis phase and anti-phase described. Sagittal plane motion also contributes to tension arc formation and release.

Similar research in soccer in-step kicking reported mostly in-phase with thorax dominancy during the backswing, indicating that the thorax is more influential in tension arc formation. During the forward swing, the tension arc is released, and the CA moves to pelvis dominancy in the transverse plane. The frontal and sagittal plane also displayed pelvis dominancy (Gosling *et al.*, 2017). During the initial phase of tension arc release, pelvis dominancy was seen in X-, Y-, and Z-directions in the current study. The pelvis dominancy seen during the forward swing could suggest the pelvis was the main contributor to the release of the tension arc during the forward swing in the sagittal plane, which is in line with previous findings (Gosling *et al.*, 2017). Thorax angles might be different in soccer kicking as a result of a lower target. The target in soccer kicking is possibly closer therefore not requiring maximal tension arc involvement.

In the frontal plane, negative pelvic and thoracic obliquity was seen during the backswing, resulting in the most time spent in the in-phase, with areas of pelvis dominancy. During the forward swing, initially, the in-phase was present, where both segments moved in the same direction. Thereafter, the pelvis became the dominant mover when the thorax stayed constant, and the pelvis continued to have positive flexion. The anti-phase took over and then moved into the proximal phase (thorax dominancy) at the end of the forward swing where the pelvis level out and the thorax have obliquity towards the non-kicking side.

The coordination patterns in the current study, calculated from vector coding, align with research available in the field. In general, these coordination patterns stay consistent for kicking at various distances. In order to improve kicking distance, absolute joint angles may change, but it is recommended that coordination patterns should stay constant. However, further investigation is needed to confirm those described above. The relevance of well-established coordination patterns has been identified in research and discussed below.

Kicking skills are 3D multi-joint, open kinetic chain movements. Adding to the dynamic complexity of the kicking motion is the speed requirement (Naito *et al.*, 2010). The kicker is required to maximize the velocity at the distal end point of the extremity at ball contact (Anderson & Sideway, 1994). The motion of the kicking foot and shank is influenced by other joints and segments of the kicking leg, as well as the multiple joints and segments of the entire body (Naito *et al.*, 2010). Therefore, both researchers and coaches are intrigued as to how the kicker coordinated multiple whole-body segments and joints to generate powerful kicks. Understanding the process and mechanisms underlying the development of well-coordinated movement has been a focus of investigation of researchers (Anderson & Sideway, 1994). The need has been expressed for research investigating how changes in performance outcomes relate to changes in coordination patterns to accurately describe control of joints and segments interacting in goal-directed activity (Chow *et al.*, 2007).

Research into soccer chip kicking also reported that coordination patterns are influenced by skill level, where novice kickers displays greater proximal segment involvement compared to higher level kickers (Chow *et al.*, 2007). However, as the higher level kickers had less hip ROM and increased foot and ball velocity, it was speculated that higher level players have better utilization of the stretch-shortening cycle (Chow *et al.*, 2007). Coordination research also reported that rapid knee extension is not only influenced by knee and thigh motion, but also complex interaction of a combination of mechanical factors including trunk rotation and motion-dependent moment (Naito *et al.*, 2010). Naito *et al*. (2010) were some of the first researchers to explain the phenomenon. Increased hip flexion angular velocity during the forward swing would increase knee extension velocity as a result of the centrifugal force and the motion-dependent moment (Naito *et al.*, 2010). Emphasising the importance of the interaction between the hip and the knee, it was suggested that the knee should be at approximately 90 degrees of flexion when rapid hip flexion occurs (Naito *et al.*, 2010). This will allow the centrifugal force to have the largest acceleration affect (Naito *et al.*, 2010). Therefore, it was reported that a well-coordinated intersegmental movement pattern could be the primary factor in kicking limb flexion and extension angles for optimal effect of the centrifugal force for maximal foot velocity (Naito *et al.*, 2010).

Investigation into coordination patterns is crucial in kicking analysis, as it provides a measure of how joints and segments move relative to each other. For the kicking movement the timing of events, such as maximal hip velocity should coincide with the knee at 90 degrees (Naito *et al.*, 2010), may hold the key to understanding kicking techniques better. A better understanding of the skill and various techniques may allow coaches to tailor their training to the kickers' techniques instead of a one-size-fits-all approach.

5.4 COORDINATION VARIABILITY

It has been established that coordination of multiple joints and segments is a crucial part of the kicking skill (Davids *et al.*, 2000). However, with every repetition of a movement, slight differences exist in the execution, even with well-trained movement patterns (Bartlett *et al.*, 2007; Preatoni *et al.*, 2013). In recent literature movement variability is associated with health, flexibility and adaptability to change of a movement system. In rugby kicking quantifying movement variability could provide insight into how a kicker controls the multiple degrees of freedom to achieve different task requirements.

It is recommended that a more substantial portion of sports biomechanics research should focus on MV, including coordination and the control of movement (Bartlett *et al.*, 2007). A combination of motor control theories and biomechanical measurement techniques are required to comprehensively investigate the process of coordination and control of movement in soccer kicking (Davids *et al.*, 2000) as movement variability could be used as a source of further information on biomechanical measurements (Preatoni *et al.*, 2013). Variability in coordination patterns has been commonly studied as coordination variability and is inherent in a functional movement strategy (Cunningham, 2012).

The hypothesis that there will be no significant difference in coordination variability between place kicks at 22 m, 32 m, and 40 m was accepted as no significant difference was found in the coordination variability between kicking distances for all joint couplings. This suggests that the same amount of variability was present in the coordination pattern for each datapoint between groups kicking from various distances from the posts. The kickers displayed the same amount of flexibility in their movement pattern between groups, suggesting that the same movement strategy is used for kicking at 22 m, 32 m and 40 m from the posts.

Research in soccer chip kicking reported no differences in variability (normalised root mean square), when kickers were asked to kick at different distances. It was, however, reported that the novice players were unable to adjust the interlimb coordination patterns in order to achieve altered task requirements (Chow *et al.*, 2007). Similarly, no change in coordination patterns were seen in the current sample when asked to perform kicks from different distances from the posts. The current study did not investigate different skill levels which might influence the coordination patterns. It could also be that real differences are masked by the group-based analysis. Lastly, soccer chip kicking might require more control of ball speed to achieve shorter range kicks, whereas in rugby kicking, the kicker could theoretically perform maximal kicks from anywhere on the field, as long as the accuracy (direction) is good. Coordination variability should also be investigated relative to the kicking success achieved by the kickers, to determine the amount of variability that is functional or dysfunctional (Chow *et al.*, 2007). In the current study no difference in coordination variability results were seen when both successful and unsuccessful trials were used for analysis compared to when only the successful trials were included in analysis.

A larger CAV has been reported between the preferred and non-preferred leg, speculating that higher variability is related to a lower ability or familiarity with movement (Bartlett *et al.*, 2007; Gosling *et al.*, 2017). In this research project no differences were found in coordination variability between kicking at different distances. It was, therefore, suggested that the kickers in the current study had no change in the movement strategy between kicking at different distances. The movement patterns were well-trained for maximal- and submaximal kicks. Conclusions based on the CAV should be interpreted with caution as various limitations have been identified. It was reported that the CAV calculations cause statistical artefact due to the circular statistics applied, increasing the variability seen with different vector lengths. The bivariate area of ellipse method is more robust as it provides variability in the direction and length of the coupling vectors by forming an ellipse around the coupling vector end-point coordinates at each timepoint (Stock, van Emmerik, *et al.*, 2018). No prior studies have been done on kicking mechanics using the bivariate area of ellipse method and no indication is available for the amount of variability that would be acceptable.

5.5 INDIVIDUALISED APPROACH

In most kicking kinematic research, a group-based analysis was used. Group-based analysis is a good way to find recommendations that will be appropriate to the entire group or sub-groups. However, it is possible that different techniques exist with kickers achieving the same outcome. Different techniques or styles are different movement patterns utilized by players to achieve the same aim (Ball & Best, 2007). The knee-dominant or hip-dominant kicking technique is an example of different kicking techniques alluded to in rugby kicking research (Atack *et al.*, 2019) and described in more detail in Australian football league kicking (Ball, 2008). It was reported that a negative effect exists between knee angular velocity and thigh angular velocity. Thus when thigh angular velocity was large, knee angular velocity was small (Ball, 2008). If there are truly different kicking styles present in the dataset, group-based analysis might be at risk of statistical errors (Ball & Best, 2007). Type I error can be made when large differences exist between the different groups in the study, thereby producing a pseudo correlation effect. A type II error can be present when the it seems like no correlation exist within the large group, but in reality, a true correlation exists within the subgroups of the data (Ball & Best, 2007). Individualized analysis provide more information on how kickers exploit variability (Button, Davids & Schöllhorn, 2006).

In groups of athletes a cluster analysis has been used to determine different coordination profiles in field hockey (Brétigny, Leroy, Button, Chollet & Seifert, 2011), discuss throwing (Button *et al.*, 2006) and golf strokes (Ball & Best, 2007). Cluster analysis follows a process where cases are grouped together based on how similar they are. The Hierarchical cluster analysis using, Squared Euclidean distance measure groups together two cases with the smallest distance between them (most similar) in every consecutive step until only one large group exist (Ball & Best, 2007), displayed in a dendrogram (Figure 98). Limitations to the clustering analysis method include that there is no consensus on the selection the number of clusters, the multiple validation techniques, the clustering strategies and methods for determining similarity between cases (Ball & Best, 2007; Milligan & Cooper, 1985; Rein, Button, Davids & Summers, 2010).

In this research study all three kicking distances of each individual kicker was clustered together. This suggests that individual kickers use the same technique or movement strategy even when the task outcome is altered. Cluster two is the largest cluster with 18 cases (six kickers), the other two clusters are significantly smaller (six cases, two kickers and three cases, one kicker). The smaller clusters might be underrepresented in the sample.

No difference in knee angle was seen at ball contact, however, at maximal knee flexion cluster one differs from cluster three, where cluster three presented with more knee flexion. For the hip motion, three distinct different profiles were observed. Cluster one starts out with the least amount of hip flexion at ball contact. Cluster three starts out with a large amount of hip extension at the top of the backswing and stay relatively extended until ball contact. Similarly, cluster three presented with a larger backward tilt in thorax compared to cluster one who presented with a forward tilt in the thorax at ball contact. Cluster three presented with increased knee flexion, and a large amount of hip extension potentially due to backward lean of the thorax. Cluster three could have increased functional flexibility.

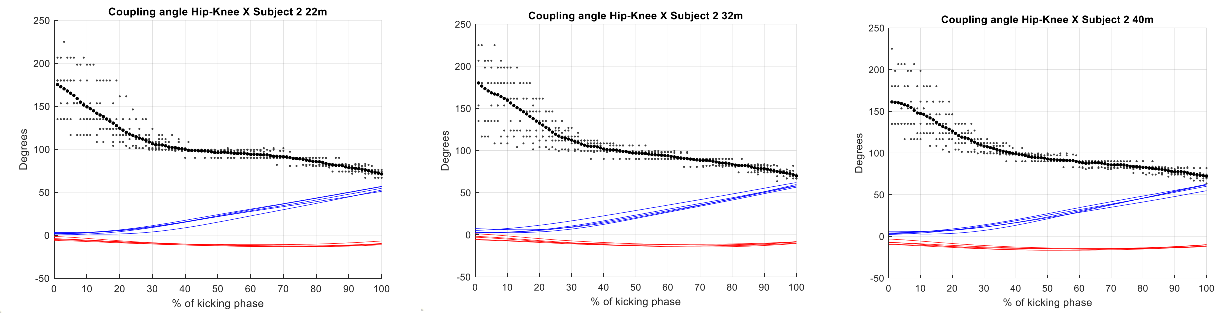
As mentioned, a knee-dominant and hip-dominant technique has been identified in literature (Atack *et al.*, 2019; Ball, 2008). In this sample cluster three could represent a knee-dominant technique with large maximal knee flexion angle while the hip stays in an extended position until ball contact (less hip flexion). Cluster one could represent a hip-dominant a hip dominant technique presenting with less maximal knee flexion and increased hip flexion during the entire forward swing of the kick. However, the largest cluster, cluster two, representing the majority of the sample, fall in between the hip-dominant and knee-dominant clusters. Most of the kickers in this study, therefore, make use of a technique consisting of a combination of a hip-dominant and knee-dominant strategy. However, no norms are available for what a knee-dominant and hip dominant strategy might look like, and it is therefore very difficult to definitively group these kickers. Previous literature reported a knee-dominant dominant strategy to be associated with more accurate kicking (Atack *et al.*, 2019).

ANOVA analysis revealed no statistically significant difference in foot speed at ball contact between the clusters, however a large effect size was seen. Even though the foot speed at ball contact differs slightly for these clusters, all the kicks used for this analysis travelled over the crossbar. Only successful kicks were used for the cluster analysis and therefore accuracy was not influenced by the different clusters.

Another facet of the sagittal plane motion includes the thorax motion. Thorax backward tilt at the top of backswing adds to the tension arc development, thereafter forward tilt of the thorax during the forward swing is associated with tension arc release. In this research study, each of the three clusters present with statistically significantly different thorax movement patterns. Cluster three presented with increased backward lean of the thorax at the top of the backswing and steadily decrease to ball contact. This cluster presents with a large tension arch development, but little tension arc release. Cluster three also presented with the lower foot speed at ball contact. Cluster one displayed less tension arc development (backward tilt in thorax at top of backswing), and more tension arc release (greater hip flexion at ball contact). Cluster two falls in between other two clusters. Interestingly, Cluster one and cluster two (more so) both displayed an increase in thorax backward lean from top of backswing to maximal knee flexion, thereafter rapid forward leaning to ball contact. Tension arc development should increase further after top of backswing. Maximal tension arc development should coincide with maximal knee flexion, and not top of backswing.

Coordination, such as angle-angle plots and coordination variability should be investigated in a cluster analysis approach, as clear differences exist across individuals below is an example of the coupling angle graphs for two kickers across three distances (Figure 102). It seems like each kicker produce a similar movement pattern when asked to kick as three different distances, however individual differences are seen in the case of the subjects below. Therefore, further investigation should focus on determining coordination profiles in rugby place kicking.

(a)



(b)

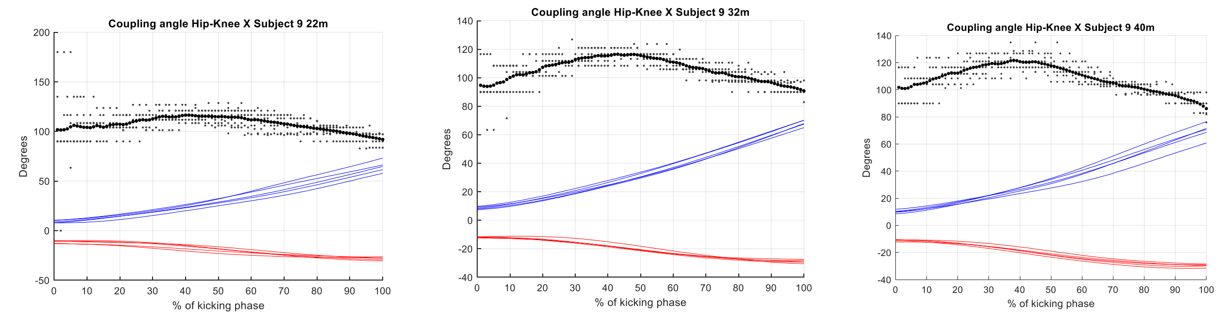


Figure 102: Hip-knee coupling angle graphs at 22 m 32 m and 40 m, where the red line, indicated hip movement, blue line indicates knee movement, black dots indicate coupling angle at each instance for (a) kicker two and (b) kicker nine.

It is proposed that in some tasks variability in some parameters might be tolerable, while other parameters might need to be consistent. It is also suggested that consistency in one point of the movement might rely on the variability of a different point(s) (Handford, 2006). Further investigation is needed in this regard, Appendix D (page 207) provides more examples of how individual coordination graphs differ. If specific areas of consistency and areas of variability can be identified in the kicking movement, it could help coaches to teach key position-action relationships (in tennis for example, ball serving peak should coincide with the start of the forward swing) for all performers. Freedom should be built into skill acquisition in order for athletes to develop a unique solution to the problem specific to their anatomy and state of learning. Therefore, solutions to movement problems could be generic yet individual (Handford, 2006). Each person may exploit system variability in a slightly different way due to organismic constraints such as learning experiences, environmental influences or genetic differences (Button *et al.*, 2006).

The vast differences in players' technique are in contrast with the idea that there is a general optimal motor pattern (Bartlett *et al.*, 2007). Therefore, it should not be advised to imitate the movement pattern of elite athletes (athletes with the best performance). Each individual will find unique solutions to execute a task or skill termed "individual-specific self-organisation" (Bartlett *et al.*, 2007).

In a review of key properties of expert movement systems in sport, it was found that there is no ideal/optimal movement pattern that everyone should strive towards (Seifert *et al.*, 2012). Instead, athletes should assemble functional movement patterns, to solve their unique sets of key constraints (Button *et al.*, 2006). It is, therefore, crucial for a coach to train athletes based on their natural technique. Youth athletes should be encouraged to explore different techniques (Baktash *et al.*, 2009; Chow *et al.*, 2005). It is recommended that the individualised self-organisation approach be used when initially analysing data, as analysis of a large, diverse group might mask individual differences where group means stay the same, but substantial individual differences occur (Button *et al.*, 2006).

5.6 SUMMARY

Discrete kinematic variables and timing variables found in the current study are consistent with the literature on kicking in rugby and other football codes, mostly soccer. Based on the findings of this study it is recommended that both discrete and continuous variables should be used in analysis of kicking mechanics to gain a complete understanding. The group comparisons made with discrete variables are not sufficient and should be used with caution when investigating movement tasks as the predominant amount of information is not used in the analysis.

In order to increase foot velocity and in turn, greater kicking distance, the Table 15 summarise the changes a kicker can make to absolute joint angles during the backswing and forward swing, while keeping the coordination of movement consistent.

Table 15: Joint and segment angle and angular velocity changes associated with long-range kicks

Plane	Joint or Segment			
	Knee	Hip	Pelvis	Thorax
Sagittal	↑ flexion angle ↑ extension angular velocity	↑ extension angle		↑ backward lean
Frontal				
Transverse		↑ external rotation angle	↑ external rotation angle	↓ external rotation

Continuous variables of joint and segment angles and angular velocities indicate that kickers change their hip extension angle and knee flexion angle in order to achieve a greater distance by increasing the pre-stretch in the thigh muscles. Increased hip extension and external rotation in 40 m kicks, compared to the 22 m and 32 m kicks, was found, likely in attempt to increase the tension arc formation. Increased hip extension angle during the 40 m kicks was influenced by increased backward lean of thorax. Increased pelvic external rotation for the 40 m kicks could also contribute to increased foot speed at ball contact as it provides the kicking leg with a larger ROM to generate foot speed. It is interesting that with long-range kicks, the majority of the joint angle and body segment changes takes place during the backswing, while during the forward swing the movements are more consistent across different distances.

It is clear from the intersegmental coordination analysis that for the hip-knee coupling an anti-phase is important for the initial 40% of the forward swing. In this phase the hip has started to flex while the knee is still extending. It is important for the pre-stretch of the thigh muscles to produce a powerful knee extension movement. The pelvis and thorax work together during the backswing to form a tension arc, thereafter the pelvis becomes the main mover for tension arc release, possibly providing a stable thorax for better accuracy.

To a large extent, it appears that coordination patterns do not change, as a kicker was asked to kick at maximal intensity; however, absolute angles might change. Segmental- and joint coupling are, therefore, not influenced by absolute changes in the joint angles. It is thus speculated that timing and relative movement are vital to achieving successful kicks. The main contributors to an increased distance include the parameters involved in tension arc formation in the transverse plane, as well as increased hip extension during the backswing. Maximal knee flexion is also greater for maximal kicks. However, the motion of the joints relative to each other stayed constant when kicking at different distances from the posts.

In addition to intersegment and interjoint coordination being consistent, coordination variability does not seem to change when kicking at different intensities, indicating similar ability in trials. These findings point to a well-trained movement pattern in the current sample for all distances with no change in the movement strategy used.

The results of this study align with earlier research on the kicking technique used in various football disciplines. However, the methodology used in rugby place kicking research is novel and unique. Potentially, the methodology and findings of the current study could lead to further investigation into the coordination patterns used in rugby place kicking. Improving knowledge on intersegment and interjoint coordination could improve evidence-based training and coaching of the rugby place kicking skill.

Cluster analysis indicated three distinct different movement patterns in sagittal plane angles for the sample of kickers. The majority of the kickers had a combination of a hip-dominant and knee-dominant technique. It was also clear that the group of kickers achieving the greatest foot speed at ball contact, presented with greatest thorax backward tilt at the instance of maximal knee flexion. These findings suggest that maximal tension arc formation should occur with maximal knee flexion, in order to achieve greatest ball speed, emphasising the importance of coordination between segments and joints in place kicking.

5.7 CONCLUSION

The objectives of this dissertation were to determine differences in kicking kinematics in place kicking at various distances from posts. To accomplish these objectives, a research design based on biomechanical methods, including discrete and continuous variables were used.

It has been determined that task constraints as well as the position on the field influence the success of the kicker. Data collection for the current study was done on a rugby field were kickers were required to kick towards rugby posts in order to replicate the actual kicking environment and allowing the kicker to orientate himself on the field.

To identify kicking characteristics related to increased foot speed at ball contact, the purpose of the first analysis was to compare the differences in preselected discrete kinematic variables in kicks from various distances from the posts. It was hypothesised that there would be no significant differences between groups. This hypothesis was accepted based on the results of the analysis. The discrete kinematics were similar to results found in previous research across football disciplines, indicating that the sample is comparable with related literature. Both discrete and continuous variables should be included in analysis to gain a complete understanding of the kicking movement.

The purpose of the second analysis was to compare continuous kinematic curves for kicks at different distances from the posts. The hypothesis that there will be no difference between groups was rejected. Significant differences were found in the sagittal plane for hip extension and maximal knee flexion between groups, indicating that the pre-stretch and energy storage in the muscles related to the stretch-shortening cycle. Adding to the tension arch formation an increase in thorax backward tilt with backswing during the longer-range kicks. Transverse plane differences included the hip, pelvis and thorax movement, possibly a power strategy in an attempt to improve tension arc formation. Mostly, differences were noted between the 40 m kicks compared to the 22 m and 32 m kicks. Increased tension arc parameters produce increased kicking distance, however accuracy of kicks decrease with 12-23 per cent, indicating a trade-off between accuracy and distance.

A quantitative investigation into interjoint- and -segmental coordination revealed the following findings: The knee-ankle coupling maintained mostly proximal- and in-phase coordination patterns. The knee was the dominant mover for the hip-knee coupling; however, the in-phase was seen in the sagittal plane during the first half of the forward swing with hip flexion, as well as knee flexion. Therefore, for both joints the flexion angle was increasing, resulting in the in-phase coordination pattern. Thereafter rapid knee extension occurs leading to an anti-phase coordination pattern. In all three directions, pelvis-thorax coupling displayed in-phase with thorax dominance during the backswing; however, for the forward swing, the anti-phase was seen, which is consistent with the release of the tension arc. Differences in absolute angular data might suggest different muscle contraction, however the coordination between joints and segments stay relatively consistent when kicking at all different distances from posts.

The coordination variability was also investigated in kicks at different distances from the posts. The hypothesis that no difference would be found between groups was accepted. During the entire backswing and forward swing, the same amount of variability was reported for kicks at various distances. It could be speculated that the kickers had a well-defined movement pattern and the movement strategy did not change when kicking at either 22 m, 32 m and 40 m from the posts. It is also likely that the difference in distances from posts were not enough to produce a change in the task constraints.

Finally, a cluster analysis was done to determine different kicking styles in a group of kickers achieving similar performance outcomes. Three distinct groups were formed based on sagittal plane thorax, hip and knee angle at different time points during the forward swing. One group presented with increase knee flexion while the other group presented with a large amount of hp extension, with the third group presenting a combination of the two extremes. From the results presented in the cluster analysis it seems preferable that maximal tension arc development should coincide with maximal knee flexion.

From these results, it could be concluded that mostly a similar movement pattern was recruited for kicking at close-range kicks such as 22 m and 32 m, while for long-range kicks (40 m), the kickers slightly adapted their movement. In the current study, it was found that some absolute joint angles and angular velocities changed when kickers were asked to perform long-range kicks (40 m) compared to close-range kicks (22 m and 32 m); however, the joint couplings indicated no difference. The kickers in the current study had well-trained movement coordination patterns and did not deviate from their natural pattern when asked to kick at different distances. The kickers had a refined coordinated ability to kick at various distances.

5.7 PRACTICAL IMPLICATIONS FOR PLACE KICKING

Based on the findings, a summary is provided regarding the translation of data into practice. In order to achieve greater distance with kicks, absolute angles of the hip, pelvis, and thorax in the transverse plane could be increased during the backswing. Maximal hip extension and knee flexion could also be increased in the sagittal plane. These variables emphasize the importance of tension arc formation. Coaches could focus training drills on raising awareness to the tension arc formation, such as creating a stretch across the body with greatest distance between kicking foot and non-kicking side arm. After planting of the support leg, the tension arc should be release in a snapping motion, where thorax mirrors the motion of the lower limbs. Coaching cues could include: Stretch-Plant-Snap. Increased tension arc formation can be beneficial for increasing kicking distance however, it has been associated with a decrease in accuracy of the kicker.

Functional flexibility of the hip, knee, and trunk would improve the ease of creating more extensive ranges of motion for the hip, knee pelvis and thorax during the backswing, and thereby improving kicking distance. However, the movement of the joints and segments relative to each other should be kept consistent.

Kickers should train and get comfortable with kicking at various distances from the posts, and based on the results of the current study, kickers should aim to keep the movement pattern, including timing of joints and segments relative to each other, consistent regardless of distance of kick. Coaches could use words like *rhythm* or *flow* for the kickers to concentrate on their coordination patterns. It is suggested that coaches advise players to be aware of their own ability and should kick with the same timing of segments from anywhere on the field. Further investigation is required to confirm these findings.

Hopefully, the methods used and the conclusion made within the ambit of this research study can be used to build knowledge on coordination in kicking and spark interest in rugby research.

5.8 LIMITATIONS

A limitation of this study is that only male kickers volunteered to participate in the research limiting the generalizability of the results. Apparent differences exist in kicking between male and female soccer players. Most research focuses on male kickers, with a clear lack of research on female rugby place kickers. A future recommendation will be to involve female rugby place kickers and quantify gender differences.

As a result of the data collection on a rugby field, a force plate could not be added. This is a limitation as no kinetic parameters nor loading parameters of the support leg was investigated and could also be a potential performance indicator as reported in punt kicking in Australian Football (Ball, 2013). Previous literature also emphasised the importance of the support leg in distance kicking as support leg musculature contraction can maximise linear foot velocity at ball contact (Augustus, Mundy & Smith, 2017).

Each kicker was allowed make use of their personalised kicking tee. The kicking tee's may vary in height as well as the tilt of the ball placement. The use of kicker's own kicking tee is seen as a limitation; however, it was purposefully decided to keep the movement pattern of the kickers as natural as possible.

The current study did not report on foot-ball interaction. Ultimately, foot-ball interaction reflects the end of the kicking movement and point of contact between the kicker and the ball. Foot-ball interaction is, therefore, a vital aspect of the kick. Foot progression angles could be used to provide a reference of the kicking leg foot position just before ball contact.

5.9 RECOMMENDATIONS FOR FUTURE RESEARCH

This research study has laid the foundation in understanding coordination patterns in rugby kicking, however there is still a lot of unanswered questions, and new research directions identified. Apart from aspects mentioned in the previous section, recommendations for further study in this field are listed below.

In terms of coordination, future investigations should examine the coordination patterns associated with different skill levels (novice, intermediate, skilled) to verify the learning technique. This could benefit the skill development and training of young athletes. Furthermore, it could be useful to do a fatiguing protocol on the rugby kickers and evaluate the amount of variability in specific variables in a fatigued and non-fatigued condition. This would provide insight into the coordination patterns and how they might change during the course of a match. It is recommended that future studies should use an individualised approach, such as a cluster analysis, to determine the technique differences, especially in skilled athletes. The skill level might influence the kicking technique of the kicker.

In a rugby match a kicker is required to kick from various distances and angles from the posts. The latter was not investigated in the scope of the study. It is recommended that future research aim to identify the change in coordination patterns as solution space changes (as with angled kicks). These findings could provide insight into the change movement strategies used as the task constraints change.

The importance of accuracy and distance in kicking success has been highlighted. An investigation into the trade-off between accuracy and distance on coordination and coordination variability could provide exciting findings on how much variability is acceptable. Due to the limited amount of research on coordination and coordination variability it is difficult to determine typical or altered movement patterns. In addition to the protocol followed in the current study, the suggested research should include an accuracy measurement (more than a success measure). Accuracy could be determined by drawing a central line from the kicker through the middle of the posts and assess the landing position of the ball (Green *et al.*, 2016).

Lastly, an intervention study can be done focussing on coaching cues such as *rhythm, flow* to focus on coordination, as well as *Stretch-Plant-Snap* to focus on the tension arc formation and release, in attempt to increase kicking distance in short-range kickers

Coordination and coordination variability calculations are tools used to identify changes in movement strategies used. Hopefully, the methodology and outcome of this study would lead to further investigation and more studies on the coordination pattern used in rugby place kicking.

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APPENDIX A: INFORMED CONSENT

UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

STELLENBOSCH UNIVERSITY

CONSENT TO PARTICIPATE IN RESEARCH

Analysis of rugby place kicking

You are asked to participate in a research study conducted by Dawie van Den Heever (PhD), John Cockroft (PhD), Elizabeth Mathewson (MSc), Daniel Lombard (B.Eng) from the Engineering Faculty and the Department of Sport Science at Stellenbosch University. The results will form part of a PhD dissertation and MEng thesis. You were selected as a possible participant in this study because you have a specific rugby place kicking skill.

1. PURPOSE OF THE STUDY

This study aims to identify technique characteristics of optimal goal kicking.

2. PROCEDURES

If you volunteer to participate in this study, you will be asked to do the following things:

Attend two testing sessions; including one lab-based test and one field-based test.

The indoor testing will consist of a short warm-up. Markers will be placed on your legs, torso, arms, and head; thereafter, you will be asked to kick at the posts ten times.

The outdoor testing will start with marker placement; thereafter, you will be required to kick 25 kicks at the posts – five kicks from five different positions on the field.

Every testing session will last about 60 minutes.

3. POTENTIAL RISKS AND DISCOMFORTS

We do not anticipate any risks or discomfort. The subject will be able to test as much as needed between every kick.

4. POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

This study will improve the manner in which place kicking is coached. Little evidence-based research exists on the movement pattern of kicking mechanics. Creating a framework of optimal movement patterns for successful goal kicking will improve the performance of players.

5. PAYMENT FOR PARTICIPATION

The subject will not receive any payment but will be reimbursed for their travel expenses.

6. CONFIDENTIALITY

Any information that is obtained within the ambit of this study will remain confidential and will be disclosed only with your permission or as required by law. Confidentiality will be maintained by means of the Central Analytical Facilities (CAF) unit. The CAF unit is responsible for the data processing and extraction and the researchers will receive anonymous data.

The subjects will be able to view their own trials of the Vicon software directly after the testing session. No names or specific participant results will be published; all the results will be grouped.

7. PARTICIPATION AND WITHDRAWAL

You can choose whether to partake in this study or not. If you volunteer to partake in this study, you may withdraw at any time without any consequences. You may also refuse to answer any questions you do not want to answer and will be allowed to remain in the study. The researcher(s) may withdraw you from this research if circumstances arise which warrant doing so.

8. IDENTIFICATION OF INVESTIGATORS/RESEARCHER

If you have any questions or concerns about the research, please feel free to contact Dawie van den Heever (email: dawie@sun.ac.za, Tel: 021 808 4856) or Elizabeth Mathewson (email: emathewson@sun.ac.za, Tel: 021 808 3915)

9. RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact Ms Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] at the Division for Research Development.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

The information above was described to [*me/the subject/the participant]* by [*name of relevant person]* in [*Afrikaans/English/Xhosa/other]* and [*I am/the subject is/the participant is]* in command of this language or it was satisfactorily translated to [*me/him/her*]. [*I/the participant/the subject]* was given the opportunity to ask questions, and these questions were answered to *[my/his/her]* satisfaction.

[I hereby consent voluntarily to participate in this study/I hereby consent that the subject/participant may participate in this study.] I have been given a copy of this form.

____

Name of subject/participant

____

Date

SIGNATURE OF INVESTIGATOR/RESEARCHER

I declare that I explained the information given in this document to __________________ [name of the subject/participant]. He/she was encouraged and given ample time to ask me any questions. This conversation was conducted in Afrikaans/English ___________ by _______________________.

____ ______________

Signature of investigator/Researcher Date

APPENDIX B: PLAYER HISTORY QUESTIONNAIRE

WORLD RUGBY rugbyready

Player profile form

Personal details			
Name			
Address			
Telephone		Mobile	
Email			
Date of birth			
Emergency contact			
Name			
Address			
Relationship to player			
Telephone		Mobile	

Medical history	
Do you have any medical conditions, disabilities or allergies?	
If the answer is yes, please list each condition, disability or allergy and any medication you take for it, below	

Condition / disability (e.g. asthma, diabetes, epilepsy, anaemia, haemophilia, viral illness, etc)	**Medication** (e.g. tablets, inhalers, creams, etc - give drug names)	**Frequency** (e.g. twice daily, only with symptoms, etc)
Allergy (e.g. bee stings, etc)	**Medication** (e.g. tablets, inhalers, creams, etc - give drug names)	**Dose / frequency**

History of injury (list any injuries, when they happened and who treated you)

Injury (e.g. concussion)	When (e.g. Sept 2007)	Treatment received	Who treated you (e.g. doctor)	Current status of injury (fully recovered or not)

Rugby Ready / Pre-participation / Player profile

Player profile form

Health and fitness assessment	
In which other sports / physical activities are you involved?	
How many hours per week, in total, do you train?	
How many hours do you train kicking?	
Height	
Weight	

Cardiac questionnaire (please tick each box that applies to you)			
Fainting		Palpitations	
Dizzy turns		Chest pain or tightness	
Breathlessness or more easily tired than team-mates		Sudden death in your immediate family of anyone under 50	
History of high blood pressure		Smoking (how many per day)	
Diabetes			

Signatures	
Date of profile completion	
Player's signature (or guardian if under 18)	
Profiler's signature	
Follow-up date (if applicable)	

Kicking history			
How many years of place kicking experience do you have?			
What team do you currently represent?			
Have you received any place kicking coaching previously?	Yes	No	Quality / 10
Are you receiving any place kicking coaching currently?	Yes	No	Quality / 10

APPENDIX C: MARKER SET

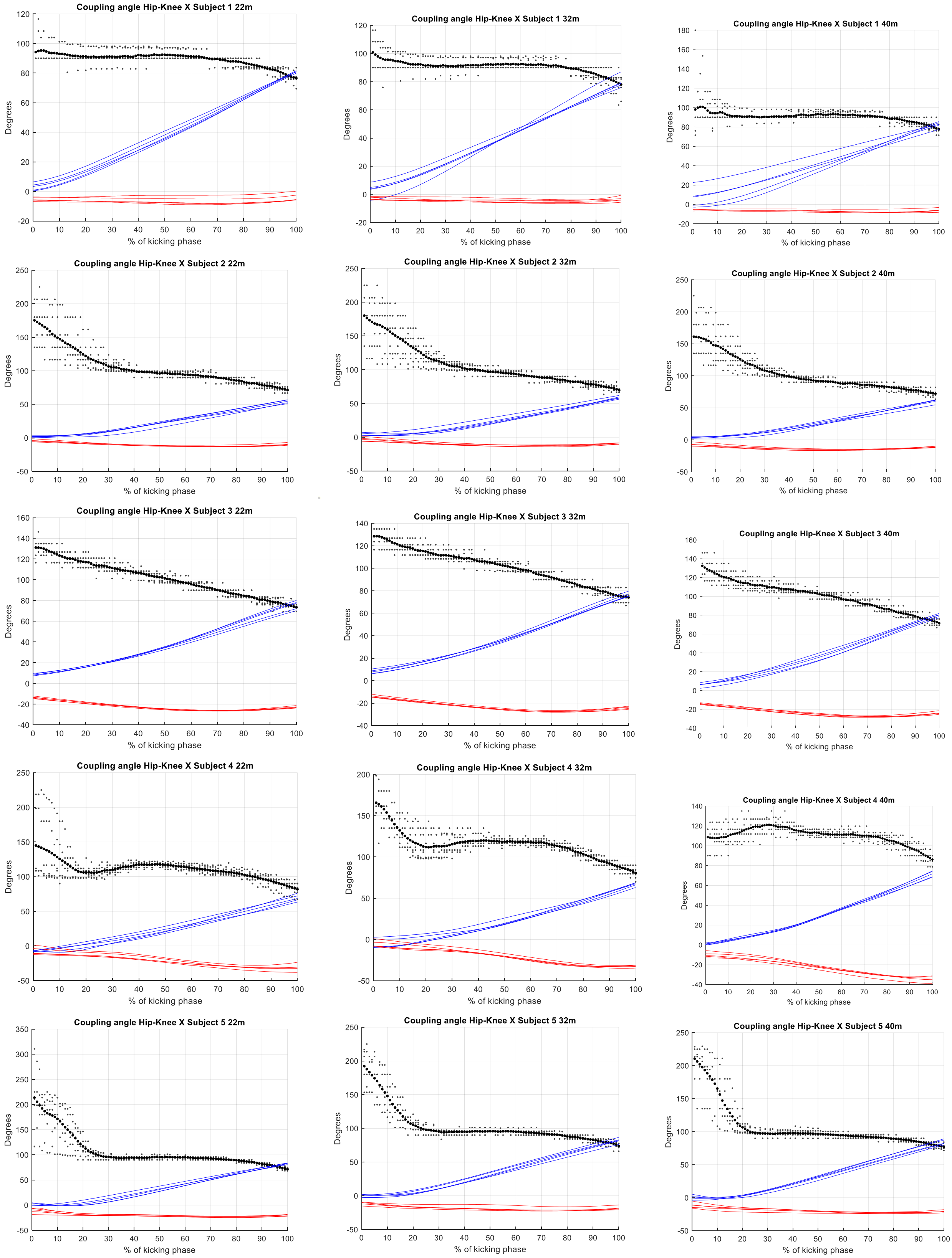
Table C.1: Marker set

Num.	Segment	Mark ID	Location Description
1	Head	LFHD	Left Front of Head
2	Head	RFHD	Right Front of Head
3	Head	LBHD	Left Back of Head
4	Head	RBHD	Right Back of Head
5	Trunk	C7	7th Cervical Vertebrae
6	Trunk	T10	10th Thoracic Vertebrae
7	Trunk	CLAV	Clavicle
8	Trunk	STRN	Sternum
9	Trunk	RBAK	Right Back
10	LArm	LSHO	Left Shoulder
11	LArm	LUPA	Left Upper Arm
12	LArm	LELB	Left Elbow
13	LArm	LFRA	Left Forearm
14	LArm	LWRA	Left Wrist Thumb Side
15	LArm	LWRB	Left Wrist Pinkie Side
16	LHand	LFIN	Left Finger
17	RArm	RSHO	Right Shoulder
18	RArm	RUPA	Right Upper Arm
19	RArm	RELB	Right Elbow
20	RArm	RFRA	Right Forearm
21	RArm	RWRA	Right Wrist Thumb Side
22	RArm	RWRB	Right Wrist Pinkie Side
23	RHand	RFIN	Right Finger
24	Pelvis	LASI	Left Anterior Superior Iliac Spine
25	Pelvis	RASI	Right Anterior Superior Iliac Spine
26	Pelvis	LPSI	Left Posterior Superior Iliac Spine
27	Pelvis	RPSI	Right Posterior Superior Iliac Spine
28	Pelvis	SACR	Sacral Wand
29	LLeg	LTHI	Lower lateral third of thigh
30	LLeg	LTHA	Left Thigh Anterior
31	LLeg	LTHP	Left Thigh Posterior
32	LLeg	LKNE	Left Knee
33	LLeg	LMFC	Left Medial Femoral Condyle
34	LShank	LFIB	Left Fibula
35	LShank	LSHI	Left Shin
36	LShank	LSHD	Left Shin Distal
37	LShank	LANK	Left Ankle
38	LShank	LMMA	Left Medial Malleolus
39	LFoot	LHEE	Left Heel
40	LFoot	LTOE	Left Toe
41	LFoot	LFLA	Left Foot Lateral Anterior
42	LFoot	LFLC	Left Foot Lateral Centre

43	LFoot	LFLP	Left Foot Lateral Posterior
44	LFoot	LFTM	Left Foot Medial
45	RLeg	RTHI	Right Thigh
46	RLeg	RTHA	Right Thigh Anterior
47	RLeg	RTHP	Right Thigh Posterior
48	RLeg	RKNE	Right Knee
49	RLeg	RMFC	Right Medial Femoral Condyle
50	RShank	RFIB	Right Fibula
51	RShank	RSHI	Right Shin
52	RShank	RSHD	Right Shin Distal
53	RShank	RANK	Right Ankle
54	RShank	RMMA	Right Medial Malleolus
55	RFoot	RHEE	Right Heel
56	RFoot	RTOE	Right Toe
57	RFoot	RFLA	Right Foot Lateral Anterior
58	RFoot	RFLC	Right Foot Lateral Centre
59	RFoot	RFLP	Right Foot Lateral Posterior
60	RFoot	RFTM	Right Foot Medial
61	Ball	Ball1	Ball Top
62	Ball	Ball2	Ball Front Centre
63	Ball	Ball3	Ball Right Centre
64	Ball	Ball4	Ball Left Centre

Source: Vicon, 2019

APPENDIX D: INDIVIDUAL COUPLING ANGLES



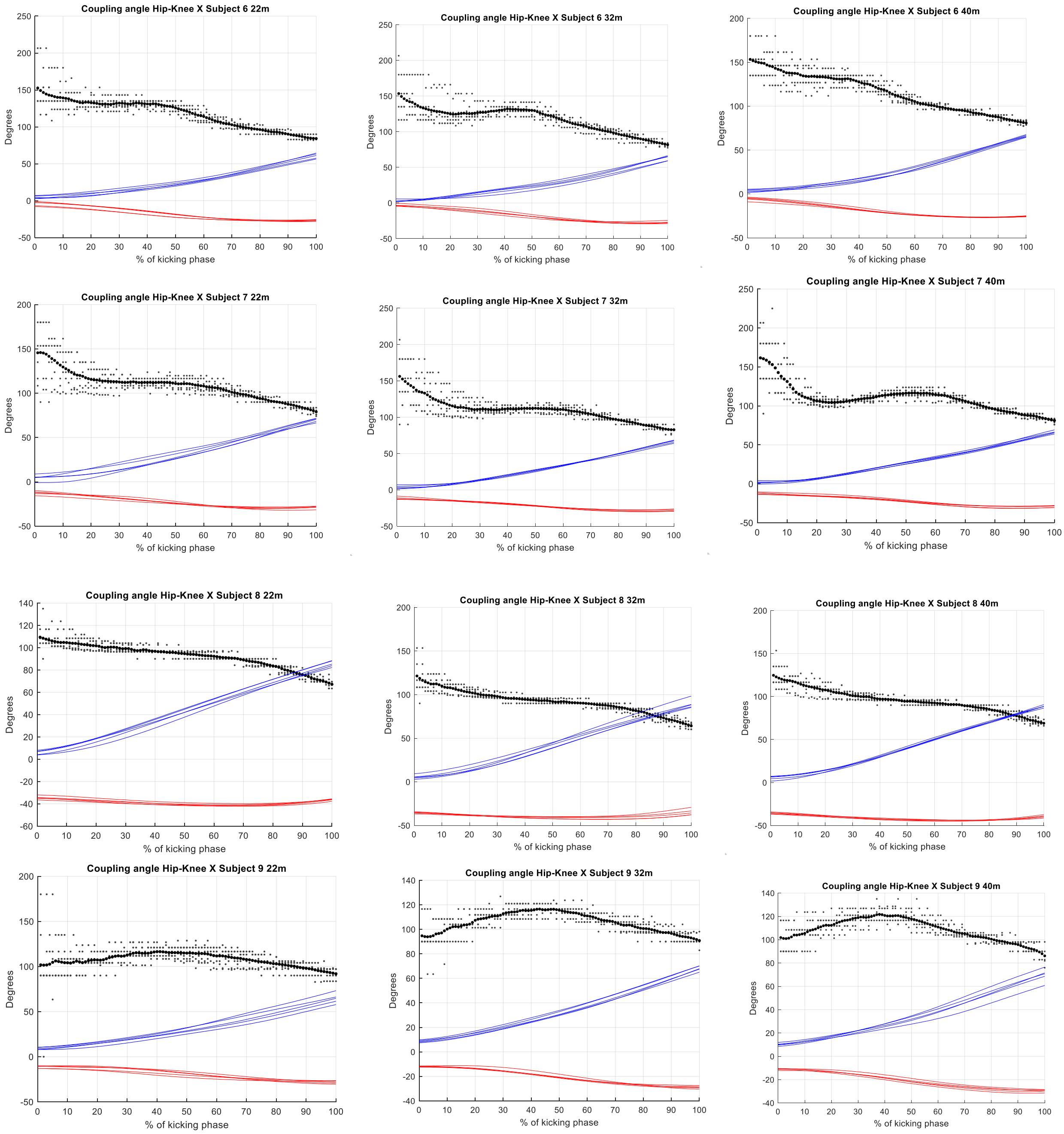


Figure D.1: Coupling angle (hip-knee sagittal) backswing for 22 m, 32 m, and 40 m kicks

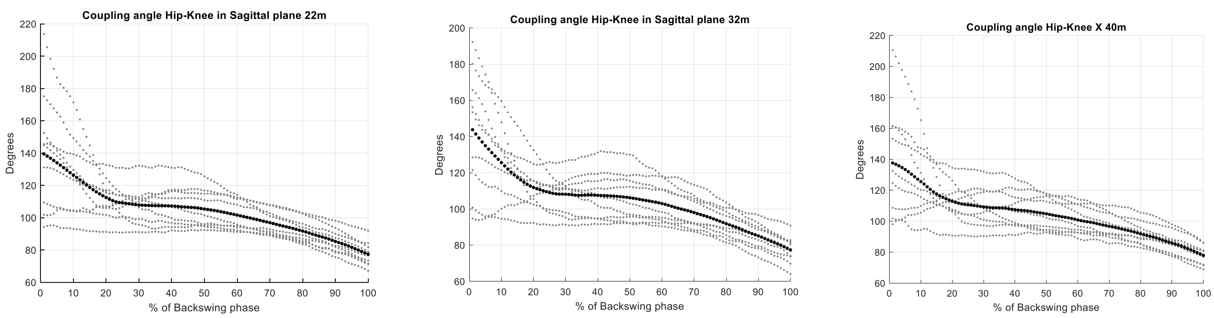
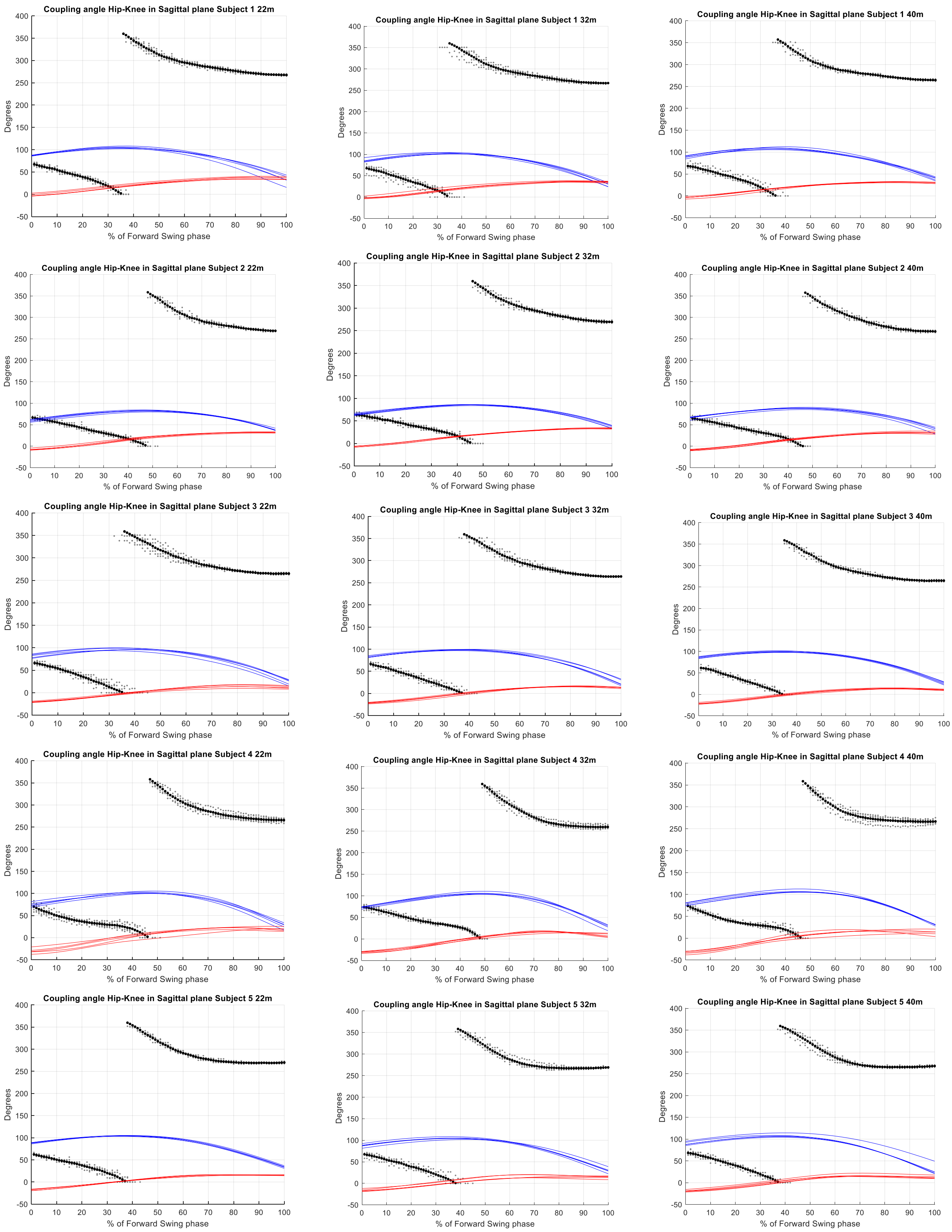


Figure D.2: Group means


Coupling angle Hip-Knee in Sagittal plane Subject 1 22m
Coupling angle Hip-Knee in Sagittal plane Subject 1 32m
Coupling angle Hip-Knee in Sagittal plane Subject 1 40m
Coupling angle Hip-Knee in Sagittal plane Subject 2 22m
Coupling angle Hip-Knee in Sagittal plane Subject 2 32m
Coupling angle Hip-Knee in Sagittal plane Subject 2 40m
Coupling angle Hip-Knee in Sagittal plane Subject 3 22m
Coupling angle Hip-Knee in Sagittal plane Subject 3 32m
Coupling angle Hip-Knee in Sagittal plane Subject 3 40m
Coupling angle Hip-Knee in Sagittal plane Subject 4 22m
Coupling angle Hip-Knee in Sagittal plane Subject 4 32m
Coupling angle Hip-Knee in Sagittal plane Subject 4 40m
Coupling angle Hip-Knee in Sagittal plane Subject 5 22m
Coupling angle Hip-Knee in Sagittal plane Subject 5 32m
Coupling angle Hip-Knee in Sagittal plane Subject 5 40m
Degrees
% of Forward Swing phase

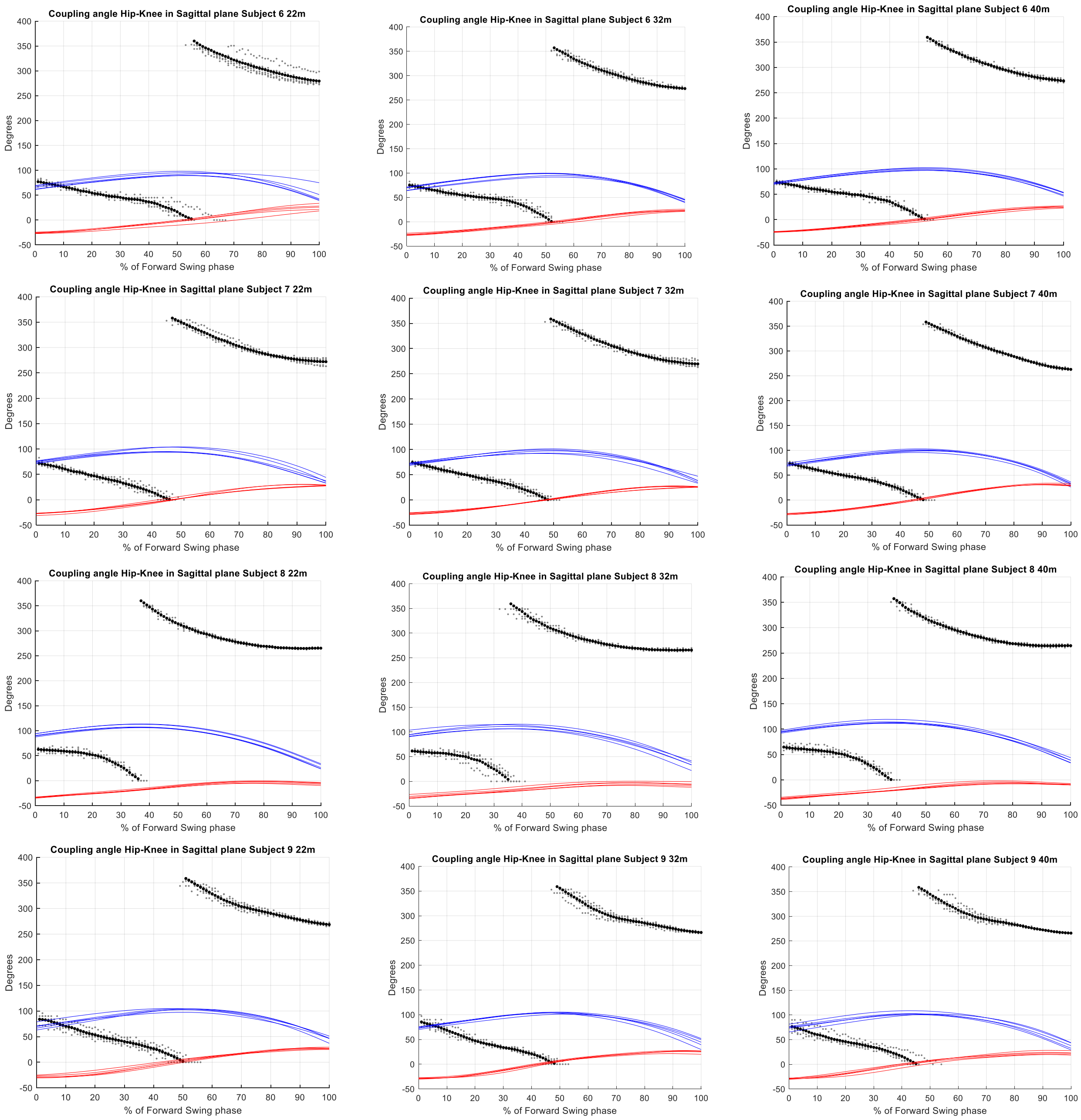


Figure D.3: Coupling angle (hip-knee sagittal) forward swing for 22 m, 32 m, and 40 m kicks

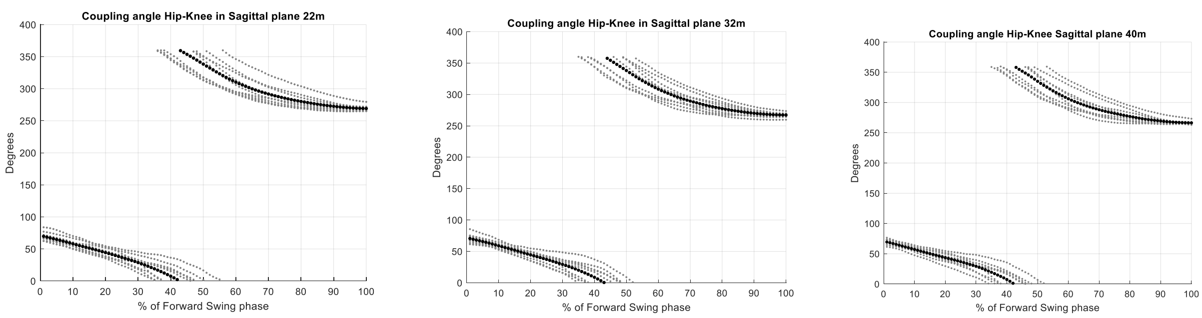
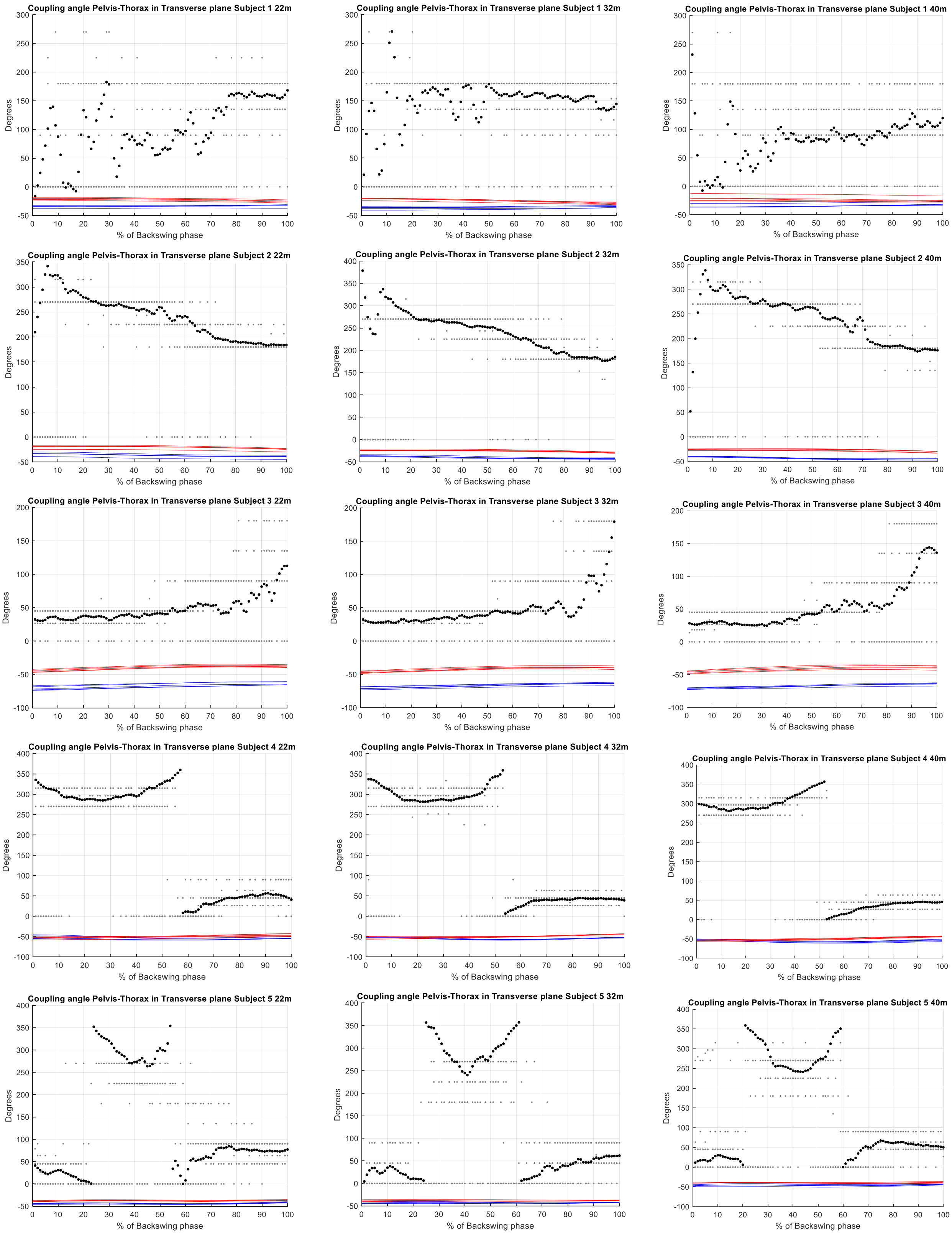


Figure D.4: Group means


Coupling angle Pelvis-Thorax in Transverse plane Subject 1 22m
Coupling angle Pelvis-Thorax in Transverse plane Subject 1 32m
Coupling angle Pelvis-Thorax in Transverse plane Subject 1 40m
Coupling angle Pelvis-Thorax in Transverse plane Subject 2 22m
Coupling angle Pelvis-Thorax in Transverse plane Subject 2 32m
Coupling angle Pelvis-Thorax in Transverse plane Subject 2 40m
Coupling angle Pelvis-Thorax in Transverse plane Subject 3 22m
Coupling angle Pelvis-Thorax in Transverse plane Subject 3 32m
Coupling angle Pelvis-Thorax in Transverse plane Subject 3 40m
Coupling angle Pelvis-Thorax in Transverse plane Subject 4 22m
Coupling angle Pelvis-Thorax in Transverse plane Subject 4 32m
Coupling angle Pelvis-Thorax in Transverse plane Subject 4 40m
Coupling angle Pelvis-Thorax in Transverse plane Subject 5 22m
Coupling angle Pelvis-Thorax in Transverse plane Subject 5 32m
Coupling angle Pelvis-Thorax in Transverse plane Subject 5 40m
Degrees
% of Backswing phase

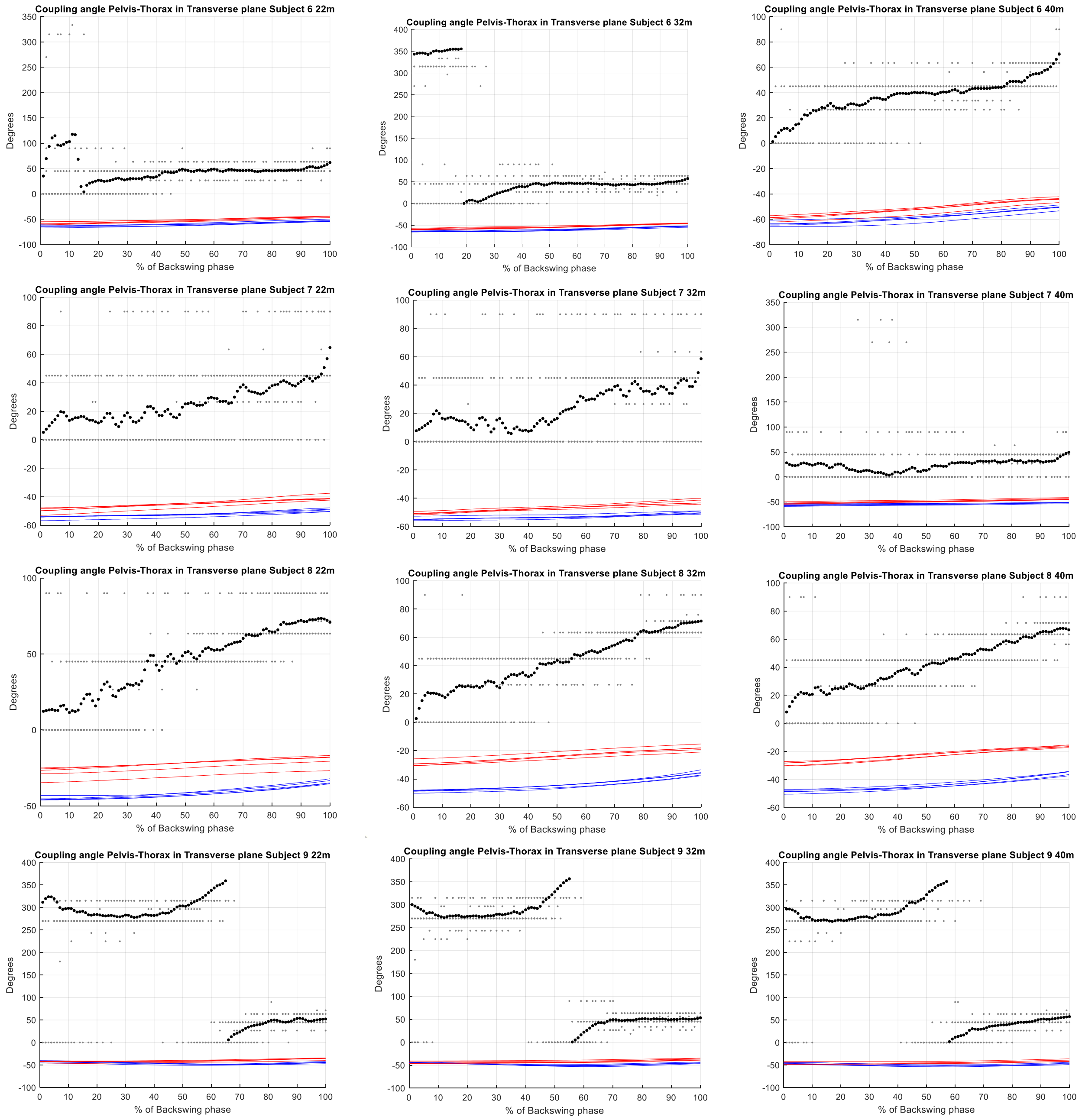
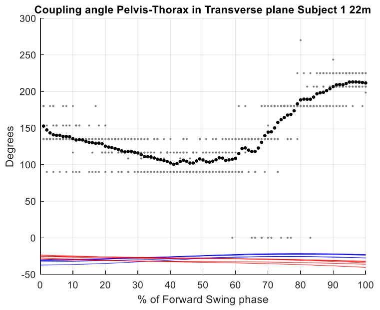
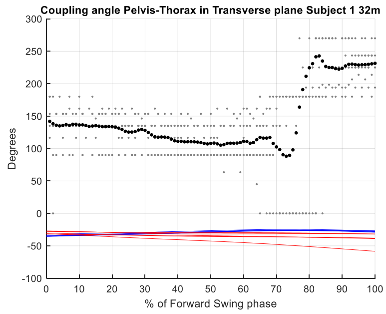
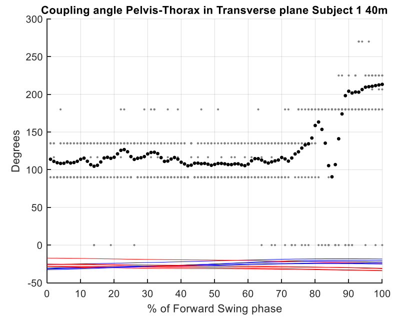


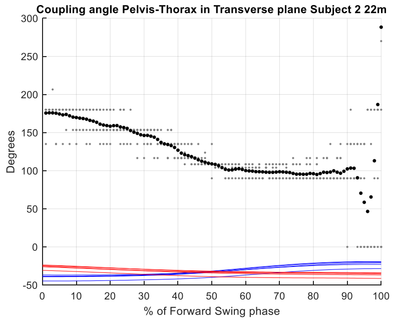
Figure D.5: Coupling angle (pelvis-thorax transverse) backswing for 22 m, 32 m and 40 m kicks

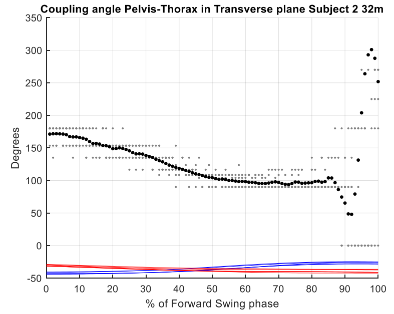
Figure D.6: Group means

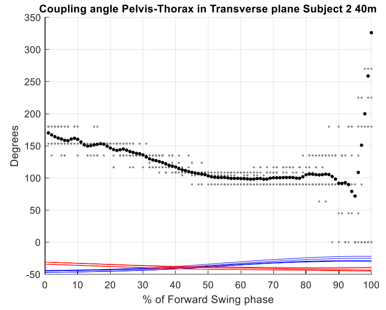

Coupling angle Pelvis-Thorax in Transverse plane Subject 1 22m
Degrees
% of Forward Swing phase

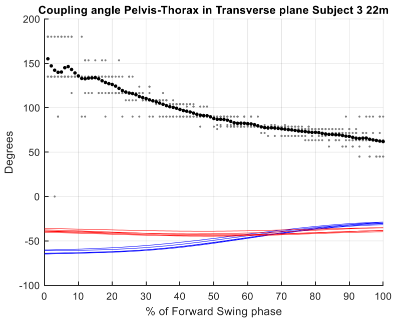

Coupling angle Pelvis-Thorax in Transverse plane Subject 1 32m
Degrees
% of Forward Swing phase

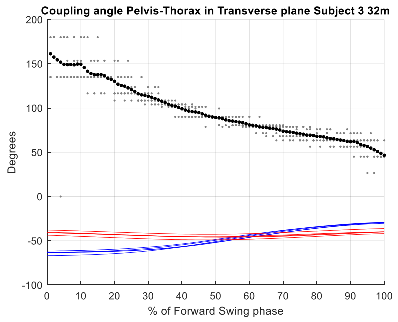

Coupling angle Pelvis-Thorax in Transverse plane Subject 1 40m
Degrees
% of Forward Swing phase

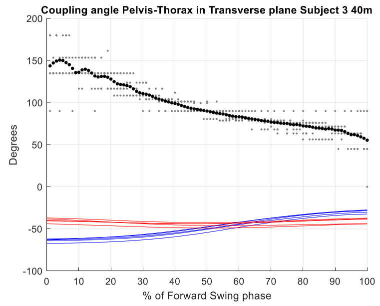

Coupling angle Pelvis-Thorax in Transverse plane Subject 2 22m
Degrees
% of Forward Swing phase

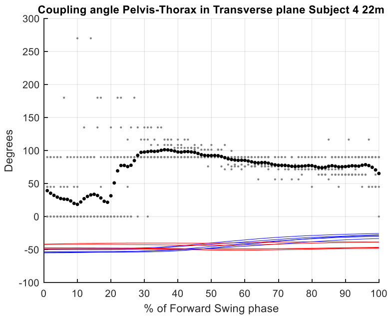

Coupling angle Pelvis-Thorax in Transverse plane Subject 2 32m
Degrees
% of Forward Swing phase

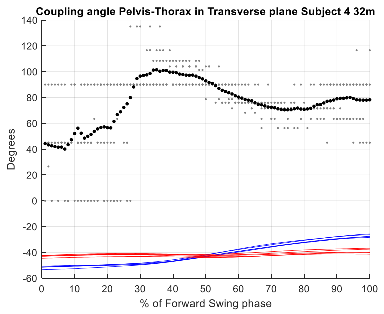

Coupling angle Pelvis-Thorax in Transverse plane Subject 2 40m
Degrees
% of Forward Swing phase

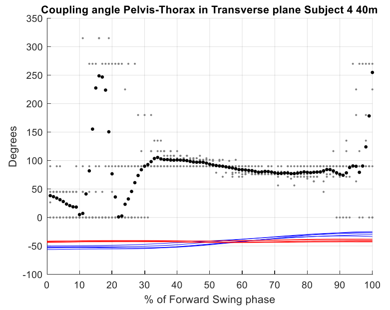

Coupling angle Pelvis-Thorax in Transverse plane Subject 3 22m
Degrees
% of Forward Swing phase

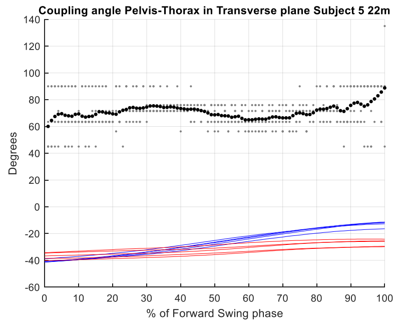

Coupling angle Pelvis-Thorax in Transverse plane Subject 3 32m
Degrees
% of Forward Swing phase

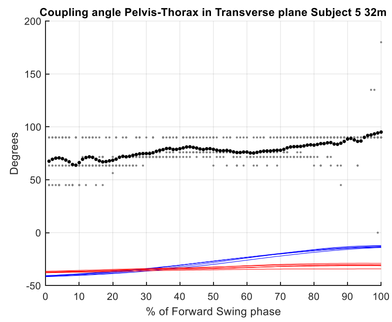

Coupling angle Pelvis-Thorax in Transverse plane Subject 3 40m
Degrees
% of Forward Swing phase

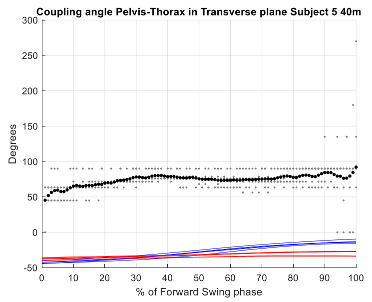

Coupling angle Pelvis-Thorax in Transverse plane Subject 4 22m
Degrees
% of Forward Swing phase


Coupling angle Pelvis-Thorax in Transverse plane Subject 4 32m
Degrees
% of Forward Swing phase


Coupling angle Pelvis-Thorax in Transverse plane Subject 4 40m
Degrees
% of Forward Swing phase


Coupling angle Pelvis-Thorax in Transverse plane Subject 5 22m
Degrees
% of Forward Swing phase


Coupling angle Pelvis-Thorax in Transverse plane Subject 5 32m
Degrees
% of Forward Swing phase


Coupling angle Pelvis-Thorax in Transverse plane Subject 5 40m
Degrees
% of Forward Swing phase

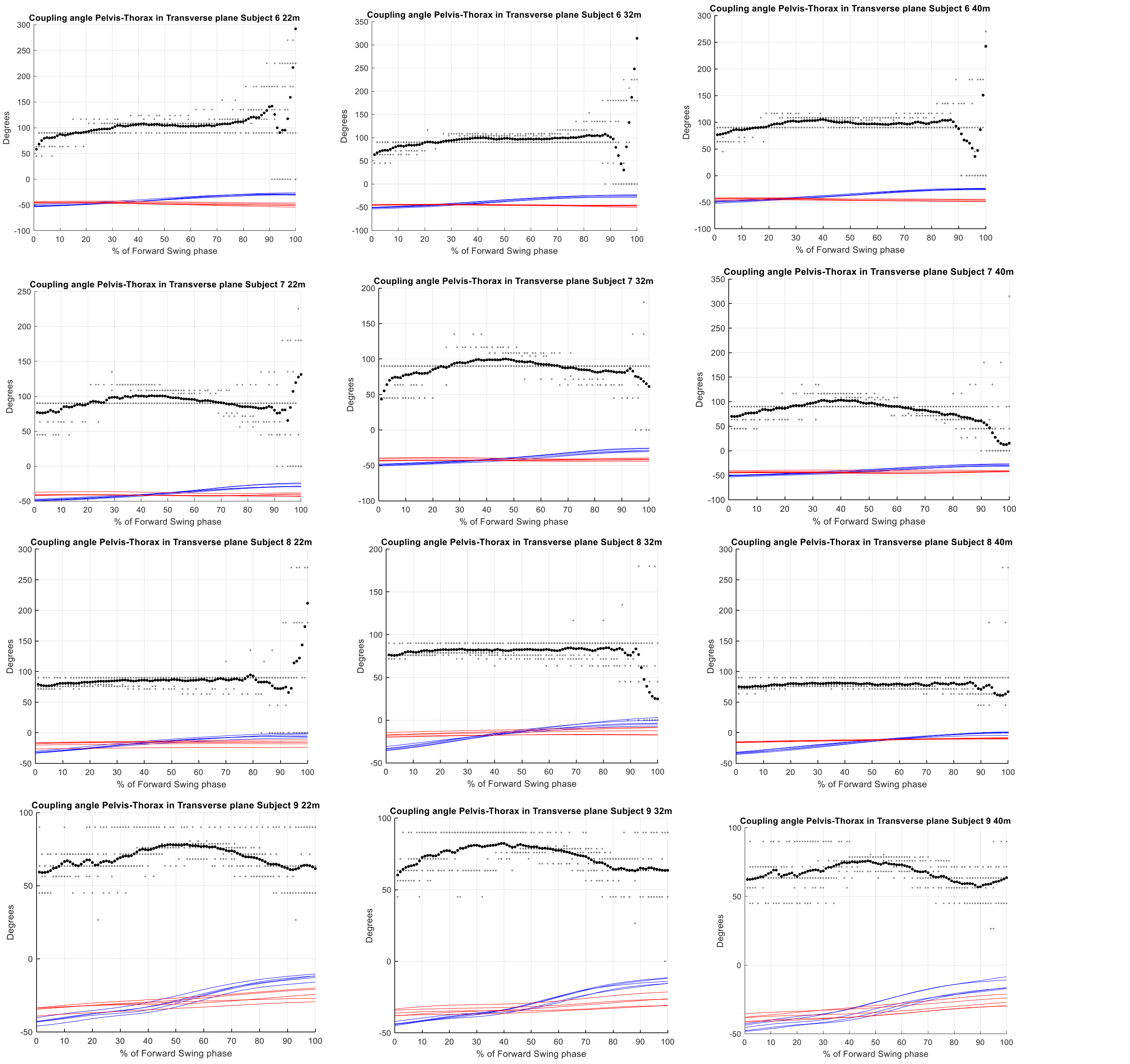


Figure D.7: Coupling angle (pelvis-thorax transverse) forward swing for 22 m, 32 m, and 40 m kicks

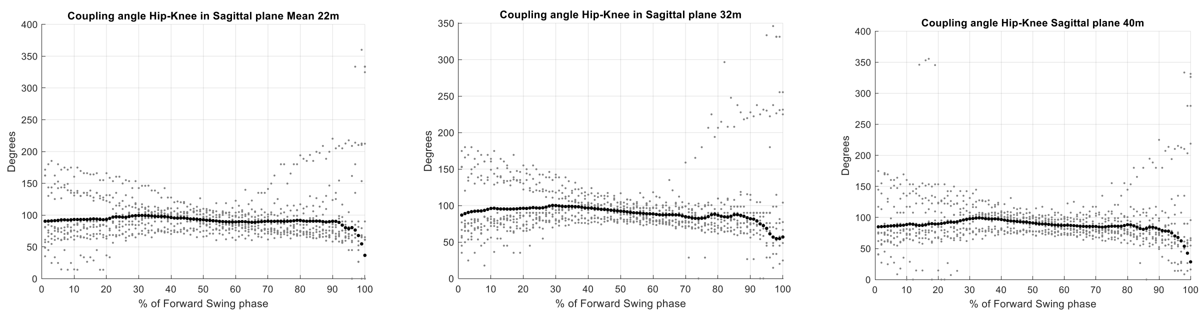


Figure D.8: Group means

APPENDIX E: TURNITIN REPORT

E.Mathewson_Final

ORIGINALITY REPORT

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SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

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