Biomechanical aspects of postural balance strategy in dynamic sport activities

By

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ABSTRACT

Postural balance is one of the most important aspects in everyday movement, especially in complex movements such as jumping, kicking or movements involving overhead/arm motion. In sporting activities, players often need to complete goal-directed tasks of an end-effector (e.g. tennis racket), while also needing to control their balance, in order to produce a successful task. However, studying the interaction between postural balance and end-effector control, in a biomechanical context and particularly in the tennis serve is difficult and remains largely unexplored. Traditionally, to explore postural balance researchers have to observe the whole-body centre of mass (CoM) location. However, for marker based motion capture systems, collecting and processing data is time consuming. If the researchers are interested in examining the movements of only some parts of the body, then reductions in model complexity may be possible while still retaining an ability to track CoM location. Therefore, the first aim of this research was to find an appropriate biomechanical model to quantify accurate whole-body (X)CoM representation. The second aim was then to investigate the interaction between postural balance control and end-effector performance, during the tennis serve, within a single target location and between different serving locations.

The first study of this thesis showed that antero-posterior and medio-lateral displacement profiles of the CoM representation, based on the lower limbs, trunk and upper limbs showed strong agreement with the full-body model, and this only slightly reduced for the lower limbs and trunk only. Representations based on the lower limbs only showed less agreement, particularly for the extrapolated CoM (XCoM) in kicking. Our results justified the use of some model reductions for specific needs, saving measurement effort whilst limiting the error of tracking (X)CoM trajectories in the context of whole-body balance investigation.

The second study of this thesis demonstrated that there is no direct interaction between the XCoM displacement, the changes in arms/trunk angular momentum, and maximum racket velocity during the preparation, propulsion and forward swing phases of a tennis serve. Only in the forward swing phase, a significant relationship between trunk angular momentum and maximum racket velocity was found which means the trunk segmental acceleration may play a role in controlling balance when generating the maximum racket velocity during the serve towards this target location.

The third and final study in this thesis focussed on only the forward swing phase, and indicated that only the change in arms angular momentum influenced the maximum racket velocity. This was found specifically when serving into the wider part of the advantage court. Furthermore, individual relationships were evident between serving conditions.

The novel approach introduced in this thesis, and the key outcomes of the work, have the potential to give researchers, coaches and athletes, who are working and playing in relevant dynamic sporting tasks, an opportunity to better understand the interaction between how control of the end-effector adapts while maintaining postural stability during the serve. Moreover, the work also guides the choice of biomechanical marker sets to estimate centre of mass during dynamic activity.

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PUBLICATIONS AND COMMUNICATIONS

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GLOSSARY OF TERMS AND ABBREVIATIONS

A/P: Antero-Posterior

BoS: Base of Support

cm: Centimetre

CoM: Centre of Mass

CoP: Centre of Pressure

FB: Full Body Biomechanical/Kinematic Model

g: Acceleration of Gravity

Hz: Hertz

I: Moments of Inertia

kg: Kilogram

LL: Lower Limbs Model

LL+T: Lower Limbs and Trunk Model

LL+T+DUL: Lower Limbs, Trunk and Dominant Upper Limbs Model

LL+T+UL: Lower Limbs, Trunk and Upper Limbs Model

l: Pendulum Length

LoA: Limits of Agreement

min: Minute

M/L: Medio-Lateral

MoS: Margin of Stability

m/s: metre per second

SD: Standard Deviation

SPM: Statistical Parametric Mapping

SPM1D: One-Dimensional Statistical Parametric Mapping

T+DUL: Trunk and Dominant Upper Limbs Model

T+UL: Trunk and Upper Limbs Model

XCoM: Extrapolated Centre of Mass

β: Beta

ω: Angular Velocity

BACKGROUND

Dynamic tasks are an inherent part of sports as dynamic interceptive movement and are fundamental to sports performance (Davids et al., 2001). Most dynamic sporting tasks are complex and multi-directional which involve a task-specific and goal-directed component such as jumping, kicking, and throwing/striking together with a whole body balancing component. The task-specific demand has been of particular interest to improve sports performance. Most sports performances need both speed and accuracy, however, it is difficult to have high speed with high accuracy at the same time. High-speed movement has to be reduced in order to increase movement accuracy, also reducing the variability in performance. However, an increase in the amount of movement variability could affect the tennis serve performance in a negative way by reducing speed and accuracy of the ball (Antúnez et al., 2012). This is, for example, evident in tennis where an increased success rate of a second serve is typically guaranteed by reducing the serving speed. The consideration that reduced variability leads to better performance has been a key principle for learning new skills. Nevertheless, even elite athletes who have top performance still show some variability. In fact, whereas previously it was believed that there are optimal or ideal movement patterns which athletes should follow to achieve the best performance, it has now been shown that functional movement variability exists even in elite athletes who are well trained (Bartlett et al., 2007). That variability could represent performer adaptations to environmental conditions and facilitate optimizations in coordination patterns (Langdown et al., 2012; Bartlett, 2007).

Generally, coaches and athletes still believe that good whole body balance (often referred to also as stability) and end-effector consistency (focusing on stroke arm and racket) in dynamic movements such as the tennis serve are key performance indicators. However, a movement like the tennis serve involves upper limb movement for tossing and striking of the ball, combined with balancing the whole body over the base of support, and so it may be expected that both aspects of the movement interact with each other. The player is expected to control their whole body balance while moving their arms and other segments to strike the ball. Understanding how tennis serve key performance characteristics affect balance mechanisms and vice versa is therefore of importance for coaches, athletes and researchers.

The investigation of balance mechanisms in dynamic sporting tasks has been limited, let alone in combination with end-effector performance indicators. One prior concern is the difficulty of gathering the motion capture data required for such investigation. There is still a need for reliable and time-efficient evaluation of whole body movement, and improving this will advance our abilities to investigate balance strategies in dynamic sporting tasks in future studies.

CHAPTER 1: Literature Review

The aim of this literature review is to provide the reader with information as to the current literature on 1) the tennis serve; 2) the role of movement variability in the performance of a serve; 3) the control mechanisms of postural balance and the interaction between postural balance control and movements that control racket motion (end-effector) and, finally, 4) biomechanical marker models employed to quantify whole-body centre of mass motion during dynamic sports movements. The aims and objectives of this thesis are further outlined at the end of this chapter.

1.1 Tennis serve

Performance in tennis is dictated by tactical aspects, physical aspects, psychological aspects and, to a great extent, the ability to execute a wide variety of stroke techniques. The serve is arguably the most important stroke as it is the start of every play and the only stroke in which the player has full control over its outcome (Reid, Whiteside, & Elliott, 2011). However, the serve is also the most difficult stroke to learn because of the coordination required of the complex motions of both upper and lower limbs. Most biomechanical studies produced to help understand the tennis serve have been limited to addressing either the kinematics of ball, racket, and upper extremities (Reid et al., 2011; Reid et al., 2013; Whiteside et al., 2013a; Whiteside et al., 2013b), kinetics of joints (de Subijana and Navarro 2009; Martin et al., 2014) or biomechanics of tennis injury (Bylak and Hutchinson, 1998; Eygendaal, et al., 2007; Kibler & Safran, 2000; Van der Hoeven and Kibler, 2006).

In term of tennis performance, biomechanics plays a role in the process of serve mechanics change and provides modifications that can be made, as well as an understanding of individual stroke mechanics that can lead to improved performance. Tennis serve speed is primarily a factor of tennis technique using the kinetic chain. The serve requires power and a number of body segments must be coordinated in such a way that a high racket speed is generated at impact. Efficient function, with maximal performance and minimal risk of injury, requires optimum activation of all the links in the kinetic chain designed for power (Elliott, 2006). The coaches and players often focus on the critical points (shown in figure 1.1 the model of the power serve) when aiming to produce a power serve (Elliott et al., 2003). However, postural balance control is not included in the model of power serve, yet it might be considered essential for effective segmental coordination and the development of racket speed.

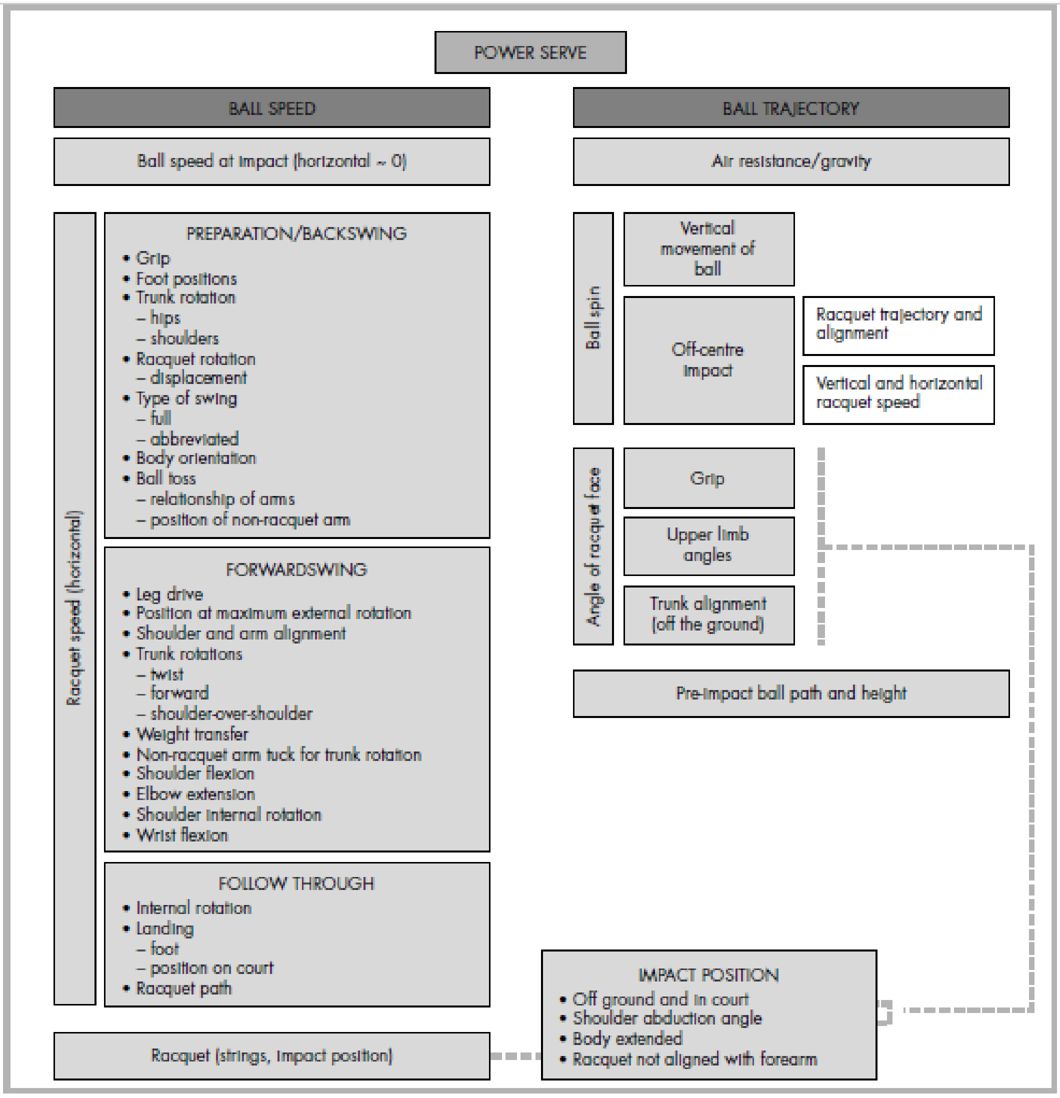

Figure 1.1. A model of the power serve in tennis (Reid, Elliott, and Crespo, 2003).

The tennis serve comprises a number of phases, including preparation, the swing to the ball (propulsion) and the follow-through (Elliott et al., 2003; D. Whiteside, et al., 2013a). The tennis serve is a complex movement with many segmental rotations contributing to the end-effector motion (the end effector is defined as the end of the dominant arm or a tool that is connected to the end of the dominant arm, in this case, it is a racket). The serve motion starts from the ready position. Then there is ball release from the non-dominant hand, the shoulder of the dominant arm begins moving up and externally rotating, the legs start to drive up before the arm begins its internal rotation, the body twists, while the knees and hips flex and the back extends and rotates. Finally shoulder internal rotation and then wrist flexion add to the transfer of force and velocity to hit the ball (Elliott, 2006; Marshall & Elliott, 2000; Tanabe & Ito, 2007).

At the same time, pronation and extension at the elbow act to orientate the racket in a manner befitting the desired impact (Bahamonde, 2005; Elliott, 2006). This serving strategy can be explained by kinematics that befit the kinetic chain theory as the skilled execution of the serve involves a movement sequence in which to control lower limbs, trunk and serving arm to generate racket head speed and to ultimately transfer the force, velocity and momentum of the racket to the ball (Bahamonde, 2000). The momentum is transferred to the serving arm particularly through transverse, frontal and sagittal plane trunk rotations (Bahamonde, 2000; Elliott, 2006; Martin, et al., 2013). A series of photographs of different part of the tennis serve is shown in figure 1.2.

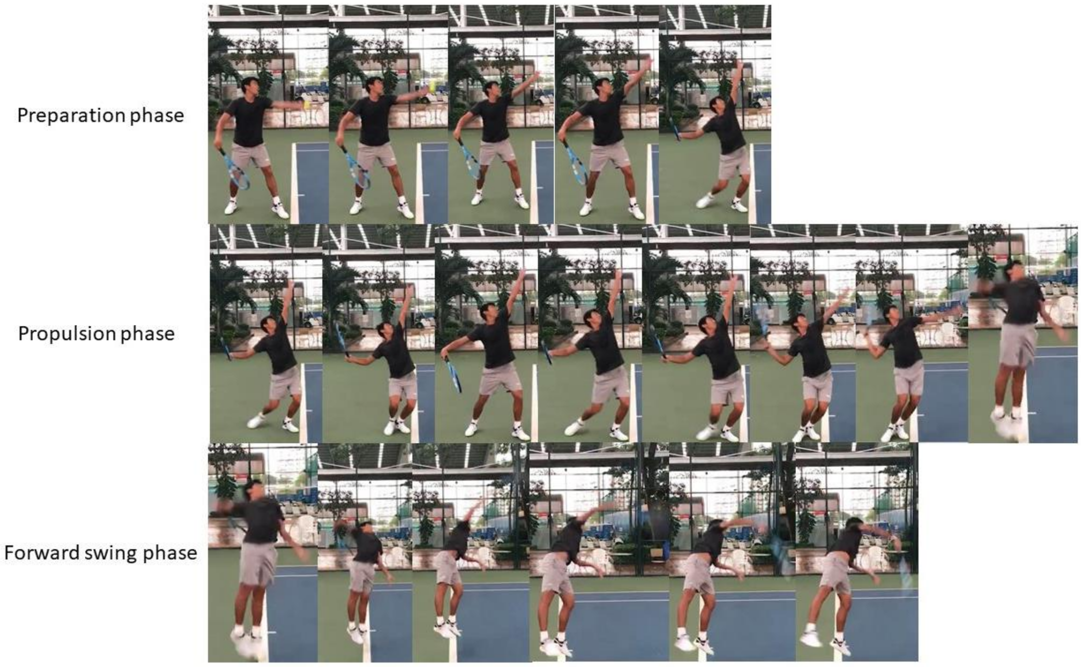

Figure 1.2. A series of photographs of different part of the tennis serve.

As the execution of the serve relates to the coordination of many segments, considerable variations in this execution are expected to exist between individuals as well as within individuals (inter-trial variation). There are many possible technique variations that exist for executing a tennis serve and would explain between variations – e.g., the standing position to preparing to serve (foot position techniques). For example, based on player preference and schooling background, players typically use either a foot-up (FU) or foot-back (FB) technique for the upward drive of the trunk, with the FB technique allowing the player to get more drive from the back leg. In the FB technique players leave the rear foot back during the early movement of the racket and then swing this foot around and forward prior to impact, while with a FU technique players bring the back foot up to the front prior to pushing forward and upwards to the ball (Elliott et al., 2003). Furthermore, based on game situation, three main types of commonly performed serves exist – flat, kick and slice (Elliott, 1983). A flat serve is characterised by faster ball speeds and less spin than the kick or slice serve, usually used as the first serve. Kick serves have larger ball spin rates and are typically used as second serve (Chow et al., 2003), and slice serves can be used as either first or second serves and the spin direction causes the ball to bounce away from the opposing player. Notably, the racket and subsequent ball velocity changes from the first to second service action (Chow et al., 2003). Flat serves provide the maximum momentum transfer to the ball, while slice serves provide an appropriate mix of speed and spin and a kicker serve primarily produces topspin (whereby the ball bounces up) and slice. Slightly different body segment orientations produce the various racket face alignments needed for impact in the different serve types. Additionally, ball toss location may vary due to technique variations, and it forces the players to adjust their body movement from serve to serve (Whiteside et al., 2015). It is important to note that the skill level of each player – i.e., beginner, moderate or expert – may affect the technique variations employed, with the different locations served to also being impacted upon. So overall, many factors can affect the variations in serve execution between players, but due to the complexity of the movement also within players.

The tennis serve is a complex and highly dynamic movement. Hence, the control of whole body balance during the serve requires a complex interaction of intersegmental movements, ultimately moving the whole body centre of mass (CoM) along a desired trajectory, which may not be within the base of support (BoS). One can see this complexity come to the fore when observing the many counter rotations of segments in a tennis serve that ultimately serve to avoid building undesirable angular momentum of the body, i.e. avoid generating forward or backward lean that compromises subsequent on-court positioning. During the serve, the tennis player attempts to lean in a forward direction during the serve, flexes their knee to add power to their serve, or moves their trunk and upper limbs backward in the backward swing (and forward in the forward swing phase). Due to the consequent change in CoM location, some players may change the BoS by taking a step to maintain stability. As momentum can be transferred to drive a segment forward or backward and ultimately maximize the velocity and spin on the ball after impact, it is advantageous for tennis players to generate as much linear momentum as possible. However, the serve also requires balance control (see section 1.3) in which excessive amounts of segmental angular momentum tend to be undesirable. Therefore, the extent to which the performance of the serve may well interfere with balance control, or vice versa, makes it worthwhile to look into how balance control mechanisms are used and whether these interact with end-effector performance. First, the notion that within-individual variation in the execution of a tennis serve exists and may hold relevant information for this investigation is considered.

1.2 Movement Variability

The study of movement variability has become popular in the sports biomechanics community (Davids et al., 2006; Hamill et al., 2006; Preatoni et al.,, 2010; Preatoni et al., 2013; Bartlett, 2007). Preatoni and colleagues (2013) have revealed, in a review as to the role of movement and coordination variability in sports movement, as well as the skills monitoring of athletes that movement variability may contain important information about the neuro-musculo-skeletal organisation regarding the nature of the movement variability that happened during sports movements (Preatoni et al., 2013). Notably, when a movement is performed repeatedly, even if the goal remains constant, the motions of the body segments will exhibit some variability and even the elite athlete does not reproduce identical motor patterns (Bernstein, 1930; Preatoni et al., 2013; Bartlett, 2007). The traditional interpretation of movement variability used to be that this is undesirable noise in an otherwise uniquely optimal movement pattern (Elliott et al., 2009; Dhawale et al., 2017; Davids et al., 2003; Preatoni et al., 2013; Bartlett, 2007). However, in the past 15 years researchers have identified that variability may well be functional in order to allow for subtle adaptations to environmental constraints. Such ability to adapt for environmental constraints, with weather conditions as only one of many examples, may have a positive effect on consistency of performance, and may in fact reduce injury risk (Davids et al., 2003; Preatoni et al., 2013; Bartlett, 2007). Knudson (1990) has illustrated that movement variability that occurred when the players hitting the forehand drives and found that wrist and elbow angular positions were generally consistent at impact, yet this consistency was not the result of highly stable patterns of angular velocity or acceleration at the same joints. Instead, the position of the racket at impact was achieved through different movement strategies, particularly by variations in the joint speeds of motion. In other sports – like javelin throwing and basketball shooting – similar patterns of action (variable joint motion leading to a more consistent end point) have been observed (Bartlett, 2007), whereby it has been demonstrated that mechanical variability exists even within the 'same' shot. Moreover, the amount of variability in relation to performance and coordination can change with the skill level held (Schöllhorn et al., 2009; Scholz et al., 2000). As such, movement variability may contain relevant information in sporting tasks.

A possible explanation for variability in end-effector could be that it is a consequence of variations elsewhere in the system. For example, the variability of movement patterns near the time of hitting the ball may well be the consequence of movement alterations to compensate for variations in the ball toss (Whiteside et al., 2014). Despite the variable ball toss, the temporal composition of the serve is nonetheless highly consistent as players use the location of the ball to regulate their movement. This means that one can expect players to be able to adapt or to modify their tennis stroke to accommodate for variations in the serve. It is also possible that other aspects determine end-effector variations, such as, for example variations in the controlling of whole body postural balance, but to our knowledge has yet to be investigated.

1.3 Control Mechanisms

In building upon the above discussions as to movement variability, attention is turned to the control mechanism. When studying the interaction between postural balance and end-effector performance, it is important to briefly review the literature around the control of both aspects individually. Firstly, control of postural balance is introduced, with particular focus on the movement of segments for controlling the position of the centre of mass (CoM) relative to the base of support (BoS). Secondly, control of the end-effector is explored, with particular attention to the role of inter-segmental motions.

1.3.1 Postural Balance Control

Postural balance is an essential aspect of our daily life activities and directly relates to the central nervous system. Sensorimotor control of postural balance is a complex interplay between various sensorial systems (vision, proprioception, vestibular) and neural control (Horak, 2006). The strategies employed depend upon many factors including the characteristics of the external postural displacement, the individual's expectations, goals and prior experience. Any voluntary limb movements interfere with postural balance, demonstrated as anticipatory postural adjustments to maintain postural stability by compensating for the destabilising forces associated with the moving of the limb. Besides the sensorimotor control aspects of postural balance, there is an important biomechanical constraint to postural balance. The most essential biomechanical constraint on balance control is the size and quality of the BoS. This BoS determines at any moment in time the confines over which an individual can move their CoM and maintain equilibrium. Thus, equilibrium is not a particular position but movement within a space determined by the limits of the support base, taking into account the limitations of joint ranges of movement, muscle strength, and sensory information available in detecting those limits.

From a mechanical perspective, three mechanisms of balance have been described (Hof, 2007). Mechanism 1 pertains to moving the centre of pressure (CoP) with respect to the vertical projection of the CoM, a well-known mechanism typically referred to as the inverted pendulum mechanism (see Figure 1.3a). Mechanism 2, the so-called counter-rotation of segments, is seen in situations where the boundaries of the BoS provide insufficient room for displacement of the CoP to control the CoM. In this mechanism, parts of the body (mostly the trunk and upper limbs) are rotated with respect to the CoM (Otten, 1999), and the conservation of the whole body angular momentum makes that the rest of the body (typically the lower extremities) will rotate or intend to rotate in the opposite direction (see Figure 1.3b). Finally, Mechanism 3 corresponds to the use of an external force being applied to the environment – such as when the subject would lean against a wall (see Figure 1.3c).

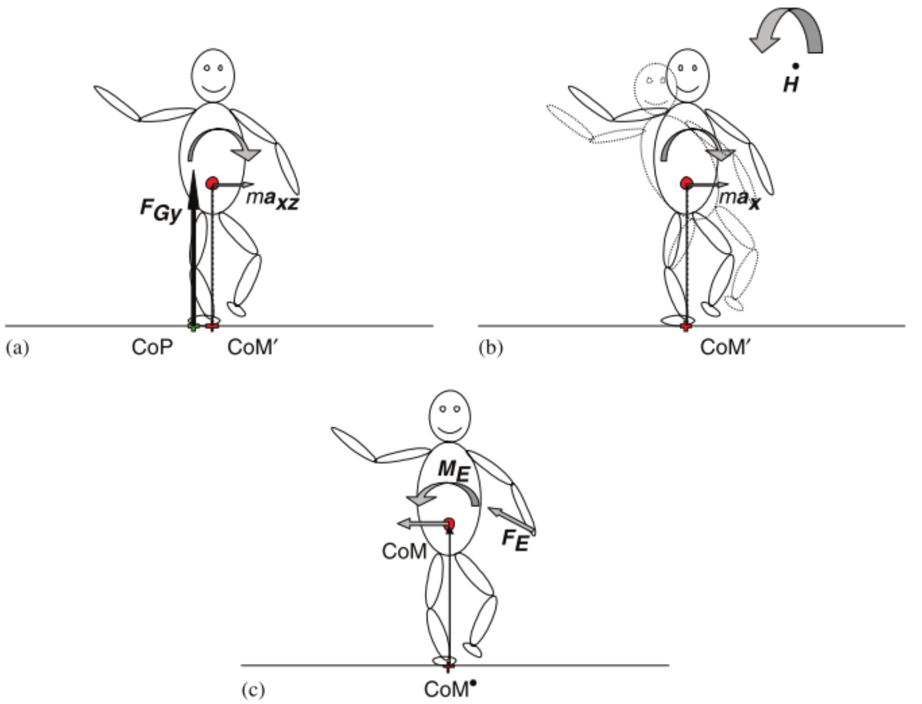

Figure 1.3. The three mechanisms for balance, as outlined by Hof (2007), which correspond to (a) Mechanism 1 and the moving of the CoP, (b) Mechanism 2 and the counter-rotation of segments and (c) Mechanism 3 and the application of an external force. H represented the rate of change of angular momentum (adapted from Hof, 2007).

The general balancing behaviour in terms of the interaction between the XCoM and the moving BoS during the serve. The figure shows the XCoM displacement relative to the boundary of the front foot (left foot) during the serve when both players are on the floor and during the flight phase shown in figure 1.4. Furthermore, the figure 1.4 was introduced in which the unstable situation towards the end of the propulsion phase and the stability options following the landing from the serve was described (regain stability in a baseline serve.

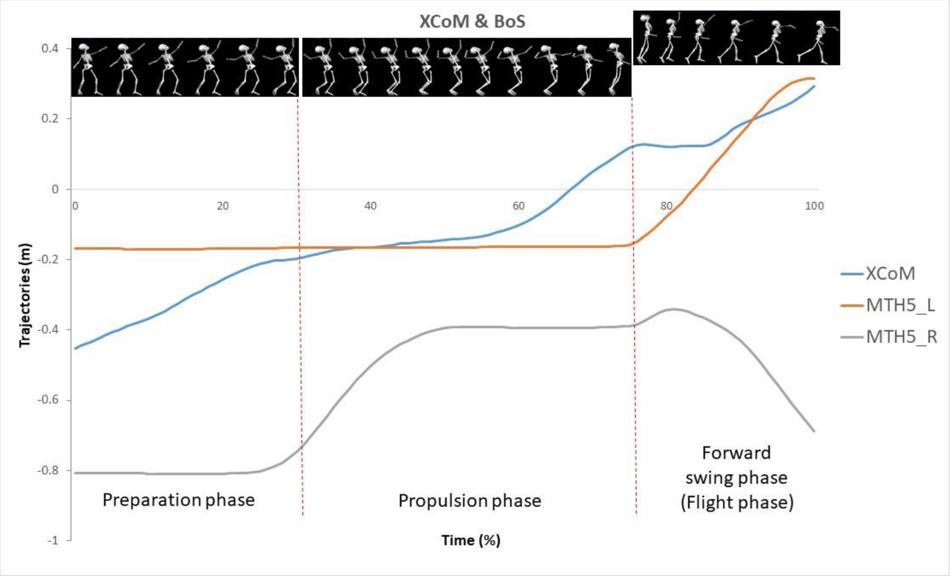

Figure 1.4. The relationship between the XCoM and moving BoS during the serve.

The figure has been complemented with an improved justification of our approach "From a mechanical perspective, the BoS can move to support the moving CoM, expressed as XCoM, in order to maintain balance. During the preparation phase of the serve, the BoS is wide with the XCoM location nicely centred within it. Once moving into the propulsion phase the BoS is narrowed by the rear foot (right foot for a right handed serve) moving towards the front foot (left foot). The boundary of the front foot remains the same and in the late propulsion phase the XCoM is moving outside the BoS, indicating an unbalanced situation of no return just prior to both feet leaving the ground for the jump. Following the flight phase, the XCoM is expected to be back within the boundaries of the BoS in case the player serves and stays at the baseline, which can be seen around the end of the serve. The player achieves this primarily by placing the front foot in front of the XCoM.

This thesis focuses on the interaction between the balance control and how the player moves their segments during the tennis serve when in contact with the floor. Therefore, the above described movement the BoS was in itself not the main parameter to be observed in this thesis." This thesis focuses on the interaction between the balance control and how the player moves their segments during the tennis serve. Therefore, the above described movement the BoS in itself was not the main parameter to be observed.” Only the first two of the three mechanisms will be of immediate relevance, for which some further detail will be provided below.

1.3.1.1 Inverted Pendulum Control

The inverted pendulum model is a mechanical control mechanism of postural balance that has received considerable attention in the literature (Winter, 1995). Although the human body is a multi-segmental structure, and is capable of independently moving all of the joints involved, it is possible to assume that under certain circumstances humans maintain their balance according to the control of a simple rigid structure above the ankle (Winter, 1995). The inverted pendulum control allows one to reduce the control parameters to the CoM and CoP. There are three assumptions to acknowledge including that (1) the balance can be described by the movement of the whole-body CoM, (2) the distance from the axis of rotation to the CoM (the pendulum length) remains constant, and (3) the excursions of the CoM are small with respect to pendulum length. A key violation of these assumptions when considering a tennis serve is likely the notion of constant length of the pendulum with players moving upward/downward through knee and hip flexion and extension. Considering that from a mechanical perspective the inverted pendulum would strictly spoken not allow for major counter rotations, and that any of these counter rotations will lead to pendulum length changes if these are not taking place exclusively in the transverse plane, i.e. involving sagittal or coronal plane rotations, one needs to allow for some minor pendulum length changes. As per that notion, based on qualitative interpretations, violations to the assumptions were expected to be small during the propulsion phase and the beginning of the swing phase, which are the phases that were of greatest interest in this work. The inverted pendulum model in both sagittal (anterior/posterior direction, A/P) and frontal (medial/ lateral direction, M/L) planes states that the horizontal acceleration of the pendulum is proportional to the difference between horizontal locations of the CoP and CoM. The small horizontal distance between CoP and CoM projection on the ground produces a destabilising moment that has to be controlled by a timely displacement of the CoP. In this mechanism, balance is maintained under an unstable situation, controlled by moving the CoP, mostly through means of muscle action in the sagittal plane by the ankle plantar and dorsiflexors (Winter, 1995). As long as the CoP is kept beyond the CoM (with respect to the rotation centre at the ankle), the body is accelerated back to the upright position and vice versa if the CoP is behind the CoM.

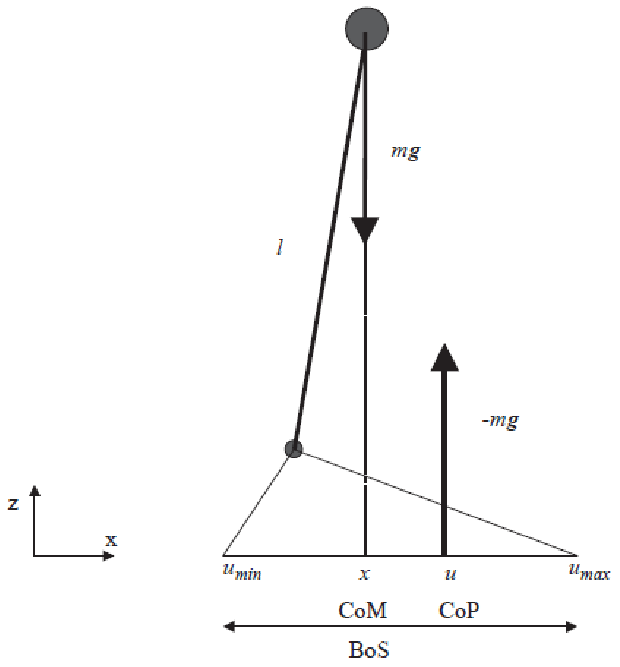

Figure 1.5. The inverted pendulum model, whereby the body is modelled as a single mass (m) balancing on top of a stick with length (l). Indicated are the CoP (u), the location of the effective ground reaction force and the vertical projection of the CoM. The BoS is the area in which the CoP is confined. The CoM location in vertical direction (x). Gravity (g), minimum of CoP (u_{min}) *and maximum of CoP* (u_{max}) *(from Hof et al., 2005).*

Whilst from a quasi-static perspective the basic inverted pendulum model has helped explain many sensori-motor aspects of postural balance control, the inverted pendulum mechanism is insufficient for explaining the control in more dynamical situations (Iqbal and Pai, 2000; Pai and Patton, 1997). Hof and colleagues (2005) have therefore proposed an extension of the inverted pendulum rule for dynamical situations, defining the quantity 'extrapolated centre of mass' (XCoM) to incorporate that extension. The vertical projection position of CoM is combined with its velocity to a factor of $\sqrt{l}/g$ (*l* being the pendulum length and *g* the acceleration of gravity). A consequence of this is that, even if the CoM is above the BoS, maintaining balance may be impossible if the CoM velocity is directed outwardly. Also the opposite holds true, that is, balance can be achieved even when the CoM is outside the BoS and sufficient velocity is directed towards it. Stability is in this circumstance defined by the distance of the XCoM to the boundaries of the BoS, also termed the margin of stability (MoS). In this thesis, MoS

1.3.1.2 Counter Rotation of Segments

The mechanical boundary of the inverted pendulum mechanism is determined by the XCoM having to be within the BoS and the availability of sufficient inwards acting moment from locating the CoP within the margin of stability (Horak and Nashner, 1986; Winter, 1995). The counter rotation of segments mechanism is a postural balance control mechanism that is primarily seen in situations where the available BoS is insufficiently large to still accommodate for sufficient displacement of the CoP within the margin of stability (Hof, 2007). Parts of the body rotate with respect to the CoM (Otten, 1999)– for instance, arm motions are seen when balancing on narrow supports in an effort to maintain stability. As the angular momentum is a conserved quantity, such arm movements are countered with opposite motion of the rest of the body. If the rest of the body is constrained, for example through contact with the ground, then this can lead to a balance recovering horizontal force on the body. Importantly, the mechanism takes place through a local change in angular momentum, which occurs when accelerating the motion of segments. In fact, such counter rotation of segments occurs with many daily living activities, primarily in cases where reactive movement of the trunk segment aids the recovery of balance after a perturbation (Wada et al., 2014). Considering that rapid segmental movements are an essential component of many dynamic sporting tasks, the counter rotation of segments mechanism is likely to play an important role when the boundaries of the inverted pendulum model are exceeded. The angular momentum of trunk and arms can play a role in end effector control as well as in postural balance. A partial objective of the thesis was trying to see to which extent this dual role can be observed from experimental data. As the mechanism 2 of Hof (2005), the counter rotation of segments, is appropriate to observe balance control during dynamic activity. Therefore, the trunk and arms angular momentum were also included to investigate the balance control not only the XCoM relating to the BoS (inverted pendulum). Moreover, during the serve the segmental rotation and forward movements creating the trunk and arms angular momentum from proximal to distal sequence which help to maintain stability

1.3.2 End-Effector Control

In a tennis serve, the end-effector performance is dictated by the launch parameters that relate to the trajectory and orientation of the end-effector (the racket), whereby its terminal location, orientation and velocity will ultimately determine the outcome of the task. To achieve optimal performance, the segments of players transfer momentum from the proximal to distal segments and then to the end of the racket. This movement strategy is typically referred to as a proximal-to-distal movement sequence (Wagner et al., 2014; Wang et al., 2010). This is also known as kinetic chain motion, sequentially transferring momentum from the lower extremity, trunk, upper extremity and hand to the racket. To support proximal-to-distal movement sequence, Wang et al., (2010) revealed that the kinetic striking motion chain is an open-linkage system and represents the effective transfer of linear and angular momentum from the lower extremity to the trunk.

1.4 Kinematic Models to Estimate CoM Displacement

In building upon the previous research, one can assume that a good performer should be able to modify their end-effector behaviour to take into account the variation produced in relation to maintaining their balance. This therefore means that end-effector motion may relate to the performer’s postural balance, or vice versa. To explore this relationship, it is necessary to measure both upper and lower extremity motions, something for which an appropriate kinematic model is needed. Considering that with current optoelectronic motion capture systems this is still a demanding task, it was decided to explore any options that may facilitate more efficient measurement, particularly of the CoM displacement.

Estimating the CoM can be time consuming when having to measure and calculate the motion of all body segments. Full-body models including high complexity at the lower limb would need costly high resolution camera systems and a large lab space.

Particularly in dynamic activities this can be challenging as sometimes markers are lost with complex or rapid movement, or they are difficult to keep in view of more than two cameras at any moment in time. Therefore, if the researcher is interested in the detailed kinematics and/or kinetics of a specific part of the body or joint only, but wishes to retain a good representation of the CoM for the purpose of investigating aspects of balance, then one could save considerable time and effort if adequate CoM representation were still possible while reducing the amount of modelled segments (refer to chapter 2, Vanrenterghem et al., 2010). Measurement of whole-body CoM displacement is key when investigating the mechanics of balance control (Hof et al., 2005). By default, the estimation of the CoM for multi-segment human movement requires the kinematic measurement of all body segment displacements and an anthropometric model of the body (Winter, 2009). In previous research, the CoM has been calculated through the use of various biomechanical marker models (Mapelli et al., 2014; Tisserand et al., 2016). If one focuses only on observing the CoM, then marker models have ranged from a single marker on the body, via a single marker per segment (Mapelli et al., 2014), to 3 or 4 markers in a cluster per segment (Vanrenterghem et al., 2010). Often, the choice of a more complex model in fact depends on various factors such as activities (static vs. dynamic), two-dimensional or three-dimensional biomechanical analysis being used to investigate the CoM representation. It also depends on other kinematic signals that one wishes to observe, for example joint angular displacements of the lower extremities during the observation of kicking, or of the upper extremities in technique analysis of a tennis stroke as it depends on the intersegmental motions involved. The number of segments used in this regard also depends upon the selected source(s) of anthropometric reference data. For instance, Winter (1998) employed 21 markers to reconstruct 14 segments; namely legs, thighs, lower arms, upper arms, pelvis and trunk (Winter, 1998), while (Bahamonde, 2000) used 21 markers but constructed 15-segments (including racket). In contrast, (Yang and Pai, 2014) calculated full-body kinematic data of 13 segments from 26 retro-reflective markers placed on the body. Tisserand and colleagues (2016) used 3 different marker models including a reference model as comprised of a 16-segment whole-body model built on 38 markers, a simplified model using 13 markers to reconstruct 9 segments, and the sacral model based on a single marker. The latter authors concluded that the sacral model is able to satisfactorily estimate the whole-body CoM displacement in the static task, but is inappropriate for estimating mediolateral stability in dynamic tasks. Tisserand and colleagues further suggested their simplified model as an accurate three-dimensional estimation of both the whole-body CoM and the XCoM.

To measure CoM displacement and at the same time other kinematic variables such as joint angular data, a careful selection of the appropriate model is required to keep the demands of the measurement as low as possible. Particularly with regards to dynamic activities, this can be challenging as markers are sometimes lost with the complex or rapid segmental movements, as the markers may not stay in view of more than two cameras at any given moment in time. To avoid marker dropouts, even more markers must be added, guaranteeing that at any moment in time at least three markers per modelled segment are visible. Therefore, if one were able to reduce the amount of segments that are modelled and focus only on segments that the researcher held an interest in whilst still retaining a good representation of the CoM, then that could considerably reduce the time-consuming nature of future research. Several approaches have been used to represent the CoM during dynamic tasks such as running (Halvorsen et al., 2009), side cutting (Vanrenterghem et al., 2010) and jumping (Mapelli et al., 2014). However, the trade-off between representation details and measurement demands remains a concern, and for the estimation of three-dimensional body CoM kinematics in sport the choice of kinematic model continues to be a difficult choice in the protocol design stage.

1.5 Aim and Objectives

The overall aim of the research presented in this thesis was to investigate the interaction between the control of postural balance and end-effector in a highly dynamic sporting task, using the tennis serve as an example. The reason to explore the interaction between these two aspects comes from the assumption that variations in end-effector performance are likely affected by variations in movement that are related to postural balance control. It was therefore deemed worthwhile exploring the association.

In order to do so, a number of sub-goals will be addressed, leading to 3 inter-linked studies being conducted:

- Study 1: To investigate biomechanical model reductions that allow more efficient data collection procedures yet still provide an accurate CoM representation.

- Study 2: To describe interactions between end-effector performance and postural balance that are manifested through variability in the execution of a tennis serve (The rest of the thesis starting from chapter then focussed exclusively on the tennis serve).

- Study 3: To explore the consistency of the interaction between postural balance control and end-effector performance as well as the individuality of that interaction, manifested during tennis serves across serving locations.

CHAPTER 2 Can Segmental Model Reductions Quantify Whole-body Balance Accurately during Dynamic Activities?

2.1 Abstract

When investigating whole-body balance in dynamic tasks, adequately tracking the whole-body centre of mass (CoM) or derivatives such as the extrapolated centre of mass (XCoM) can be crucial but add considerable measurement efforts. The aim of this study was to investigate whether reduced kinematic models can still provide adequate CoM and XCoM representations during dynamic sporting tasks. Seventeen healthy recreationally active subjects (14 males and 3 females; age, 24.9 ± 3.2 years; height, 177.3 ± 6.9 cm; body mass 72.6 ± 7.0 kg) participated in this study. Participants completed three dynamic movements, jumping, kicking, and overarm throwing. Marker-based kinematic data were collected with 10 optoelectronic cameras at 250 Hz (Oqus Qualisys, Gothenburg, Sweden). The differences between (X)CoM from a full-body model (gold standard) and (X)CoM representations based on six selected model reductions were evaluated using a Bland-Altman approach. A threshold difference was set at ±2 cm to help the reader interpret which model can still provide an acceptable (X)CoM representation. Antero-posterior and medio-lateral displacement profiles of the CoM representation based on lower limbs, trunk and upper limbs showed strong agreement, slightly reduced for lower limbs and trunk only. Representations based on lower limbs only showed less strong agreement, particularly for XCoM in kicking. Overall, our results provide justification of the use of certain model reductions for specific needs, saving measurement effort whilst limiting the error of tracking (X)CoM trajectories in the context of whole-body balance investigation.

2.2 Introduction

The whole body centre of mass (CoM) is a key variable when investigating balance in dynamic sporting tasks. Estimating the CoM can however be time consuming when having to measure the motion of all body segments. Many markers need to be placed on the body (at least three per modelled segment) and tracked to calculate the CoM.. Particularly in dynamic activities this can be challenging as sometimes markers are lost with complex or rapid movement, or they are difficult to keep in view of more than two cameras at any moment in time. Therefore, if the researcher is interested in the detailed kinematics and/or kinetics of a specific part of the body or joint only, but wishes to retain a good representation of the CoM for the purpose of investigating aspects of balance, then one could save considerable time and effort if adequate CoM representation were still possible while reducing the amount of modelled segments.

Several approaches have been used to represent the CoM during dynamic tasks such as walking (Tisserand et al., 2016), running (Halvorsen et al., 2009), side cutting (Vanrenterghem et al., 2010) and jumping (Mapelli et al., 2014), but the trade-off between detail of the representation and accuracy has been a continued concern. For example, One study investigated three different representations (38 markers, a simplified 13-marker model, and a single marker model at sacral) to estimate the three dimensional CoM during quiet standing, gait and balance recovery (Tisserand et al., 2016). Whilst the simplified 13-marker model or single marker model could serve a purpose in those movements, they no longer allow a detailed investigation of one part of the body. In one of our previous studies we compared CoM representations between four different marker sets that gradually reduced the amount of modelled upper limb segments, retaining the lower limb segments, and found that a CoM representation based on lower limbs and trunk segments have a strong enough agreement with CoM values from a full body model in terms of relevant velocity values for side cutting manoeuvres (Vanrenterghem et al., 2010). This model has allowed numerous studies to investigate lower limb kinematics and/or kinetics of side cutting whilst controlling whole body running speed. The question remains though, whether a similar model reduction is justified for other dynamic sporting tasks such as drop vertical jumping or kicking, and whether similar model reductions would be possible when one wishes to retain detailed kinematics and/or kinetics of the upper limb, for example when performing a tennis serve.

When evaluating balance during dynamic tasks, the extrapolated CoM (XCoM) has been proposed based on controlling balance through pendulum like behaviour. The XCoM adds a velocity-based correction to the CoM and has seen considerable attention in recent literature (Hof, 2008; Hof et al., 2005; Hof et al., 2010; Lugade et al., 2011; Tisserand et al., 2016). Therefore, scientists interested in associating detailed lower or upper limb kinematics/kinetics with dynamic balance strategies would benefit from knowing whether reduced CoM and XCoM representations can still be sufficiently accurate. Our aim was therefore to investigate whether CoM and XCoM representations of reduced kinematic models can be sufficiently accurate whilst retaining detailed kinematics of the lower or upper limbs in commonly observed dynamic sporting tasks such jumping, kicking, or overarm striking.

2.3 Methods

Participants

17 healthy recreationally active athletes, 14 males and 3 females, mean (±SD) age 24.94 ± 3.23 years, height 177.32 ± 6.94 cm, and body mass 72.64 ± 7.02 kg, participated in the study. Participants were questioned on their injury history and none had a recent (< 6 month) muscle injury. This study was approved by the Liverpool John Moores ethics committee (15/SPS/016).

Experimental design and protocol

Seventy-two reflective markers were placed on anatomical landmarks to record segmental motions. Participants then completed a 10 min warm up (consisting of light jogging and dynamic movements). After a standardised warm-up routine, subjects performed 5 trials of 3 different dynamic sports activities: a drop vertical jump (bilateral drop vertical jump from a box with height of 30 cm, jumping up with an arm swing and then landing on the same spot), a kicking imitation (starting with forward run about 5 meters before kicking point then using the left leg as the lead leg and then imitating a maximum kicking motion with the right leg and then keeping moving forward using a countering arm swing, and an overarm tennis serve imitation (standing on both feet and completing a tennis serve action). No ball or racket was used.

Data collection and model reductions

Kinematic data were collected with 10 infrared cameras at 250 Hz (Oqus Qualisys, Gothenburg, Sweden) and using a full-body six-degree-of-freedom kinematic model (FB). This kinematic model allows calibrating and tracking of segmental motion of 13 segments, that is, head, upper arms and forearms (including hands), thorax, pelvis, thighs, shanks and feet, with segmental data based on Dempster's regression equations (Dempster, 1955) and using geometrical volumes to represent each segment (Hanavan, 1964). The FB model was used as the gold standard measurement against which to compare CoM representations for models with different segmental reductions (see figure 2.1). Segmental reductions existed of neglecting the mass of certain segments in the calculation of the (X)CoM. A first reduction was the removal of the head segment, leaving the lower limbs, trunk, and upper limbs (LL+T+UL). This segment is expected not to move much relative to the much heavier trunk, and with a segment mass of only 7.8 percentage of total body mass this would be expected not to play an important role (Dempster, 1955). For throwing or striking actions though, it may be possible to also ignore motion of the non-throwing or non-striking arm, keeping detailed kinematics of lower limbs, trunk as well as the dominant upper limb (LL+T+DUL). A further reduction was the omission of upper limbs altogether, keeping lower limbs and trunk (LL+T), which is, including thorax, pelvis, thighs, shanks, and feet. This reduction has already been shown to sufficiently accurately represent the CoM velocity characteristics for side-cutting manoeuvres (Vanrenterghem et al., 2010). When a focus on segmental motion of the lower limbs only exists, then one may also consider a further reduction to lower limbs only (LL), considering pelvis, thighs, shanks and feet only. Alternatively, in serving or throwing actions the interest may be solely on detailed upper limb segmental motion, and one may wish to ignore lower limb motion altogether. Hence, we also considered a trunk and upper limbs reduction (T+UL), as well as a trunk and dominant upper limb only reduction (T+DUL).

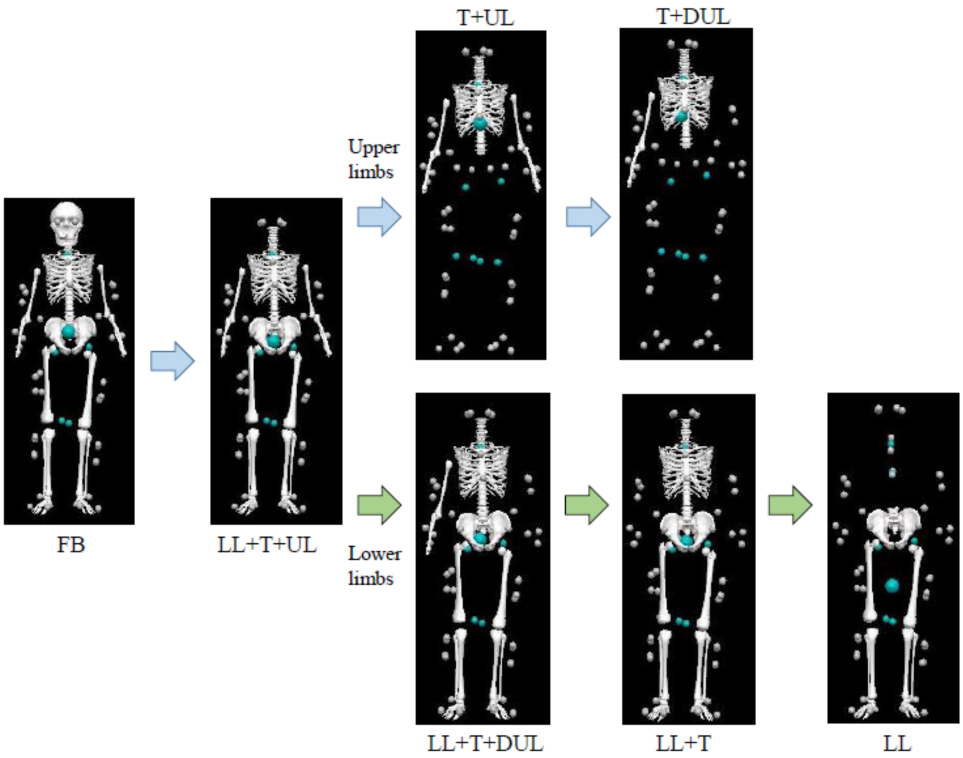

Figure 2.1. The details of biomechanical models, FB, LL+T+UL, T+UL T+DUL, LL+T+DUL LL+T, and LL model. Model reductions either were done to allow detailed kinematics/kinetics on upper limbs (top part) or lower limbs (lower part).

Data reduction and analysis

The position of the whole body CoM, and reductions thereof, was estimated according to basic principles of adding segmental mass locations. The CoM of the total system is located at (x0, y0, z0) and each of these coordinates can be calculated for an n-segment body (Winter, 2009). Equations were implemented through the use of Visual3D (C-motion, Germantown, MD, USA). In this study, we estimated the (X)CoM position, yet because we considered this over the duration of each task this reflects displacement and we hence refer to the 'displacement profile' or 'displacement trajectory'. The (X)CoM trajectories were extracted from touch down until landing in the drop vertical jump, from touch down and take off of the support leg for the kicking, and from the moment when the hitting arm started moving up until the moment when the wrist of the hitting arm finished the follow-through in the tennis serve imitation. The antero-posterior and medio-lateral displacement trajectories were evaluated considering their role in balance evaluation. Evaluations of vertical displacement of CoM have been presented in Appendix B.

The 95% limits of agreement (LoA) and bias used for comparison two methods. The 95% limits of agreement estimated by mean difference ±1.96 standard deviation of the difference that provide an interval within which 95% of differences between measurements (Bland & Altman, 1999). It carried out to compare trajectories of the six (X)CoM representations against the gold standard FB model. Bias between methods is shown as the mean difference between the methods (subtracting data of model reductions from the full body model data), and in theory could be corrected for as long as the bias were consistent. Consistency of this bias is indicated by the limits of agreement, as measured by the amount of variation of the difference between methods. A lack of agreement is therefore a consequence of the fact that the (X)CoM representation is a mismatch from the (X)CoM (bias), or due to the fact that the (X)CoM representation does not consistently follow the actual (X)CoM (LoA). To help the reader interpret the agreement between methods, an arbitrary threshold range was set at ±2 cm, yet one should adopt a suitable threshold for every application or study. Butterworth second order low pass filter with cut off frequency of 15 Hz has been applied to the data and the filtered outputs have been visually checked.

2.4 Results

The average of CoM and XCoM trajectories in M/L and A/P direction during a drop vertical jumping, kicking, and tennis serve depicted in Figure 2.2. Temporal profiles of CoM and XCoM for the three tasks can be found in Appendix C. Temporal profiles of bias and LoA for CoM and XCoM representations showed considerable similarity for all three tasks as depicted side-by-side in Figure 2.3, 2.4 and 2.5.

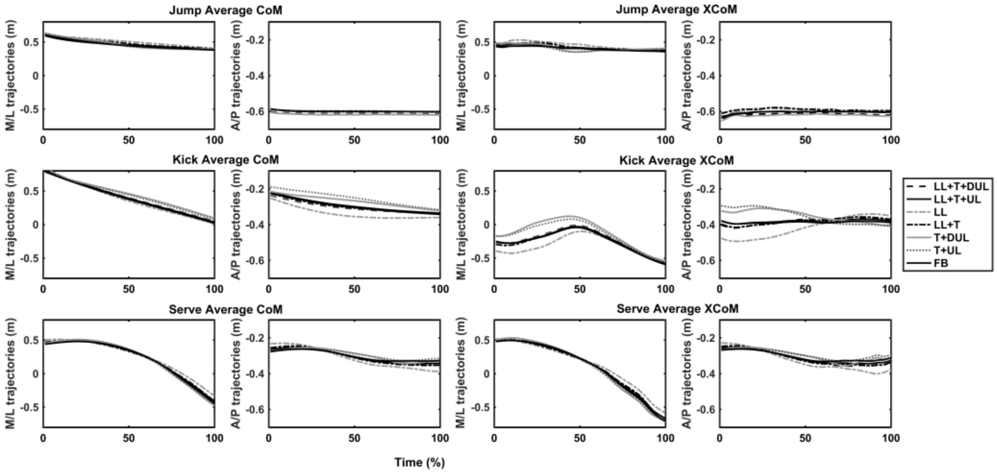

Figure 2.2. The average of CoM and XCoM trajectories in M/L and A/P direction during a drop vertical jumping (top panels), kicking (middle panels), and tennis serve (bottom panels).

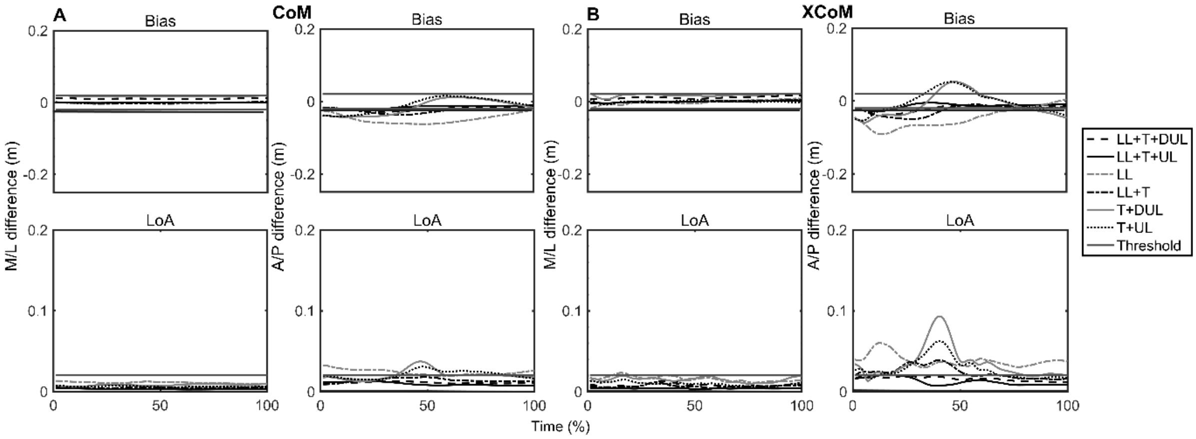

Figure 2.3. (A) The difference of CoM trajectories, whereas (B) shows the differences of XCoM trajectories in M/L (left panels) and A/P (right panels) directions between FB kinematic model and selective model reductions during a drop vertical jump.

Jumping

In the M/L direction, all model reductions stayed within the threshold range of ±2 cm. Three models (LL+T+UL, LL+T+DUL, and LL+T) had less bias than other model reductions (T+UL, T+DUL, and LL) and limits of agreement were around 0.5 cm. In the A/P direction, LL+T+UL was closest to the FB model. Only during the first 30% of the contact phase, the limits of agreement slightly exceeded 2 cm. All other model reductions had considerable bias and showed excessive limits of agreement (see figure 2.3 A). For the effect of model reductions on XCoM trajectories, LL+T+UL was found to be the best model reduction in the M/L direction. In the A/P direction, during the first 20% of time, LL+T+UL exceeded 2 cm but most of the time the LL+T+UL model did not exceed 2 cm. Furthermore, when exploring the LoA it also supported that LL+T+UL has moderate to good agreement with the actual XCoM trajectory (see figure 2.3 B).

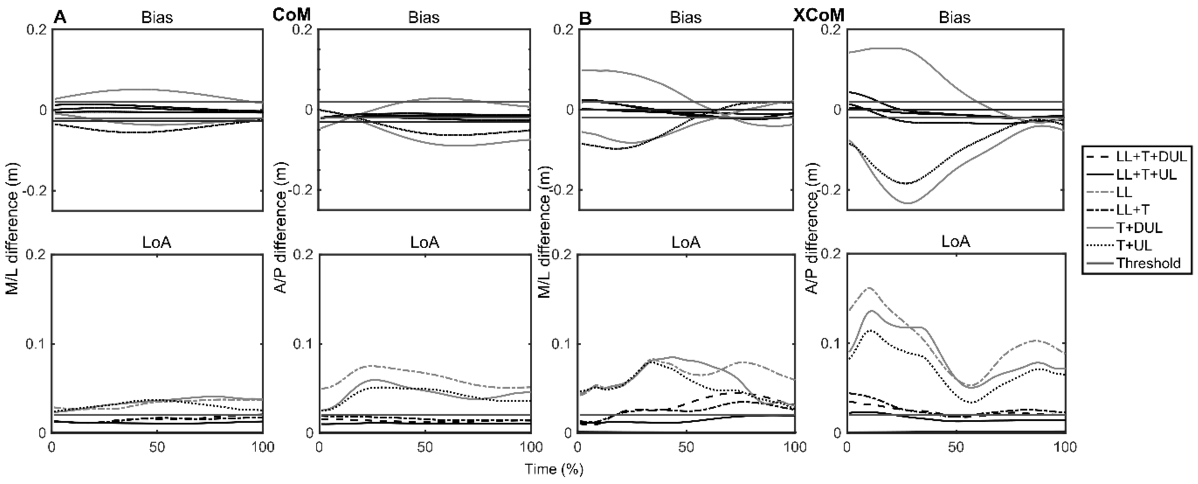

Figure 2.4. (A) The difference of CoM trajectories, whereas (B) shows the differences of XCoM trajectories in M/L (left panels) and A/P (right panels) directions between FB kinematic model and selective model reductions during kicking.

Kicking

In M/L direction, three models (LL+T+UL, LL+T, and LL+T+DUL) had less bias than other model reductions and limits of agreement although in A/P direction only LL+T+UL and LL+T could be accepted. All other model reductions had considerable bias and showed large limits of agreement (see figure 2.4 A). For the XCoM representations, LL+T+UL was again closest to the gold standard and had small variation for both M/L and A/P directions even though limits of agreement of differences between LL+T+UL and the gold standard slightly exceeded for about 20%

of time in A/P direction. Other model reductions exceeded the threshold range considerably; particularly T+DUL, T+UL, and LL model reductions (see figure 2.4 B).

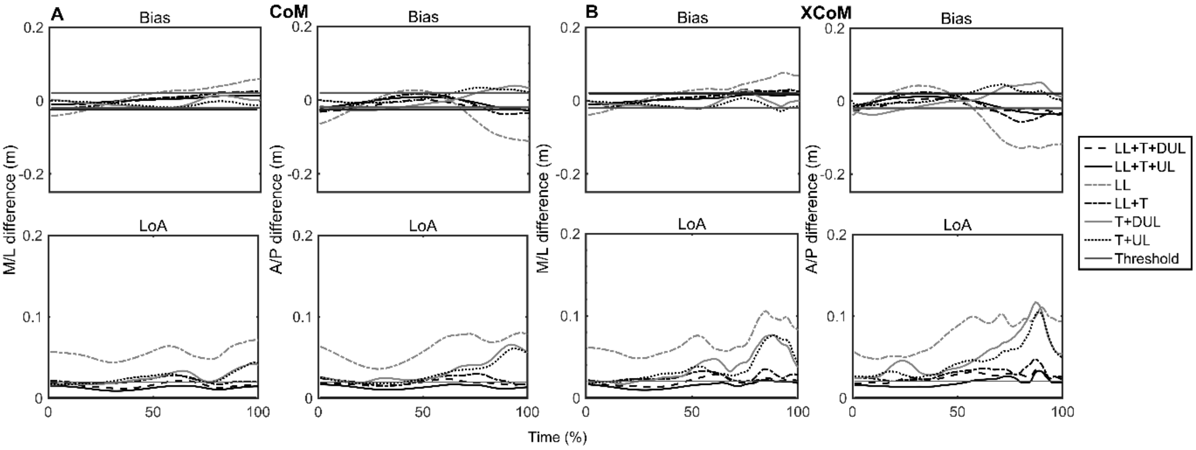

Figure 2.5. (A) The difference of CoM trajectories, whereas (B) shows the differences of XCoM trajectories in M/L (left panels) and A/P (right panels) directions between FB kinematic model and selective model reductions during tennis serve.

Tennis serve

In M/L direction, both LL+T+UL and LL+T+DUL representations of CoM had limited bias and limits of agreement. The LL+T+UL model was better than the LL+T+DUL model. During the last 20% of the movement LL+T+DUL exceeded the 2 cm threshold and the limits of agreement also showed that LL+T+DUL exceeded 2 cm between 60%-70% of the movement time (see figure 2.5 A). In A/P direction LL+T+UL was the best model reduction even if the bias at beginning and end of the movement slightly exceeded the threshold. All other model reductions had considerable bias and large limits of agreement. For XCoM representations, both bias and limits of agreement for the M/L direction showed that only the LL+T+UL model reduction is acceptable. For the A/P direction, also only the LL+T+UL could be within reason but in the bias plot it exceeded the threshold for approximately 20% of the time while in the limits of agreement plot for almost 50% (see figure 2.5 B).

2.5 Discussion

The aims of this study were to find the most appropriate reduced kinematic models that still provide adequate (X)CoM representations during dynamic sport activities. Our results demonstrated that modelling the head is unnecessary to obtain a good CoM representation during dynamic manoeuvres, but further model reductions tend to generate inadequate CoM representations for some of the sporting movements we measured.

In jumping activities one may have an interest in lower limb segmental motion only, but retaining CoM information. Our results showed that the LL+T+UL model reduction accurately represents CoM motion, but any further reductions that exclude upper limbs and/or trunk are inadequate to track the CoM.. Importantly, the jump task that we observed involved an arm swing. If the arm swing were not present, such as by crossing the arms in front of the chest, or by holding the arms akimbo, which is common in laboratory based experiments, then LL+T model may have been sufficiently accurate but this remains unconfirmed. In fact, this has been assumed in previous work investigating lower limb kinematics and kinetics during standing vertical jumps (Bobbert and van Ingen Schenau, 1988; Vanrenterghem et al., 2004).

Concerning kicking, in the M/L direction the results showed that three models including LL+T+UL, LL+T, and LL+T+DUL could be accepted as indicated by a low bias and limits of agreement. In the A/P direction, only LL+T+UL and LL+T could be accepted. The acceptable CoM representation through LL+T could be explained by opposite (out-of-phase) motion between both arm segments, which leads to negligible effects on the CoM. Hence, if one uses LL+T with dominant arm only (LL+T+DUL) then this leads to inadequate CoM representation as the CoM representation is expected to be off by the motion of the non-dominant arm. The other model reductions also showed considerable error. Our findings are similar to a previous study (Vanrenterghem et al., 2010) where an LL+T model reduction was deemed suitable for side cutting. This offers opportunities for researchers who wish to investigate detailed lower limb mechanics in kicking, as it may well be possible to save a considerable amount of time for placing markers and tracking marker locations on upper extremities for getting an acceptable CoM representation.

During overarm motion activities with the tennis serve as an example, both in the M/L direction and in the A/P direction we found that only the LL+T+UL was suitable. The LL+T+DUL may also be acceptable but slightly exceeded the threshold. Any other model reductions showed considerable error. Hence, the results of this study suggest that for evaluating balance mechanisms based on CoM motion, one most likely needs both upper limbs included in the kinematic model. The tennis serve task has both arms mostly extended and swinging upwards and forwards (partly in-phase) during ball tossing and striking, and this leads to a considerable effect on CoM motion. We expect this to be similar for the majority of dynamic tasks involving overarm motions and suggest that using LL+T+UL model is needed for quantifying CoM motion, and any further reductions based on tracking only upper limb kinematics even when including the trunk would be inadequate.

The comparison between the M/L and A/P CoM motion revealed that in jumping there were only small differences between model reductions and the gold standard, but that only for the M/L direction. This is a consequence of the fact that there was only a minimal movement in M/L direction during the predominantly symmetrical and sagittal plane task. This means that despite small differences based on a 2 cm threshold, these differences would still be meaningful if one were to investigate M/L whole-body balance effects. Both the kicking and tennis serve tasks involved more M/L movement than the drop vertical jump, and hence differences between model reductions and the gold standard were increased and likely of more importance in those tasks compared to the jump.

The main reason for this study was to investigate CoM motion in the context of postural balance strategies in dynamic sporting tasks. As XCoM adds a velocity-based component to the CoM, its motion in activities that involve rapidly changing movement would be expected to be considerably different from CoM motion. We found though that XCoM results were largely similar to the results of the CoM for all dynamic activities with the only major differences observed in kicking. While LL+T was good for CoM representation in kicking, the accuracy of the LL+T model reduction was deemed unsuitable for XCoM. The kicking activity is a rapid dynamic movement, especially in the A/P direction, which involves forward running and one leg stays on the floor while the kicking leg is rapidly swinging forward, and also the arms have a considerable velocity component.

2.6 Limitations

A limitation of this study is the choice of the threshold range, which was done arbitrarily and only intended to help the reader interpret which model is likely appropriate for their studies. If a higher accuracy is required for example for observing small effect sizes, then the reader should make their own judgement for what they believe to be an acceptable (X)CoM representation. Also, other model reductions such as T+UL with pelvis and thighs could be explored further as these might still be acceptable in term of accuracy and consistency of (X)CoM representation. Moreover, the kinematic model used segmental data based on Dempster's regression equations (Dempster, 1955) and simple geometrical volumes to represent each segment (Hanavan, 1964). At first sight, this may be seen as inappropriate to use for this study as this segmental data came from American cadavers that may not be representative of Asian segmental proportions. However, using other model parameters would likely not have had a meaningful impact on the data, as the variations between the different available parameter sets (Zatsiorsky, 1983) is small, let alone that using other parameters could have altered the main conclusions of our work. The impact of using other parameters was in fact expected to have mainly an impact on inverse dynamics calculations if these had been undertaken (joint moments etc.), and a negligible impact on the kinematics calculations that were used in this project.

2.7 Conclusion

Our recommendation would be that studying (X)CoM motion based on a LL+T+UL model reduction would be considered suitable for dynamic sporting tasks. As a consequence of this model reduction, only a small amount of time could be saved. This study for example involved 17 participants, with three conditions and 5 trials each. Reducing the FB model to the LL+T+UL model could have theoretically saved approximately 4 hours of work associated with placing and tracking the head markers. Whilst for the CoM representation, the LL+T model was good for kicking, its accuracy was less accurate for representing XCoM motion. Further model reductions, for example ignoring upper limbs or trunk, or ignoring lower limbs, generally showed poor agreement and are likely unsuitable if one wishes to evaluate whole body balance control in dynamic tasks based on CoM or XCoM motion.

CHAPTER 3

Does Whole Body Balance Control Interact with Controlling the End-effector during the Serve in Experienced Tennis Players?

3.1 Abstract

Background: The serve is the most important stroke in tennis providing the players with the first chance of winning the rally. Balance control is vital in most dynamic sports activities, yet the relationship between whole body balance control and the end effector control during the tennis serve is still unexplored. The aim of this study was to investigate whether there is an interaction between mechanisms used to control whole body balance and racket performance. Methods: 14 experienced tennis players (nine males and five females; age, 21.50±3.85 yr; height, 1.74 ± 0.06 m; body mass 65.79 ± 8.05 kg) participated in this study. Participants completed 10 successful tennis serves. Marker-based kinematic data were collected with 12 optoelectronic cameras at 200 Hz (BTS bioengineering, Milan, Italy). Linear regression using 1D Statistical Parametric Mapping was used to identify interactions between firstly the extrapolated centre of mass (XCoM) displacement in the anteroposterior direction and secondly changes in arms/trunk segment angular momentum, and peak anterior-posterior racket velocity. Overall, no meaningful relationships were found, except for a small time interval during the forward swing phase in which a greater increase in trunk angular momentum was associated with increased maximum racket velocity. In summary, trunk segmental accelerations were found to play a moderating role in controlling whole body balance during the forward swing phase and generating maximum racket velocity, yet this role was deemed to be limited.

3.2 Introduction

The serve in tennis is arguably the most essential stroke for successful performance (Reid et al., 2011). Two key features of the tennis serve are that it is performed under player controlled circumstances, and that it is goal-directed. When serving, the players have to control the stroke arm and racket, from here on referred to as end-effector, to hit the ball at the right place, in the right direction and most of all, with the highest speed possible. Many previous biomechanical studies have investigated the tennis serve, often focusing on kinematics of upper limbs, trunk, lower limbs and racket (end-effector). From these investigations, key performance indicators for the tennis serve have been proposed, such as for example shoulder, elbow, arm, and hand angular velocity and racket velocity (Whiteside et al., 2015; Whiteside et al., 2013; Reid et al., 2008; Reid et al., 2013; Sakurai, 2013; Whiteside et al., 2013; Whiteside et al., 2014). However, end-effector performance is also likely to be affected by simultaneous motions associated to maintaining postural balance, and this to our knowledge has not been previously investigated.

It is important for practitioners to gain a better understanding of the interaction between postural balance control mechanisms and end-effector performance. In training and coaching there is a general awareness of the importance of good postural balance for the successful execution of a tennis serve. For example, it has been suggested that a sport-specific balance exercise should be included in a daily training to increase the players' performance (Malliou et al., 2010). However, it remains unclear whether balance training should always be done explicitly in the context of the tennis serve, or whether one can train upper extremity racket control and lower extremity balance control separately. Therefore, gaining a better understanding of how balance and end-effector control may well interact with each other is paramount to supporting developments in training and coaching

Postural balance is often observed through centre of pressure (CoP) evaluations, mechanically considering balance control of a standing human as the control of an inverted pendulum, however for a dynamic and complex task such as the tennis serve this is not sufficient and requires expansion. The balance mechanisms as described by

Hof are more suitable. First, there is the notion of whole body CoM velocity that is taken into account through evaluation of the displacement of the so-called extrapolated CoM (XCoM) relative to the edge of the base of support (also called the margin of stability). Second, there is the incorporation of accelerated segmental motions that influence whole body balance (called counter rotation of segments), which particularly concerns the trunk and upper extremity motions (Hof, 2005; Hof, 2007). The mechanisms permit the quantitative interaction between motion associated to maintaining postural balance and end-effector performance, but the question remains which balance mechanism will be used and whether that interaction will occur during the tennis serve. For the counter rotation of segments, trunk and arms movement play the role in both balance and serving performance. However, this thesis focussing on only balance related. It has two roles but the researchers aware that it has also performance enhancing therefore, the player benefit from increasing their trunk and arms angular momentum. The balance control can associated with performance outcome which is the end effector using maximum racket speed in this thesis. It has been used as the main dependent variable in this chapter (chapter 3) and next chapter (chapter 4) because the racket velocity is one of the key factor that influence to the serving performance as well as the ball velocity has not been recorded.

The aim of this study was to describe the interaction between postural balance control and end-effector performance in a standardized tennis serve. It was hypothesized that if there was an interaction it would be revealed throughout the serving motion, and most strongly in the later phases of the serve.

3.3 Methods

Participants

Fourteen right-handed experienced Thai tennis players (nine males and five females; age, 21.50 ± 3.85 years; height, 1.74 ± 0.06 m; body mass 65.79 ± 8.05 kg) participated in this study. Inclusion criteria were that the player had participated at least for 5 years at a national or international level. Participants were questioned on their injury history and none had a recent (< 6 month) muscle injury. This study was approved by the

Liverpool John Moores ethics committee (15/SPS/016) and Mahidol university ethics committee (MU-CIRB 2016/013.2201).

Data collection, experimental design and protocol

Sixty eight reflective markers were placed on anatomical landmarks to record segmental motions. Kinematic data were collected with 12 infrared cameras at 200 Hz (BTS bioengineering, Milan, Italy). The markers were placed on 13 segmental landmarks to allow calibrating and tracking of segmental motion consisting of head, upper arms, forearms (including hands), thorax, pelvis, thighs, shanks, and feet (Figure 3.1). Prior to performing the task, a static recording was obtained for use in marker definition and model scaling, after which the dynamic trials were recorded.

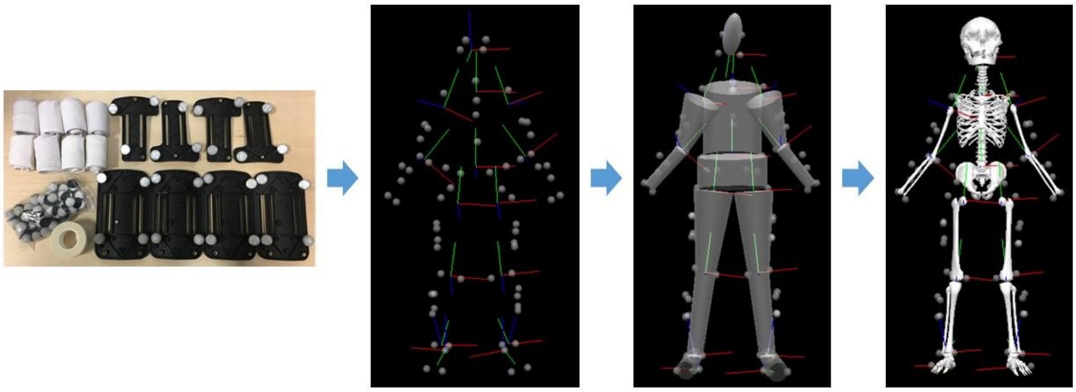

Figure 3.1. The reflective markers and biomechanical model used.

Participants then completed a 10 min warm up (consisting of light jogging and tennis serve movement). Players used their own rackets to complete the protocol. After a standardised warm-up routine, subjects performed at least 10 maximal effort first serves directed at a 1 x 1 metre target bordering the T of the service box in the deuce court (Figure 3.2), with a 2-min rest between serves. Ten successful serves were analysed. Participants were allowed to use a “foot-up” or “foot-back” service technique depending on their preference.

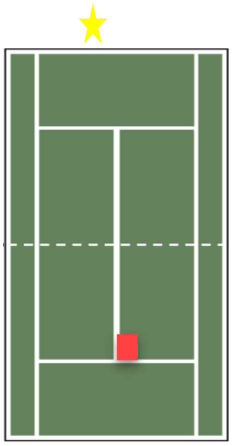

Figure 3.2. Indicative top view over the tennis court. The player's position is indicated by the yellow star, the red square represents the target location (1x1 metre) that the players were asked to serve to.

Data reduction and analysis

In this study, firstly, the inverted pendulum mechanism was observed by observing the XCoM in anteroposterior direction. Secondly, the counter rotation of segments mechanism was observed via the changes in angular momentum of the upper part of the body, i.e. arms and/or trunk segment. A 13-segment model was used to calculate the whole-body CoM (see previous chapter). The XCoM was calculated using the position of the vertical projection of the CoM added with its velocity multiplied by a factor $\sqrt{l}/g$ (l being leg length and g the gravitational acceleration) (Hof, 2005). The trunk segment has been defined using the location of the markers at C7, T8, sternum, and xiphoid process, as such representing mostly the movement of the thorax rather than lower abdomen. The angular momenta of the arms (both arms together) and trunk segment relative to the whole-body CoM were separately calculated as the product of their principal moment of inertia (I) and angular velocity in the arms/trunk segment coordinate system (ω). The reason that both arms were combined together was because individual arm momentums/momenta would - during certain parts of the serve – be expected to counter each other. If they counter each other they no longer contribute to balance, and therefore it was the net angular momentum by both arms that was of interest to us. The time derivative was calculated to represent the changes in angular momentum using instead of angular momentum as the researchers wanted to observe the rate of change of momentum, which represents the counter rotation mechanism. In other words, it is the rate at which the angular momentum changes that quantifies the impact of rotational acceleration of segments, which is what constitutes the segmental counter rotation mechanism. The coordinate system in this study was aligned with the baseline of the tennis court, with the X axis pointing towards the net, the Y axis pointing upwards, and the Z axis parallel to the baseline pointing to the right. Fitt's law refers to speed and accuracy trade off and explains the time to get to the different targets. However, this differs to my work. In my case, accuracy is not taken into account as the accuracy in tennis is a constraint to achieve the serving target. The successful tennis serve in this study was identified by the serve that hit the ball to the target locations. Speed strongly determines the accuracy and cannot play a role even if the player is less accurate but as long as the player hit the target it was considered a successful serve. Therefore, in this case, the researchers were not concerned with accuracy, only speed. The tennis racket represented an end effector segment in this study. End-effector performance was quantified through maximum racket velocity, calculated from the peak forward velocity of a marker on the top of the racket. In term of margin of stability (MoS) is about the XCoM location relative to the BoS. In this thesis the MoS is represented by XCoM offset relative to boundary of the BoS which is 5th metatarsal was taken as a referent point. Therefore, the XCoM that presented in this study represent MoS. Fixed position as long as the foot is on the floor that is MoS. MoS can tell how far the location of XCoM can go.

All calculations were implemented in Visual3D software version 6.0 (C-motion, Germantown, MD, USA). Each trial was time normalised to 101 samples (0-100% of cycle time) over the duration of the movement (see figure 3.3). The start of the tennis serve was taken as the time when the upper limb of the non-racket arm was parallel to the ground. The end of the movement was when the upper limb of the hitting arm was parallel to the ground, shortly after assumed ball contact. Using two further intermediate events, namely the highest point of the distal end of the non-racket arm and the lowest point of the racket head, the serve was divided into a preparation phase, a propulsion phase and a forward swing phase. Data was low-pass filtered using a fourth order recursive Butterworth filter with cut off frequency of 15 Hz. To compensate for noise amplification due to double differentiation, angular momentum data was filtered with a cut off frequency of 6 Hz prior to differentiation.

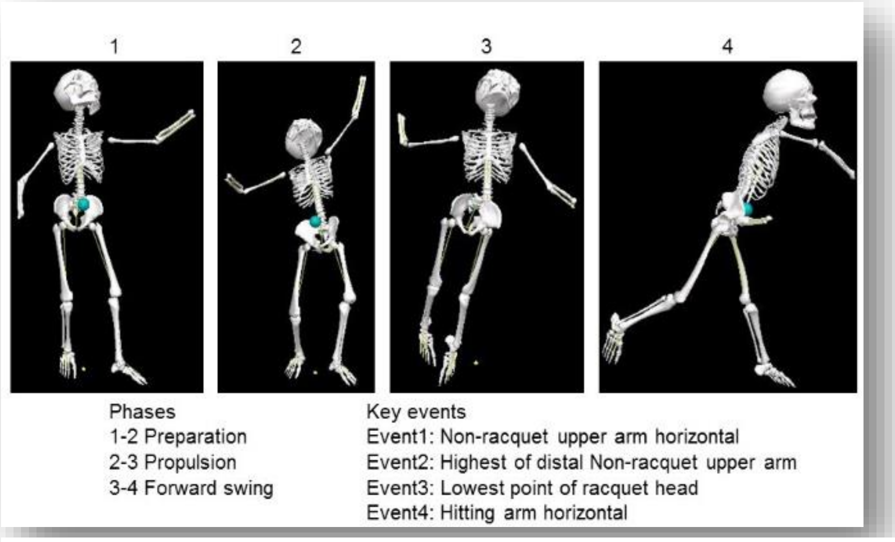

Figure 3.3. The key events that divide the tennis serve in three separate phases.

Statistical analysis

Statistical Parametric Mapping (SPM) was used to analyse the kinematic continua associated with the two balance mechanisms. Linear regression was used to examine the within-subject interaction between the XCoM in A/P direction and maximum racket velocity, as well as the interaction between changes in arms and trunk angular momenta and maximum racket forward velocity. The slopes of these relationships were computed at each time t, resulting in β trajectories. The β is standardised. These β trajectories were computed for each subject and were subsequently submitted to a population-level one-sample t test, yielding t-statistic curves, or a Statistical Parametric Map. The significance of each SPM{t} was then determined topologically using random field theory (Adler and Taylor, 2007). The greater the values of the β-trajectories, the stronger the relationship. Positive values indicate a positive relationship, negative values indicate a negative relationship. A key SPM assumption is that trajectories have been appropriately smoothed and registered such as temporally normalized (Sadeghi et al., 2003). SPM is, however, very robust against this assumption, and so in this study the data was visually inspected to check for temporal variations. This gave us the confidence to believe that an individual's mean trajectories were unbiased by smoothing/registration. SPM further allows to (1) eliminate regional focus bias, allowing hypotheses to be proposed over the entire spectrum, and (2) eliminating covariance bias from multiple comparisons by using a family-wise approach for inference of significance. SPM also permits statistical results to be presented in their original spatiotemporal data spectra, resulting in a more intuitive context for understanding of temporal or spatial regions where significant differences are detected. SPM analyses were implemented using the open-source spm1d code (www.spm1d.org) in Matlab (R2016a, 8.3.0.532, The Mathworks Inc, Natick, MA).

3.4 Results

The first three figures below reveal an example for one participant of the application of SPM1D to evaluate the relationship between XCoM in A/P direction (figure 3.4), the change in arms angular momentum (Figure 3.5) and the change in trunk angular momentum (Figure 3.6), on the one hand, and maximum racket velocity, on the other hand. Top panels show the data for 10 trials of one participant, respectively in the preparation (left), propulsion (middle) and forward swing (right) phase. Bottom panels show β-curves representing the strength of the relationship between variations in the data and variations in maximum racket velocity, respectively. The greater the values of these β-curves, the stronger the relationship. Positive values indicate a positive relationship, negative values indicate a negative relationship.

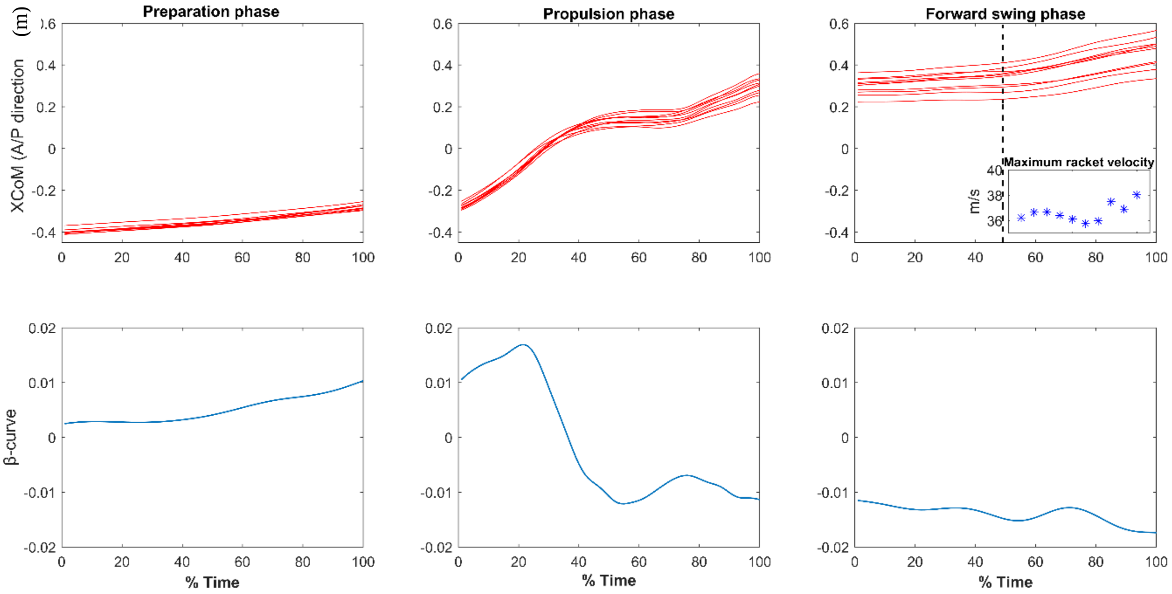

Figure 3.4. An example of one participant of the relationship between XCoM in A/P direction and maximum racket velocity during the three phases of the tennis serve. The vertical line represented at 48% of the forward swing phase indicates the time at which maximum racket velocity was reached.

The XCoM moved gradually forward throughout the preparation phase, and moved forward faster in the propulsion phase. In the forward swing phase, the XCoM trajectories continued to move slightly forward, and showed the largest amount of variation between trials. Qualitative interpretation indicated that the β-curve did not show a clear relationship between XCoM in A/P direction and maximum racket velocity.

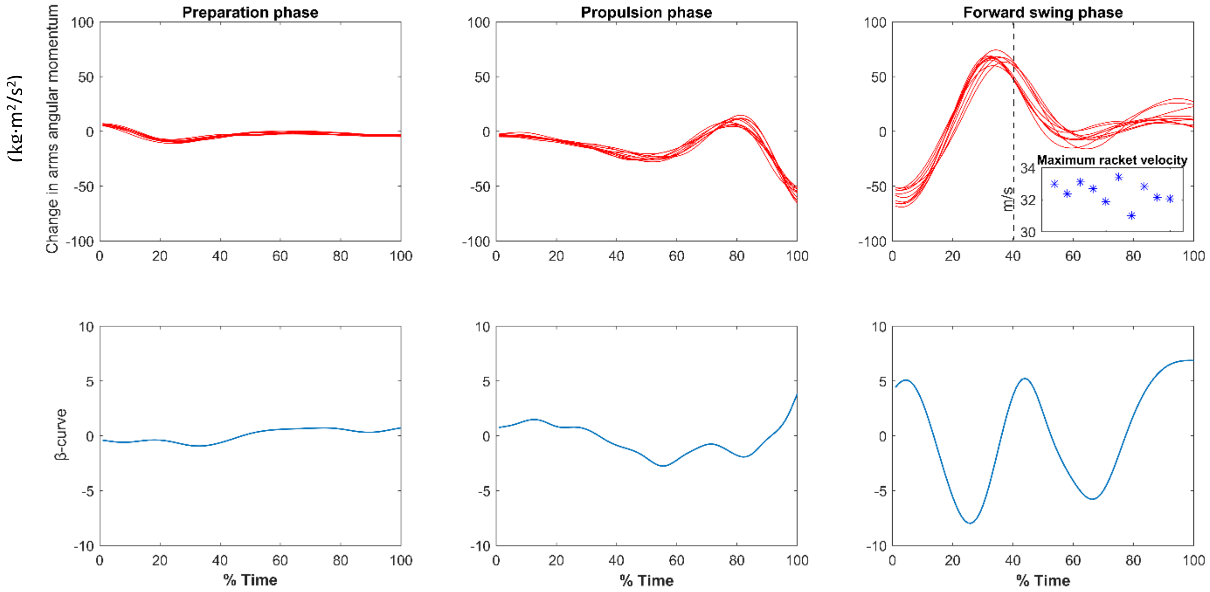

Figure 3.5. An example of one participant of the relationship between change in arms angular momentum and maximum racket velocity during the tennis serve. The vertical line represented at 40% of the forward swing phase indicates the time at which maximum racket velocity was reached.

Only very small changes of arms angular momentum were seen throughout the preparation phase. Around 20-65% of the propulsion phase notable changes in angular momentum were registered, with the greatest reductions in angular momentum identified around the transition from the propulsion to the forward swing phase. In the forward swing phase, changes in angular momentum were greatest, reaching the greatest increase when the racket reached its maximum forward velocity. The β-curve in the preparation and propulsion phase indicated no strong relationship, and in the forward swing phase there were great fluctuations in the relationship.

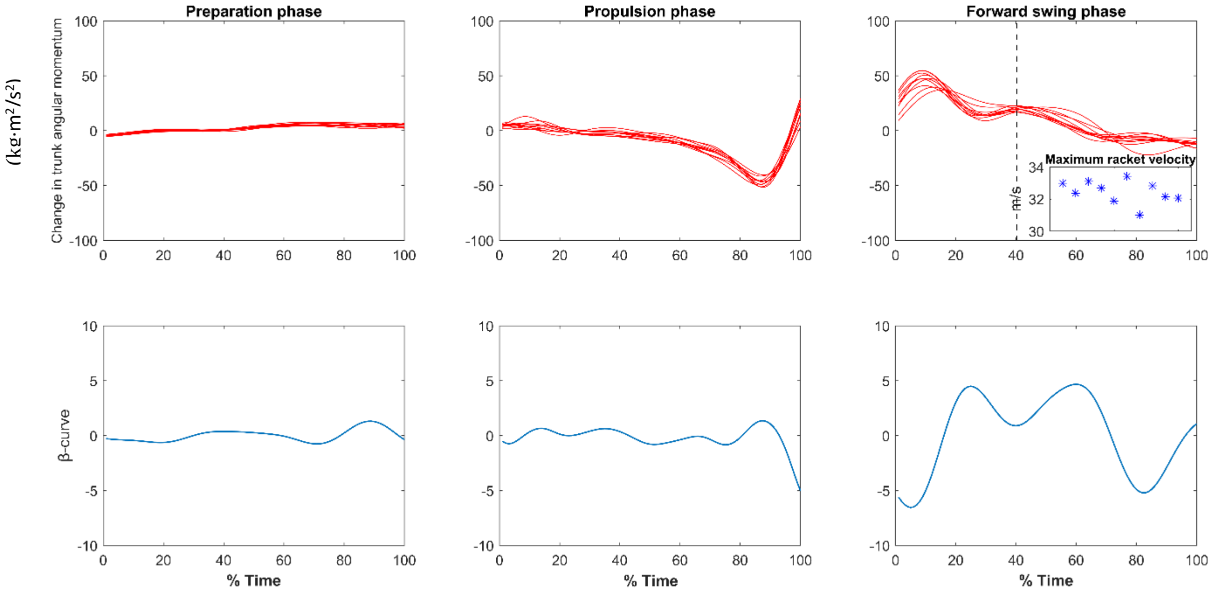

Figure 3.6. An example of one participant of the relationship between the change in trunk angular momentum and maximum racket velocity during the tennis serve. The vertical line represented at 40% of the forward swing phase indicates the time at which maximum racket velocity was reached.

Changes in trunk angular momentum were again very small in the preparation phase, and only marginally larger in most of the propulsion phase. Only towards the end of the propulsion phase, and in the forward swing phase, more variation can be seen compared to the two phases earlier. Similar to changes in arms angular momentum, the β-curve for the trunk angular momentum in the preparation and propulsion phase indicated no strong relationship, and in the forward swing phase there were great fluctuations in the relationship.

The next three figures below illustrate the sample-wide relationships between the XCoM (figure 3.7), the changes in arms angular momentum and maximum racket velocity (figure 3.8), and changes in trunk angular momentum and maximum racket velocity (figure 3.9). Top panels show the average data for each individual. In the middle panels, β-curves for each individual are presented, identifying the strength of the relationship for each participant. In bottom panels the SPM linear regression test outcomes are presented, identifying where the β-curves differ significantly from zero. The average time point at 47 % of forward swing phase at which maximum racket forward velocity is reached is again indicated by the dashed vertical line.

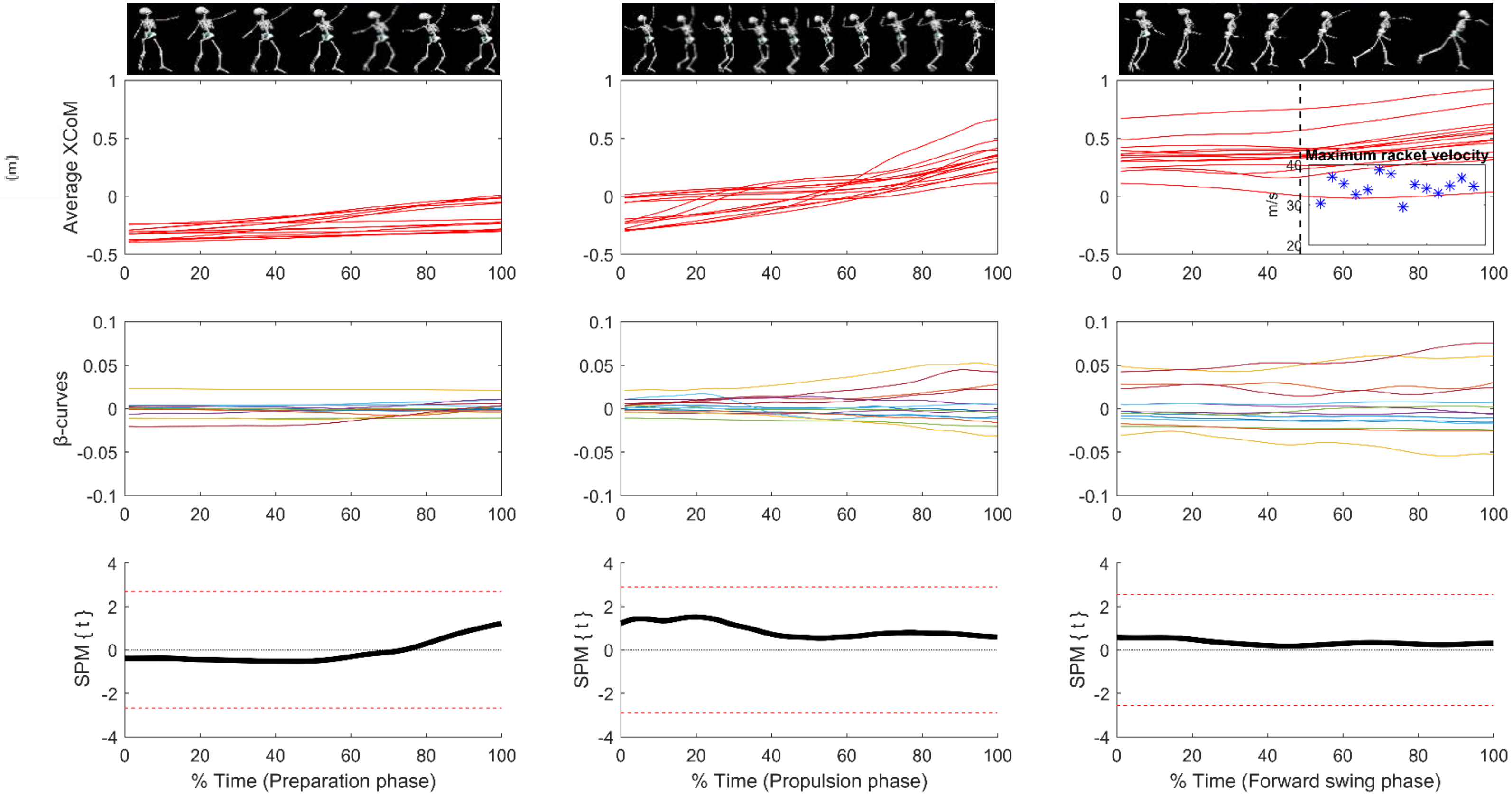

Figure 3.7. The relationships between XCoM in A/P direction and maximum racket velocity of 14 participants during the serve.

The general pattern of XCoM movement in A/P direction across the three phases is confirmed from what was reported earlier for the example participant data. The β trajectories of all participants present little variation in the preparation phase, more variation in the propulsion phase, and the greatest variation in the forward swing phase. The SPM linear regression test indicated no instants of significant sample-wide relationship, so there was no systematic relationship between XCoM in A/P direction and maximum racket velocity.

The average of the changes in arms (figure 3.8) and trunk (figure 3.9) angular momentum in the preparation phase showed minimal to no variation between participants, with averages fluctuating around the zero line. However, more amplitude variation was seen in the second half of the propulsion and in forward swing phase for both the changes in arms and trunk angular momentum. The graphs of all participants showed a similar pattern in the change in arms angular momentum representative of an early positive change leading into a zero change in the second half of the forward swing phase. The majority of the graphs show a similar pattern for changes in trunk angular momentum. The majority of the β-curves (the changes in arms angular momentum and maximum racket velocity) were in the negative direction except for 2 participants. In the forward swing phase, the average of the changes of all participants show again more variation compared to the two phases earlier. For the β-curves (the changes in trunk angular momentum and maximum racket velocity) of all participants present little variation in the preparation phase, more variation in the propulsion phase, and the greatest variation in the forward swing phase. Based on the large variability in β-curves, SPM linear regression confirmed that there was no significant relationship between the changes in arms/trunk angular momentum and maximum racket velocity throughout almost the entire serving movement. Only a significant relationship was found between changes in trunk angular momentum and racket velocity between 15% and 30% of the forward swing phase (figure 3.9).

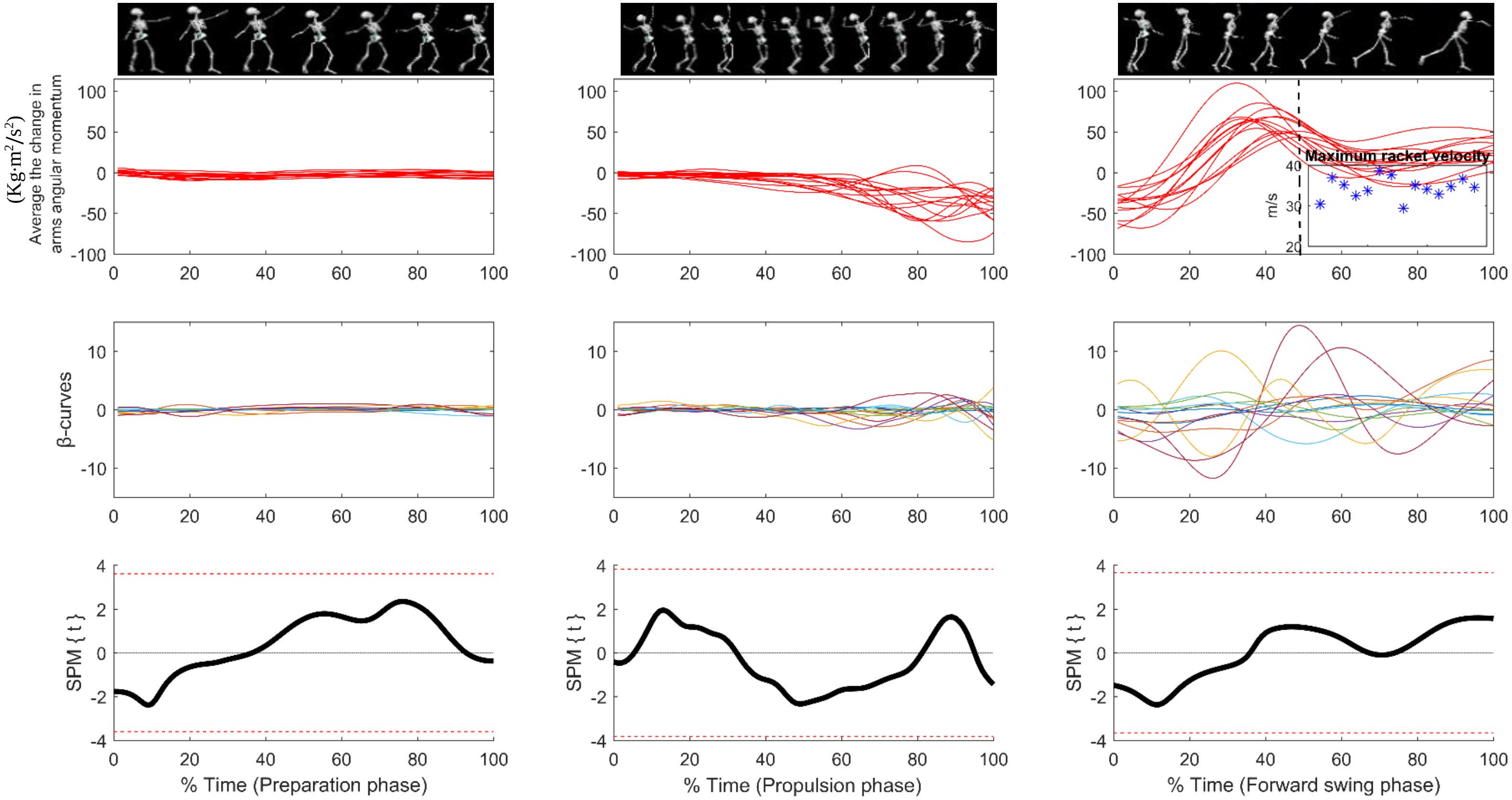

Figure 3.8. The relationships between changes in arms angular momentum and maximum racket velocity of 14 participants during the serve.

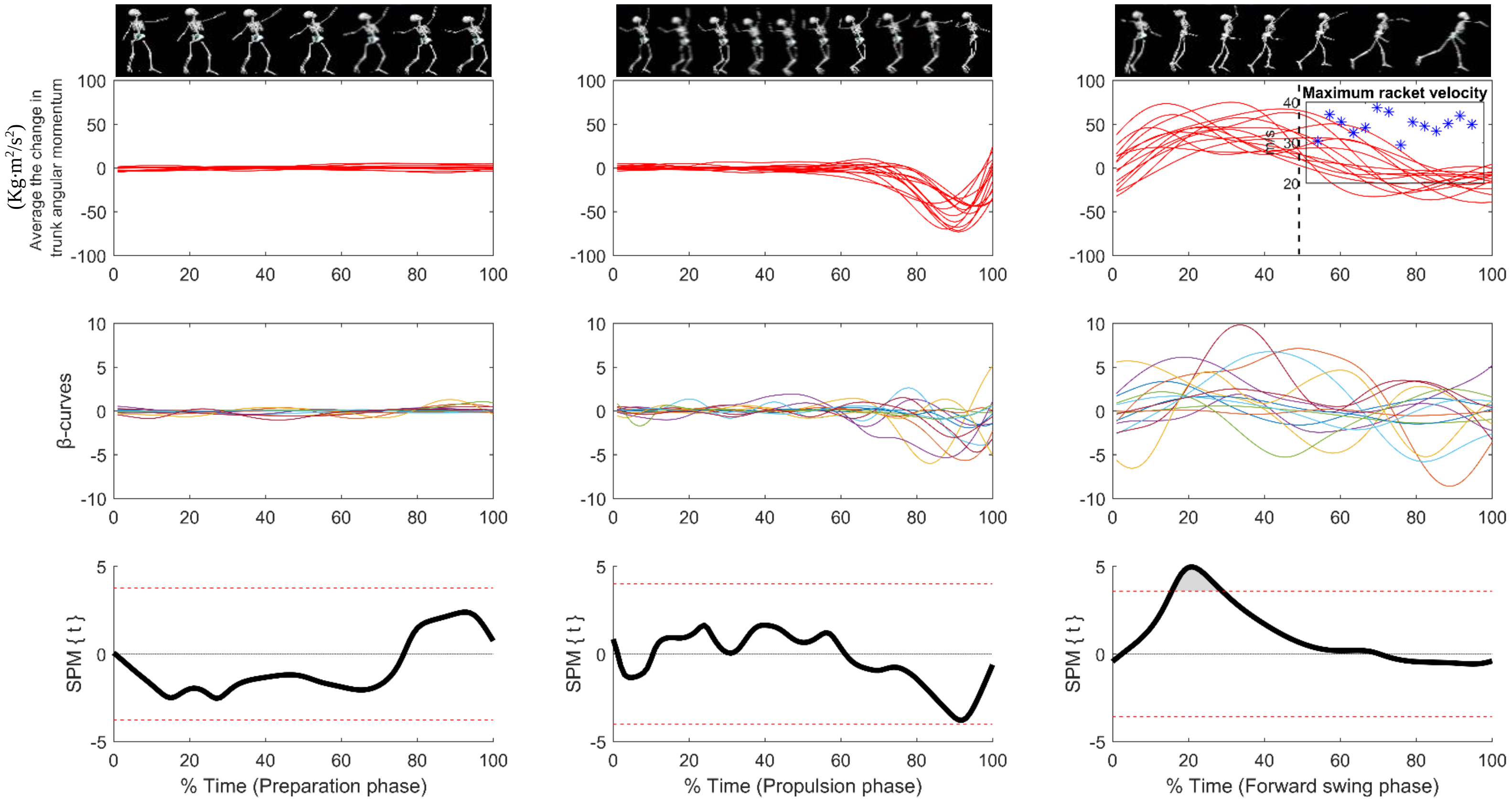

Figure 3.9. The relationships between changes in trunk angular momentum and maximum racket velocity of 14 participants during the serve.

3.5 Discussion

The aims of this study were to investigate whether there is an interaction between postural balance and end-effector performance in the tennis serve of experienced players. The results expressed that there were mostly no systematic relationships between the XCoM or the changes in arms/trunk angular momentum in the A/P direction, and maximum forward racket velocity. The only significant relationship observed was between the change in trunk angular momentum and maximum racket velocity in the forward swing phase, just prior to the time at which maximum racket velocity was reached.

It is worth first reflecting on the possibility that shortly before maximal racket velocity is achieved there may be some interaction with counter rotation of the trunk segment. The kinetic chain theory could be used to explain this through the generation of forces to propel the racket to hit the ball. For example, the coordinated movement starts at the feet pushing against the ground, moving through the trunk and eventually to through the upper extremity to the hand as there is a subsequent increase in velocity of body segments (Abrams et al., 2011). As the last phases have high velocities, it is not unthinkable that the acceleration of the trunk segment determines the end-effector performance. This is also supported by the notion of Crespo and colleagues (1998), stating that trunk and arm rotation work together towards racket velocity. This counter rotation of segments is however also expected to play a role in the maintenance of balance. As the trunk segment moves rapidly from backward to forward during the forward swing phase, the acceleration of this motion is expected to cause an opposite change in angular momentum of the lower extremities, which in turn would generate backwards directed ground reaction forces. Our findings seem to support a relevant interaction between balance control and end-effector performance, yet this would have to be confirmed through further investigation in other serving locations as well as comparing the interaction across the locations (see chapter 4) to explore that whether this interaction is maintained.

Our findings suggest that individual interactions between balance mechanisms and end-effector outcome were present, but that these were not systematically the same.

For example, the β-curves of the interaction between the changes in arms/trunk angular momentum and maximum racket velocity of all participants present little variation in the preparation phase, more variation in the propulsion phase, and the greatest variation in the forward swing phase. Even, the β-curves of these interactions seem to be similar patterns but the β-curve trajectories were not exactly the same. No consistent relationships were observed across all participants. This could be explained due to each player having their own strategy to maintain the balance when executing a maximum racket velocity even when serving to the same serving location. This supports previous suggestions that each individual has a unique ability to maintain their balance depending on what compensatory strategies are required to complete the task successfully (Horak, 2006). It also supports the notion that different athletes perform the same task in different ways, and that there is no single optimal movement pattern to achieve that task for athletes as a whole (Bartlett et al., 2007). Several factors may explain the individuality. First, whilst this study selected a relatively homogenous population (Thai experienced players), there is still a great level of heterogeneity within the population (e.g., gender). Hence, players may have different serving techniques. Second, players are able to adapt differently to the ball toss outcome. The implication of advanced individuality would be that coaches should not just generalise across a population, but that they should provide the attention carefully to their individual players. More so, it likely makes little sense to try to copy specific details of a successful players' technique and apply these to other players or even new learners when it comes down to subtle adaptations of a trained skill. Further research (see chapter 4) will need to verify the meaningfulness of this individuality.

The practical implementation of the benefit of understanding the interaction between balance mechanisms and end-effector performance, or the lack of such interaction as we found, is for coaches to understand the importance of intrinsic behaviours during the tennis serve that serve multiple purposes. Players need to coordinate the motion of trunk movement and arms swing to maximise performance, but at the same time balance is controlled. Therefore, whilst balance control and performance maximisation can strictly spoken not be mechanically separated, our findings could not find that there is a tight relationship between postural balance control and serving performance. Therefore, there is no strong evidence that they have to be trained simultaneously. In term of learning the complex task, the optimal range of variability is needed to learn and adapt motor skills (Stergiou et al., 2006) especially, in early in learning, player attempts to acquire an idea of the movement (Gentile, 1972) and inter-trial variability may be high due to exploration of new coordination modes during practice. However, in skilled performers, variability can also need to be high to provide flexibility in adapting and refining movements to new performance contexts or challenges (Davids, 2003). These might be a reason why our results suggest that these two roles are not directly related to each other based on observation of the intrinsic variations in movement as the players flexible in adapting and refining movements to the ball location. Furthermore, the findings suggest that the interaction between balance control and end-effector performance may well be highly individualised and hence requires an individual training approach. Concerning the latter, one may suggest that technical training through a trial-and-error approach may well be more suitable than a strictly prescriptive instructional approach based on technique observations from the average elite player.

Exploring the interaction between postural balance control and end-effector performance during the tennis serve is a novel approach in this field of work. There are both strengths and weaknesses in this study. In previous research, discrete variables have been used most commonly to analyse human movement. This is powerful but may not be sufficient to provide an exhaustive description of the observed movement (Preatoni et al., 2013). Therefore, an important strength of using SPM is that it partly overcomes this issue and avoids unnecessary reduction of an inherently time-bound observation. However, there is still a weakness in the fact that the interactions are evaluated only for changes in the amplitude of the signal. Any temporal changes in the profiles were omitted with the use of SPM as analysis technique. After qualitatively checking the temporal variation of the 10 trials of each participant, we found that temporal variations were limited (see appendix D). This mostly justified the use of SPM, but in further research one may wish to consider the use of analysis techniques that take into account temporal variations, such as cross-correlation techniques (Nelson-Wong et al., 2009). On the other hand, a weakness to the present study, which should be taken into account. The interaction found could be useful if the further investigation in other locations (chapter 4) also found some generic interactions between postural balance control and end-effector performance. The data was collected on an actual tennis court but not as part of competitive match play.

Therefore, the results may be different as in actual competition the player will be under pressure and also has to combat external conditions such as wind and unfamiliar surroundings. This may contribute to a player changing their serving mechanics. We still believe that the premise of a maximal serve to a real target on an actual tennis court allowed us to establish inherent relationships between balance mechanisms and end effector behaviour for experienced tennis players. Moreover, this finding represents only small number of experience players thus it could not represent the results in other skill levels

3.6 Conclusion

No direct relationship was observed between balance control mechanisms and end-effector behaviour. Experienced players appear to have individualised strategies to maintain their balance during a tennis serve. Therefore, under the constraints of our observations, in experienced players the variation in end-effector behaviour is not directly influenced by behaviours that are associated to maintaining balance. For coaches, this supports the notion that training balance and end-effector control separately remains justified.

CHAPTER 4 How Consistent is the Interaction between Postural Balance Mechanisms and End-Effector Performance in Tennis Serves across Different Target Locations?

4.1 Abstract

Background: The control of balance is essential for all human movement (Hof et al., 2005) and instrumental to the execution of a tennis serve. The relationship between the control of postural balance and the performance of a tennis serve has been investigated in the previous chapter but the consistency of the relationship between different serving locations remains largely unexplored. The aim of this study was to evaluate this relationship across 4 serving locations at both a group and individual level. **Methods**: 11 right-handed experienced tennis players (six males and five females; age, 22 ± 4.11 years; height, 1.74 ± 0.07 m; body mass 65 ± 8.06 kg) participated in this study. Participants completed 10 successful tennis serves to 4 target locations each. 12 optoelectronic cameras at 200 Hz (BTS bioengineering, Milan, Italy) were used to collect whole body kinematic data. Statistical parametric mapping (SPM) with regression and one-way repeated ANOVA were used to identify the relationship between postural balance control (XCoM displacement and changes in arms/trunk angular momentum in forward/backward direction) and end-effector performance (maximum racket forward velocity), and to explore the relationship across serving locations, respectively. A qualitative evaluation was done of whether subject-specific relationships were evident. **Results**: The results showed no systematic relationship between postural balance control mechanisms and end-effector performance across 4 different serving locations, as well as no evident individual relationships. It was concluded that serving to different locations likely involves different balance control mechanisms to adjust for target-specific serve technique

constraints. For practical application, we found no evidence that balance control and end-effector performance are tightly related within an elite tennis serve performance and that these could be trained separately.

4.2 Introduction

The tennis serve is the most important stroke in tennis, with players having two chances per ball exchange to put pressure on the opponent (Reid et al., 2011). Furthermore, the serve is a goal-directed sporting task as the players have to serve to various serving locations. A player can create an advantage if they are capable of producing efficient serves (high speed and accuracy) into the targeted areas to make the opponents return more difficult. Generally speaking, three main techniques for the tennis serve exist, that is, the flat, kick, and slice serve (Reid et al., 2008). The serve performance is dictated by many factors. In the first serve, more than the second serve, one of the key factors is the generation of maximal ball speed, which is priority in a flat serve technique. This ball speed is generated by moving the body segments, and not only upper extremity segments but also lower extremity segments. In fact, the tennis serve is a complex activity, in which the player needs to control balance whilst controlling the movement of body segments and racket (Gillet et al., 2009).

The ability to serve to an appropriate location is the most beneficial for winning the point. Importantly, the serve location of first serves dictates the serve technique, namely, flat first serves are used significantly more often down the T corner near the centre serve line, whereas the kick and slice serves are used more often into the wide location, especially on the advantage side of the court (Gillet et al., 2009). This means that across target locations the body kinematics, balance control strategy, and end-effector performance are likely to change. However, Reid and colleagues. (2011) stated that a player serving to different parts of the court uses the same ball toss, and hence a constant relationship between balance control mechanisms and end-effector performance across serving locations may still be expected.

This research allows coaches to learn from understanding whether the interaction between postural balance mechanisms and the end-effector performance is different between altered serving locations. Also, coaches may gain more understanding about which balance control mechanisms players may use to execute the serve to altered target locations. Hence, coaches may need to take these interactions into account to improve players' performance as well as may be able to use the knowledge to apply and develop an appropriate training programme.

Interestingly, the study comparing the kinematics of serves to different locations in the service box are limited (Chow et al., 2009). Furthermore, the previous chapter found little relationships between individuals serving to one location. We found only an interaction between trunk movements and end-effector performance during the forward swing phase (see figure 3.9). Also, the results show that preparation and propulsion phases had little meaningful interactions. The comparison of the interaction between dynamic balance control mechanisms and serving performance in a maximum tennis serve across the serving locations are still unexplored. Therefore, the purposes of the study were primarily to explore the interaction between postural balance control and end-effector performance between serving conditions. Secondly, we wanted to explore individuality of interactions that become manifest during tennis serves across serving locations, considering that a high level of individuality seems to have been noticed in the relationships in the previous chapter.

4.3 Methods

Participants

Eleven right-handed experienced Thai tennis players (six males and five females; age, 22 ± 4.11 years; height, 1.74 ± 0.07 m; body mass 65 ± 8.06 kg) participated in this study. The inclusion criteria were that the player had an experience participating ≥ 5 years at the national and international level, and being or used to being a Tai national level tennis player. Participants were questioned about their injury history and none had a recent (< 6 month) muscle injury. This study was approved by the Liverpool John Moores ethics committee (15/SPS/016) and Mahidol university ethics committee (MU-CIRB 2016/013.2201).

Experimental design and protocol

The main aspects of the experimental design and protocol in this study are described in chapter 3 but summarised briefly below. Sixty-eight reflective markers were placed on anatomical landmarks to record segmental motions. Participants then completed a 10 min warm up (consisting of light jogging and tennis serve movement). Players used their own rackets to complete the protocol. After a standardised warm-up routine, subjects performed at least 40 maximal effort first serves successful shots directed at a 1 x 1 metre of 4 different target locations (Figure 4.1). Participants were asked to produce the maximum serve (first serve) in every trial. For serving purposes, the tennis court is divided into two sections, deuce court and advantage court. If the server stands facing the net, the half court on the right hand side is called the deuce court and the left hand side called the advantage court. The different serving locations were called, condition1 (C1) located at the junction of the service line represented the location of a wide serve of the deuce court, condition2 (C2) was the broader location of the T line of the deuce court, condition3 (C3) was the broader location of the T line of the advantage court, and condition 4 (C4) was the location of the wide serve of the advantage court (Figure 4.1). A 2-min rest was foreseen between serves. Forty successful serves were analysed. Participants were allowed to use a “foot-up” or “foot-back” service technique depending on their preference. Six players used foot-up and five players used foot-back technique.

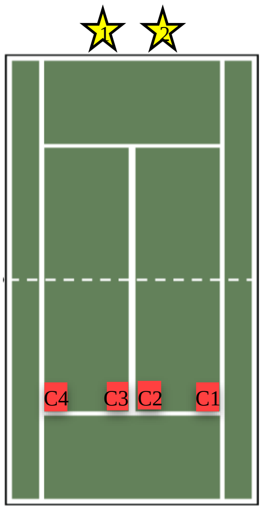

Figure 4.1. Shows the red squares represent 4 target locations (1x1 metre) that the players were asked to serve to. The yellow stars represent the participant’s standing position. The star 1 represents where the participant stands to serve to C1 and C2 location on the deuce while, the star 2 represents where the participant stands to serve to C3 and C4 location on the advantage court.

Data collection

Kinematic data were collected with 12 infrared cameras at 200 Hz (BTS bioengineering, Milan, Italy). The markers were placed on 13 segments to allow calibrating and tracking of segmental motion consisting of head, upper arms, forearms (including hands), thorax, pelvis, thighs, shanks, and feet (Figure 3.2). Prior to performing the task, a static recording was obtained for use in marker definition and model scaling, after which the dynamic trials were recorded. The order of serving to the different locations was randomised.

Data reduction and analysis

In this study, firstly, the inverted pendulum mechanism was observed by observing the XCoM in anteroposterior direction. Secondly, the counter rotation of segments mechanism was observed via the changes in angular momentum of the upper part of the body, i.e. arms and/or trunk segment. A 13-segment model was used to calculate the whole-body CoM (see chapter 2). The XCoM was calculated using the position of the vertical projection of the CoM added with its velocity multiplied by a factor $\sqrt{l}/g$ (l being leg length and g the gravitational acceleration) (Hof, 2005). The angular momenta of the arms (both arms together) and trunk segment relative to the whole-body CoM were separately calculated as the product of their principal moment of inertia (I) and angular velocity in the arms/trunk segment coordinate system (ω). The time derivative was calculated to represent the changes in angular momentum. The coordinate system in this study was aligned with the baseline of the tennis court, with the X axis pointing towards the net, the Y axis pointing upwards, and the Z axis parallel to the baseline pointing to the right. End-effector performance was quantified through maximum racket velocity, calculated from the peak forward velocity of a marker on the top of the racket.

All calculations were implemented in Visual3D software version 6.0 (C-motion, Germantown, MD, USA). Each trial was time normalised to 101 samples (0-100% of cycle time) over the duration of the movement (see figure 3.3). The start of the tennis serve was taken as the time when the upper limb of the non-racket arm was parallel to the ground. The end of the movement was taken when the upper limb of the hitting arm was parallel to the ground, shortly after assumed ball contact. Using two further intermediate events, namely the highest point of the distal end of the non-racket arm and the lowest point of the racket head, the serve was divided into a preparation phase, a propulsion phase and a forward swing phase. Data was low-pass filtered using a fourth order recursive Butterworth filter with cut off frequency of 15 Hz. To compensate for noise amplification due to double differentiation, angular momentum data was filtered with a cut off frequency of 6 Hz prior to differentiation. Further analysis was conducted on only data from the forward swing phase.

Statistical analysis

Statistical Parametric Mapping (SPM) was used to analyse the kinematic continua associated with the two balance mechanisms. SPM linear regression was used to examine the within-subject interaction between the XCoM in A/P direction and maximum racket velocity, as well as the interaction between changes in arms and trunk angular momenta and maximum racket forward velocity. In addition to the test statistic (SPM{t}), the slopes of these relationships were computed at each time t, resulting in β trajectories. These β trajectories were computed for each subject and for each serve direction. The β trajectories were subsequently examined across subjects between target locations using a SPM one-way repeated measures ANOVA resulting in a SPM{F} test statistic. The statistical analysis approached of this study was shown in figure 4.2. The significance of each SPM{t} and SPM{F} curve was then determined topologically using random field theory (Adler & Taylor, 2007). SPM analyses were implemented using the open-source spm1d code (www.spm1d.org) in Matlab (R2016a, 8.3.0.532, The Mathworks Inc, Natick, MA). Finally, qualitative observations of the β trajectories were undertaken to observe their variability within and between participants for the four serving locations.

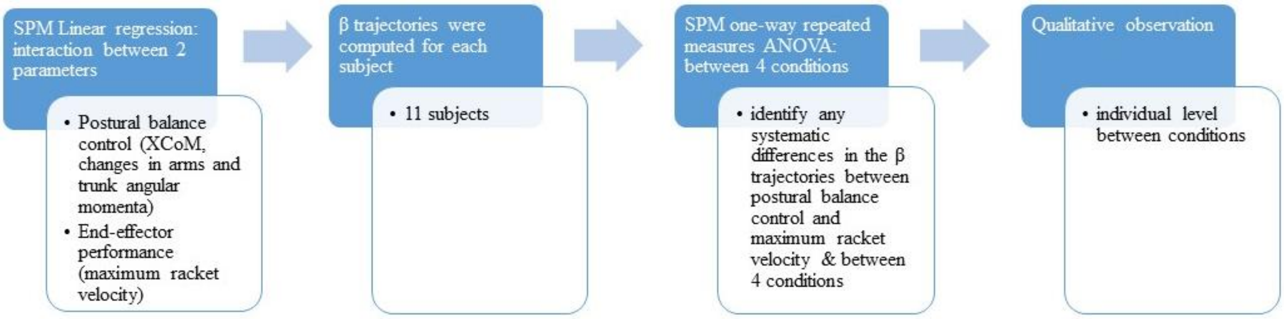

Figure 4.2 Statistical analysis diagram

4.4 Results

The average time point at which the participants generated the highest racket velocity was between 38-58% of the forward swing phase, and this was consistent between serving conditions.

A detailed presentation of the SPM linear regression approach to describe the relationship between the XCoM in A/P direction and maximum racket velocity in each serving condition is presented in Appendix E1-4. Similarly, detailed results of the SPM linear regression approach to describe the relationship between the changes in arms or trunk angular momentum, on the one hand, and maximum racket velocity, on the other hand, are described in Appendix F1-4 and Appendix F5-8, respectively. These β trajectories that were computed from the SPM linear regression approach have been focused on in this study. Then the β trajectories used to examine between serve conditions using a SPM one-way repeated measures ANOVA. Ultimately, the key outcomes are described below.

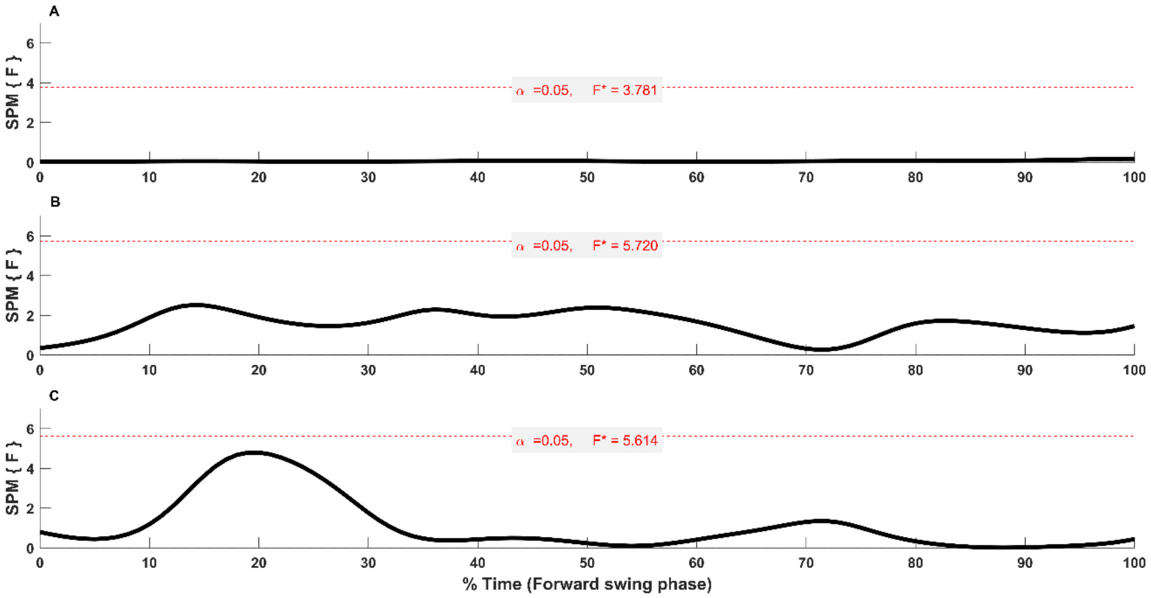

Figure 4.3. One-way repeated measure ANOVA graphs reveal the comparison of the relationship between the different postural balance control mechanisms and the end-effector performance within 4 conditions in forward swing phase. In figure 4.3A the comp arison of the relationship between XCoMx in A/P direction and maximum racket velocity. Figure 4.3B the change in arms angular momentum and maximum racket velocity. In figure 4.3C the results show no systematic differences between the relationship between XCoM in A/P direction and maximum racket velocity.

The SPM one-way repeated measure ANOVA results show no systematic differences between the relationship between XCoM (figure 4.3 A), the changes in arms (figure 4.3 B) /trunk (figure 4.3 C) angular momentum in A/P direction and maximum racket velocity within 4 conditions during the serve in the forward swing phase.

Figures 4.4, 4.5 and 4.6 below illustrate the comparison of the interaction between postural balance control and end-effector performance in the forward swing phase between 4 serving locations. The graphs on the top panel show the average of the XCoM (figure 4.4), and changes in arms (figure 4.5)/trunk (figure 4.6) angular momentum of 10 trials of 11 participants. The graphs in the middle panels show the β-curves which represent the relationship between the postural balance parameter and maximum racket velocity. The graphs in the bottom panel show the SPM one-way repeated ANOVA test outcomes. The average of the maximum racket velocity of each participant for 4 conditions as well as the average and standard deviation for all participants present in table 4.1. Target conditions C1, C2, C3 and C4 are ordered from the left to the right, respectively. The vertical dotted line indicates the time at which maximum racket velocity was reached. Overall, the interaction of the postural balance parameters and the maximum racket velocity showed no systematic differences between conditions. Overall, the β-curves showed considerable variation between participants, yet the relationship between the change in arms angular momentum and maximum racket velocity in condition 4 was systematically positive between 50%-70% of the forward swing phase (see figure 4.5 or appendix F4).

Table 4. 1. Presents the average of the maximum racket velocity of each participant for 4 conditions.

Participant	**Means of maximum racket velocity (m/s)**			
	Condition 1	**Condition 2**	**Condition 3**	**Condition 4**
1	30.5	30.5	29.4	24.7
2	43.1	44.6	44.4	43.7
3	42.1	37.1	39.0	32.9
4	33.7	31.3	35.0	29.3
5	35.7	33.1	36.9	35.3
6	32.0	33.0	32.3	35.0
7	39.0	38.9	38.6	36.3
8	30.5	29.5	31.1	29.7
9	42.5	33.9	40.6	38.9
10	33.2	40.1	34.7	37.7
11	34.2	32.7	40.7	39.4
Mean ± SD	36±4.6	35±4.4	36.6±4.4	34.8±5.1

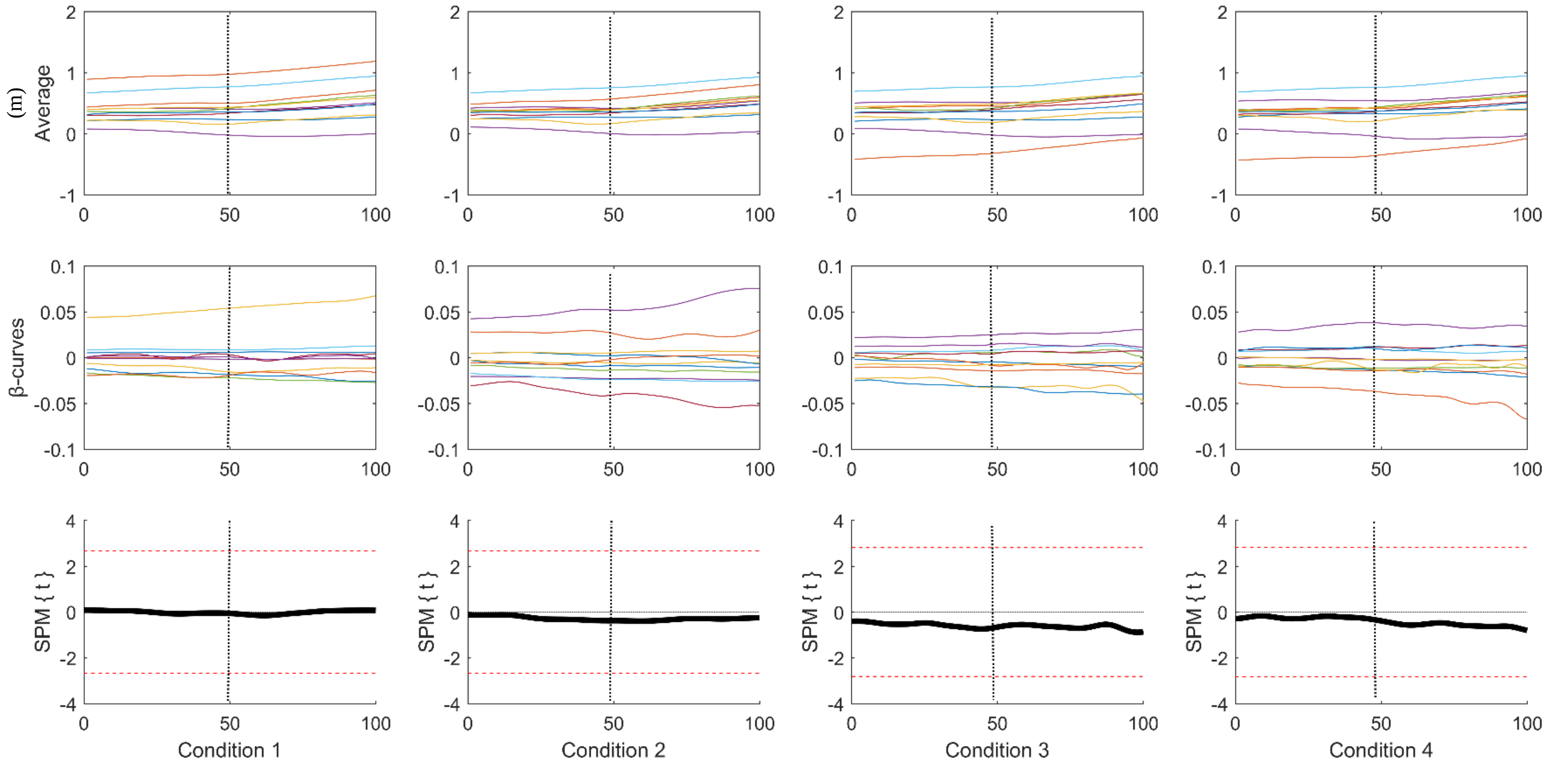

Figure 4.4. The relationship between XCoM and the maximum racket velocity in A/P direction in forward swing phase (4 conditions)

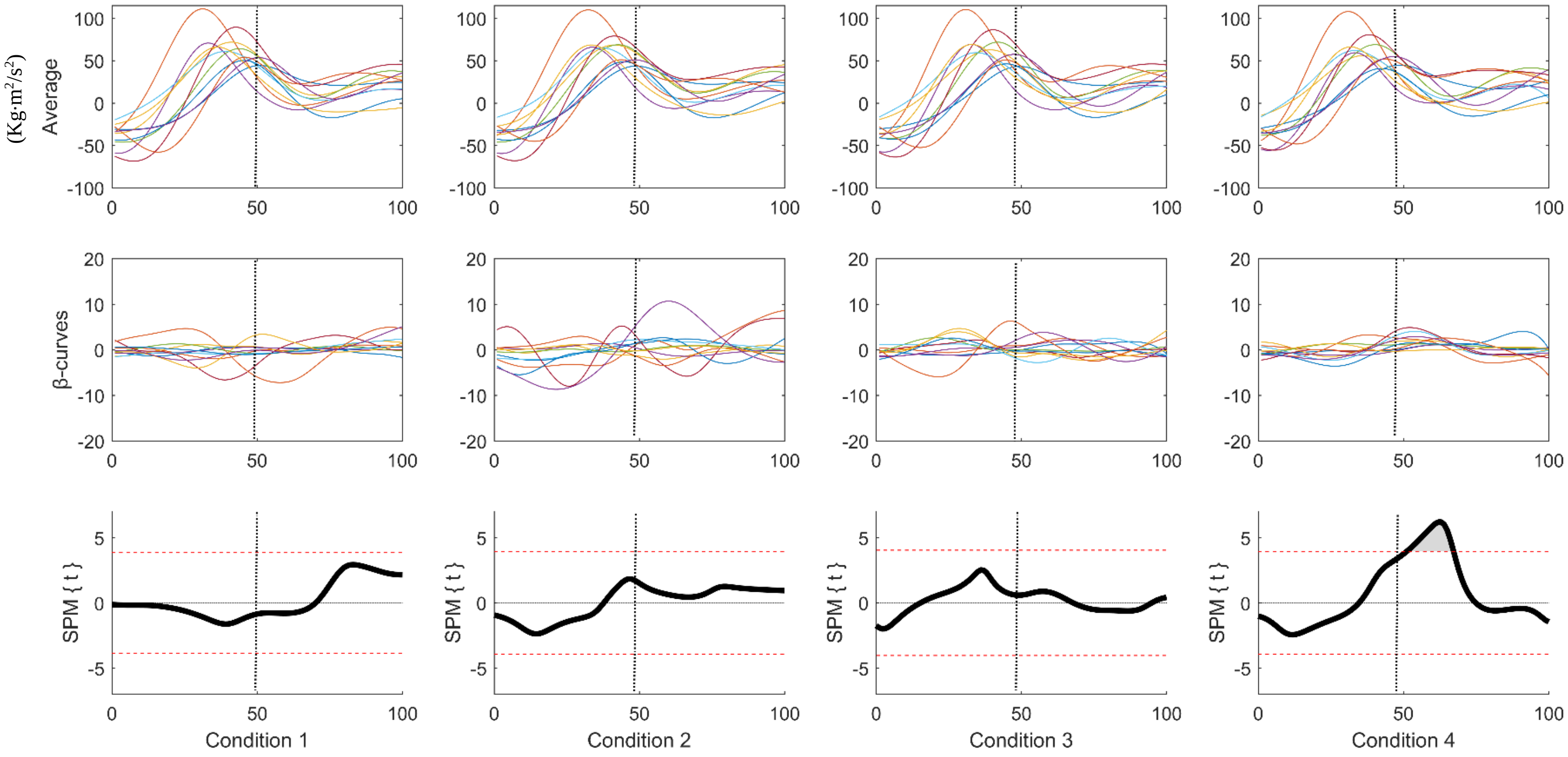

Figure 4.5. The relationship between the change in arm segments angular momentum and the maximum racket velocity in forward swing phase (4 conditions).

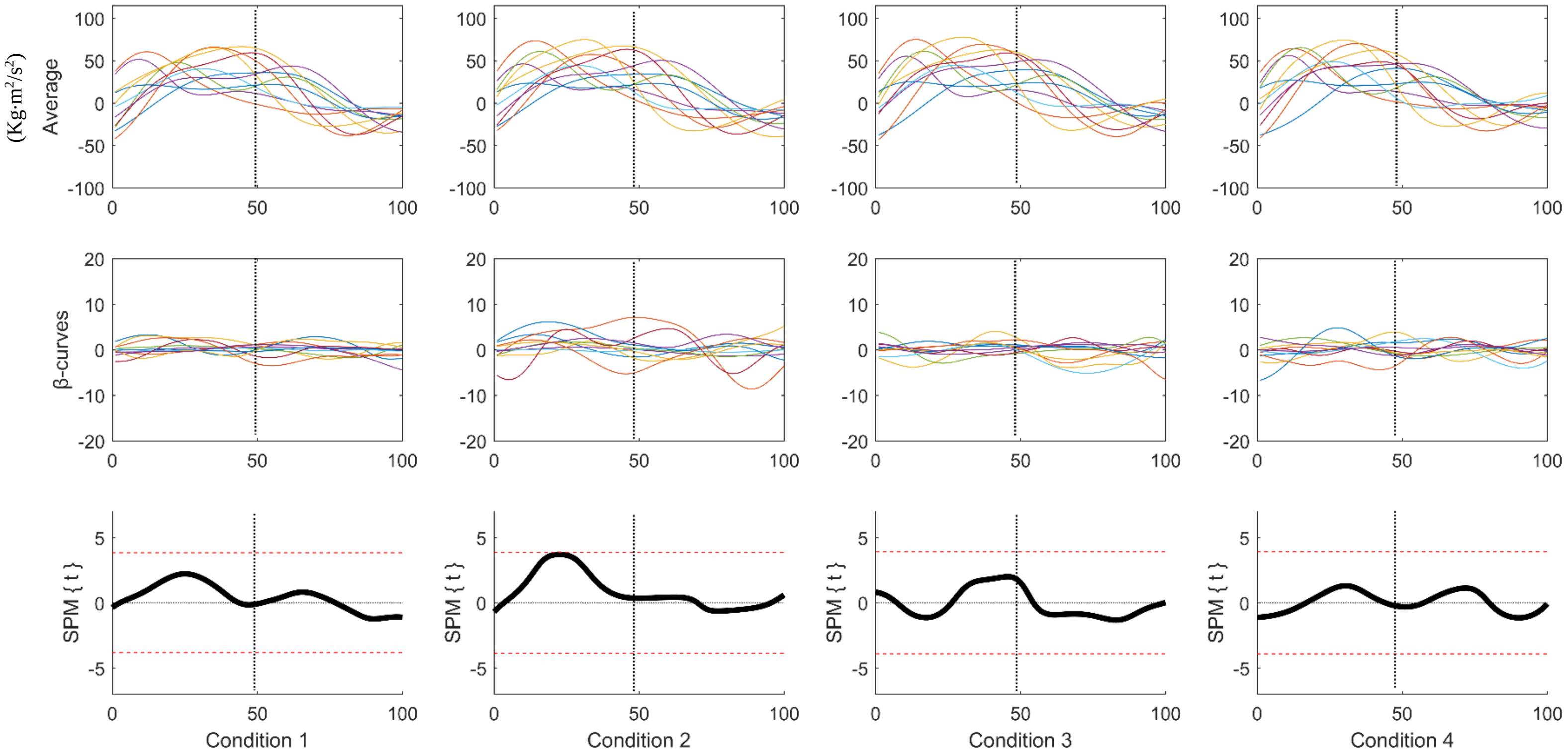

Figure 4.6. The relationship between the change in trunk segment angular momentum and the maximum racket velocity in forward swing phase (4 conditions).

Individuality of relationships was explored through qualitative analysis. Thus, the β-curve trajectories of 4 conditions of each participant were presented below. Figure 4.7 below shows no individual relationship between the XCoM in A/P direction and the maximum racket velocity as no similar trends can be seen within participants. In the figure 4.8 and 4.9 reveal more variations can be seen in the relationships between the changes in arms/trunk angular momentum and maximum racket velocity, but these were typically not consistent across the 4 conditions within individuals.

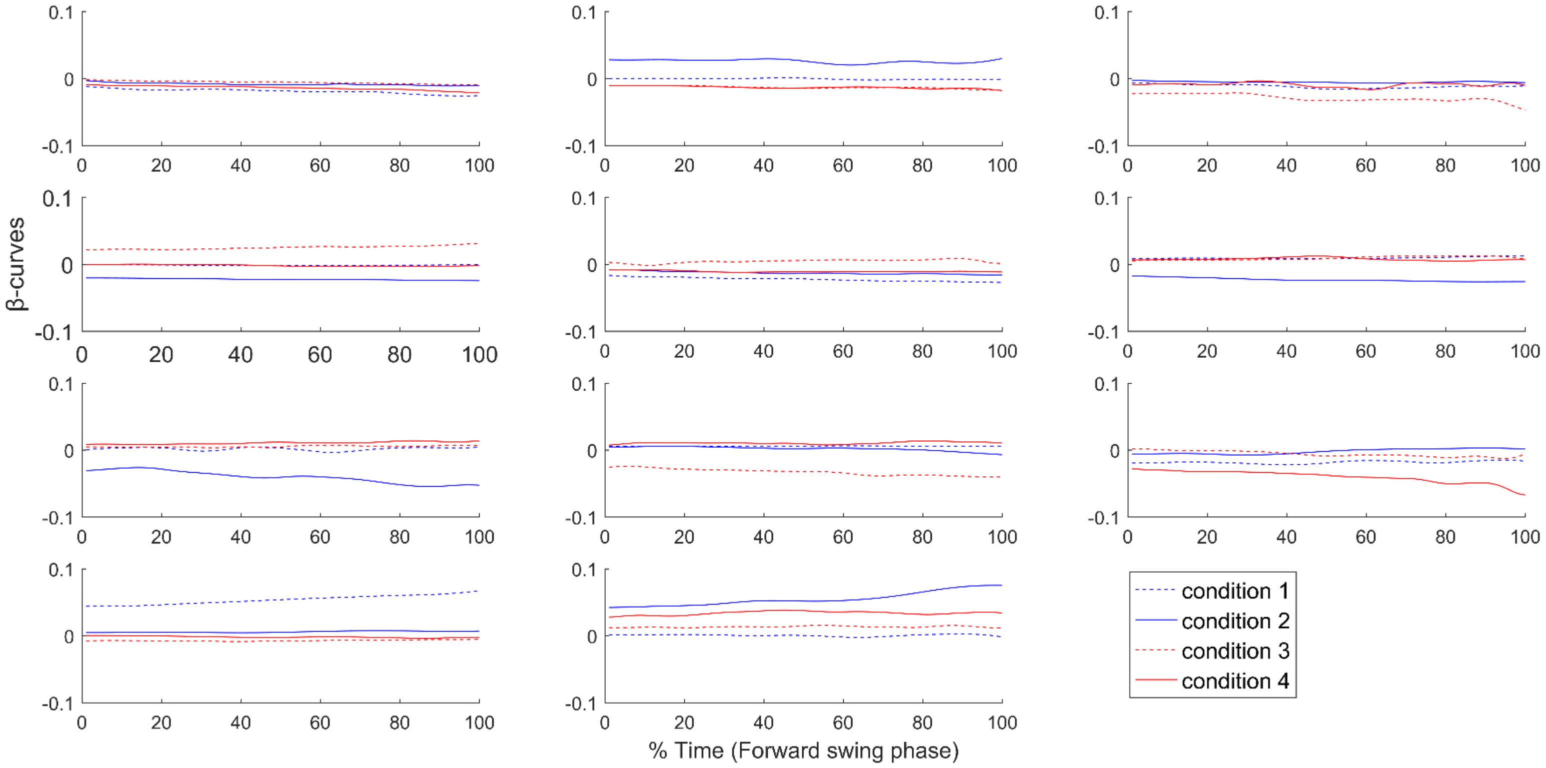

Figure 4.7. A comparison of the relationship between the XCoM in A/P direction and the maximum racket velocity in forward swing phase of 11 individual players between 4 serving locations.

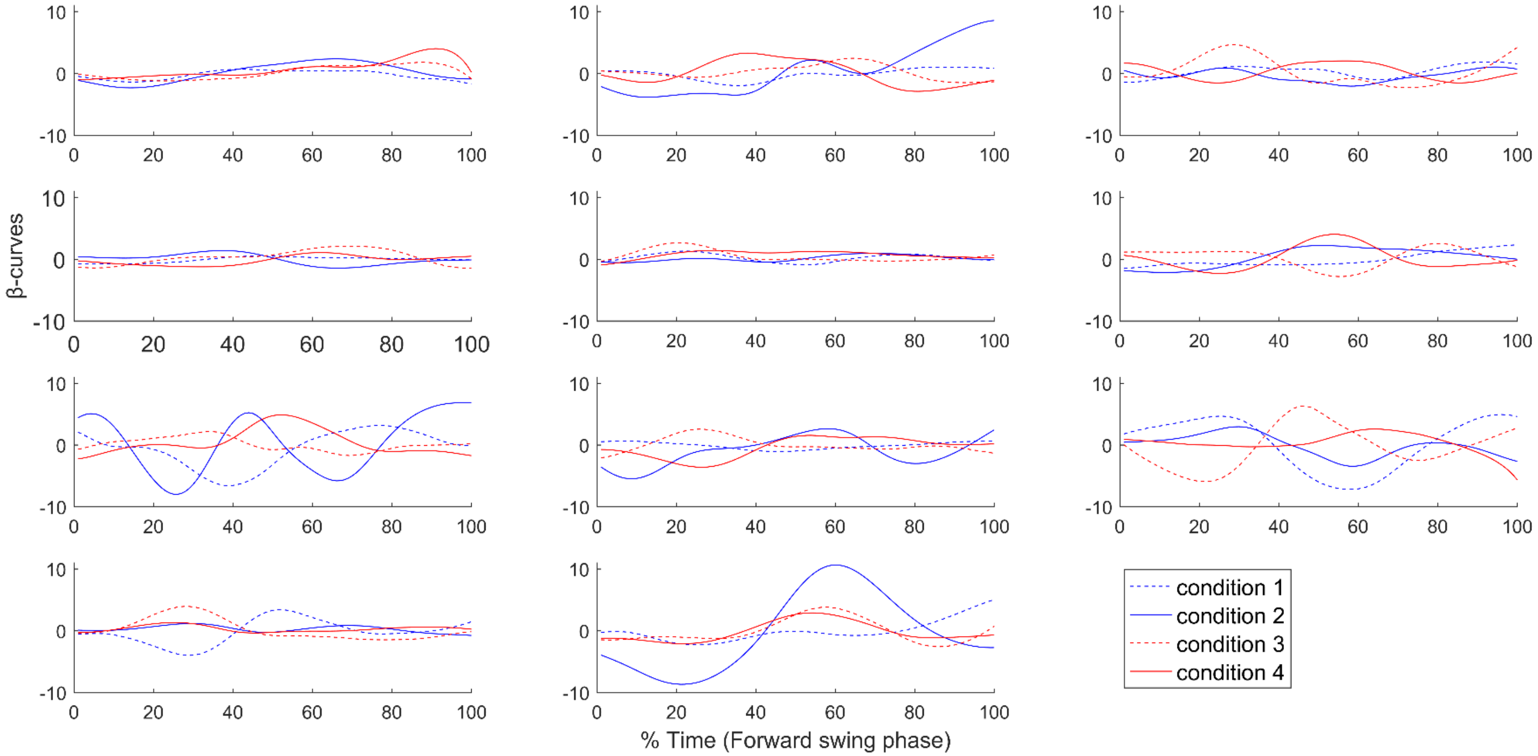

Figure 4.8. A comparison of the relationship between the changes in arms angular momentum and maximum racket velocity in forward swing phase of 11 individual players between 4 serving locations.

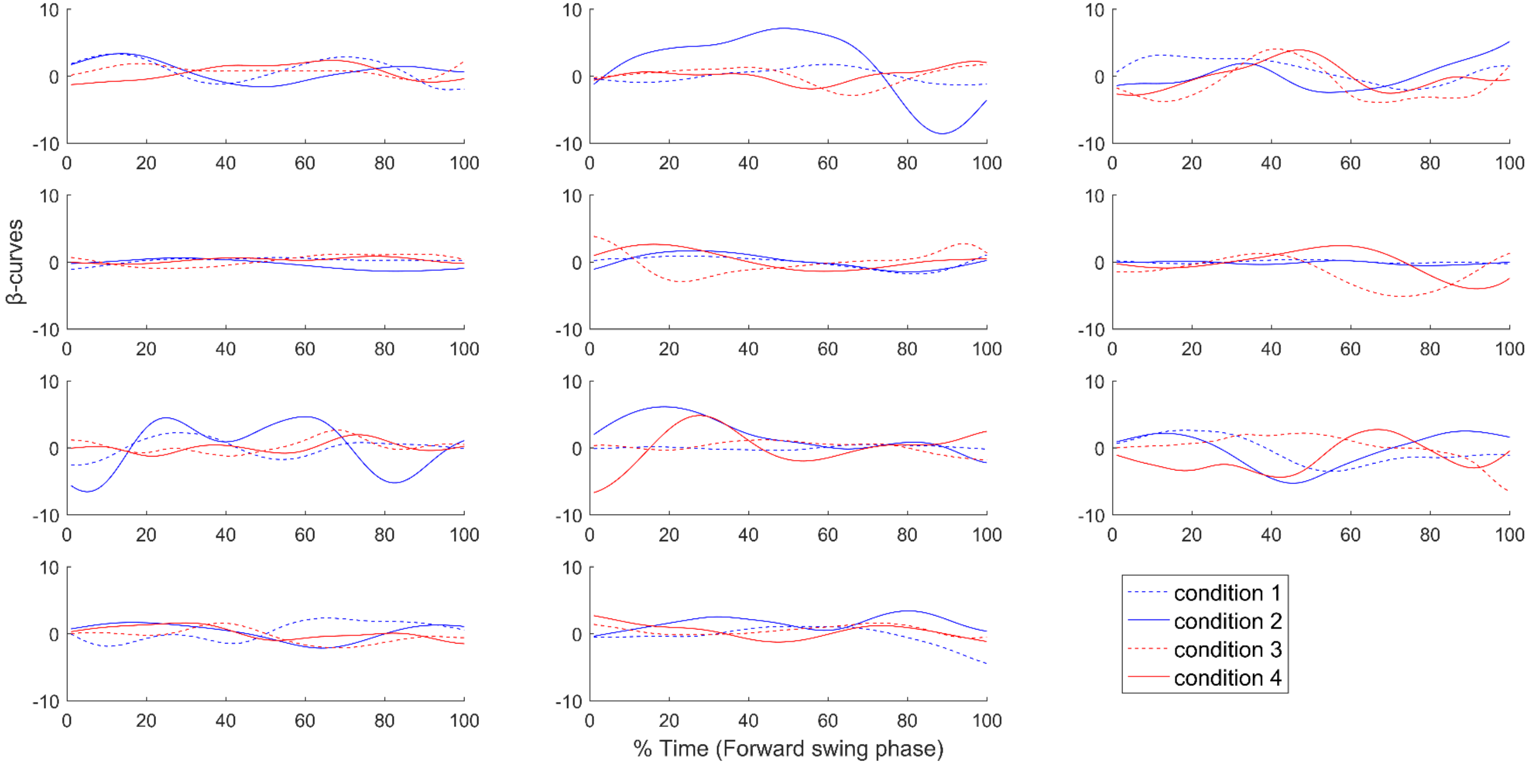

Figure 4.9. A comparison of the relationship between the changes in trunk angular momentum and maximum racket velocity in forward swing phase of 11 individual players between 4 serving locations.

4.5 Discussion

The previous chapter (chapter 3) showed there were mostly no systematic relationships between postural balance control and end-effector performance. Only an association was found between changes in trunk angular momentum and maximum racket velocity in the forward swing phase. The first aim of this study was to explore the consistency of the interaction between postural balance control and end-effector performance across 4 serve locations, focussing on the forward swing phase. The second aim was to explore the individuality of the interaction that becomes manifest during tennis serves across serving locations. The results showed no significant differences in the relationship across serving locations. The only exception was the relationship between the change in arms angular momentum and maximum racket velocity when serving into the right corner of the advantage court (condition 4). Furthermore, no evident individual relationships were observed across serving conditions.

The SPM one-way repeated measures ANOVA showed no differences between the interaction between balance control mechanisms and end-effector performance across the four serve conditions. It means that the players control their postural balance in A/P direction when producing the maximum racket velocity similarly even when serving to different locations. However, in figure 4.3C, there is a trend indicating that the relationship may well be different between conditions around 20% of the forward swing phase. Therefore, the players might move their trunk differently in that period of time (move from back swing to forward swing) to generate the maximum racket velocity. Otherwise, it might be because of when the XCoM, and the changes in arms/trunk angular momentum values were high while, the maximum racket velocity was also high or vice versa. However, these interactions between different serving locations of each participant show different patterns across four locations. Therefore, we might assume that each player used particular modifications to keep the postural stability during the maximum serve as well as used particular strategies to serve into different target locations.

This research found that variability in the end-effector is not necessarily related to variability found in other parts of the system that represent balance control. This finding agrees with the notion of Preatoni and colleagues (2013) that when analysing sporting movements, one needs to be careful not to confuse variability present within global movement outcome parameters (in this study maximum racket velocity) with variability that is present within kinematic (technique) parameters. For example, the global performance parameter might have a low variability but within the system there might be considerably high variability or vice versa. One reason might be the distal segment of the hitting arm moving freely to adjust to the changing impact location as the proximal-distal sequencing behaviour.

Chapter 3 sought to identify relationships between the XCoM, changes in arms/trunk and maximum racket velocity, but found no meaningful relationships, except for the relationship between the change in trunk angular momentum and maximum racket velocity, between 15-30% of the forward swing phase. The same analysis using SPM linear regression was repeated for the 4 conditions in this chapter (can be seen in appendix E and F) and similarly no meaningful relationships between postural balance control and end-effector performance were found. The exception was the interaction between the change in arm angular momentum and maximum racket velocity in condition 4 (see in figure 4.5 or appendix F-4). This was systematically positive between approximately 50%-70% of the forward swing phase. The reason might be the upper extremities were used to contribute to racket velocity at impact to produce the power serve. Furthermore, especially, for the kick serve (often used when serving to condition 4) upper limb was used to generate spin to send the ball to the target area. This reason agrees with Elliott (2006) stated that the internal rotation of the upper arm play an important role in the serve action.

In this study, the relationship between the change in trunk angular momentum and maximum racket velocity in condition 2 was not significant unlike the results of the previous chapter. This partly justifies the cautious interpretation from the previous chapter and could be due to the different number of players tested in this study. However, the relationship is close to the threshold for significance indicating that this may be an area for further investigation in the future (see SPM {t} plot in condition 2 of figure 4.6).

Whilst there were no consistent significant relationships across conditions there were some trends towards a relationship that may well deserve some further attention. For example, there was a trend towards a relationship between the changes in trunk angular momentum and maximum racket velocity that was most prominent in condition 2. The timing of this relationship occurs slightly prior to another trend towards a relationship between the changes in arms angular momentum and maximum racket velocity in condition 4. This could first of all be explained by the typical proximal-to-distal movement sequence in a tennis serve. Rapid changes in angular momentum of the trunk are expected to precede those of the arms, the latter which are most likely to in fact occur after peak velocity is reached. Both mechanisms are expected to influence balance, but their impact is likely different. While the trunk mechanism occurs at a time when the player is still in contact with the ground, the arms mechanism occurs when the player is in the air. This means that the trunk mechanism acts according to the counter rotation of segments mechanism as described in the literature, generating a backwards directed horizontal force on the ground. The change in arm angular momentum is likely to compensate for undesirable changes in angular momentum elsewhere in the body, for example excessive forwards rotation of the lower extremity, leading to an overall body angular momentum that is not excessively rotating the body forwards.

The question then remains why the trunk mechanism would be more pronounced in condition 2, and the arms mechanism in condition 4. When executing the first serve, players will attempt to favour service speed (flat serve) over spin variation (topspin or slice serves). However, kick first serve, despite reduced service speed, can be employed with the intention of introducing tactical variations by opening up the court with sharp angles. The kick serve strategy is therefore used more often to send the ball down on the wide side of the service box in the advantage court, and in the deuce court to push back the receiver behind the baseline. In the advantage court, the player attempts to find more angles to open up the court. Condition 2 is located at the broader location of the T line of the deuce court, whilst condition 4 was the location of the wide serve from the advantage court (Figure 4.1). In condition 2, for right-handed players, a flat serve was optimal. From the results, we believe that the player puts more effort in the trunk increase ball speed. In condition 4, the flat serve would in theory also produce the highest speed for a first serve, but this location is unique compared to the other conditions as it is very difficult to execute a flat serve towards this location. Therefore, the players will more often choose a kick serve for this location (Gillet et al., 2009). The kick serve involves more spin, and players are likely to use more arm angular momentum to generate that spin on the ball.

Following the findings from the previous chapter, experienced players appeared to have highly individualised strategies to maintain their balance during a tennis serve to one serving location. From the findings in the present chapter this belief can be rejected. Different relationships were found between conditions within players, and none of these relationships were shown to be very meaningful. The most likely explanation for this is that there is no direct relationship between variations in maximum racket velocity and the observed balance mechanisms.

This study applied a novel approach to explore the interaction between postural balance control and end-effector performance during the tennis serve, and this comes with several limitations. First, the players may use different strategies to control postural balance when performing the different serve techniques (flat, kick, or slice serve). Second, the ball toss may have an important impact on balance strategy, end-effector performance, and the relation between both (Reid et al., 2011). Therefore, observing the ball toss outcome may be a relevant factor for further investigation. Third, the participants were experienced tennis players and were considered to be a homogeneous group in terms of serving skill. Their variation in performance is expected to be considerably less than in recreational players, so the knowledge gained from this study likely only applies for experienced players.

In terms of the practical application for coaches and players, the results from this study will hopefully help gain a greater understanding of how balance might interact with end-effector performance, and eventually support efforts to improve the training protocol for teaching the serve. Our findings suggested that for the flat serve the counter rotation associated with the trunk is the main mechanism, whereas for the kick serve the counter rotation associated with the arms is the main mechanism. The balance aspect is a key feature of stroke development such as the serve (Elliott et al., 2009), and these findings suggest that these counter rotation mechanisms have a different impact on whole body postural balance, meaning that learning different serve techniques likely involves learning different balance mechanisms. Concerning the arms mechanism, the impact of the counter rotation will also differ when the player serves without jumping, so during the learning process towards a jumped serve this involves the learning of a coping with a different effect of the arms counter rotation balance mechanism. Coaches may also consider based on our findings that there is likely an important individual component to the control of postural balance when producing the maximum serve. Altogether, we can support the general notion that balance training should be added to the usual training activities as it will likely improve general performance (Hrysomallis, 2011), and it should be included as part of learning and/or practising the performance of all serve techniques. With not having seen a population-wide interaction between end-effector performance and postural balance mechanisms, the focus should more be on methods in which players can search for a movement execution that fits them rather than methods that impose a certain movement strategy upon them.

4.6 Conclusion

Our findings showed no population-wide interaction (balance control vs end-effector performance) in the first serve. Hence, no evidence to support that balance and serving technique should be trained simultaneously thus, balance and end-effector performance could be trained separately. In terms of postural balance control, players might use the counter rotation associated with different segments depending on serving type-specific and condition-specific when attempting to reach the peak racket velocity. Furthermore, the relationship between postural balance control and end-effector could not be presumed to be individualised during serves across serving locations. The relationship between serving performance and these angular momentum will likely also effect balance because angular momentum is a parameter that component of maintaining balance (counter rotation of segments). If the relationship exist that means balance is affected by how do the serve how performance in the service.

Positive relationship between speed and angular momentum is mean with higher speed create more forward angular momentum. Then the consequence that is if player want to create high speed then they need to create more angular momentum.

CHAPTER 5 General Discussion

5.1 Summary

The aim of this chapter is to interpret and reflect upon the potential application of the main findings obtained within this thesis with respect to balance measurements, the role played by movement variability in the performance of a sporting task, and the postural balance mechanism and end-effector control aspects witnessed during dynamic activities. Therefore, the overall aim of this thesis has been to investigate the interaction that arises between XCoM, the changes in arms/trunk angular momentum and maximum racket velocity during dynamic sport activities, using the tennis serve as a complex movement task model. A necessary precursor to this investigation has been to identify whether simplified biomechanical models could be used to adequately represent whole-body CoM during dynamic sporting tasks, whereupon a better understanding has been found as to the importance of the various body balance control mechanisms that play a role during a tennis serve.

The findings in this study reveal that only LL+T+UL biomechanical model reduction would be considered appropriate to be used to estimate the (X)CoM for dynamic sporting tasks. For kicking, the LL+T model was accurate for the CoM representation but it was less accurate for representing XCoM motion. Whilst, other simplified biomechanical models were likely unsuitable if one wishes to evaluate whole body balance control in dynamic tasks based on CoM or XCoM motion. As the tennis serve was used as an example dynamic task and it required whole-body movements. Therefore, according to the results from chapter 2, LL+T+UL model reduction should be use to acquire the whole-body (X)CoM unfortunately, this model reduction allows the researchers to reduce only 4 markers on the head segment off. Hence, Full-body biomechanical model still was used to acquire balance variables in subsequent studies (chapter 3 and 4). The findings after exploring the interaction between balance control mechanisms and end-effector behaviour during tennis serve within one target location and between various target locations show no interaction between these variables. Furthermore, our study does not put us in a position to conclude whether or not balance and serving technique should be trained simultaneously, but our findings at least did not suggest that the two are closely intertwined. Hence, balance and end-effector performance could be trained separately. Moreover, the counter rotation associated with different segments was serving type-specific (flat, kick, or slice serve) and condition-specific (target locations) when attempting to reach the maximum racket velocity. Likewise, the relationship between postural balance control and end-effector performance is likely to be individualised during serves within one target location. However, it could not be presumed to be individualised during serves across serving locations.

The novel aspects introduced in this thesis are finding an appropriate biomechanical model to quantify whole-body CoM during dynamic sporting tasks and using SPM to interpret the interaction between postural balance mechanism and end-effector control aspects during dynamic activities. Recommendations for future research for whole-body balance control could extend to various player groups, characteristics, different skills levels and different types of serve.

5.2 Balance Measurement in Dynamic Tasks

In tennis, balance is a key aspect of stroke development (Elliott et al., 2009). The maintenance of balance, in the first place, depends upon the control of CoM position relative to the BoS. However, the XCoM is more suitable to investigate balance in dynamic sporting tasks. During the serve, the BoS can move (widen and narrow) to support the moving XCoM, in order to maintain balance depending on the phase of the serve. To make this possible in field contexts, simple yet accurate tools are necessary (Yang and Pai, 2014). Traditionally, CoM position has been computed by using the segmental analysis method where measurements require expensive equipment, are time-consuming and almost impossible to apply in everyday practice. Nonetheless, technology is developing rapidly and now allows for semi-automatic segmental tracking. With current marker-based optoelectronic systems, biomechanical model reductions can be explored as results have shown in Chapter 2. Eng and Winter

(1993) expressed that marker-based system method has often been considered a gold standard in CoM calculation. This study expresses that, with regards the validity of simplified marker models, the head segment can be ignored within the full-body model and an accurate CoM estimation can still be produced (chapter 1). Generally, we could conclude that minor model reductions may well be possible in certain cases – such as in leaving out the hand, foot or head segments. Further model reductions involving segments with greater inertia are typically not appropriate for exclusion. Our results justify the use of certain model reductions for specific needs, thus saving measurement effort whilst limiting errors in tracking (X)CoM trajectories within the context of whole-body balance investigations. These findings however, cannot be generalised across a variety of tasks and researchers are still required to use their own judgement in choosing which marker model is suitable for their respective purposes. In taking note of such advances in modelling, attention must also be given to the respective drawbacks that arise.

A disadvantage of this marker-based motion capture system pertains to the need to place markers on body landmarks, with this precluding data from being gathered in actual competitive and realistic environments. Abrams and colleagues (2012) have questioned the accuracy of marker-based systems being employed in relation to dynamic motion. Such disputes have arisen due to the finding that skin markers can lead to experimental errors (Abrams et al., 2011; Cappozzo et al., 1996; Reinschmidt et al., 1997) and the weight of markers and their potential to fall off may change the arm and body movements during a serve (Abrams et al., 2011). Thus, it is believed that in the very near future full-automatic segmental tracking may become necessary and more popular – for example, through the use of markerless motion capture (Abrams et al., 2011; Abrams et al., 2014) or the use of inertial measurement units (IMUs). Particularly markerless motion capture systems eliminate the potential influences of skin-mounted markers on player movement and the system's allowance of testing taking place outdoors, with a minimal time commitment from players (Sheets et al., 2011), and playing more naturally (Abrams et al., 2011; Cappozzo et al., 1996; Reinschmidt et al., 1997). In relation to the use of IMUs when tracking one or a few segments, it remains widely debated what the appropriate number of segments should be. Ultimately, this problem is the same as the one we were faced with in Chapter 2, with a key difference being that an IMU can overcome the need for a segment to be visible to cameras mounted around the participant. The latter benefit of IMUs over optoelectronic systems has made researchers consider the use of both a motion capture system and IMUs to analyse complex sports performance but this solution has usually been restricted to elite research groups due to the high cost and long processing time required. Altogether, in previous studies both marker based systems (Martin et al., 2013; Whiteside et al., 2014b) and markerless systems (Abrams et al., 2011; Sheets et al., 2011) have been used to analyse the biomechanical aspects of the tennis serve . At this juncture, the choice typically depends on convenience and cost implications. Our work has demonstrated that when considering model reductions with any of these systems, then this should be done on a task-by-task basis.

5.3 The relationship between Postural Balance and the End-Effector

Individual players adopt different postural movement strategies to generate the stability required to produce a successful shot. Our study mostly found no meaningful relationship between the postural balance variables (XCoM and the changes in arms/trunk angular momentum) and the end-effector performance (maximum racket velocity) when serving to different target locations. Interestingly, the trunk segmental acceleration was found to play a role generating maximum racket velocity during the forward swing phase when serving to the broader part of the T line of the deuce court (condition 2). Furthermore, the change in arms angular momentum influenced maximum racket velocity during forward swing phase when serving into the broader part of the advantage court (condition 4). This may suggest that the counter rotation of trunk and arms are used to control balance and to influence serve performance, but depending on the targeted serving location. This finding helps to emphasise, to coaches and players alike that one may need to consider training protocols that incorporate serve location specific postural balance aspects.

Besides balance mechanisms demonstrating a location specific interaction between postural balance and racket performance, this also means that a serve type-specific interaction may need to be considered. The tennis serve is divided into first and second serves, and serve types including flat, topspin, or slice serve. The type of serve used depends on the serving location and an opportunity to gain an advantage. The flat serve, particularly aimed inside the T location of both deuce and advantage court is located in the condition 2 and condition 3 area, respectively (see in figure 4.1, chapter 4). The slice serve is often executed to the wide side of the service box in the deuce court, whilst the topspin serve is executed most often to the wide side of the service box in the advantage court (Gillet et al., 2009). According to our findings, chapter 3 results show only an association between the change in trunk angular momentum and maximum racket velocity in the forward swing phase (condition 2). Whilst, chapter 4 results found a relationship between the change in arms angular momentum and the maximum racket velocity in the forward swing phase (condition 4). The flat serve requires high speed and less spin, kick serve requires more topspin, while slice serve requires sidespin applying to the ball. The racket movement pattern, relative to the body is different among these serves. Such as, the level of the forearm pronation will vary between serve types as the angle of the racket face at the impact changes (Elliott et al., 2003). Therefore, the reasons found for the counter rotation of different segments used, when producing maximum racket velocity, might relate to the specific service style and the specific condition, as the different serving locations require the player to alter their types of serve.

5.4 Consideration of Inverted Pendulum and Counter Rotation of Segments in Sporting Tasks

One may at first sight expect that during the tennis serve, the ankle strategy restores equilibrium by moving the XCoM forwards or backwards while the player shifts their body weight between their front and rear foot in the beginning stages of the serve. However, this inverted pendulum mechanism is not likely to be an important mechanism in this dynamic task. This strategy is only appropriate to maintain balance for small amounts of sway with rotation around the ankles (Horak and Kuo, 2000), but in the tennis serve the mechanism of sway is generated more through shifting balance between feet. As a result of that, and somehow as expected, our results did not reveal an interaction between the inverted pendulum mechanism and racket performance. It is more likely the counter rotation mechanism is mainly used in a tennis serve to maintain or restore balance. This was supported by our results showing considerable segmental counter rotations of arms and trunk during the serve, in particular during the forward swing phase. In fact, the arms demonstrate asymmetrical movements during the serve, for instance when the non-racket arm moves up to toss the ball the racket arm moves downward and backward to swing the racket. This produces a reaction force at the shoulder level to rotate the trunk. Furthermore, the trunk segment leans forwards to adapt to the ball toss location and to transfer power to hit the ball. Our results showed a trend that there is a consistent relationship between the change in trunk angular momentum and maximum racket velocity around 20% of forward swing phase across the 4 conditions (see figure 4.3C). This suggests that counter rotation of arms and trunk segments are used – albeit differently – to maintain postural balance during the serve. Importantly, while the observations from this study around the counter rotation of segments pertain specifically to tennis, it can nonetheless be applied to explore the balance mechanism in other sports with similar contexts, for example the serve in volleyball, or the baseball pitch.

5.5 Variability Influences upon Sports Performance

The study of movement variability has been gaining increasing interest in the sports biomechanics community (Preatoni et al., 2013). Understanding the role and impact of movement variability in sporting tasks (such as the tennis serve) may be of interest to coaches in their attempts to improving player performance. Whiteside and colleagues (2015) examined coordinated joint rotations and variability in the lower limbs, trunk, serving arm and ball location among elite female tennis serves – whereupon they suggested that players coordinate the proximal elements of the kinematic chain to ensure that they leave the ground at a consistent time and with a consistent posture. However, variability at the elbow was witnessed as becoming significantly greater the closer to impact, with this possibly explaining the mechanical adjustments employed by players in managing variability in impact location from serve to serve. A kinematic analysis of the variability was not the focus of this work as this has been explored in other studies (Langdown, 2012; Whiteside et al., 2015). Yet the novelty of this thesis was to explore the interaction between balance control and the serve performance, based on inherent movement variability between different trials. The temporal composition of the serve was found to be highly consistent, a result which supports previous assertions that players accommodate primarily for special variations, for example the ball location, to regulate their movement. Also, technique variations (such as foot position techniques (FU or FB technique) and different types of serve) may induce movement variability. The raw data as to the variability in arms/trunk angular momentum in each serving phase was presented in Appendix D. Overall, in relation to the three phases of change in arms/trunk angular momentum, only limited variability was found within individuals, with this being indicative of individualised “movement signatures”. Moreover, the average changes in arm/trunk angular momentum presented a similar pattern between the 4 conditions, while inter-individual variation appeared to be greater. The limited intra-individual variability found may arise due to the flexibility and adaptability of individuals in maintaining and recovering stability during serves. This agreed with the notion of Horak (2006) that players adjust their body due to the influences of their learning, expectations, goals and prior experience.

5.6 Strengths

A key strength of this work has been the application of novel approaches to a complex biomechanical problem. Arguably the most novel approach employed in this study pertains to the quantification of changes in angular momentum to represent the counter rotation of segments strategy – with this being detailed in Chapter 3 and Chapter 4. Another novel approach has been the use of the Bland-Altman method for data consisting of a temporal profile rather than discrete data (e.g. a blood pressure value) in Chapter 2. This novel application of an existing method may in the future help researchers compare temporal profiles across methods, rather than being restricted to the comparison of single variable outcome measures derived from those profiles (e.g. peaks or averages). Similarly, the SPM statistical analysis for evaluation of interactions between end-effector performance and postural balance mechanisms which allows uniquely for temporal considerations of this interaction during the tennis serve had to date never been tried. It is hoped that these novel applications of existing tools help inspire future research to undertake comprehensive analyses of how balance plays a role in dynamic activities. Namely, balance has been suggested to play an important role in dynamic sport activities, yet to date very few researchers have taken on the challenge to investigate this in further detail.

5.7 Practical Application for Coaches and Players

This work may help players and coaches to become more aware of the role of postural balance mechanisms when trying to improve player performance. Based on our findings, coaches may consider the key elements of each tennis phase, but the focus should in particular be on the forward swing phase to improve balance and consequently the serve performance. Whilst one may focus on foot position, trunk rotation, and general body orientation during the preparation phase, during the forward swing phase one should probably focus more on arm alignment and rotations, trunk rotations, and weight transfer. This confirms what others have suggested before that that these biomechanics aspects are a key area in player development as all strokes have a fundamental mechanical structure (Elliott, 2006).

A strong interaction between postural balance and racket performance was not found, so the practical application for the coaches would be that training postural balance can be done separately from training the serve technique. Previous studies have studied balance ability and athletic performance in various sports (Hrysomallis, 2011; Zemková, 2014), but there is limited knowledge on the influence of training balance in combination with training sport technique, and how that would affect players' performance, so the impact of our work on training effectiveness remains to be seen.

Changes in angular momentum of arms and trunk appear to be serve type specific. As our results found that when the researchers study different serving locations, there was no significant difference. However, there was a significant interaction between the changes of trunk/arms angular momentum and maximum racket velocity in particular serving location. Therefore, the findings may support Gillet et al., 2009 as when serving to different serving locations, players most likely used a different type of serve, i.e. flat or kick serve, and therefore this was expected to be the explanation for the serve location specific interactions. This means that one could emphasise muscle training depending on the serve type that is being trained. For example, when training specific serving locations, players could emphasise to train the trunk muscle group to improve performance of a maximum flat serve while, arm muscles could be trained specifically to produce the maximum kick serve. Furthermore, core stabilization has been considered important for tennis players as it helps to increase functional strength and dynamic balance during the serve, by dynamic stabilization of the entire kinetic chain during functional movements. Examples of such core stability muscle exercises could incorporate centre of gravity control (e.g. multi-planar lunges), eccentric control (e.g. med ball twists on Swiss ball) and isometric control (e.g. abdominal hollowing) to enhance dynamic postural balance control (Samson et al., 2007).

The findings of our work were tested against the viewpoint of an expert coach (Thanakorn Srichaphan – Thai national team coach, ITF coach level 2, USPTR coach level 1 and RPT Europe coach level 2, tennis Grand slam commentator in Thai language). He expressed his view that there is a relationship between postural balance control and end-effector performance, whereby each player has an individual serving technique strategy to control their balance. However, the ball toss location is the main factor to influence player stability as well as the optimal contact point. Thanakorn further stated the importance of trunk and arm rotation as well as the standing techniques (foot-up or foot-back) of players, noting these as being necessary factors in controlling balance during a serve. Furthermore, children need to practice such balance, as a fundamental skill, whereupon coaches can provide balance practice separately or together with end-effector control practice (e.g., ball toss practicing during feet together). For elite player training, expert coaches may be able through observation to identify those individuals who need to improve their balance based primarily on segmental interaction, and tailor their training programmes to the individual and even the serve type, rather than deploying generalised serve training programmes. Our findings appear to support a need for such tailored approach.

Finally, Crespo and Miley (1998) have underlined how balance could be affected by other skills such as a player’s agility, speed, response time, footwork and flexibility. Notably, dynamic balance can be improved through an individual’s participation in other sports, whereupon there are various exercises (both general and specific) through which to improve one’s balance. A combination of general exercise (i.e., walking/running on a line and hexagon jumping) and specific exercise (i.e., practising tennis) is believed to be the best way of improving balance for tennis performance (Crespo and Miley 1998). To our knowledge, this remains unconfirmed through research and as such it is speculative that dynamic balance training can improve tennis performance. However, the knowledge from this study provides coaches and players supportive evidence for this line of thinking, or more correctly, it does not generate objections against this line of thinking.

5.8 General Limitations

There are several limitations of the work presented in this thesis that should be recognised here. Firstly, the different types of tennis serve – including flat, kick and slice serve – have not been explored separately (in chapter 3 and 4). This is problematic as previous work has identified significant differences in the kinematics for flat, kick and slice serves during both the preparation and ball impact phases and that, furthermore, differences are found in the direction of the racket velocity vector between serves (Sheets et al., 2011). As participants in our studies were not explicitly asked to alter their serve type, there was insufficient ground to justify separated analyses. Secondly, this research has only investigated experienced players and thus the results may not be generalisable to recreational or novice players. Thirdly, this study could not undertake measurements in an actual competition and thus although serves (studies 3 and 4) were performed on a tennis court these are still simulations of a real serve. Therefore, it is important to note that our findings may have differed in from serves performed in actual competition due to the pressures and environment of a real competitive match. Fourthly, the ball toss location is one of the main factors that affects body balance, but unfortunately it was technically not feasible to record this and therefore not the focus in this study. Fifthly, only one approach (SPM approach) has been used to explore the interaction between postural balance control and end-effector performance, however, in the future researchers might use different approaches such as relative motion plots, angle-angle plots or phase plane representation (Preatoni et al,. 2013). Sixthly, one would want to take into account the trade-off between ball speed and accuracy, that one would have to design a rather complex experiment in which the interaction between balance mechanisms and this two-factor performance is studied as the researchers indicate only a speed in this thesis the researchers have not quantified an accuracy. For example, in second serve in elite player the accuracy of getting closer to the line within your serve box could mean more chance of success but then have to be observe whether player are trade off speed and accuracy. Finally, the lower limbs were not considered in this thesis in the context of how their angular momentum may have changed during the serve. The researchers were primarily interested in the balance mechanisms that occur in the lead up to the moment of ball impact (maximum racket velocity).

5.9 Recommendations for Future Research

In light of the general discussion above, it is recommended that future research focuses on exploring different ages of players - including young players (up to approximately 6 years of age) as balance at this age is still developing whereupon it will exhibit mature control and the level of postural adjustment required to maintain balance reduces (Elliott et al., 2009). Consideration could also be given to the respective height, gender and skill level of players, as the results of this present research suggest that these could be influencing factors. The different types of tennis serve and the ball location should also be explored, via the approach taken in this study. Furthermore, it is expected that markerless motion capture systems will in the foreseeable future become available to observe the role of postural balance in dynamic tasks such as a tennis serve during an actual competition.

5.10 General Conclusion

This thesis represents in the first place an attempt to produce a simplified biomechanical model through which one can efficiently estimate whole-body balance variables during dynamic sports activities. The novel biomechanical model introduced in this thesis has shown promising results in regards to its ability to estimate the CoM and XCoM exhibited during dynamic sporting tasks. Our work will hopefully make researchers and perhaps practitioners aware that they could select appropriate biomechanical model reductions, as identified in this study, to efficiently explore whole-body balance variables in their own research. The undertaking of such measurements could, in the near future, occur in real life contexts due to developments of in-field technology such as markerless motion capture systems. When subsequently examining the relationship that arises between postural balance and end-effector control within a serving location (chapter 3) and across serving locations (chapter 4), the findings showed mostly no systematic association between the postural balance control and end-effector performance during the serve. However, in the researchers' opinion, the movement of arms and trunk may still affect end-effector performance depending on the type of the serve used. Ultimately, the novel approach introduced in this thesis has the potential to provide researchers and practitioners with a better understanding of the association between postural balance control (e.g., the XCoM, the changes in upper extremities, trunk angular momentum) and end-effector performance (e.g. peak racket velocity), or vice versa, in dynamic sport activity.

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APPENDICES

Appendix A: Full-body biomechanical model which has been used to be the gold standard in chapter 2 and which was used in subsequent chapters.

The Full Body Model with Functional Hip, Functional Knee, and Offset Shoulder is based on a 6DOF model, using a specific functional hip joint and functional knee axis recording to define the location of the hip and knee joints, and an offset value of 7 cm down in vertical direction relative to the acromion to define the shoulder joint. This model is useful when full body information is needed such as for centre of mass calculation. 68 markers are used in total for the static trial, with 50 remaining for dynamic trials.

Marker list (68 markers)

Table A- 1 shows upper body markers

Marker name	Description
ANT_HEAD_L	Anterior Head Left
ANT_HEAD_R	Anterior Head Right
POST_HEAD_L	Posterior Head Left
POST_HEAD_R	Posterior Head Right
C7	C7
STERNUM	Sternum
XIP_PROC	Xiphoid Process
T8	T8
ACROM_L	**Acromion Left**
ACROM_R	**Acromion Right**
UA_PR_ANT_L	Upper Arm Proximal Anterior Left
UA_PR_POST_L	Upper Arm Proximal Posterior Left

Marker name	**Description**
UA_DI_ANT_L	Upper Arm Distal Anterior Left
ELB_MED_L	**Elbow Medial Left**
ELB_LAT_L	**Elbow Lateral Left**
LA_PR_ANT_L	Lower Arm Proximal Anterior Left
LA_PR_POST_L	Lower Arm Proximal Posterior Left
LA_DI_ANT_L	Lower Arm Distal Anterior Left
WRI_ANT_L	**Wrist Anterior Left (Radial)**
WRI_POST_L	**Wrist Posterior Left (Ulnar)**
UA_PR_ANT_R	Upper Arm Proximal Anterior Right
UA_PR_POST_R	Upper Arm Proximal Posterior Right
UA_DI_ANT_R	Upper Arm Distal Anterior Right
ELB_MED_R	**Elbow Medial Right**
ELB_LAT_R	**Elbow Lateral Right**
LA_PR_ANT_R	Lower Arm Proximal Anterior Right
LA_PR_POST_R	Lower Arm Proximal Posterior Right
LA_DI_ANT_R	Lower Arm Distal Anterior Right
WRI_ANT_R	**Wrist Anterior Right (Radial)**
WRI_POST_R	**Wrist Posterior Right (Ulnar)**

Bold markers can be removed after static trial

Table A- 2 shows lower body markers

Marker name	**Description**
ASIS_L	Anterior Sacral Iliac Crest Left
PSIS_L	Posterior Sacral Iliac Crest Left
ILCREST_L	Iliac Crest Left
GTROC_L	**Greater Trochanter Left**
ASIS_R	Anterior Sacral Iliac Crest Right
PSIS_R	Posterior Sacral Iliac Crest Right
ILCREST_R	Iliac Crest Right
GTROC_R	**Greater Trochanter Right**
UL_PR_ANT_L	Upper Leg Proximal Anterior Left
UL_PR_POST_L	Upper Leg Proximal Posterior Left
UL_DI_ANT_L	Upper Leg Distal Anterior Left
UL_DI_POST_L	Upper Leg Distal Posterior Left
KNEE_MED_L	**Knee Medial Epicondyle Left**
KNEE_LAT_L	**Knee Lateral Epicondyle Left**
LL_PR_ANT_L	Lower Leg Proximal Anterior Left
LL_PR_POST_L	Lower Leg Proximal Posterior Left
LL_DI_ANT_L	Lower Leg Distal Anterior Left
LL_DI_POST_L	Lower Leg Distal Posterior Left
MAL_MED_L	**Maleolus Medial Left**
MAL_LAT_L	Maleolus Lateral Left
HEEL_L	Heel Left

Marker name	Description
MTH1_L	Metatarsal Head 1 Left
MTH5_L	Metatarsal Head 5 Left
UL_PR_ANT_R	Upper Leg Proximal Anterior Right
UL_PR_POST_R	Upper Leg Proximal Posterior Right
UL_DI_ANT_R	Upper Leg Distal Anterior Right
UL_DI_POST_R	Upper Leg Distal Posterior Right
KNEE_MED_R	**Knee Medial Epicondyle Right**
KNEE_LAT_R	**Knee Lateral Epicondyle Right**
LL_PR_ANT_R	Lower Leg Proximal Anterior Right
LL_PR_POST_R	Lower Leg Proximal Posterior Right
LL_DI_ANT_R	Lower Leg Distal Anterior Right
LL_DI_POST_R	Lower Leg Distal Posterior Right
MAL_MED_R	**Maleolus Medial Right**
MAL_LAT_R	Maleolus Lateral Right
HEEL_R	Heel Right
MTH1_R	Metatarsal Head 1 Right
MTH5_R	Metatarsal Head 5 Right

Bold markers can be removed after static trial

Table A- 3 shows landmarks

Name	Description
THORAX_PROX	The midpoint between C7 and STERNUM (used for Thorax / Ab segment)
THORAX_DIST	The midpoint between T8 and XIP_PROC (use Thorax / Ab segment)
SHOUL_JC_L	Offset from ACROM_L
SHOUL_JC_R	Offset from ACROM_R
F_LHIP	Functional hip joint
F_RHIP	Functional hip joint
F_LKNEE	Functional knee joint
F_RKNEE	Functional knee joint
F_LKNEE_X	Functional knee joint offset along functional knee axis
F_RKNEE_X	Functional knee joint offset along functional knee axis
LK	Lateral knee joint marker projected onto functional knee axis
ML	Medial knee joint marker projected onto functional knee axis

Table A- 4 illustrates segment definitions

Segment	**Proximal**	**Distal**	**Tracking**
Head (RHE)	POST_HEAD_L + POST_HEAD_R	ANT_HEAD_L + ANT_HEAD_R	POST_HEAD + ANT_HEAD
Thorax (RTH)	THORAX_PROX + ACROM_R	THORAX_DIST	C7 + STERNUM + XIP_PROC + T8
Upper Arm (LAR & RAR)	SHOUL_JC	ELB_LAT + ELB_MED	UA cluster
Lower Arm (LFA & RFA)	ELB_LAT + ELB_MED	WRI_ANT + WRI_POST	LA cluster
Pelvis (RPV)	ILCREST_L + ILCREST_R	GTROC_L + GTROC_R	ASIS + PSIS + ILCREST
Upper Leg (LTH & RTH)	F_HIP	LK + MK	UL cluster
Lower Leg (LSK & RSK)	F_KNEE	MAL_MED + MAL_LAT	LL cluster
Foot (LFT & RFT)	MAL_MED + MAL_LAT	MTH1 + MTH5	HEEL + MTH1 + MTH5 + MAL_LAT (+ MAL_MED)

Functional Hip and knee joint calculation use the following markers

Functional Joint	Tracking Markers
F_LHIP	Pelvis markers + Upper leg markers
F_RHIP	Pelvis markers + Upper leg markers
F_LKNEE	Upper leg markers + Shank markers
F_RKNEE	Upper leg markers + Shank markers

The knee joint markers are created by the functional joint method, computing also a second landmark on the mean helical axis (offset 5 cm).

Pelvis tracking: All 8 markers on the pelvis are required for the static trial to determine the hip. Keep any 4 of these for tracking the pelvis during the motion files.

Shoulder joint centre: Defined by axial 0.05m offset landmark from acromion markers (LSHO & RSHO)

Appendix B: Centre of mass (CoM) bias and Limit of agreement's (LoA) in the vertical direction.

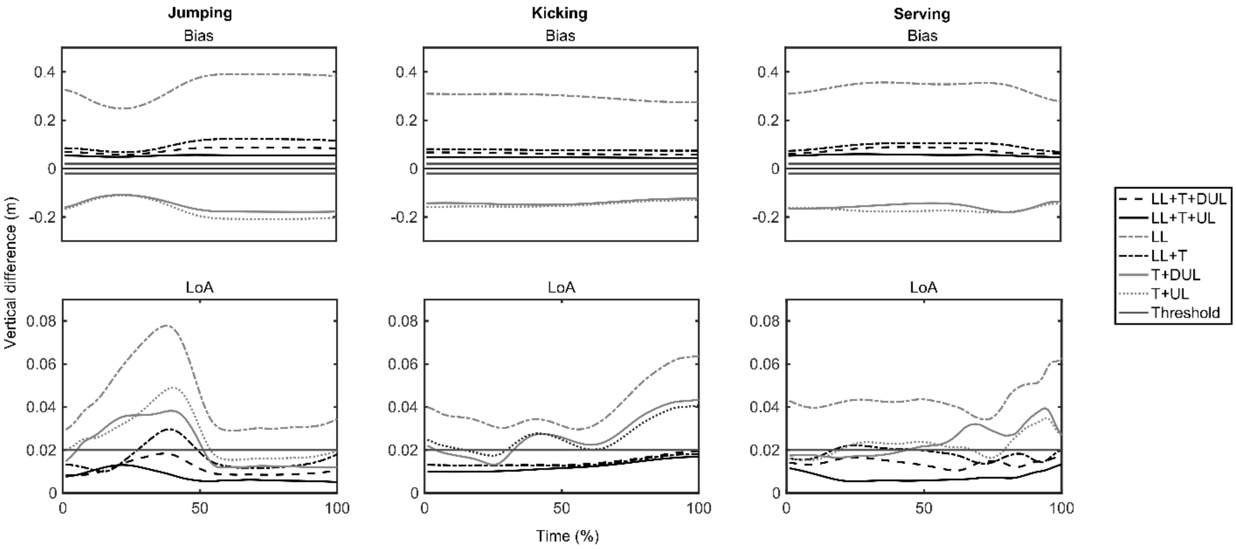


Figure B-1. Bias and limits of agreement for trajectories of CoM representations in the vertical direction.

Appendix C: (X)CoM trajectories

In this appendix the trajectories of (X)CoM representations in Anterior-Posterior and Medio-Lateral direction for the full-body model and the six model reductions are provided.

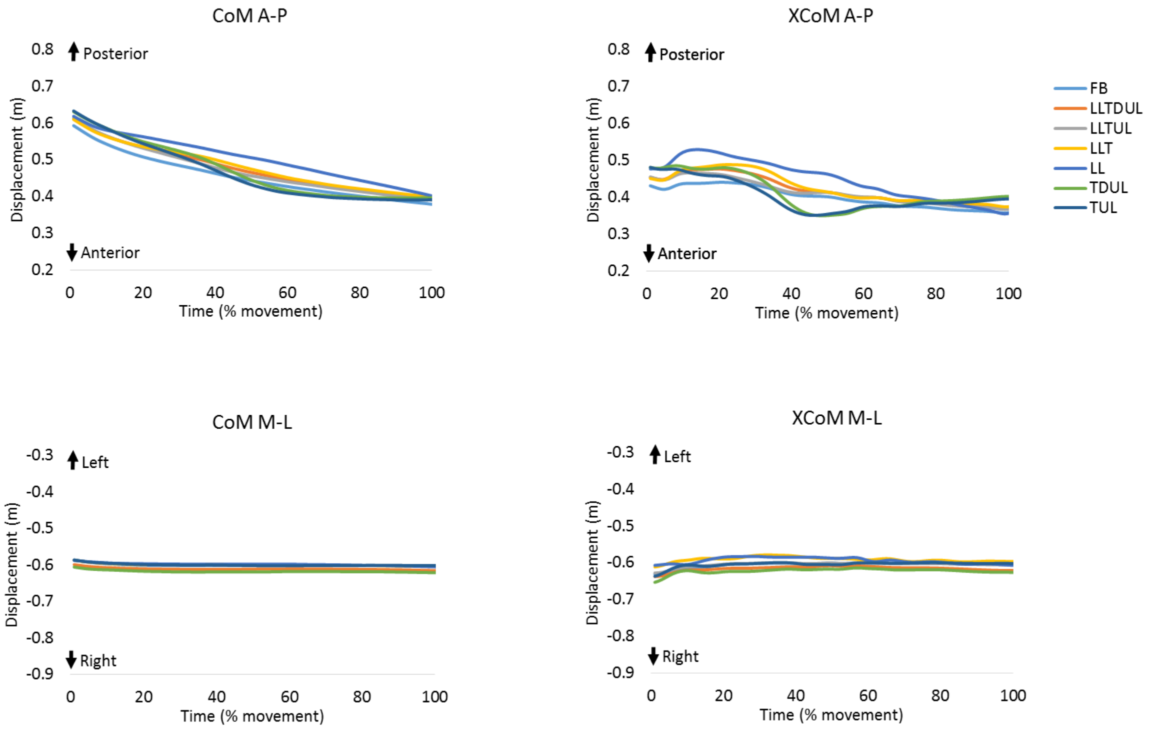


Figure C-1. (X)CoM trajectories in anterior-posterior (A-P) and medio-lateral (M-L) direction for jumping.

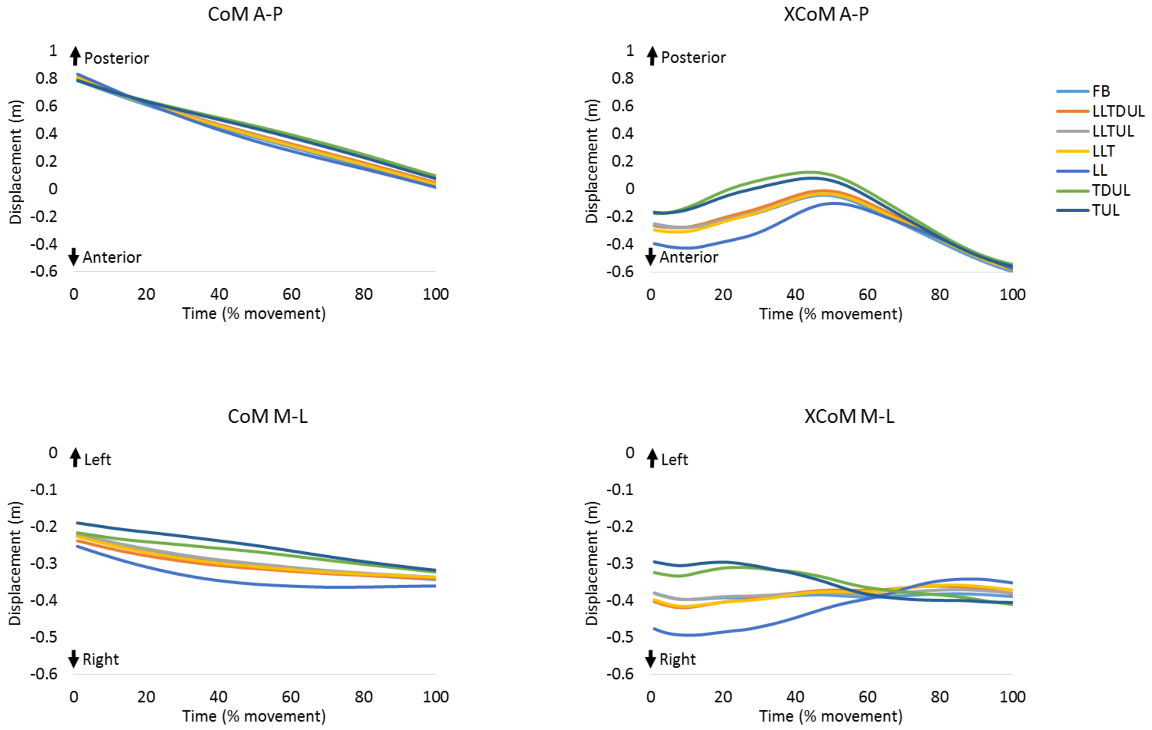


Figure C-2. (X)CoM trajectories in anterior-posterior (A-P) and medio-lateral (M-L) direction for kicking (right footed)

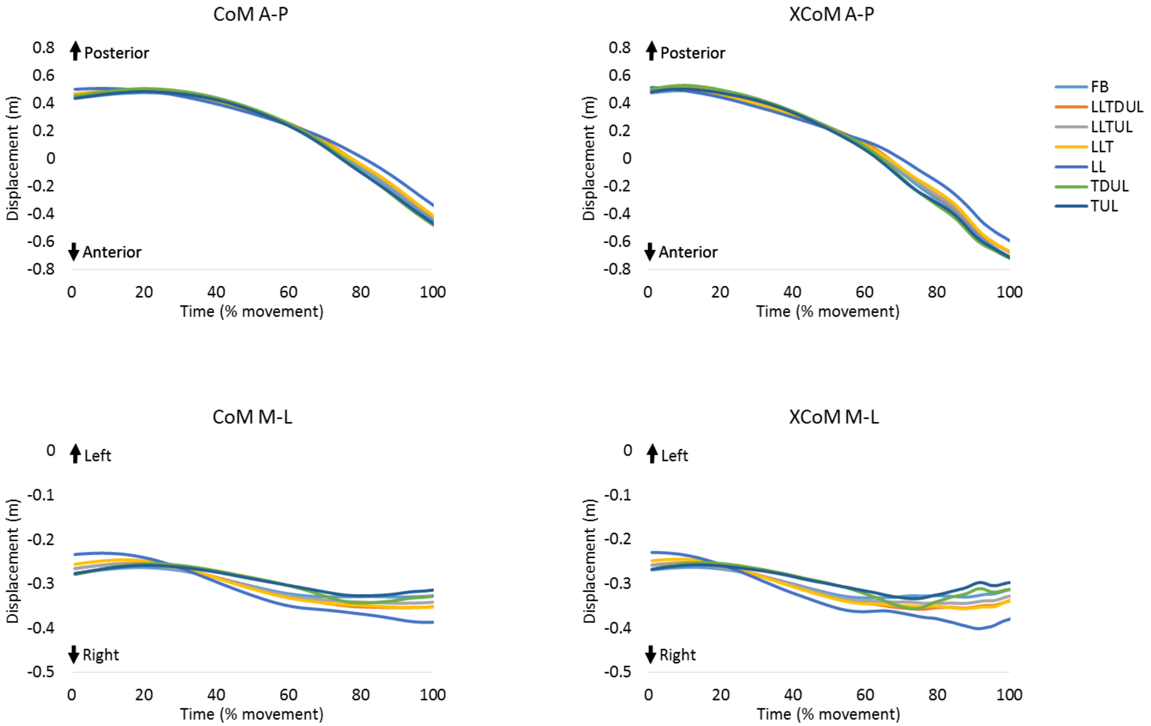
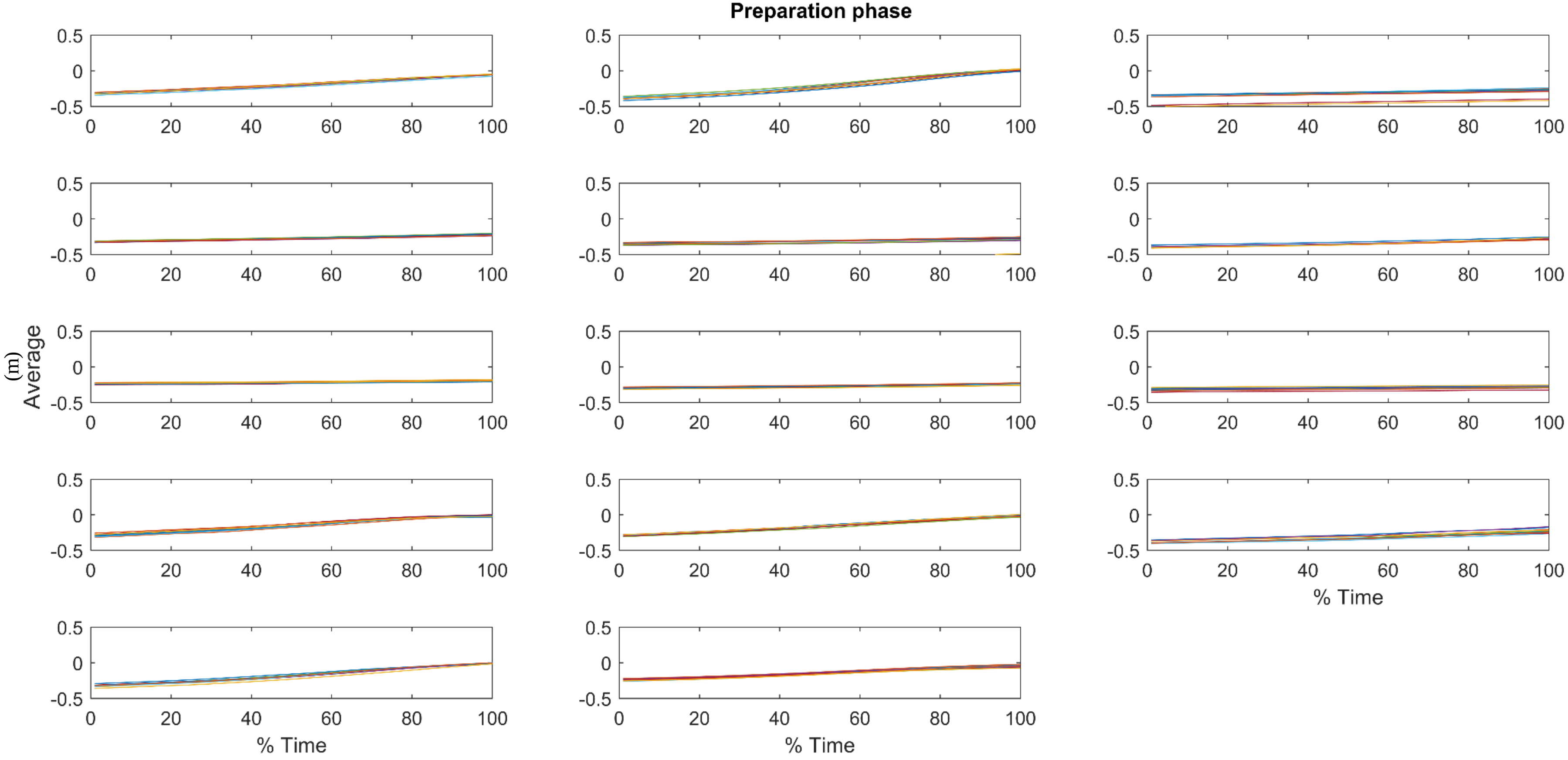
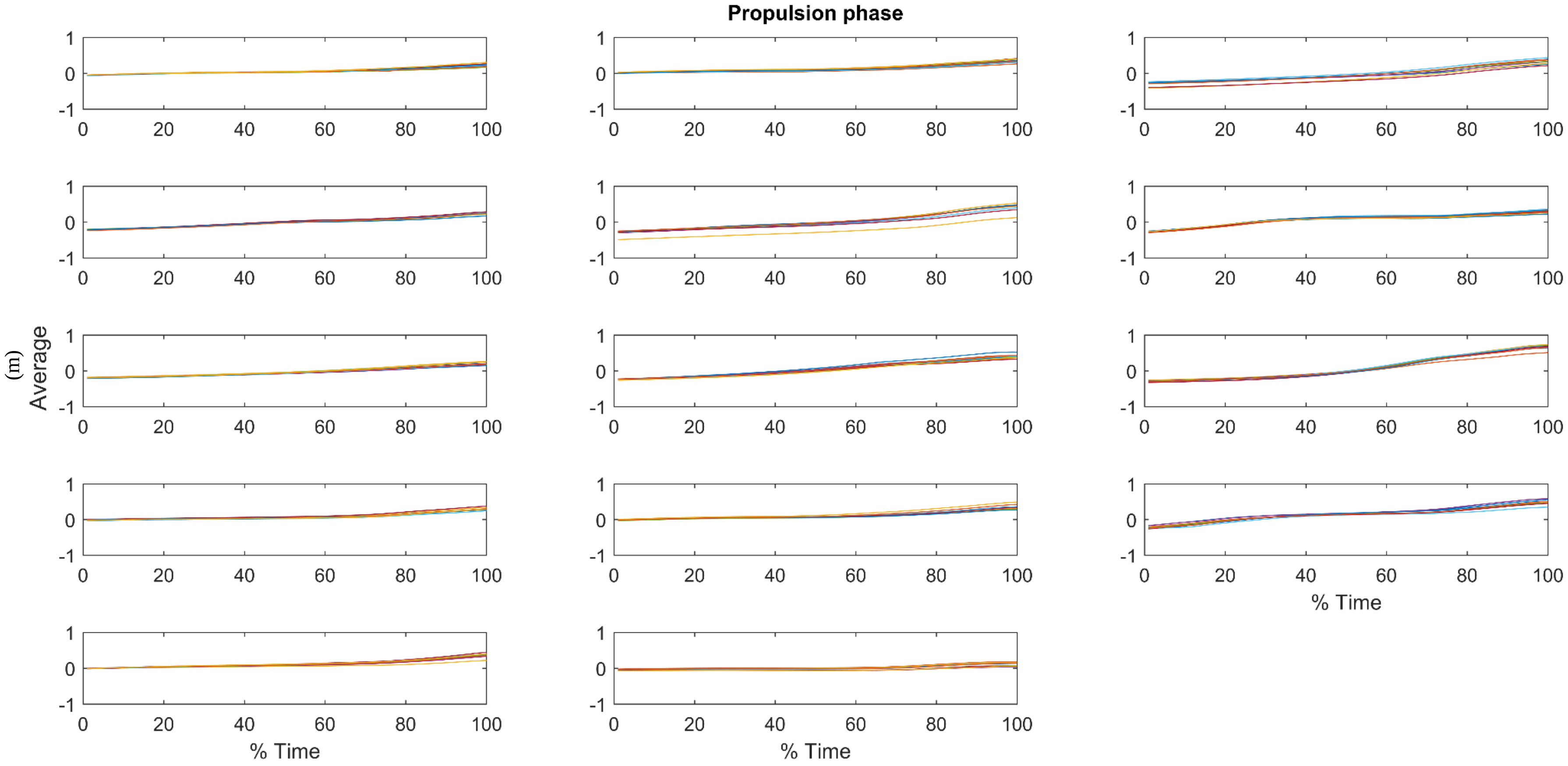


Figure C-3. (X)CoM trajectories in anterior-posterior (A-P) and medio-lateral (M-L) direction for a tennis serve (right-handed).

Appendix D: Raw data of the XCoM (D-1), change in arms (D-2)/trunk angular momentum (D-3) (study2; n=14) in each phase. The graphs below show average trials per individual in preparation, propulsion, and forward swing phase.




Propulsion phase
Average (m)
1
0
-1
0
20
40
60
80
100
% Time

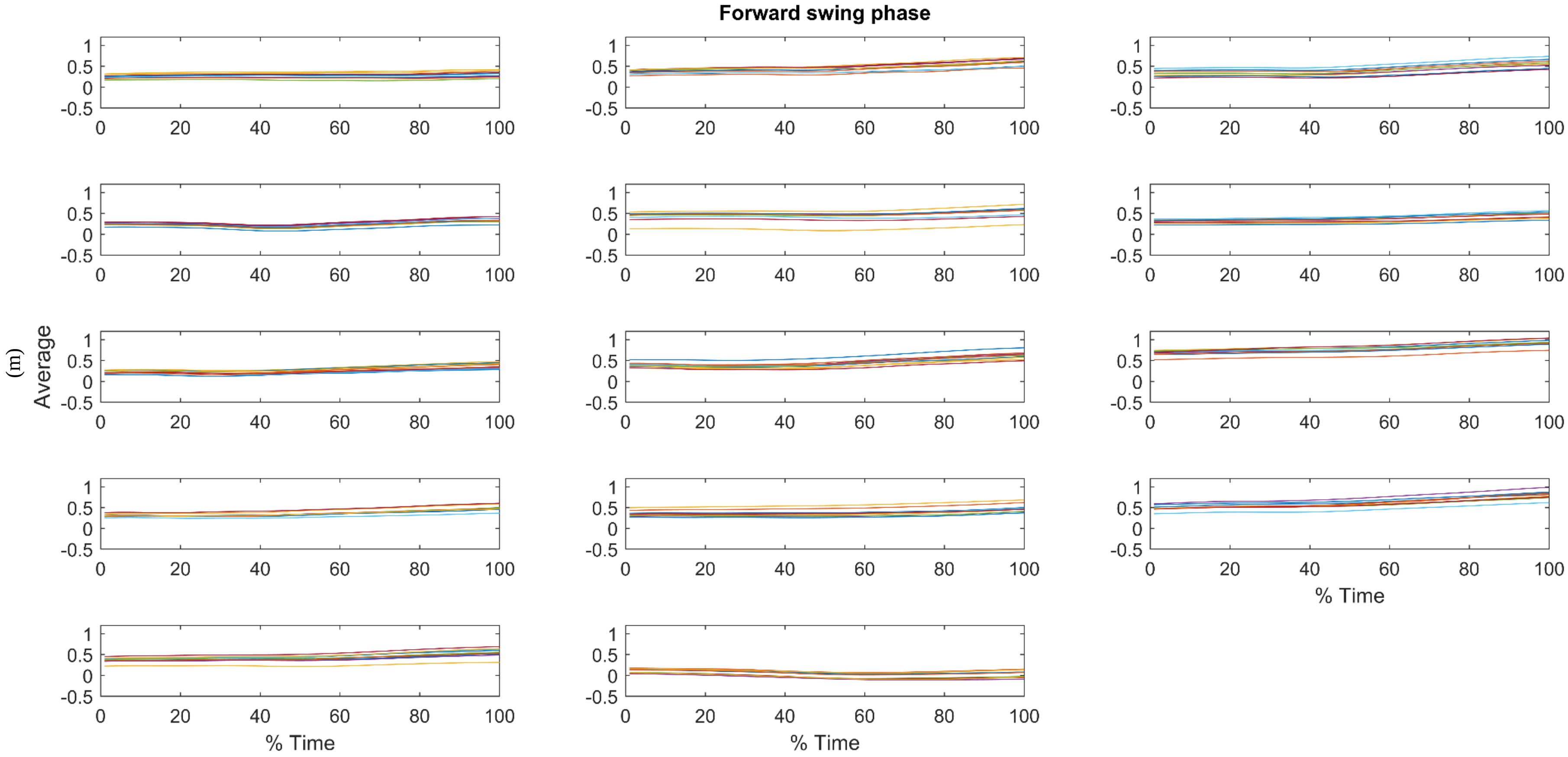
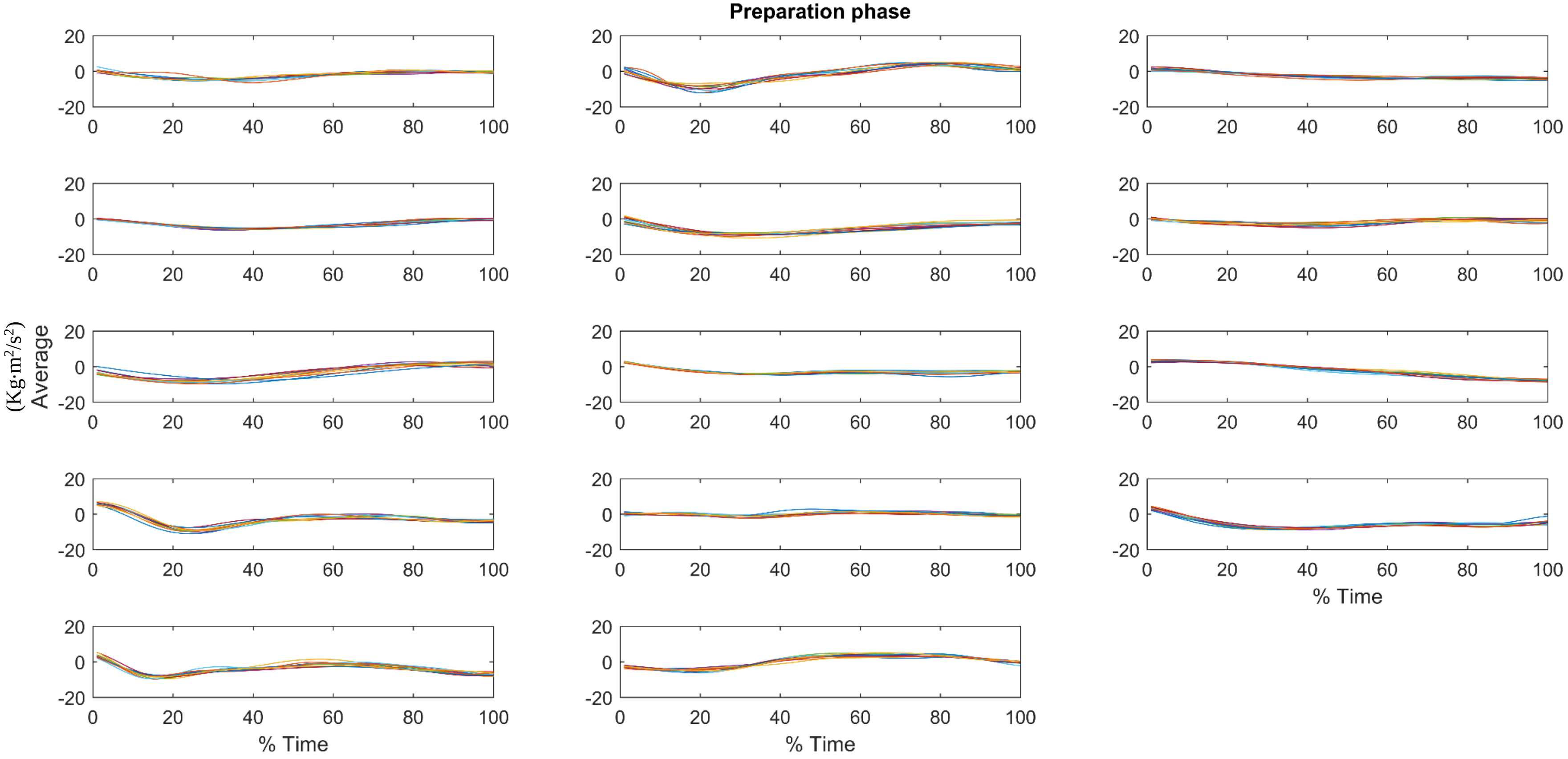
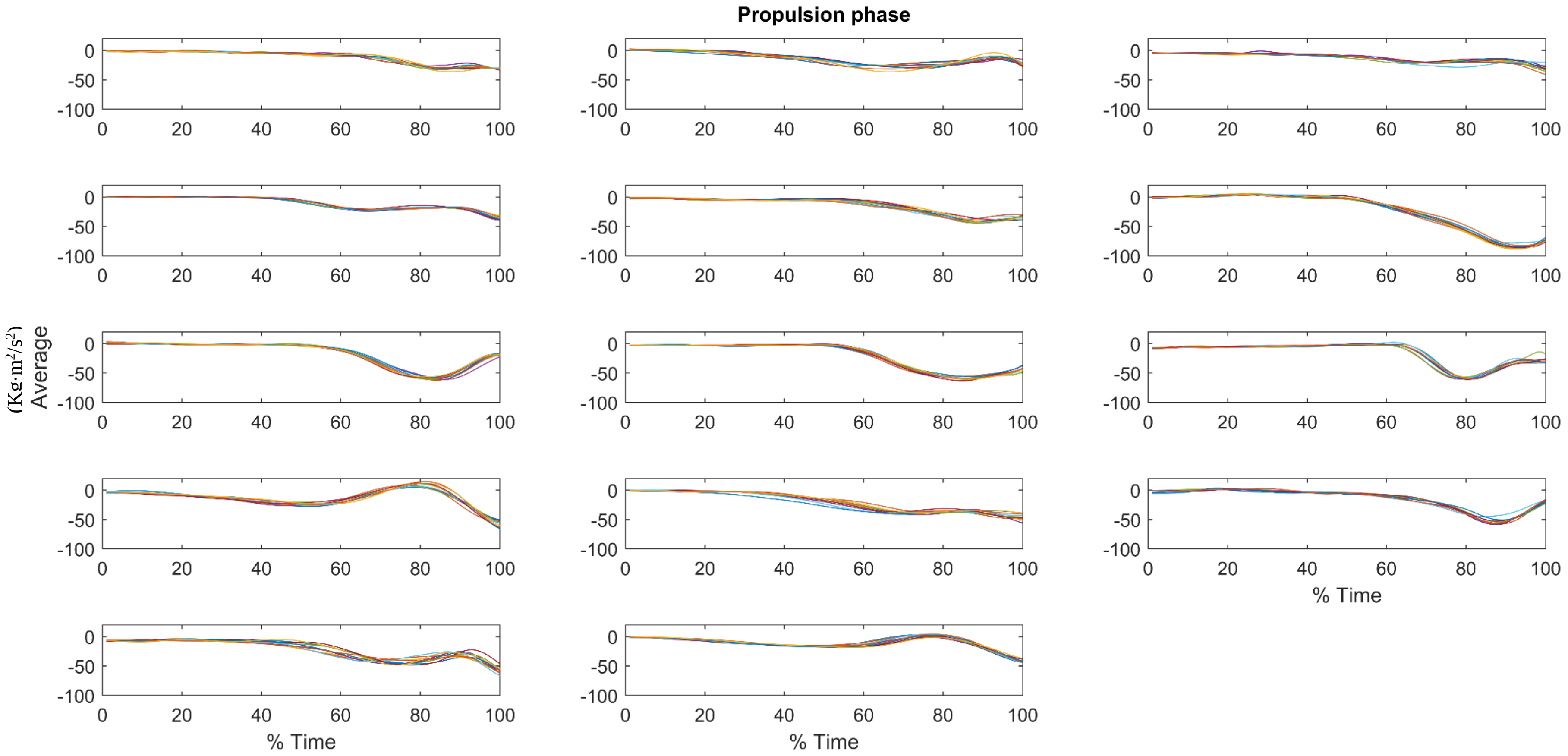


Figure D-1. The individual XCoM in A/P direction of all 14 participants, during the three phases of a tennis serve.


Preparation phase
Average
(Kg·m²/s²)
20
0
-20
0
20
40
60
80
100
% Time


Propulsion phase
Average
(Kg·m²/s²)
0
-50
-100
0
20
40
60
80
100
% Time

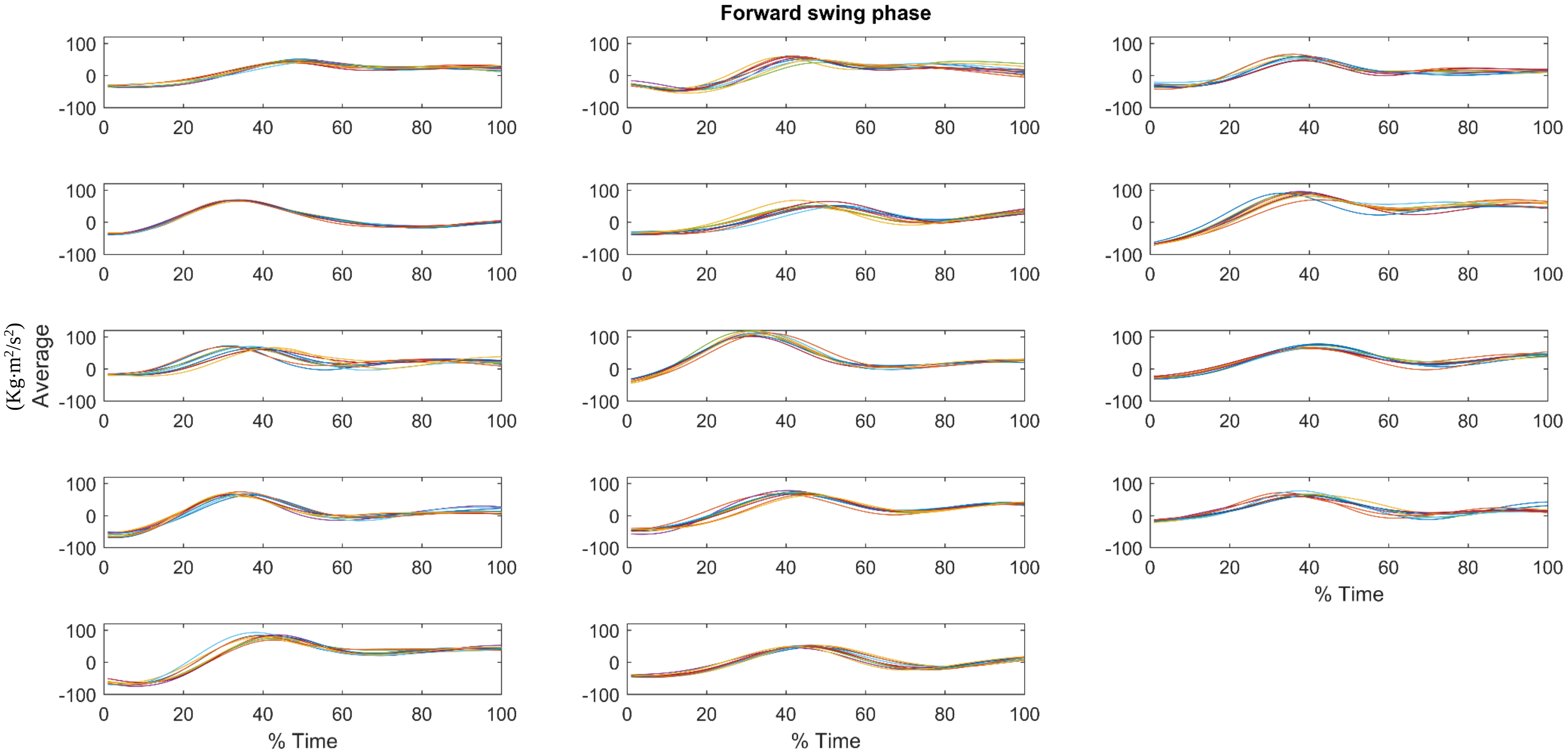
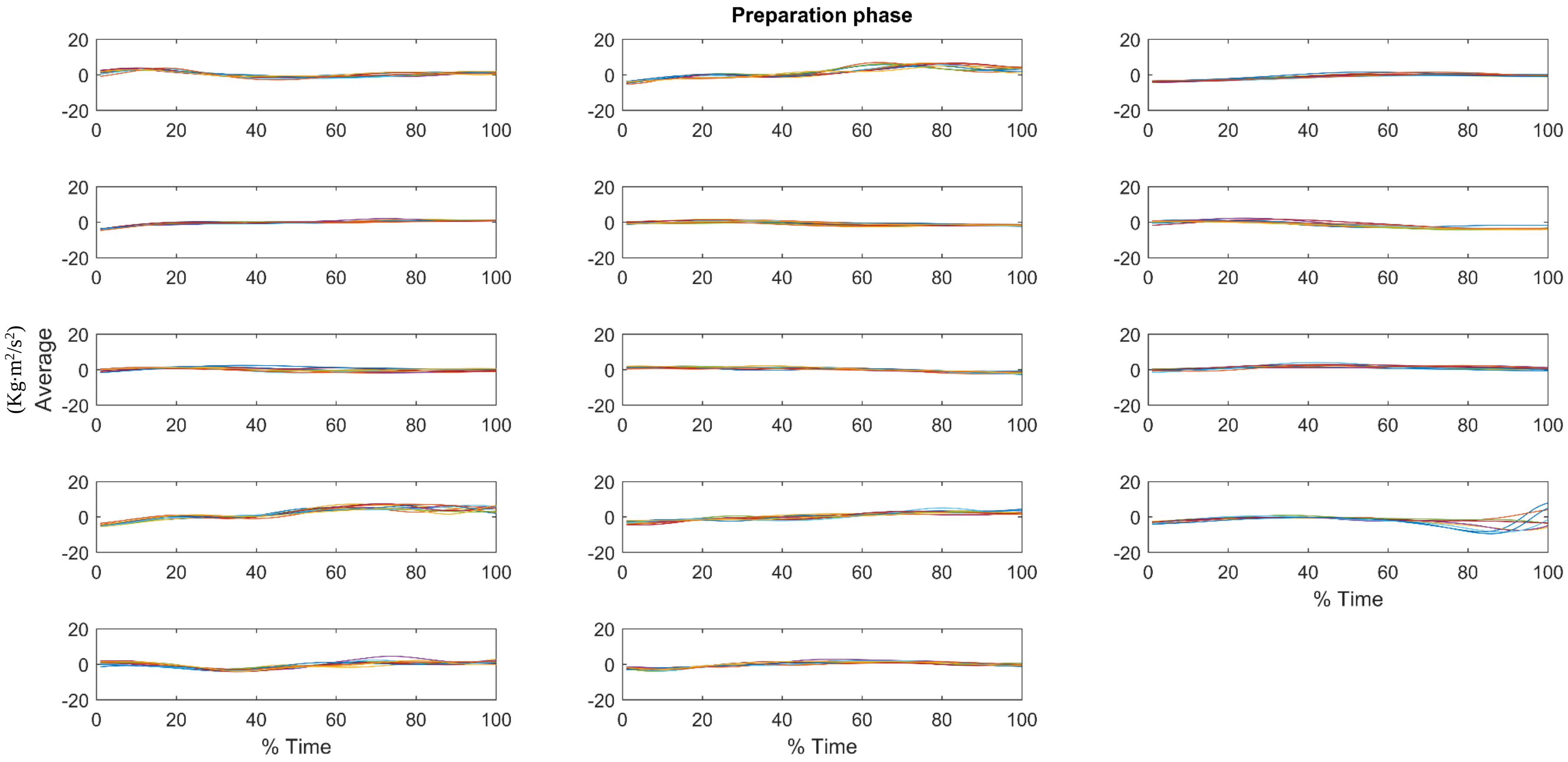
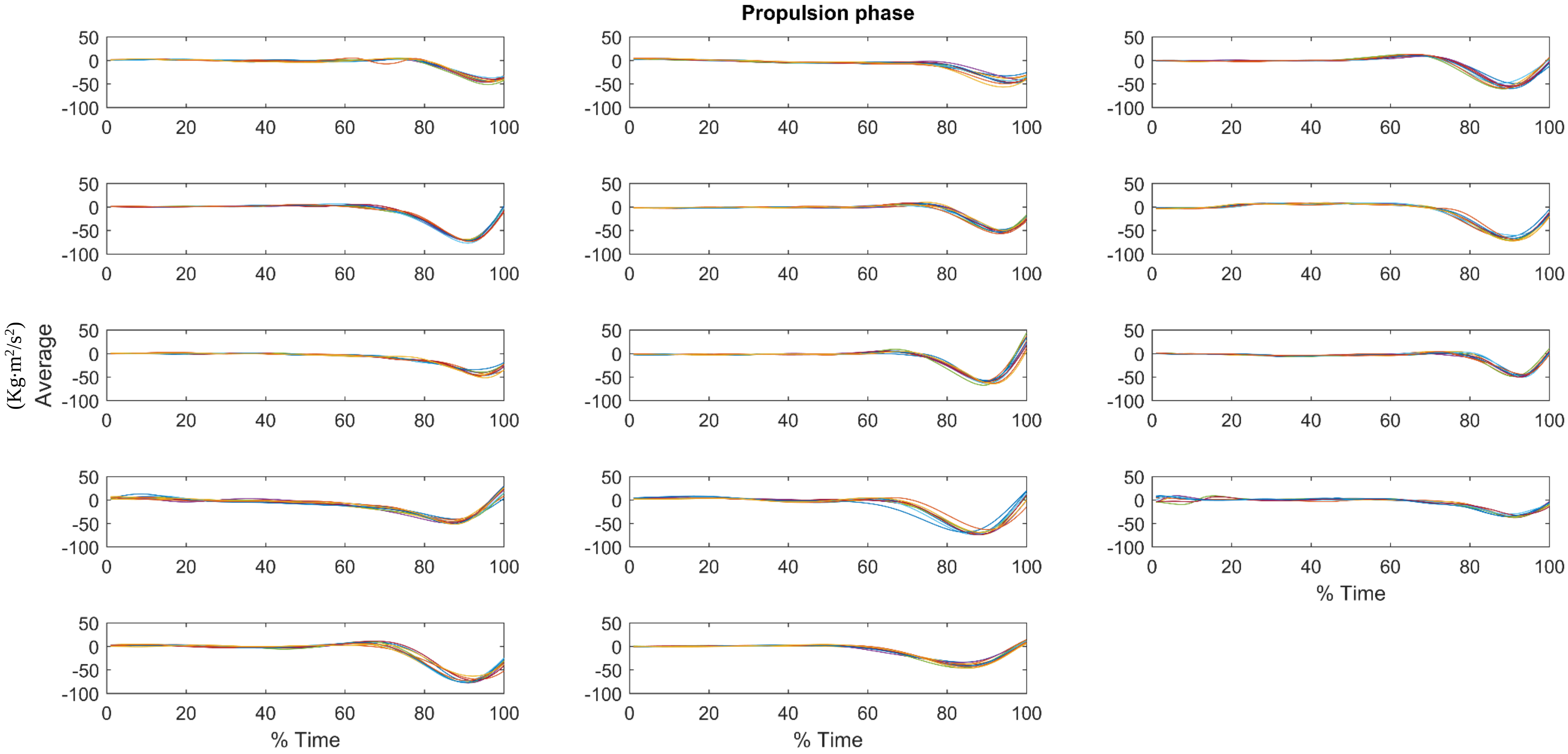


Figure D-2. The individual change in arms angular momentum of all 14 participants, during the three phases of a tennis serve.

The average trials per individual of XCoM (A/P direction) in preparation and propulsion phase showed small variations. However, more inter-trial variations can be seen in forward swing phase. The pattern of the XCoM trajectories were similar between participants. During the preparation phase the changes in both arms angular momentum were generally small, with little variation notable within participants. During the propulsion phase, changes in arms angular momentum were larger, particularly in the second half while, the change in trunk angular momentum were also larger in the last third of that phase. Qualitatively, the profile patterns were similar but were not exactly the same between individuals, yet with limited variation within each individual, which would be indicative of individualised movement signatures. During the forward swing phase, both the changes angular momentum graphs show particularly more variation between trials and also between participants. Over all three phases of the XCoM, the changes in arms/trunk angular momentum, these graphs demonstrate that there was only limited variability within the individual. Furthermore, variability presents both in terms of amplitude of signals and in terms of timing (temporal variability) were found but some graphs showed amplitude variation as well as very little in term of temporal variation.


Preparation phase
Average
(Kg·m²/s²)
20
0
-20
0
20
40
60
80
100
% Time


Propulsion phase
(Kg·m²/s²)
Average
50
0
-50
-100
0
20
40
60
80
100
% Time

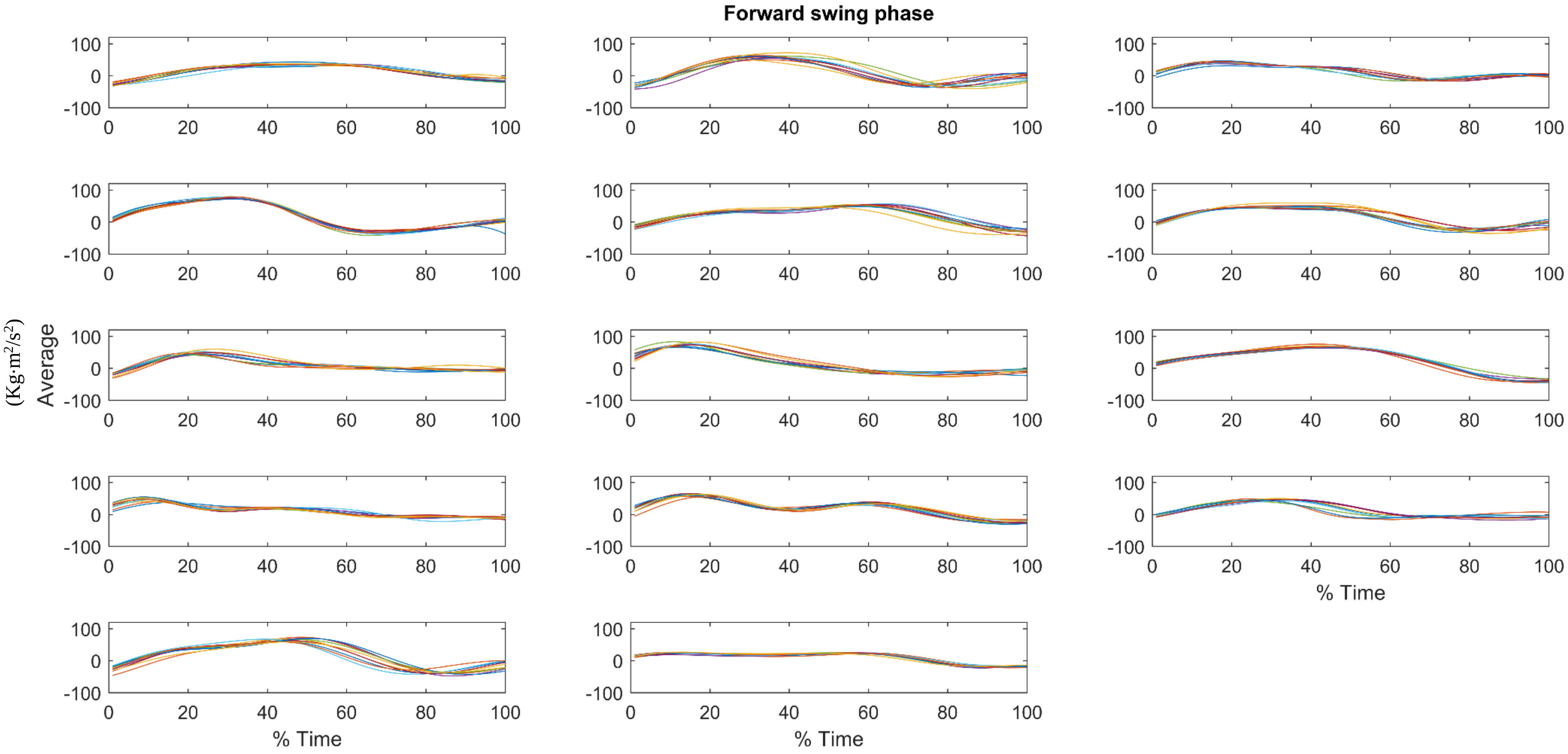


Figure D-3. The individual change in trunk angular momentum of all 14 participants during serving.

Appendix E: the figures below illustrate the relationships between the XCoM in A/P direction (E1-4) and maximum racket velocity in each serving condition. Top panels show the average of the XCoM in A/P direction for each participant. In the middle panels, β-curves are presented, identifying the strength of the relationship between the the XCoM in A/P direction and maximum racket velocity for each participant. In bottom panels the SPM linear regression test outcomes are presented.

In summary, the profile patterns of both the average XCoM in A/P direction and Β-curve graphs illustrate that there are limited variations in the preparation phase, then more variation in propulsion and forward swing phase, respectively in all 4 conditions. The SPM linear regression results of the relationship between XCoM and maximum racket velocity of 4 conditions, are constant around zero line, indicating that there are no systematic relationships between this postural balance control mechanism and the serve performance.

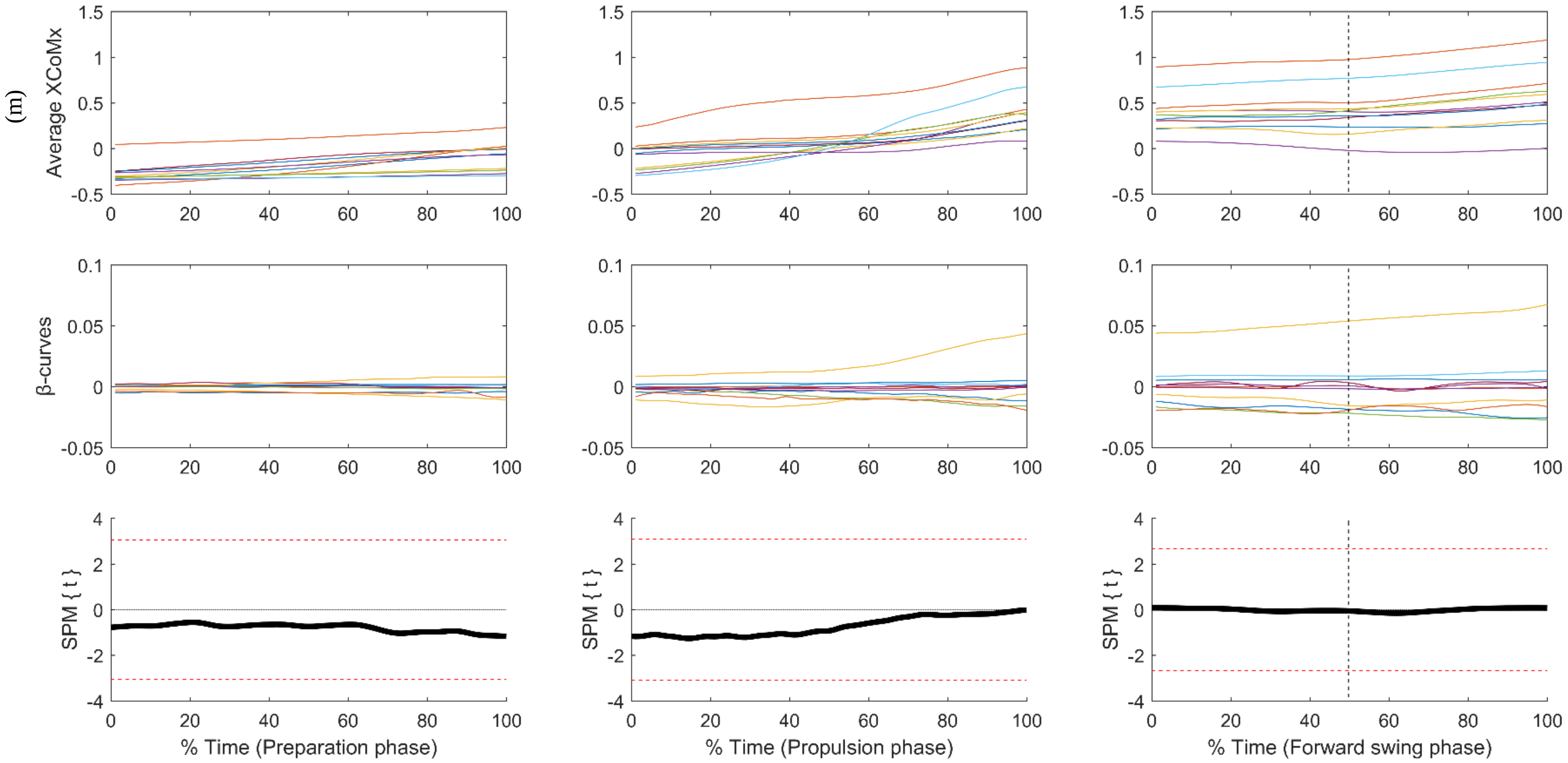


Figure E-1. The XCoM data of 11 participants during the serve in condition 1, in three phases including preparation, propulsion, and forward swing phase. The average time point at 49 % of forward swing phase, which maximum racket forward velocity is reached, is indicated by the dashed vertical line.

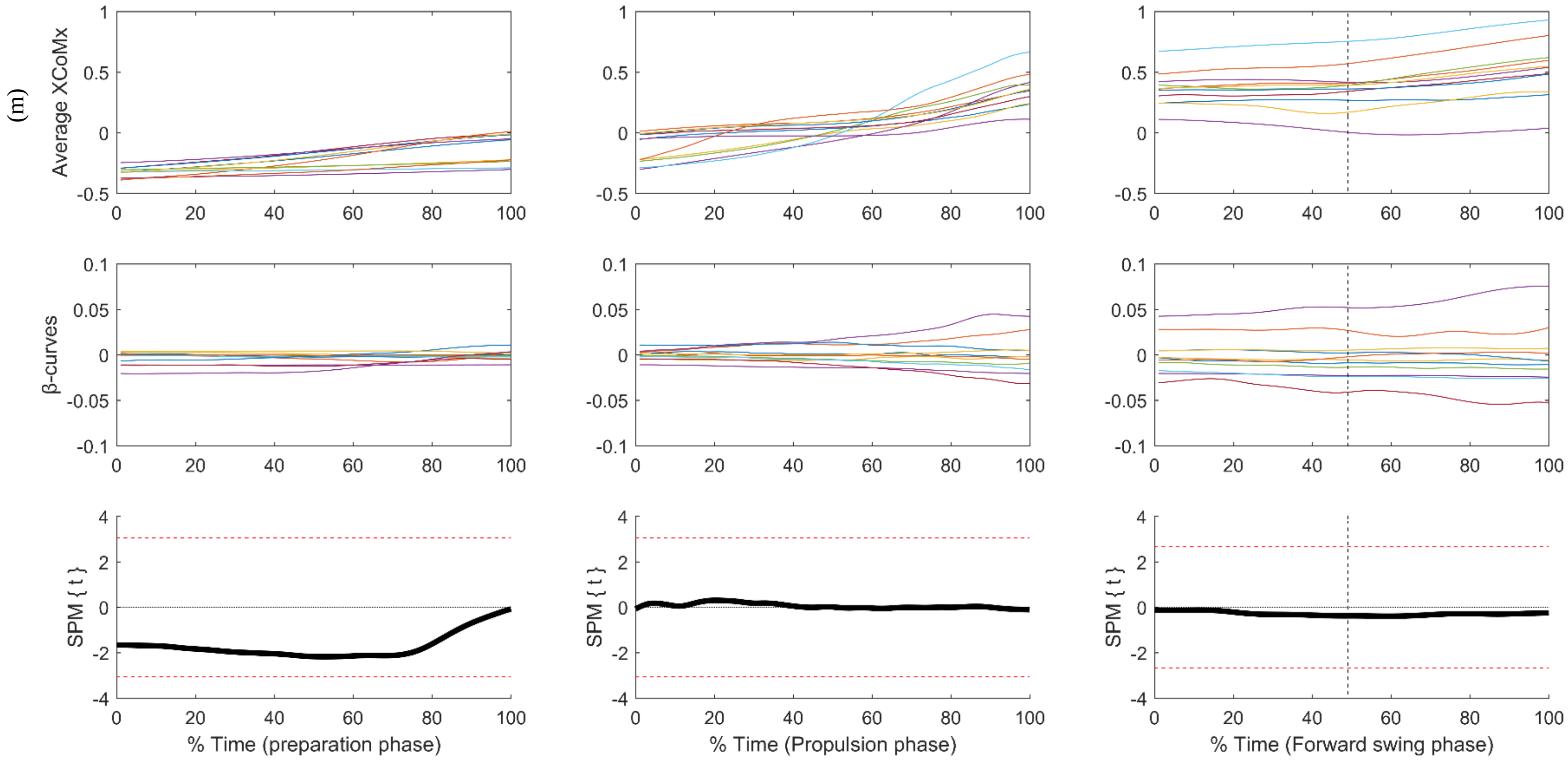


Figure E-2. The data of 11 participants, during the serve in condition 2 in three phases including preparation, propulsion, and forward swing phase. The average time point at 48 % of forward swing phase, which maximum racket forward velocity is reached, is indicated by the dashed vertical line.

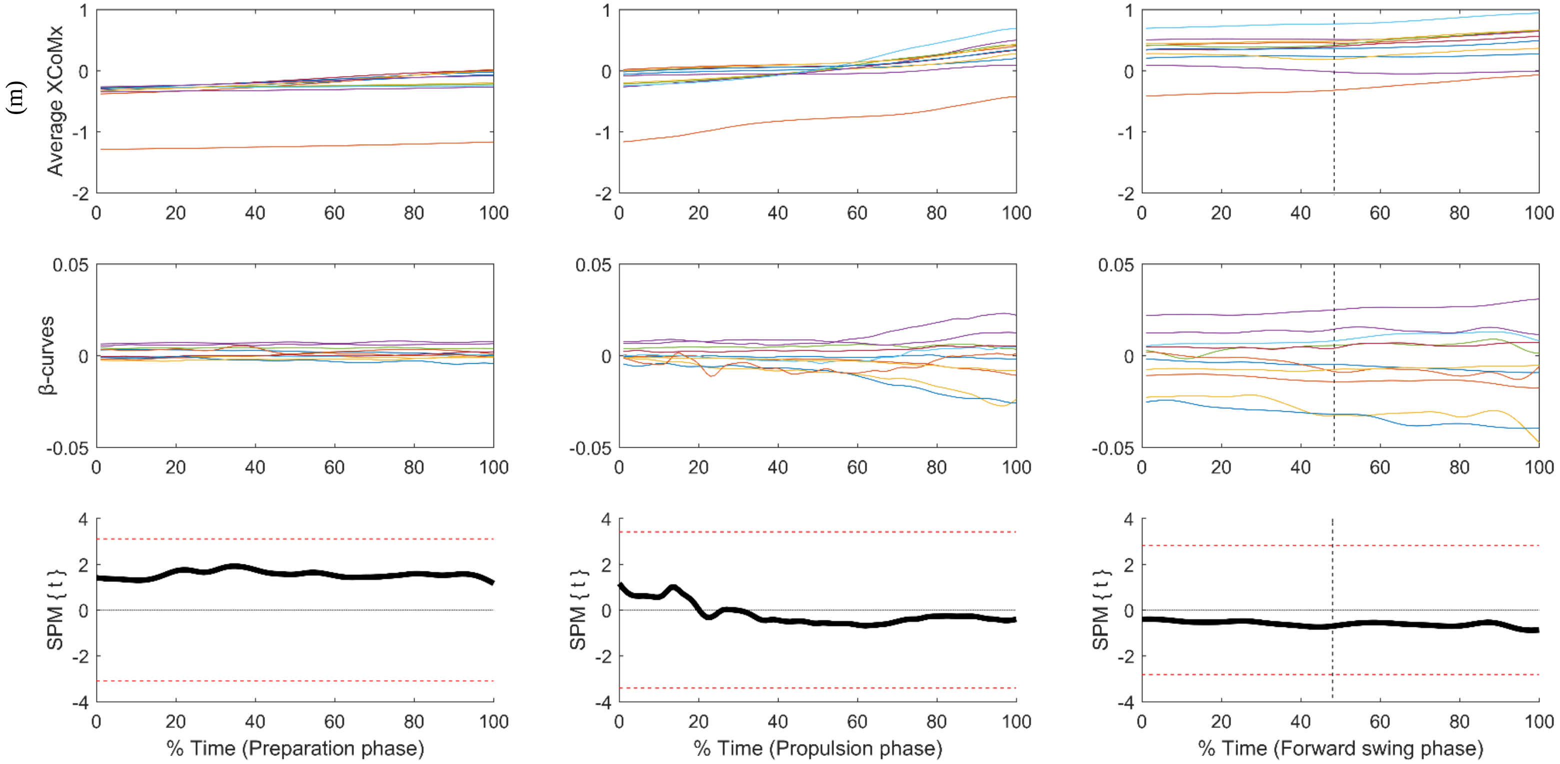


Figure E-3. The data of 11 participants during the serve in condition 3 in three phases including preparation, propulsion, and forward swing phase. The average time point at 47 % of forward swing phase which maximum racket forward velocity is reached is indicated by the dashed vertical line.

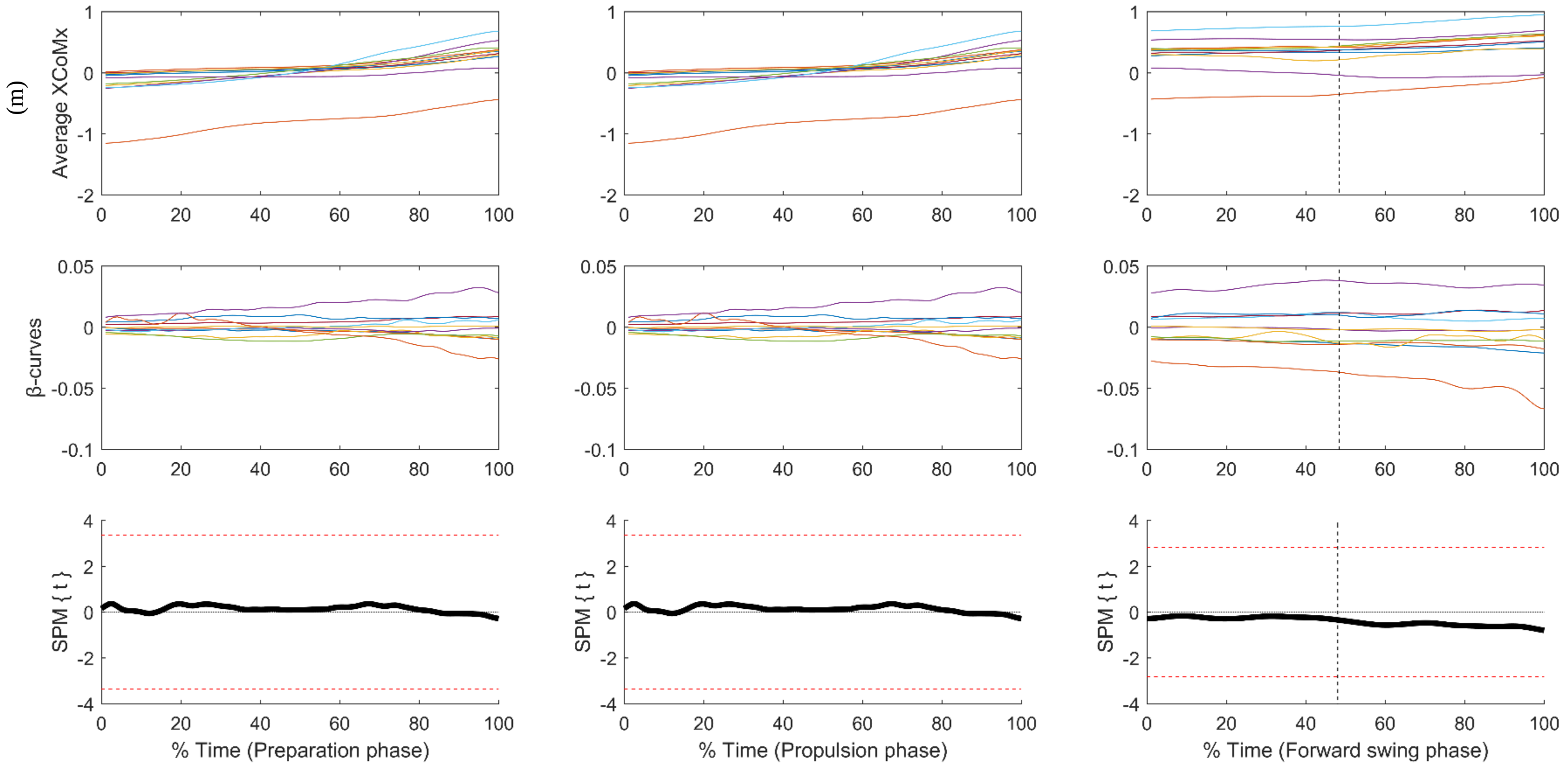


Figure E-4. The data of 11 participants during the serve in condition 4 in three phases including preparation, propulsion, and forward swing phase. The average time point at 46 % of forward swing phase, which maximum racket forward velocity is reached, is indicated by the dashed vertical line.

Appendix F: the figures below illustrate the relationships between changes in arms (F1-4) or trunk (F5-8) angular momentum and maximum racket velocity in each serving condition. Top panels show the average of the changes in arms/trunk angular momentum for each participant. In the middle panels, β-curves are presented, identifying the strength of the relationship between the changes in arms/trunk angular momentum and maximum racket velocity for each participant. In bottom panels the SPM linear regression test outcomes are presented.

In summary, changes in angular momentum are only starting to become tangible from around the second half of the propulsion phase. This makes that up until that point in time, any relationship between these changes in angular momentum and maximum racket velocity is expected to be random. Observing the relationship from that point in time onwards, it is notable that despite considerable changes in angular momentum in all participants, the relationship is not consistently large for all participants (notable mostly in the middle right hand side panels depicting the relationship for the forward swing phase). Only in condition 4 the relationship between changes in arms angular momentum and maximum racket velocity was systematically positive between 50%-70% of the forward swing phase, indicating that an individual's increase of their arms angular momentum during that phase is associated with an increase in maximum racket velocity.

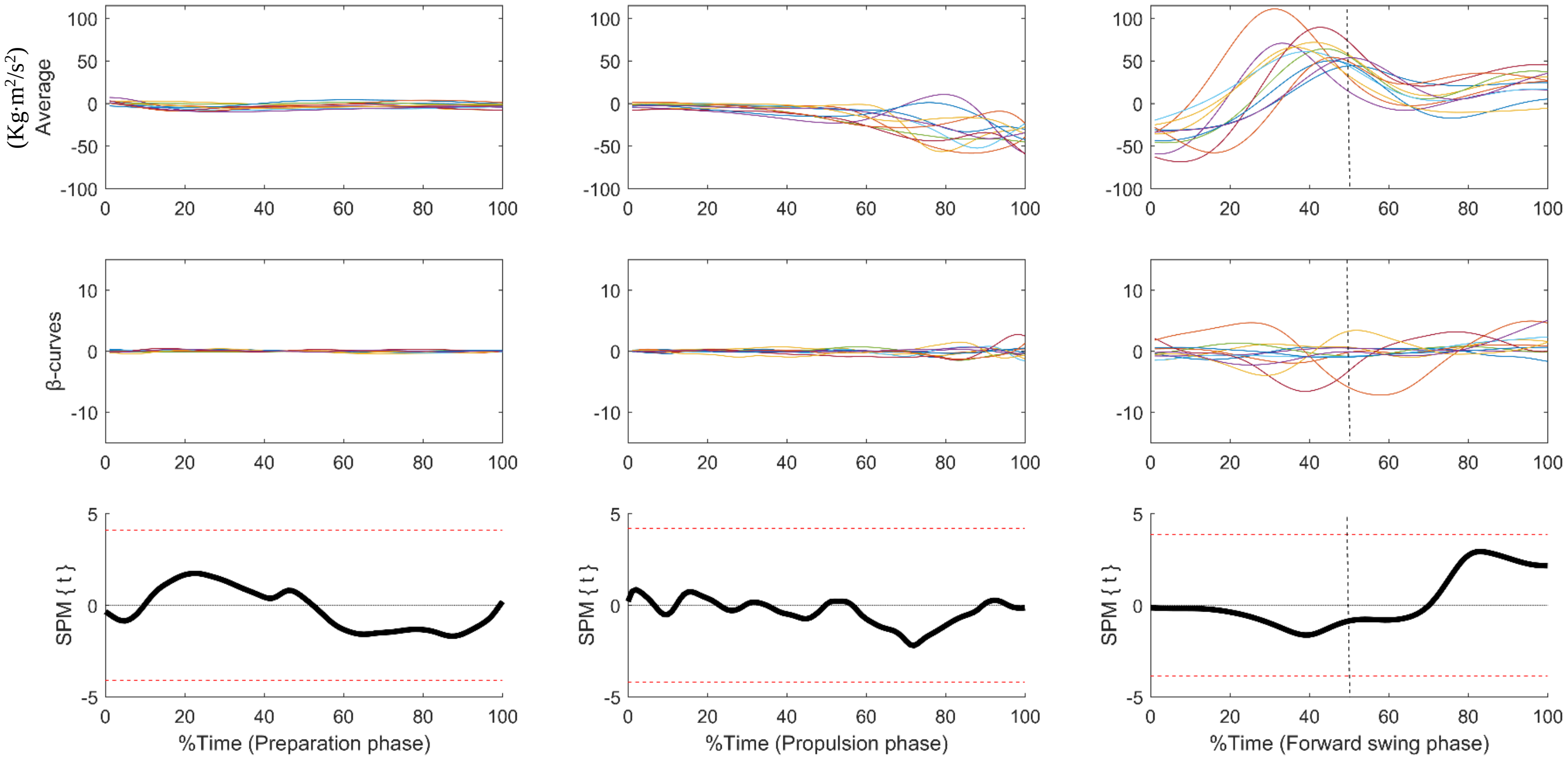


Figure F-1. The data of 11 participants during the serve in condition 1, in three phases including preparation, propulsion, and forward swing phase. The average time point at 49 % of forward swing phase, which maximum racket forward velocity is reached, is indicated by the dashed vertical line.

This figure illustrates the average of the change in arms angular momentum (top panel). The top panel graphs first show constant average results, then more variation can be seen from 60% until the end of phase2. Furthermore, significant variation has been found in phase 3. The middle panel presented the β-curves that represent the relationship between the change in arms angular momentum and maximum racket velocity. The β-curve results were similar to the results shown in the top panel as more variability can be seen in the last third of phase 2. The last phase shows more variation highlighted specifically by three participants. SPM linear regression test (bottom panel) presents no significant differences of the relationship between the change in arms angular momentum and maximum racket velocity within condition 1.

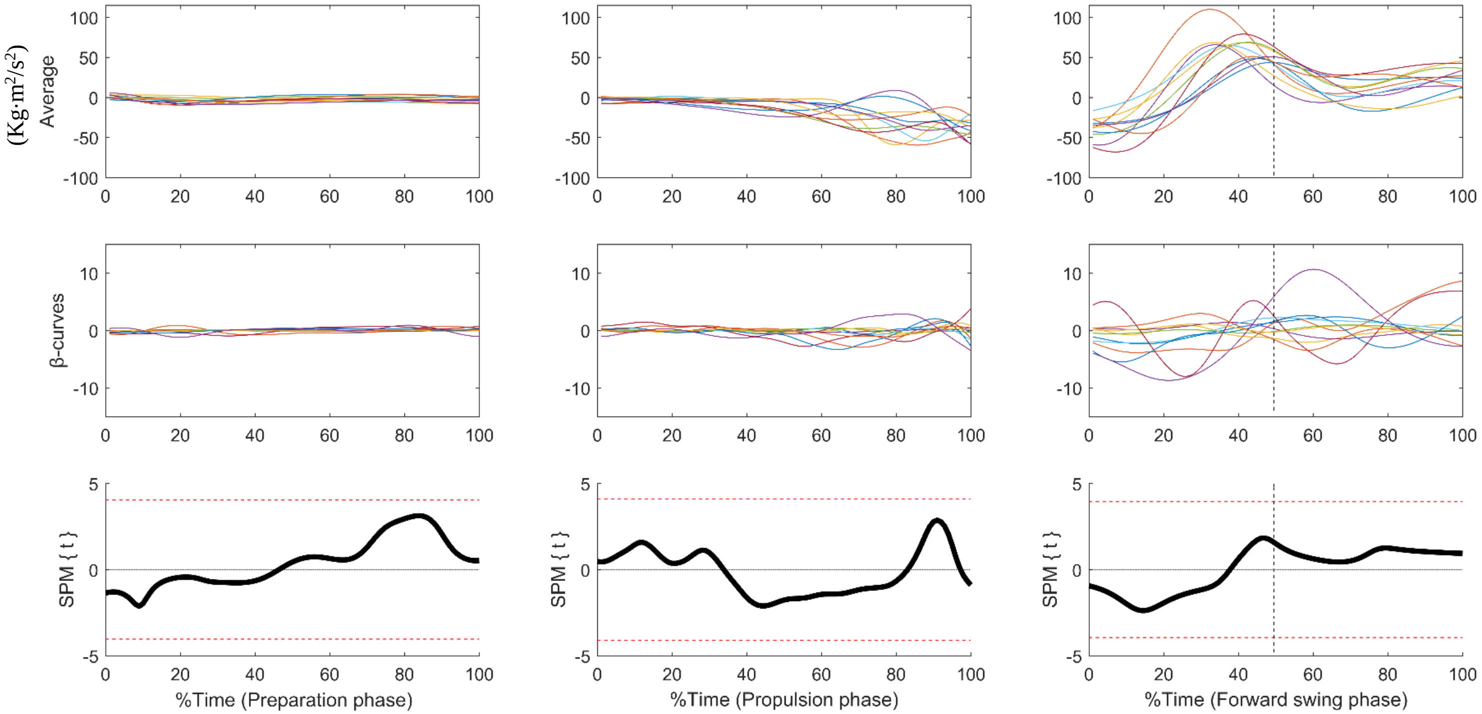


Figure F-2. The data of 11 participants, during the serve in condition 2 in three phases including preparation, propulsion, and forward swing phase. The average time point at 48 % of forward swing phase, which maximum racket forward velocity is reached, is indicated by the dashed vertical line.

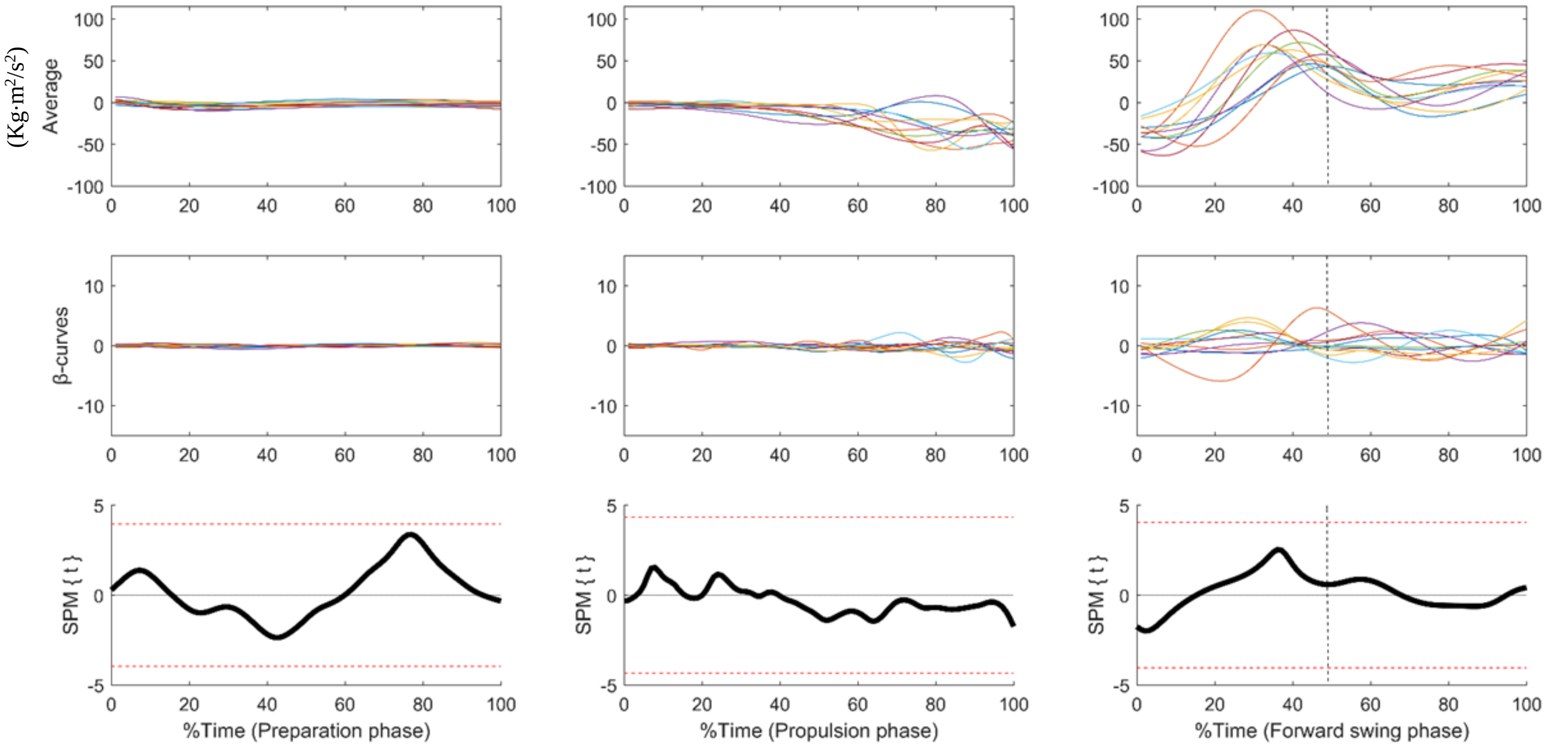


Figure F-3. The data of 11 participants during the serve in condition 3 in three phases including preparation, propulsion, and forward swing phase. The average time point at 47 % of forward swing phase which maximum racket forward velocity is reached is indicated by the dashed vertical line.

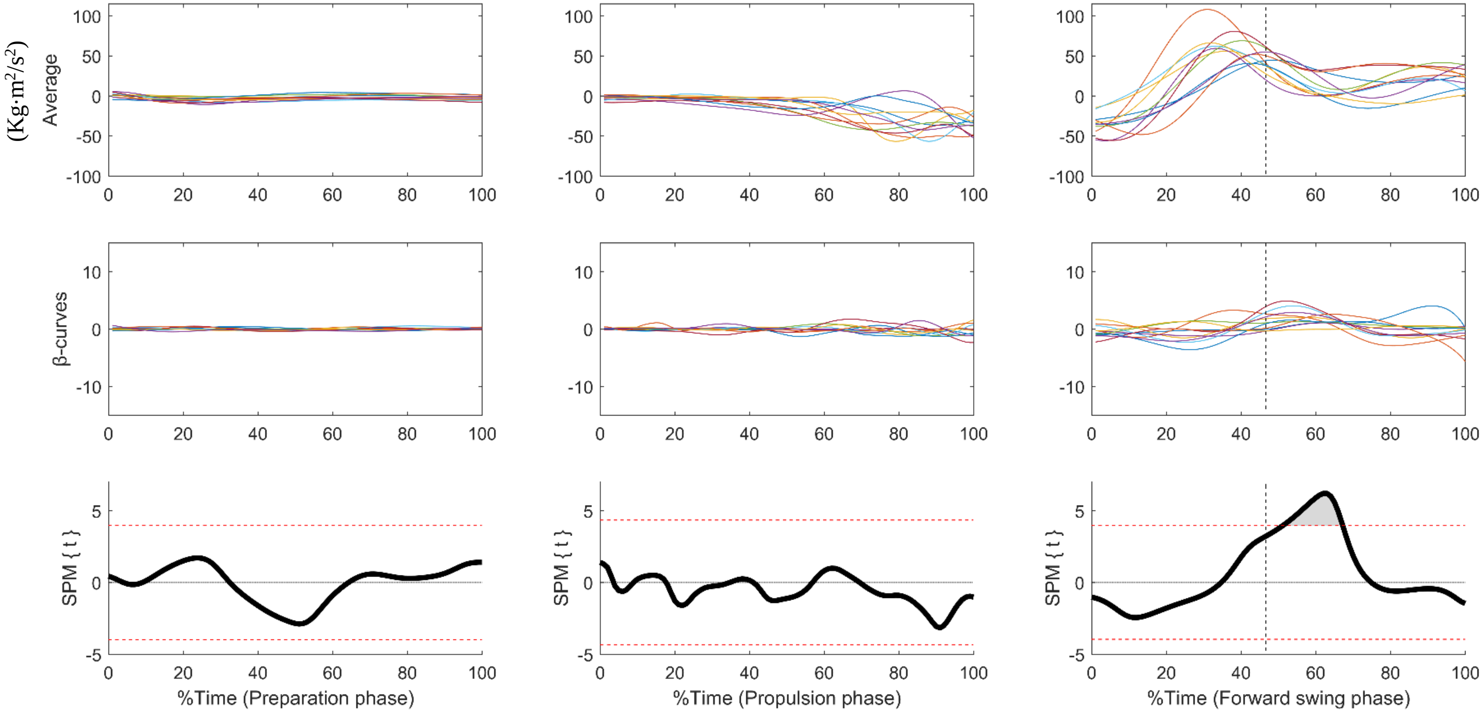


Figure F-4. The data of 11 participants during the serve in condition 4 in three phases including preparation, propulsion, and forward swing phase. The average time point at 46 % of forward swing phase, which maximum racket forward velocity is reached, is indicated by the dashed vertical line.

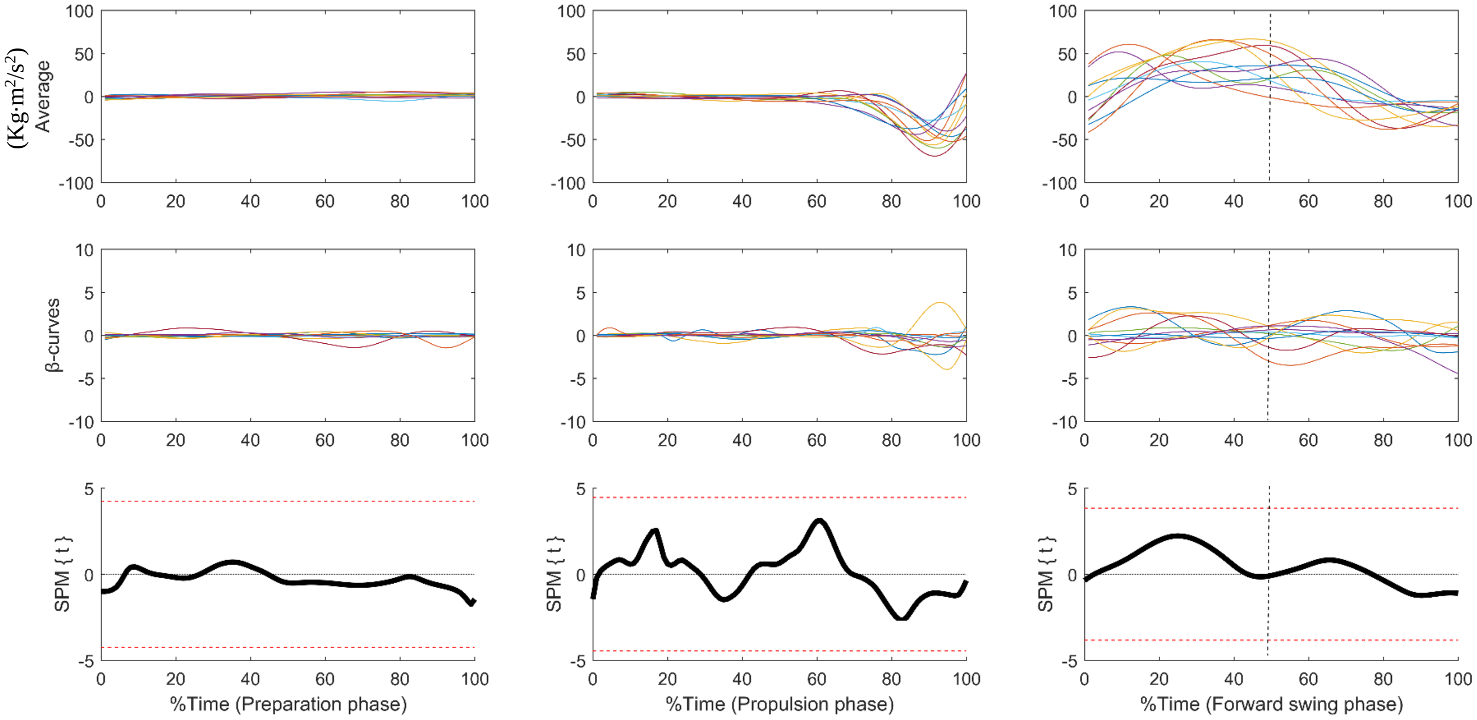


Figure F-5. The data of 11 participants during the serve in condition 1, in three phases including preparation, propulsion, and forward swing phase. The average time point at 49 % of forward swing phase, which maximum racket forward velocity is reached, is indicated by the dashed vertical line.

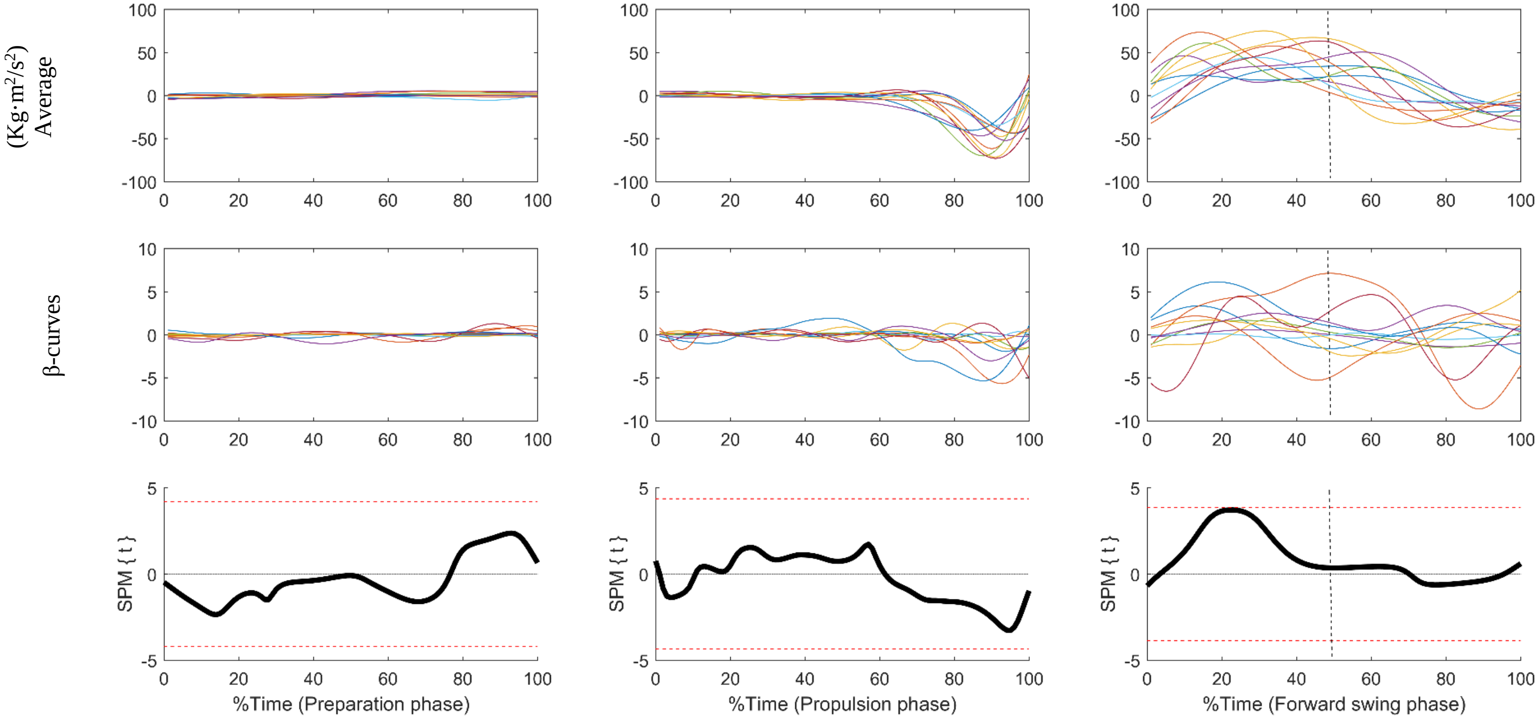


Figure F-6. The data of 11 participants during the serve in condition 2 in three phases including preparation, propulsion, and forward swing phase. The average time point at 48 % of forward swing phase, which maximum racket forward velocity is reached, is indicated by the dashed vertical line.

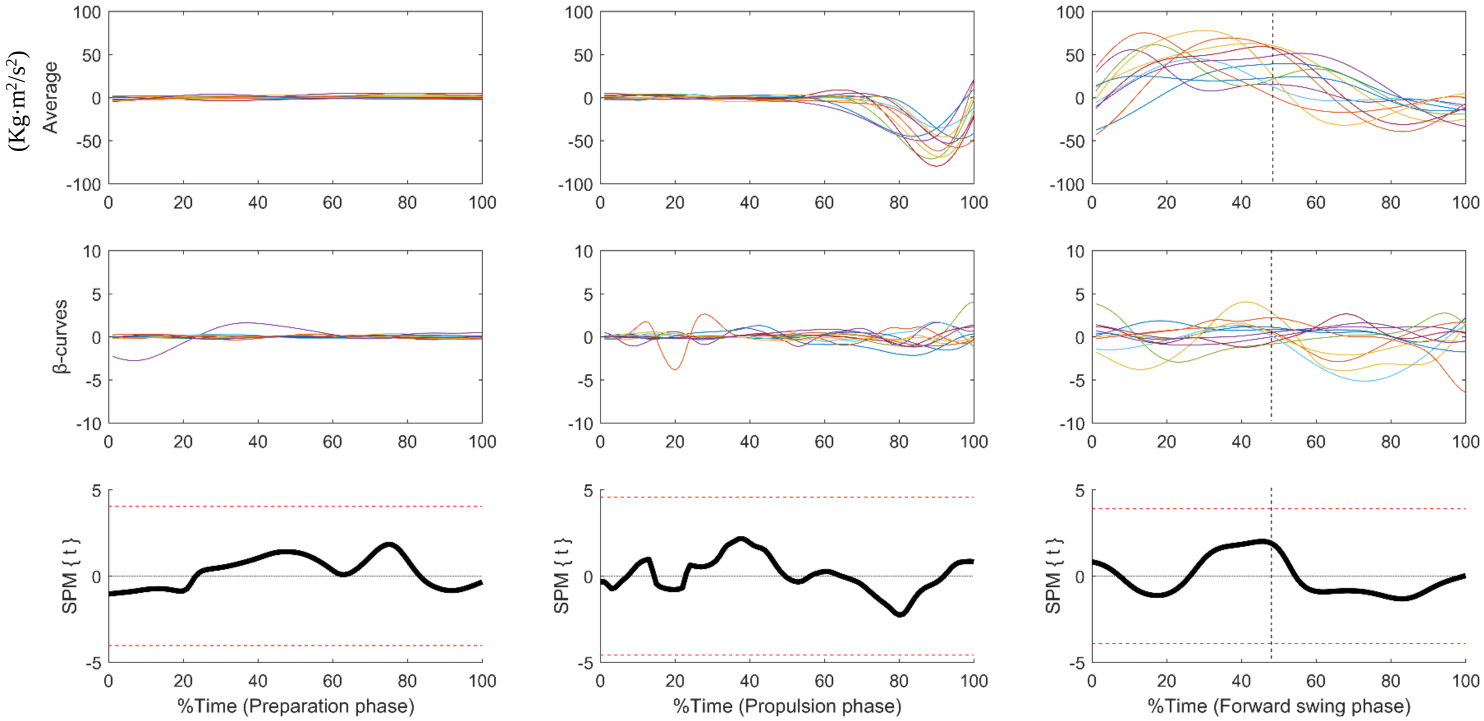


Figure F-7. The data of 11 participants during the serve in condition 3 in three phases including preparation, propulsion, and forward swing phase. The average time point at 47 % of forward swing phase, which maximum racket forward velocity is reached, is indicated by the dashed vertical line.

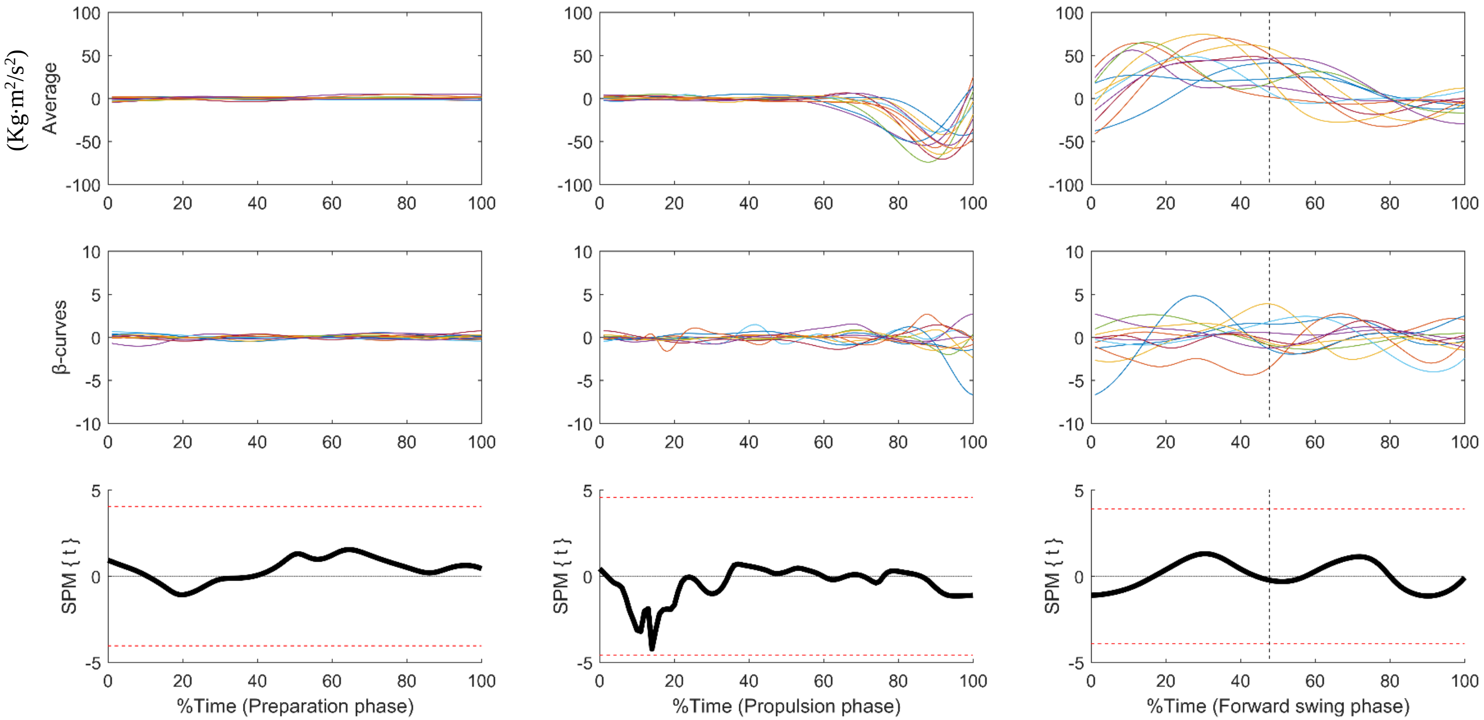


Figure F-8. The data of 11 participants during the serve in condition 4 in three phases including preparation, propulsion, and forward swing phase. The average time point at 46 % of forward swing phase, which maximum racket forward velocity is reached, is indicated by the dashed vertical line.