Universidade de Lisboa
Faculdade de Motricidade Humana

Biomechanical determinant factors in tennis forehand drive

Bruno Miguel Machado Pedro

Orientador: Professor Doutor António Prieto Veloso

Tese especialmente elaborada para obtenção do grau de Doutor em

Motricidade Humana na especialidade de Biomecânica

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Júri:
Presidente: Doutor António Fernando Boleto Rosado
Vogais:
Doutor António Prieto Veloso
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Professor Adjunto da Universidade do Algarve

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O que mantém a vida fascinante é a constante criatividade da alma”

"What keeps life fascinating is the constant creativity of the soul"

(Deepak Chopra)

Dedication

Para os meus pais, pelo seu exemplo de resiliência e coragem que são e sempre foram para mim**.**

To my parents, for their example of resilience and courage they are and have always been to me.

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Resumo

O batimento de direita no ténis é considerado decisivo na performance dos atletas. Apesar de vários estudos ao nível da biomecânica, existem questões e metodologias inexploradas que poderão contribuir para uma melhor compressão de fatores chave na performance dos tenistas. O primeiro estudo teve como objetivo comparar a contribuição do membro superior para velocidade da raquete entre jogadores de nível intermédio e experientes. Os resultados demonstraram que o que diferencia os dois grupos é a contribuição do ombro para a velocidade da cabeça da raquete. Para utilizarmos o mesmo método com atletas de elite em situação real e com uma metodologia menos pesada do ponto de vista da sua preparação, o segundo estudo teve como objetivo validar um sistema de sensores inercias. Os resultados deste estudo demonstraram que podemos recolher com confiança os dados cinemáticos neste movimento através de um sistema de sensores inerciais. Após esta validação, no terceiro estudo determinámos a contribuição dos membros superiores para a velocidade da cabeça da raquete em jogadores de elite, no campo. Os resultados demonstraram algumas diferenças quando comparados com estudos prévios utilizando a mesma metodologia, estas diferenças poderão estar relacionadas com a diferença do nível de jogadores ou o tipo de batimento. Por último, o quarto estudo teve como objetivo determinar os momentos de força do membro superior dominante entre um batimento apoiado e um batimento dinâmico. Os resultados demonstraram uma maior carga nas articulações durante o batimento em apoio. Podemos concluir que os resultados obtidos durante os vários estudos poderão contribuir para um maior conhecimento dos treinadores no sentido de ajudar os atletas a atingir uma melhor performance no batimento de direita, bem como os profissionais de saúde a perceber quais os batimentos que poderão estar associados a uma maior carga nas articulações.

Palavras-chave: direita no ténis, cinemática, velocidade da cabeça da raquete, cinética, contribuição.

Abstract

The forehand drive in tennis is considered essential in the performance of athletes. Despite several studies in biomechanics, there are unexplored issues and methodologies that may contribute to a better understanding of the key factors in performance and greater efficiency to capture kinematic data contributing to a positive impact for tennis players. Therefore, the first study aimed to compare the contribution of the upper limb to racket speed among intermediate and experienced tennis players. The results showed that what differentiate the two groups is the contribution of the shoulder to the racket head velocity. In order to use the same method with elite athletes in real situation with a simpler methodology, the second study aimed to validate an inertial measurement unit system. The results of this study demonstrated a high degree of confidence to collect kinematic data in the forehand drive. After this validation, in the third study we determined the contribution of the upper limbs to the racket head velocity in elite players, in the field. The results showed some differences when compared to previous studies using the same methodology, these differences may be related to the level of the players or the type of the stroke. Finally, the fourth study aimed to determine the moments of force of the dominant upper limb between a forehand in a quasi-static stance and a dynamic frontal weight transfer stance forehand. The results showed a higher load on the joints during the forehand in quasi-static stance. We can conclude that the results obtained during the various studies may contribute to a greater knowledge of coaches to help athletes to achieve a better performance in the forehand drive, as well as health professionals to understand which techniques may be associated with a higher load on the joints.

Keywords: forehand tennis, kinematic, racket velocity, kinetic, contribution

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List of Abbreviations

INT	Intermediate tennis players
HP	High performance tennis players
CC	Cross-court
DL	Down-the-line
IO	Inside-out
OS	Optical motion capture system
SPM-1D	Statistical parametrical mapping
IMUs	inertial measurement units system
CMC	Coefficient of multiple correlation
DOF	Degrees of freedom
QSS	Quasi-static stance
DS	Dynamic stance

Chapter 1

General Introduction

Background

Tennis is a sport played by around 87 million people representing 1.17% of the world population, of whom more than 6000 are junior ranked players and almost 4000 are professional tennis players (Cant et al., 2019). During the last decades, this sport presented a considerable evolution especially due to the racket's development. Until 1960's, the tennis rackets were generally made of laminated wood, since then, the main construction materials were steel, aluminium, and graphite (Grasso, 2011). Nowadays, the tennis rackets are bigger, lighter and stiffer allowing the tennis players to hit the ball with much more power and control (Bahamonde, 2001). As a result, the modern players try to hit the groundstrokes more aggressive almost everywhere to take control of the point (Roetert et al., 2009). This is particularly true with the tennis forehand drive which is considered the most important stroke after the serve (Reid et al., 2013a) and usually is one of the first strokes learned by beginners (Seeley et al., 2011).

Grip

The way the players hold the racket have a direct influence on the kinematics of the forehand drive technique, thus having a direct influence in the post-impact ball trajectory (Reid et al., 2013). There are four ways of players holding the racket in the forehand drive: the eastern, the semi-western, the western grip and the continental grip. The different ways to hold the racket have a direct influence in the coordination and transfer of energy in the forehand, and can provide natural strengths and weaknesses for different bounces (Duane Knudson, 2006). The western grip helps to create a more effective top spin, the eastern forehand grip benefits the forward racket speed, and the continental grip is considered a good grip to hit for lower balls, although, it is weaker for high-bouncing balls (Knudson, 2006). Currently, professional tennis players, use the semi-western and the western grips since it is easier to hit the ball with top spin (Bahamonde, 2001). To understand which rotations of the upper arm present a higher importance to the final racket velocity, Sprigings et al. (1994), developed an algorithm to calculate those contributions of anatomical rotations of each segment of the upper limb. These contributions were calculated during different grip positions in the forehand drive and significant variations were recorded for the contribution of the hand to the racket head velocity, when players hold the racket with different grip positions. However, the primary contributions of the upper limb to the racket head velocity in order of importance were the same (horizontal flexion/abduction and internal rotation of the upper arm, in addition to linear velocity of the shoulder) (Elliott et al., 1997). The grip used by the nonprofessional players with wrist injuries are related to the anatomical site of the lesion: Eastern grip with radial-side injuries and western or semi-Western with ulnar-side injuries (Tagliafico et al., 2009).

Stance

There are different forehand drive stances that could be adopted by the players, these stances can be divided in three categories: a) the square/neutral stance, where the feet are nearly in line with the direction of the shot and the hips (line connecting them) are perpendicular to the net, allows the sum of the forward movement to body rotations, thus, generating higher racket speed, and presenting higher linear and angular motion; b) the open-stance, where the line between the feet and hip alignment is almost parallel with the baseline; c) semi-open stance, where the players assume any position between the square and open stance. The stances used by tennis players are usually connected with the used grip. The square stance is generally adopted by players with an eastern grip performing the forehand drive with a more linear approach, while the open stances will mostly be performed by players with western grips, developing the trunk rotation (Elliott et al., 2009). Research showed no differences in trunk kinematics and racket velocity between the open and the square stance (Knudson & Bahamonde, 1999). Despite this important contribute, little is known between a more stationary forehand stance (maintaining the feet on the ground during the impact) and a dynamic forehand stance (when players hit the ball with their feet off the ground) in terms of kinematics and kinetics. In terms of the kinetics of the dominant upper limb, contrarily to what was expected, the squared stance presented larger torques, resulting in greater loading at the joints (Bahamonde & Knudson, 2003). On the other hand, the initial knee position in the close stance forehand were positively related with the racket velocity (Nesbit et al., 2008). In another study (Seeley et al., 2011), despite no reference to the stance used by the participants, a relationship was demonstrated between the angular velocities of the knee extension and the plantar flexion of the dominant side and the speed of the ball in the forehand drive. Few studies compared the differences between the stances, although, and due to the dynamics of the strokes in the forehand drive there is a scarcity of studies comparing between a static and a more dynamic stance as it is common during a rally. Nowadays, tennis players must react much faster and hit on the run the incoming balls, thus, they adopt an open stance (Bahamonde, 2001).

Swing Phases

The tennis forehand drive is usually divided in three main phases, the backswing, the acceleration, and the follow-through (Figure 1.1).

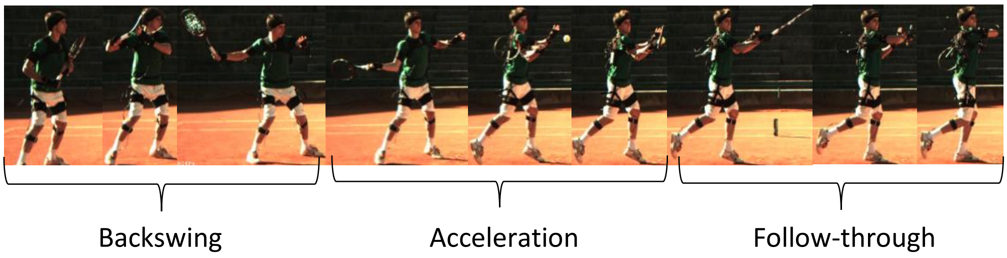

Figure 1.1 – Forehand drive phases, backswing, acceleration, and follow-through.

Backswing

The backswing is also defined as the unit turn, which involves a rotation of the whole body, including the racket, around the foot closest to the ball. This unit turn will also create a slight forward imbalance, and prepare the body for quick lateral movement (Groppel, 1984). The backswing will be essential to the storage of the elastic energy (Elliott, 1990) and to increase the pathway of the racket which is linked to racket speed in the next phase of the forehand drive (acceleration phase) (Elliott, 2001). One key factor in order to use efficiently the elastic energy is to shorten the time between the backswing and the forward swing (Elliott, 2006). The trunk and backward movement of the racket are the precursor of the backswing, where the shoulder alignment rotation presents 110°, the hip alignment around 90° with the baseline, the separation angle around 20 to 30° in transverse plane, and the racket rotation around 220° from a position pointing to the opponent (Elliott et al., 2009).

Forward swing

The back hip drive initiates the trunk rotation (Elliott et al., 2009), in addition, the trunk rotation is significantly correlated with the racket velocity, contributing in about 10% to the racket head velocity at impact (Bahamonde, 2001) that is essential to the contribution to the racket velocity. The horizontal flexion of the upper arm contributes around 25% of the racket speed. The position of the upper arm in relation to the trunk depends on the player's grip, where players with western grips have the arm closer to the trunk. The internal rotation of the upper arm have an important component for generating the final racket speed with around 35% and a combination of a palmar or ulnar flexion contributes around 25% of the final racket velocity (Elliott et al., 2009).

Follow through

After the impact, there is a gradual deceleration of the segments that are part of the shot, simultaneously with a step of recovery of the right leg (right-handed player) (Elliot, 1990). After the contact point with the ball, the shoulder, trunk, and hip joints rotate to the non-dominant side following the racket with the muscles stretching to the opposite side of the racket (Ivancevic et al., 2008).

Biomechanics in Tennis

One of the most important key factor in tennis competition is the ability to generate racket speed (Elliott et al., 2003), although, a fundamental mechanical structure must be established to achieve a higher performance and prevent injuries (Elliott, 2006). The kinematic studies played an important role to tennis coaches and players to better understand which key variables are the most important to achieve a higher performance and prevent associated injuries. Two different styles of the tennis forehand were previously described, (Elliott et al., 1989), one where players use the upper limb moving as a single unit and other with players moving the upper limb segments relative to each other where this later presents a higher racket velocity. In addition, Seeley et al. (2011) showed that a higher range of motion and angular velocity of some kinematic variables are associated to the higher ball speed of the forehand. Moreover, a study focusing the timing patterns of different skill levels tennis players (Landlinger et al., 2010b), considered that the latter occurrence of maximum angular pelvis and trunk rotations were linked to the higher horizontal shoulder and racket velocities in elite tennis players. More, Landlinger et al., (2012) showed a higher forehand ball speed of elite tennis players compared with high performance tennis players forehand and there was no evidence that players who hit faster were any less accurate than those who impact the ball slowly. Accordingly, with this study, ball speed seems to be an important factor separating elite from high performance tennis players. Therefore, it is of main importance for tennis coaches to understand which differentiate the sub-elite levels from the elite, to help these athletes to achieve a higher performance.

With regard to better understand the contribution that a segment's anatomical rotation make to racket head speed, a previous study (Sprigings et al., 1994) developed an algorithm based on the segment's angular velocity and the instantaneous position of the head of the racket to calculate the instantaneous contributions to the racket speed. These method was already used in the tennis forehand drive and concluded that the movements of the upper limb contributed approximately 90% of the linear speed of the racket head at impact and the internal rotation of the upper arm contributed approximately 42% and 44% in the forward and upward direction respectively (Takahashi et al., 1996). In other study using the same method to determine the influence of the grip position in the forehand drive (Elliott et al., 1997) the horizontal flexion/abduction and internal rotation of the upper arm, in addiction to linear velocity of the shoulder, were the primary contributors to racket head speed at impact, regardless of grip. Although some studies compare different levels of expertise, no study has compared the contributions to the racket head velocity between two different level of expertise, specifically between intermediate and high-performance tennis players to understand if there is any key differences in the rotations of the upper limb. A better understand between these two different levels could present new insights to the forehand teaching and what differentiate these two levels of expertise to achieve a higher performance. Therefore, the study of different levels of expertise should be explored.

To perform the majority of kinematic studies the optical systems have been normally used in tennis kinematic studies (Elliott et al., 1989; Seeley et al., 2011) as in other sports. Despite being considered the most acceptable method to measure kinematic variables (Cuesta-Vargas et al., 2010), optical systems are often used inside the laboratories presenting a considerable effort to capture tasks outside the lab (Robert-Lachaine et al., 2017b). An alternative to these systems are the Inertial Magnetic Units (IMUs), which are lighter, portable and with low energy usage, simplifying the obtainance of long and high quality data outside of the laboratories (Vries et al., 2009). Despite considered an alternative and being accurate to study kinematics, the degree of accuracy is specific (Cuesta-Vargas et al., 2010). Some studies have evaluated the accuracy of inertial sensors when compared with optoelectronic devices. Inertial sensors (Xsens MVN) showed to have a higher accuracy with T-pose when compared with the N-pose calibration, moreover it has been shown that passive placement of the subject is recommended for the calibration for the MVN full body model. Also, it was shown that IMUs differences against optoelectronic systems were predominantly attributed to the biomechanical model utilized (Robert-Lachaine et al., 2017a). Despite the latter studies, there is no reference to validation study in the tennis forehand drive or any other tennis technique. Thus, before recording kinematic data in an ecological environment with IMUs it is necessary to validate this system in the specific task.

Despite some kinematic studies with elite athletes these are still scarce, although, some researchers have included these level of expertise in some studies, showing high values for linear velocity of the shoulder, angular velocity of the pelvis and upper trunk at impact (Landlinger et al., 2010a) when compared with high-performance tennis players. Moreover, the elite athletes showed different timing of maximum pelvis and trunk angular velocities before impact (Landlinger et al., 2010b) compared with high-performance tennis players. Furthermore, understand which contributions of the upper limb are the most important to the racket head velocity in elite athletes could be of key importance to coaches' knowledge. Based on the literature the algorithm used to calculate the upper limb segments (Sprigings et al., 1994) were used with non-elite athletes, therefore the level of expertise could be explored in these important level, the elite level . On the other hand, the direction of the forehand drive have been mostly described in the cross-court and in down-the line direction (Elliott et al., 1989, 1997; Landlinger et al., 2010a, 2010b), as it is usually played from the right side of the court. Although, the forehand drive it's not just played from the right side of the court, nowadays, the tennis players are able to hit forehand winners from everywhere in the court (Martin-Lorente et al., 2017). Moreover, the forehand stroke is considered a key stroke due to it's easier court coverage and the natural longer reach on the forehand side, besides, experience players can cover almost the totality of the tennis court with their forehand (Brabenec, 2015). Therefore, if the tennis players have the competence to hit the ball with the forehand from the left side of the court, they will have other tactical options. The so-called inside-out forehand has an important role in tactical strategy offering the possibility of the player hit the forehand drive from the left side (considered the weaker side), and at the same time playing to the weaker side of the opponent (Martin-Lorente et al., 2017). Based on the previous studies a study exploring the contributions to the racket head velocity and unexplored directions of play in the forehand should be considered to add knowledge to coaches and all the involved in this sport.

On the other hand, the kinetic studies focusing the upper limb in the forehand drive are not explored as the serve. The known work concerning the upper limb in the forehand drive, explored the differences between the close and the open stance on the kinetics of the upper limb (Bahamonde & Knudson, 2003), and demonstrated that the close stance presented higher loads on the upper limb joints. Despite this important study to comparing these two different stances, nowadays the tennis players hit many forehand drives in a stationary position maintaining their feet on the ground as in a dynamic way with their feet off the ground to anticipate as to adapt to the height of the ball. Based on these two different stances (stationary and dynamic) there is a lack of knowledge about the kinetics of the upper limb as in the racket and ball velocity, thus, a more detailed understanding of this techniques should be focused to add valuable information to tennis coaches and players.

Thesis goals and overview

As discussed throughout this chapter, there are several key factors studied by researchers, presenting valuable insights to tennis players and coaches to achieve a higher performance. Considering the limitations of the existing literature in the forehand drive and with the aim to provide a better understanding in the forehand drive, the specific aims of this thesis were:

- To compare kinematics and the contributions of the upper limb rotations to the racket head velocity in a tennis forehand drive between intermediate and high-performance tennis players.
- To validate an inertial measurement system in the tennis forehand drive.
- To determine the contributions of the upper limb rotations to the racket head velocity in elite tennis players using an inertial measurement system.
- To determine the kinetics of the dominant upper limb between a quasi-static (when the players hit the ball with their feet on the ground) and a dynamic stance (when the players hit the ball with their feet off the ground) tennis forehand drive.

To achieve these goals four studies were conducted. The first study (Chapter 2) aimed (1) to quantify and compare the kinematics and (2) the contributions of the upper limb (upper arm, forearm, and hand) segment’s rotation to the racket head velocity in a tennis forehand drive between intermediate and high-performance tennis players. In this study, the participants performed the forehand drive inside the laboratory, and they hit the ball against a hanging cotton cloth of 3X2 to cushion the ball. The tennis balls were thrown by an experienced tennis coach placing the ball into a bounce area. The participants used they own tennis rackets to feel comfortable as possible. The 3D trajectories of passive markers placed on the participants’ skin were collected using an optoelectronic motion capture system. The markers were placed on each participant according previous reference (Wu et al., 2002, 2005) and used to build a model with 15 rigid-body segments. Kinematic variables of interest from the dominant side (upper and lower limbs) were calculated using a medio-lateral, antero-posterior, axial Cardan sequence (Grood & Suntay, 1983). The segments’ POSE was computed from the trajectories of the tracking markers using a segment optimization (Spoor & Veldpaus, 1980). All joint angles were time normalized to the period between the first movement of the racket shaft in the direction of the shot until the last frame before impact (Landlinger et al., 2010a). To estimate the contribution of segment’s rotations of the upper limb to the racket head velocity it was performed the method developed in a previous study (Sprigings et al., 1994). Differences between the kinematics and contributions of the upper limb to the racket head velocities were assessed by an independent samples t-test and the Mann-Whitney U test.

The aim of the second study (Chapter 3) was to analyse the concurrent validity of an IMUs system for the assessment of upper and lower limb angular kinematics during a tennis forehand drive, using an optical motion capture system as criterion. Participants testing protocol was the same as the study 1 (Chapter 2). The instrumentation used for the optical system was the same used in the study 1. For the IMUs it was used the Xsens MVNV Link system comprised by 17 IMUs on each segment (Roetenberg et al., 2013; Xsens Technologies, 2018) and calibration procedures was performed as previously described (Roetenberg et al., 2009). To minimize the differences attributed to the biomechanical model, the segments' origin, dimensions and anatomical axes definitions were equivalent to the ones used in the Xsens model (Robert-Lachaine et al., 2017). Joint angles were time normalized from the first movement of the racket shaft in the direction of the shot until the last frame before impact (Landlinger et al., 2010a). To analyse the concurrent validity between systems it was performed the coefficient of multiple correlation (CMC) (Ferrari et al., 2010), the root mean squared error (RMSE) and (1D) statistical parametric mapping (SPM) (Friston et al., 1995; Pataky et al., 2013, 2016) using a two-tailed paired sample t-test, differences were considered statistically significant for p-values < 0.05.

Based on the positive results of the second study (Chapter 3), the third study (Chapter 4) was performed in an ecological condition in the tennis court using the IMUs to study the kinematics and the contributions of the upper limb to the racket head velocity in elite tennis players when they hit the ball in two different directions. The participants performed the forehand strokes that were projected by a ball machine (Lobster—Phenom Electric Tennis Ball Machine D641, 437, North Hollywood, CA, USA) with a controlled horizontal velocity (24.5 m/s) similar to other studies (Landlinger et al., 2010a, 2010b), to a bouncing area where the players were able to play an attacking forehand. The opponent assumed different positions on the court and the player had to place the ball on the opposite side. Participants were encouraged to hit the ball as they would in a match when attempting to hit a winner. The kinematic parameters were collected at 120 Hz with 17 IMUs sensors (Xsens MVN Technologies, Enschede, NL) (Gandy et al., 2015), using the MVN Studio Pro software, and were continuously updated using a biomechanical model of the human body (Roetenberg et al., 2009). To calculate the contributions of segment's rotations to the racket head velocity it was used the method already used in first study (Chapter 2) (Sprigings et al., 1994). Differences between directions of the shot of the kinematics and the contributions of the upper limb to the racket head velocities were assessed by a paired samples t-test and the Wilcoxon Matched-Paired Signed Ranks test. The kinematic differences between the two shots were also assessed using the one dimensional (1D) statistical parametric mapping (SPM) using a two-tailed paired sample t-test.

The aim of the fourth study (Chapter 5) was to compare the joint kinetics of the shoulder, elbow, and wrist, between the tennis forehand drive performed in a quasi-static stance and a dynamic stance with frontal weight transfer and the racket velocity between both stances. Participants testing protocol was the same as the study 1 (Chapter 2). The instrumentation used for the optical system was the same used in the study 1. The dominant arm was modelled as a five-link kinetic chain composed of racket, hand, forearm and upper arm and trunk. The inertial parameters of the segments were computed based on Hanavan (1964), while segment masses were determined according to Dempster (1955). Moment of inertia of the racket about its medial-lateral axis was computed using the parallel axis theorem and published racket "swingweight" data (USRSA, 2010, as suggested by Elliott et al., (2003). Racket moment of inertia about the long-axis was calculated as reported in the literature (Brody, 1985). Racket moment of inertia about its anterior-posterior axis was the sum of the racket's other two principal moments of inertia (Brody, 1985). Racket moment of inertia about its anterior-posterior axis was the sum of the racket's other two principal moments of inertia (Brody, 1985). Differences between the stances were also tested with the one-dimensional statistical parametric mapping (SPM-1D). Kinematic and kinetic differences between stances were assessed by a paired samples t-test and the Wilcoxon Matched-Paired Signed Ranks test. The kinematic differences between the two stances were also assessed using the one dimensional (1D) statistical parametric mapping (SPM) using a paired sample t-test.

Finally, the main findings of each study are summarized and discussed in Chapter 6, also with the methodological considerations. This thesis constitutes a contribute to all the individuals interested in developing a higher performance of the tennis forehand drive and achieve a higher performance on this technique. Therefore, recommendations for potential future research are provided.

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Chapter 2

Upper limb kinematics and their contribution to racket head velocity during a tennis forehand: differences between intermediate and high-performance tennis players[1]

[1] Submitted as:

Bruno M. M. Pedro, Sílvia A. R. Cabral, Jerusa P. R. Lara & António P. Veloso. Upper limb kinematics and their contribution to racket head velocity during a tennis forehand: differences between intermediate and high-performance tennis players. Submitted to the *Scandinavian Journal of Medicine in Sports*.

Abstract

This study aimed to quantify and compare the kinematics and the contributions of the upper limb (upper arm, forearm, and hand) segment’s rotation to the racket head velocity in a tennis forehand drive between intermediate and high-performance tennis players. Kinematic variables were collected with an optical system (Qualisys AB, Gothenburg, Sweden) during the acceleration phase of fifteen experienced and twelve intermediate tennis players and were calculated in the Visual 3D software. The method used to calculate the upper limb’s contributions was performed with MATLAB software and used the segments (upper arm, forearm, and hand) angular velocities and their respective displacement vectors. Results suggest that what differentiate high-performance of intermediate tennis players is the shoulder velocity at impact, the maximum horizontal velocity of the shoulder and, the higher contribution to the racket head velocity of the shoulder. Moreover, the SPM-1D analysis showed significant differences during some periods of the events in frontal plane of shoulder and hand joint angles. Additionally, significant differences were present in angular velocities between both levels in shoulder frontal plane between 20-65% of the event, in elbow sagittal plane between 25-65% of the event and in hand sagittal plane between 40 and 60% of the event. Tennis coaches should focus on upper body strength training as well as to develop the trunk and shoulder rotation velocity towards the direction of the ball, whereas physiotherapists should be aware of these contributions to develop a prevention program for athletes.

Keywords: Tennis forehand, contribution, racket velocity, kinematics.

Introduction

The tennis forehand drive is the first technique usually learned by beginners (Seeley et al., 2011) and is considered the second most important technique in tennis just behind the serve (Reid et al., 2013). The key factor for a successful forehand drive is the post-impact ball velocity (Landlinger et al., 2010a). Given that ball velocity depends highly on the velocity of the racket head, many researchers have attempted to determine the most efficient mechanics for higher racket velocity (Landlinger et al., 2010b).

In terms of kinematics, racket velocity could depend on different strategies, namely, of the upper limbs, such as with the upper limb moving as a single unit or the individual segments of the upper limb moving relative to each other (Elliott et al., 1989). On another hand, the increased joint angles and angular velocities of the upper and lower limbs (Seeley et al., 2011), as well the initial knee position and range-of-motion, were also positively related to racket velocity in the forehand drive (Nesbit et al., 2008). The kinematic studies have been performed with different type of level of expertise such as state ranking tennis players, teaching professional and intermediate tennis players (Elliott et al., 1989; Bahamonde & Knudson, 2003) and also, highly skilled male tennis players (Seeley et al., 2011). Other studies compared different level of expertise between elite and high-performance (HP) tennis players demonstrating different timing patterns of the pelvis and trunk angular velocity and different linear velocity of the shoulder. Nevertheless, not many studies have investigated what the intermediate (INT) tennis players need to achieve a higher performance, moreover, it is not known the contribution of the segment rotations of the upper limb that could differentiate these two different levels of expertise.

Based on the method developed by Sprigings et al. (1994), researchers have described the most important upper limb segment rotations to the racket head velocity between different type of forehand shots (flat, top spin and lob top spin) (Takahashi et al., 1996) showing different contributions between each type of shot, demonstrated different contributions between tennis players with different grips in the forehand drive (Elliott et al., 1997), and also, compared the contributions to the racket head velocity between the cross-court and the inside-out direction (Pedro et al., 2022). This method was also used in tennis serve (Elliott et al., 1995) and in badminton (Elliott et al., 1996). Despite the importance of the latter studies comparing different techniques, no study used this method to compare the contributions of upper limb rotations to the racket head velocity between different levels of expertise. Thus, we could expect that different level of expertise could present different upper limb contribution to the racket head velocity, therefore, adding knowledge to tennis coaches to help their athletes.

This study aimed to quantify and compare the kinematics and the contributions of the upper limb (upper arm, forearm, and hand) segments rotation to the racket head velocity in a tennis forehand drive between INT and HP tennis players. We hypothesized that the different level of expertise would present significant differences in the selected kinematic variables and in the contributions of the upper limb's segments rotation to the racket head velocity.

Materials and Methods

Participants

A convenience sample of twenty-seven right-handed tennis players, fifteen HP with nine males and six females (age: 20.3 ± 2.6 years; height: 174.5 ± 11.2 cm; mass: 68.2 ± 11.0 kg), and twelve INT with eleven males and one female (age: 22.6 ± 8.1 years; height: 177.2 ± 6.3 cm; mass: 69.6 ± 11.8 kg), provided written informed consent to participate in this study, which was approved by the Institution's Ethics Committee (21/2018). All participants were free from injuries. The HP tennis players practiced regularly between 4h and 10h per week, competed at national competitions and had national ranking. The INT tennis players practiced at maximum 4h per week, did not compete and had no national ranking. All the participants were selected by their coaches following these inclusion criteria.

Testing Protocol

Participants had 15 min for an individual warm-up, and they could hit as many strokes as they wanted to become familiar with the test environment (Figure 2.1). Before the data collection, participants observed a demonstration of the experimental procedure and used their own tennis rackets to ensure they felt as comfortable as possible during the data collection. Each participant was instructed to hit the ball as fast as they could just like in a real match. Three forehand drives from each participant with 3 seconds between each stroke (Rogowski et al., 2011) were performed against a hanging cotton cloth of 3X2 m to cushion the ball (Pedro et al., 2021) and collected for analysis. The tennis balls were thrown by an experienced tennis coach placing the ball into a bounce area.

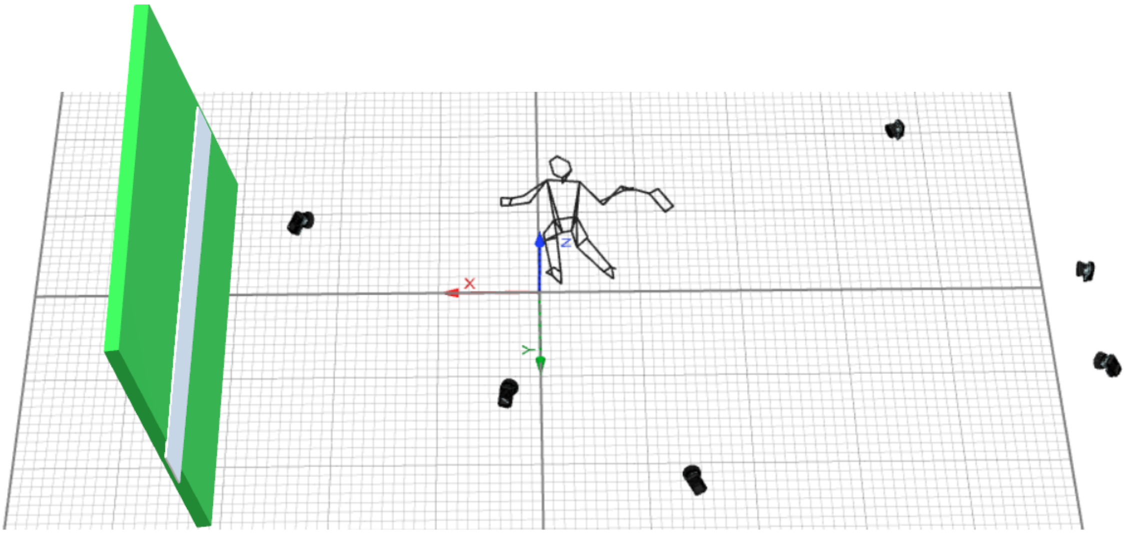

Figure 2.1 - Testing environment. Representation of test environment with fifteen infrared high-speed cameras during the beginning of the forehand acceleration phase in the Qualisys Track Manager software.

Instrumentation

Full body kinematics were recorded at 240Hz with an optoelectronic system (OS) with fifteen infrared high-speed cameras (Oqus 300, Qualisys AB, Sweden) using the Qualisys Track Manager (version 2.17, Qualisys AB, Gothenburg, Sweden) software. An additional video camera (Oqus 210c) was used to identify the instant of ball contact with the racket. Forty-three reflective markers (Figure 2.2 -) with a 25 mm diameter were placed on the following anatomical landmarks: C7, T8, suprasternal notch, xiphoid process, lateral and medial epicondyle of the humerus, acromioclavicular joint, lateral point of the radial styloid, medial point on ulnar styloid, base of the second and fifth metacarpal proximal phalanges, anterior and posterior superior iliac spines, lateral and medial femoral epicondyles, lateral and medial malleoli and 1st, 2nd and 5th metatarsal heads (Wu et al., 2002, 2005). Moreover, ten rigid light-weight clusters with four non-collinear tracking markers were placed laterally on both upper arms, forearms, hands, thighs, and shanks. Five additional tracking markers were placed on the tennis racket of each participant (racket head, shaft, at 3 and 9 o'clock positions) (Landlinger et al., 2010b). To calibrate the model, a static trial was collected while the participants were standing in an N-Pose (with arms neutral besides the body with palms facing medially). Data were analysed during the acceleration phase, which was determined from the first forward movement of the racket shaft in the anteroposterior direction (X) (Figure 2.1) until ball impact, defined as the instant where the ball–racket contact occurred.

Data Processing

For the kinematic analysis the 3D marker trajectories during the standing and forehand drive trials were identified in Qualisys Track Manager software, exported to c3d format, and filtered in Visual 3D using a 4th order low-pass Butterworth filter with a cut off frequency of 10 Hz (Seeley et al., 2011). Using the markers' coordinates during the standing trial, a biomechanical model was built with 15 rigid-body segments (head, thorax, upper-arms, forearms, hands, pelvis, thighs, shanks and foots). The segments' POSE was computed from the trajectories of the tracking markers using a segment optimization (Spoor & Veldpaus, 1980). Kinematic variables of interest from the dominant side (upper and lower limbs) during the forehand drive were calculated: 1) shoulder alignment with the baseline (defined with the virtual line between shoulders and the Y axis of the global coordinate system which simulate the baseline), 2) right hip alignment with the baseline, 3) elbow flexion angle, 4) separation angle (difference between shoulders and pelvis in transverse plane), 5) shoulder linear velocity, 6) hip linear velocity, 7) elbow linear velocity, 8) wrist linear velocity (linear velocities measured in the direction of the movement in antero-posterior direction (X), 9) maximum angular velocity of shoulder internal rotation, 10) elbow extension, 11) trunk and 12) pelvis rotation (measured in the transverse plane in the global coordinate system (Z) and 13) rear leg extension, were calculated using a medio-lateral, antero-posterior, axial Cardan sequence (Grood & Suntay, 1983). All joint angles were time normalized to the period between the first movement of the racket shaft in the direction of the shot (Figure 2.*2*1) until the last frame before impact (Landlinger et al., 2010a). The modelling and computation of the kinematic variables were done in Visual 3D (V6, C-motion, Inc. Germantown, USA). The beginning and end of the acceleration phase, determined from the first forward movement of the racket in the anteroposterior direction (X) until ball impact, were visually confirmed with model representation in Visual 3D software.

Figure 2.2 - Individual set-up. Marker set up placed on each body segment with 43 reflective markers and 10 lightweights with 4 non-collinear tracking markers.

To estimate the contribution of segment's rotations of the upper limb to the racket head velocity it was performed the method developed in a previous study (Sprigings et al., 1994). The centre of the racket (PK) (Figure 2.3) was determined with the distance from the centre of the wrist until the centre of the racket head (Figure 2.3). The method uses the angular velocity of the segments of the dominant upper limb relative to their joint axis of rotation. Data from the proximal and distal ends positions of each segment, angular velocity from the proximal and distal ends and the linear velocity of the centre of gravity of each segment were exported from Visual 3D (Visual 3D Professional V5.01.21, C-motion, Germantown, MD) to Matlab (R2010A). The anatomical rotations used to describe the contribution of the upper limb to the racket head velocity during the forehand drive was the flexion/extension, adduction/abduction, internal/external rotation for the upper arm, pronation/supination, flexion/extension for the forearm and, palmar flexion/extension, radial/ulnar flexion for the hand, chosen as previously (Sprigings et al., 1994). Figure 2.3 shows the representation of one participant with the three segments of the upper limb and the racket segment (from the hand until the centre of the racket "Pk") and the respective computed anatomical axes markers representing the beginning and the end of the segments of the upper arm (Figure 2.3). To determine the percentages of each segment rotation to the racket velocity, the latter was considered as 100% and, each rotation with a percentage of that 100%.

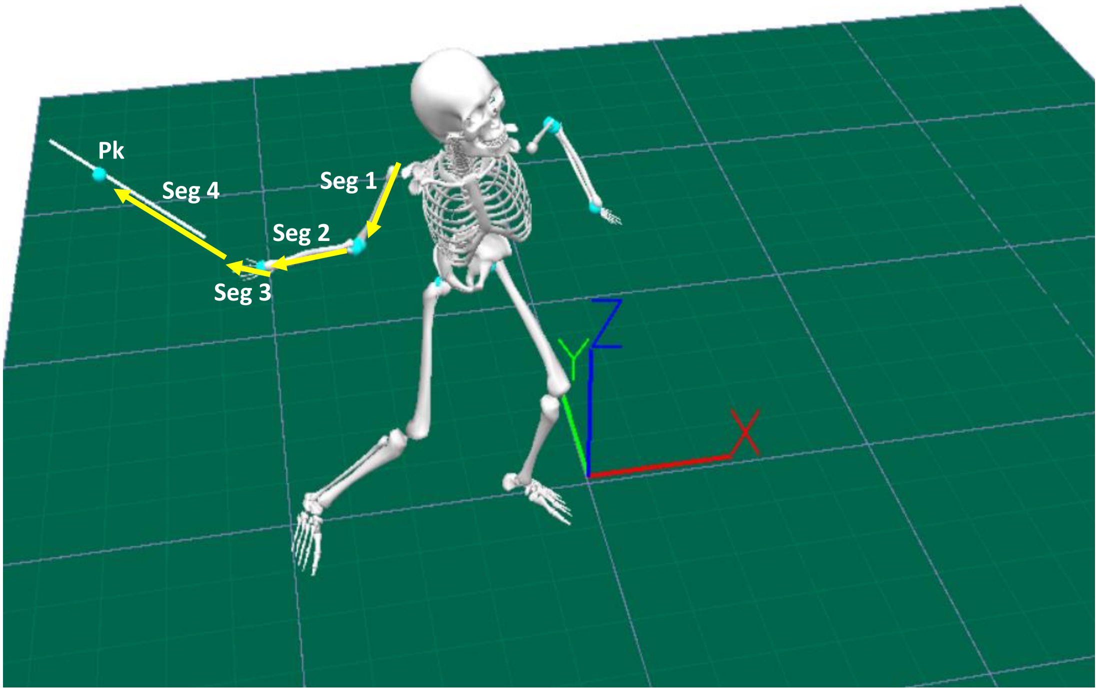

Figure 2.3 - Participant segments and derived vectors. Upper arm (segment 1), forearm (segment 2), hand (segment 3), racket (segment 4), Pk (centre of the racket).

Statistical Analyses

The mean of the three repetitions of each participant of the selected kinematics described in data processing and the contributions to the racket head velocity variables of the upper arm, forearm, and the hand, were used for analysis. Data was first tested for normality using the Shapiro-Wilk test ($p < 0.05$). Differences between variables with normal distribution were assessed with an independent samples t-test and those that deviate from a normal distribution were assessed using a Mann-Whitney U test. For all tests, significance was set at $p < 0.05$. All data are reported as mean ± SD. The effect size (ES) was calculated as the Cohen's d, where 0.2, 0.5, 0.8, represent small, medium and large effect sizes (Cohen, 1988), respectively for independent samples t-test. For the Mann-Whitney U test the effect size (r) was defined as small, medium and large when $r \leq 0.1$, $r \leq 0.3$ and $r \leq 0.5$, respectively (Pallant, 2011). All statistical analyses were performed using SPSS version 20 (SPSS Inc. Company, Chicago). The SPM-1D was also used to compare the joint angle variables between INT and HP tennis players using a two-sample t test. The SPM-1D method uses random field theory to identify field regions which co-vary significantly with the experimental design (Friston et al., 1995; Pataky et al., 2013; Pataky et al., 2016). Differences were considered statistically significant for p-values < 0.05. All SPM analyses were performed in Python 2.7 using the open source package located at http://www.spm.1d.org/ (Pataky et al., 2016).

Results

Significant differences between INT and HP tennis players were found in shoulder linear velocity at impact ($p < 0.05$), maximal horizontal velocity of shoulder ($p < 0.05$) and elbow flexion at impact ($p < 0.05$) whereas the other kinematic variables didn't show any significant differences between both groups (Table 2.1).

In terms of joint angles, the SPM-1D analysis (Figure 2.4 and Figure 2.5) showed significant differences only at the shoulder frontal plane between the 60 to 100% of the event and hand frontal plane from 0-60% of the event. Relative to the angular velocities, the SPM-1D analysis showed significant differences between both levels in shoulder abduction/adduction between 20 and 65% of the event, in the elbow flexion/extension between 25-65% of the event and in hand sagittal plane between 40 and 60% of the event.

The contributions of the upper limbs to the racket head velocity (Table 2.2) showed significant differences ($p < 0.05$) between both levels of expertise only at the shoulder (also representing the trunk and lower limbs). However, in both cases the order of importance of the upper limbs to the racket head velocity was the same with the exception to the hand flexion/extension and the upper arm adduction/abduction.

Table 2.1 - Upper limb kinematic variables of the intermediate and high-performance tennis players.

Variables	**Intermediate Mean ± SD Md, n†12**	**High Perform. Mean ± SD Md, n†15**	**t/U†**	**p**	**d/r†**
End of Backswing					
Shoulder alignment Baseline (°)	-110,3 ± 12,9	-107,7 ± 9,8	-0,590	0,560	0,2
Hip alignment (°)	-84,1 ± 11,6	-86,6 ± 19,7	0,376	0,710	-0,1
Elbow flexion (°)	59,6 ± 15,9	61,0 ± 15,1	-0,231	0,819	0,1
Separation angle (°)	-16,9 ± 6,5	-16,0 ± 4,5	-0,427	0,673	0,2
Impact					
Shoulder Alignment Base line (°)	-4,6 ± 12,8	-2,1 ± 10,1	-0,556	0,583	0,2
Hip alignment (°)	-25,1 ± 20,1	-24,7 ± 19,7	-0,058	0,954	0,0
Elbow flexion (°)	47,0 ± 16,2	64,6±15,2	-2,910	0,007*	1,1
Separation angle (°)	16,9 (12)†	16,4 (15)†	73,0†	0,407	-0,2†
Shoulder velocity (m/s)	1,2 ± 0,6	1,9 ± 0,6	-3,149	0,004*	1,2
Maximum horizontal velocity					
Hip (m/s)	1,1 ± 0,4	1,3 ± 0,3	-1,863	0,074	0,7
Shoulder (m/s)	2,4 (12)†	3,1 (15)†	42,0†	0,019*	-0,5†
Elbow (m/s)	4,9 ± 0,8	5,2 ± 0,7	-1,010	0,322	0,4
Wrist (m/s)	8,5 (12)†	8,8 (15)†	68,0†	0,283	-0,2†
Maximum angular velocity					
Shoulder internal rotation (°/s)	625,2 ± 162,0	567,1 ± 106,3	1,122	0,272	-0,4
Shoulder absolute internal rotation (°/s)	845,3 ± 114,0	896,4 ± 132,8	-1,057	0,301	0,4
Elbow extension (°/s)	195,4 (12)†	215,9 (15)†	81,0†	0,661	-0,1†
Elbow extension (°/s)	-165,8 ± 77,0	-210,2 ± 131,2	1,035	0,310	-0,4
Trunk rotation absolute ang. velocity (°/s)	590,4 ± 105,9	647,3 ± 85,6	-1,548	0,134	0,6
Pelvis rotation absolute ang. velocity (°/s)	438,0 ± 104,6	496,6 ± 104,7	-1,446	0,161	0,6
Rear leg extension max (°/s)	60,8 (12)†	113,4 (15)†	78,0†	0,558	-0,1†
Rear leg extension min (°/s)	-191,1 (12)†	-234,6 (15)†	61,0†	0,157	-0,3†

* Indicates a significant difference ($p < 0.05$) between INT and HP. † indicates statistical analyses with the Mann-Whitney U test.

Table 2.2 - Contribution of the upper limb rotations to the racket head velocity between intermediate and high-performance tennis players.

Segments	**Intermediate**		**High-Performance**				
	Mean ± SD Md, n* (m/s)	Contribution (%)	Mean ± SD Md, n (m/s)	Contribution (%)	t/U†	p	d/r†
Shoulder	1.6 ± 0.7	7,9	2.2 ± 0.6	11,9	2.695	0.012*	-1,0
Upper Arm							
Flex/Ext	8.0 ± 2.3	40,0	8.7 ± 1.7	41,5	-0.185	0.855	0,1
Add/Abd	0.2 ± 0.2	-1,5	0.0 ± 0.9	0,4	-0.334	0.741	0,1
Int/Ext Rotation	5.0 (12) †	26,2	4.7 (12) †	25,2	78.0†	0.581	-0.1†
Forearm							
Flex/Ext	3.7 (12) †	18,9	3.6 (12) †	19,8	85.5†	0.826	0.0†
Pron/Sup	2.4 ± 3.2	10,4	1.4 ± 1.9	5,0	-1,072	0,294	0,4
Hand							
Flex/Ext	0.1 ± 0.7	2,1	0.3 ± 0.9	1,6	0,667	0,511	-0,3
Addu/Abdu	-0.9 ± 0.8	-3,9	-0.8 ± 0.7	-5,4	0,408	0,687	
Centre of rk	26.0 ± 4,5		23.3 ± 3.1		-1,914	0,067	0,7

* indicates a significant difference ($p < 0.05$) between INT and HP. † indicates statistical analyses with the Mann-Whitney U test.

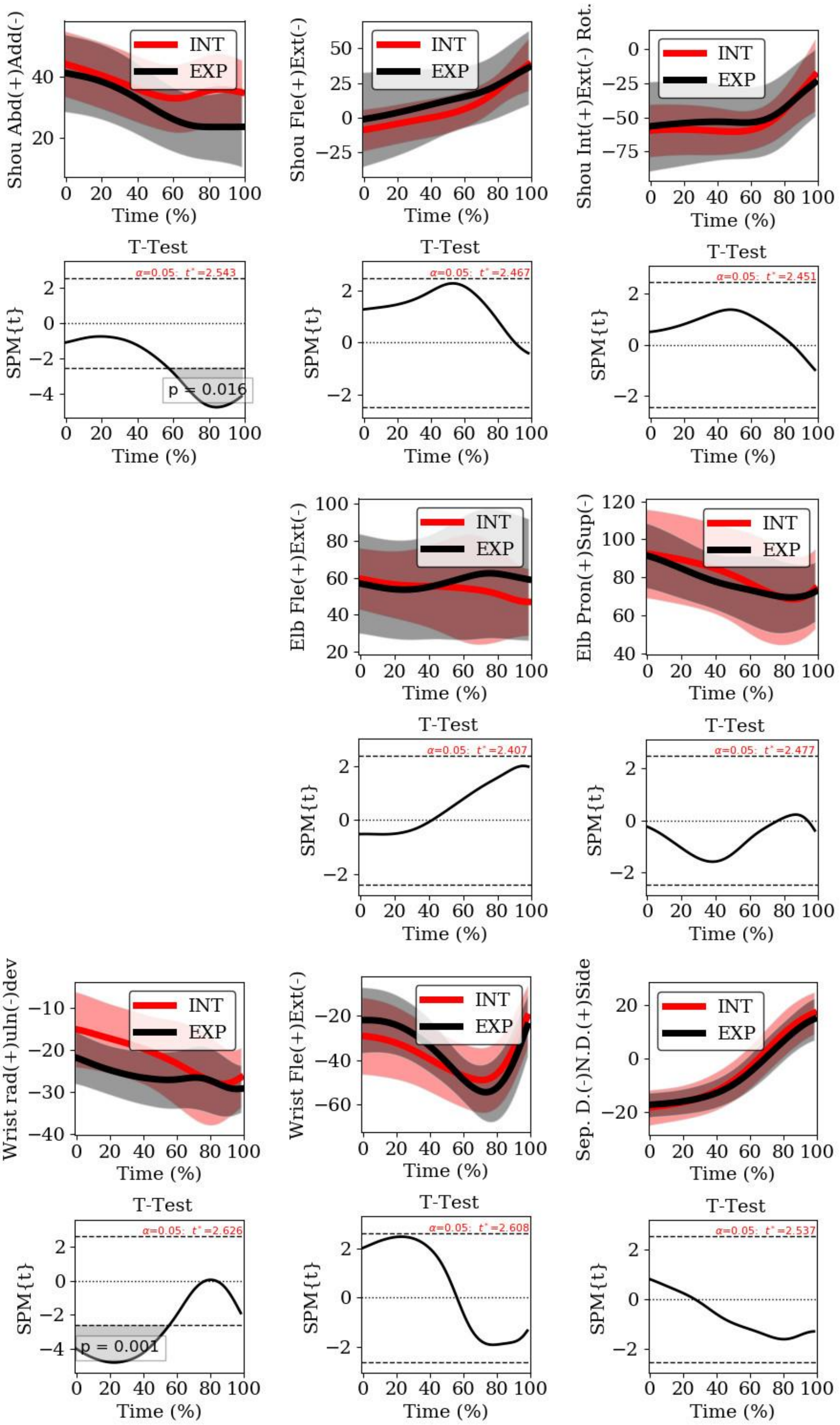

Figure 2.4 - Joint angles and the respective 1D-SPM analysis results during the time normalized acceleration phase of the forehand drive, for the INT (red line) and the HP tennis players (black line). Shoulder abduction/adduction (a), shoulder flexion/extension (b), shoulder internal/external rotation (c), elbow flexion/extension (d), pronation/supination (e), wrist radial/ulnar deviation (f), wrist flexion/extension (g), separation angle (h). Grey shaded regions indicate where differences were statistically significant.

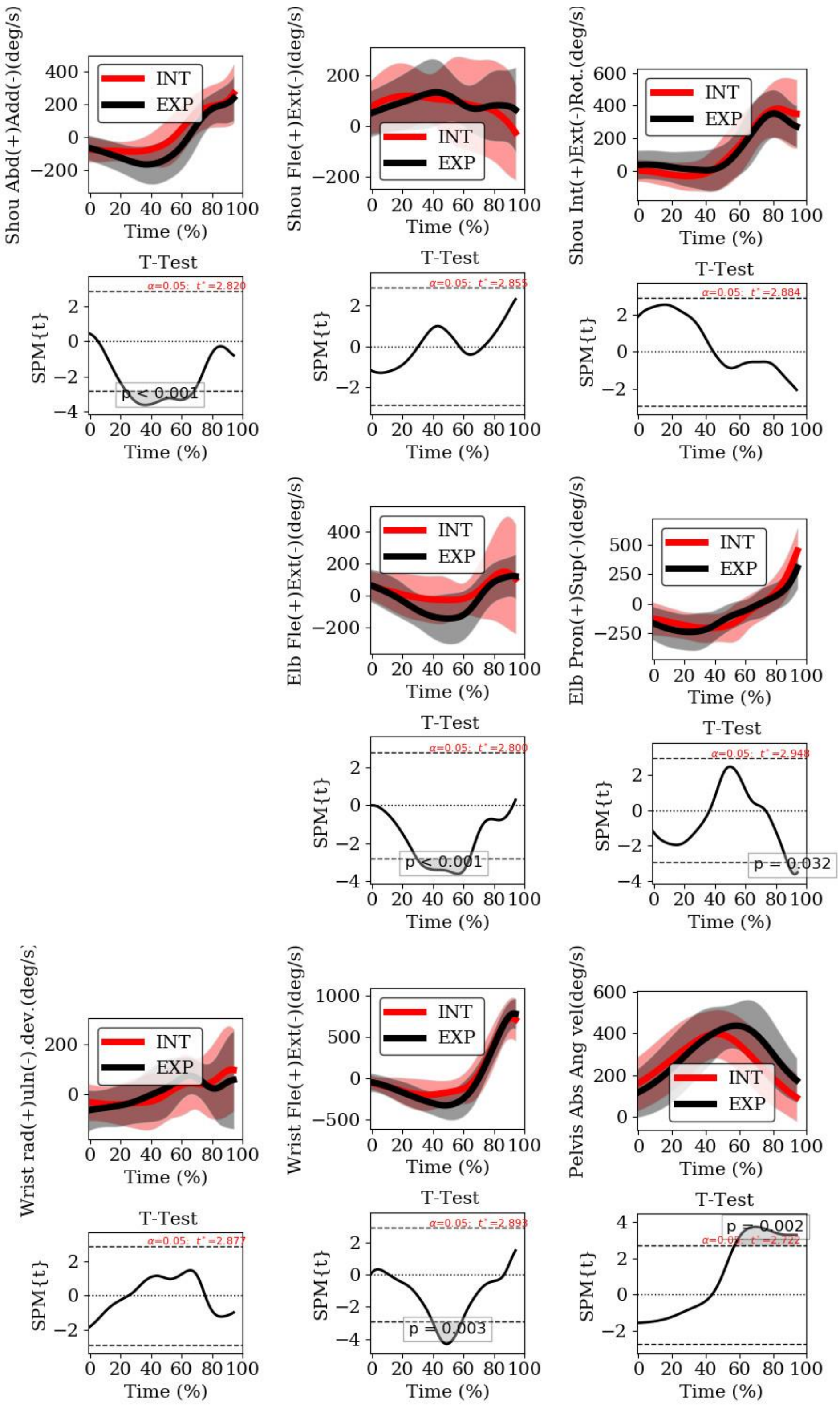

Figure 2.5 - Joint angle velocities and the respective 1D-SPM analysis results during the time normalized acceleration phase of the forehand drive, for the INT (red line) and the HP tennis players (black line). Shoulder abduction/adduction (a), shoulder flexion/extension (b), shoulder internal/external rotation (c), elbow flexion/extension (d), pronation/supination (e), wrist radial/ulnar deviation (f), wrist flexion/extension (g), pelvis absolute angular velocity (h). Grey shaded regions indicate where differences were statistically significant.

Discussion

The purpose of this study was to compare the kinematic variables of upper limb and the upper limb contributions to the racket head velocity between INT and HP tennis players. Results suggest that what differentiate HP of INT tennis players is a greater shoulder velocity at impact, elbow flexion at impact, and maximum horizontal velocity of the shoulder and, consequently, a higher contribution of the shoulder to the racket head velocity. Moreover, the higher shoulder velocity presented in the HP players could be due to the higher pelvis and shoulder adduction angular velocity showed in the SPM-1D analysis. The HP players presented also higher elbow extension angular velocity differentiating the two groups.

Limitations of the study are associated to a non-ecological design of the study and the inclusion of both male and female in both groups which could hide some gender-specific differences. However, given the good level distinction between the groups, we believe that we have reflected both levels of expertise.

Superior racket velocities were reported by Landlinger et al., (2010a) (31.1 ± 2.1 m/s and 29.1 ± 1.7 m/s) in elite and HP players respectively. Although, inferior racket velocities were reported in previous studies with racket velocities between 13.9 and 23.2 m/s (Elliott et al., 1989; Elliott et al., 1997) and similar to Knudson & Blackwell (2005), with mean racket velocities of 24.3 m/s. Despite a little higher mean value for the INT group, we did not find statistically significant differences that highlight one group over the other, nevertheless, since the comparison between the two group levels are rare these data should bring value to the tennis coaches.

The shoulder alignment is an important issue taught at early stage in tennis teaching, with greater importance in more advanced stages together with pelvis, creating the separation angle for elastic energy accumulation at the end of the backswing (Elliott, 2006). Whereas shoulder rotation at the end of the backswing were in accordance with others studies (Elliott et al., 1997; Landlinger et al., 2010a), the separation angle presented slightly inferior angles than those in

Takahashi et al., (1996). This difference could be explained because most of the forehands have been performed in close stance, despite no reference was told to the participants to perform any specific stance. The hip alignment and elbow flexion were in accordance with previous studies (Landlinger et al., 2010a), whereas Elliott et al. (1997) presented elbow flexion angles between 58.4 and 91°, reflecting differences between flat and top spin forehand plus the grip used by players between eastern and western.

At impact the shoulder alignment of both groups is parallel with the direction of the shot where a slightly separation angle towards the non-dominant arm is presented (Table 2.1), which is in accordance with Landlinger et al. (2010a). The elbow flexion at impact in INT tennis players presented an inferior flexion when compared with previous studies (Seeley et al., 2011) which were similar with the HP tennis players. The differences in elbow flexion between both levels, with a higher flexion in HP group, could be related to the grip used by the players (Reid et al., 2013). Although the participants of this study used a semi-western grip, little differences on this grip could present different impact positions. Hip alignment and the separation angle were similar between the two groups. The shoulder velocity was different between the two groups, with the HP group producing higher shoulder velocities at impact, (INT: 1,2 ± 0,6 and HP: 1,9 ± 0,6 m/s), as it was previously demonstrated (Landlinger et al., 2010a) when comparing HP with elite tennis players. Thus, we can consider that the ability to create a higher shoulder velocity should be taken in consideration by tennis coaches to develop the forehand drive and help INT tennis players to achieve a higher performance.

As in Landlinger et al. (2010b), the HP group produced higher horizontal velocities, but these differences were only statistically significant for the shoulder. These differences could represent an important key factor to differentiate INT from HP tennis players. No other significant differences were presented, however, a large effect size was recorded in hip horizontal velocity, which could add also relevant information for coaches.

Considered the most important contribution to the racket head velocity in a previous study (Elliott et al., 1997), the contribution of the internal rotation of the shoulder in this study did not show significant differences between both groups, despite being the rotation with higher angular velocities. Our results presented higher angular velocities for shoulder, elbow and trunk rotation than a fast forehand performed by skilled players (Seeley et al., 2011), although the results are in accordance with a study comparing HP to Elite tennis players (Landlinger et al., 2010b), with exception of the elbow extension. Despite no significant differences, a large effect size was found in the trunk and pelvis transverse angular velocity which could be linked to the horizontal velocity of the hip.

Considering kinematic studies presenting comparisons between level of expertise, most studies usually compare kinematic variables in specific instants at the backswing and impact, although, differences in tennis kinematics are not necessarily located at minima or maxima of time series, thus, the SPM-1D analysis could present a more complete view to analyse the variables of interest. The higher pelvis angular velocity presented in the SPM-1D analysis significantly differentiated both groups as in previous study (Landlinger et al., 2010a), being one possible explanation to the higher shoulder velocity in the HP players. Moreover, significant differences were found in the shoulder and hand frontal plane around 60-100% and 0-60% respectively (Figure 2.4). It was also found that the HP players began the acceleration phase with a higher ulnar deviation and presented a higher shoulder adduction near the impact compared with the INT tennis players. Not many studies performed this methodology, thus it is difficult to compare our results, although, nevertheless, this specific data could represent an increase value to the tennis coaches, as this SPM-1D analysis add knowledge to the state of art of tennis kinematics.

The frontal plane of the shoulder showed significant differences between both groups with the HP group presenting higher angular velocities in elbow in sagittal plane between 20-65%, whereas an inferior period was also denoted in sagittal plane of the hand also with the HP group presenting higher angular velocities. These significant differences could explain and differentiate a higher capacity from the HP group to accelerate these specific joints and could be key factor of high-skilled athletes.

Regarding the contributions to the racket head velocity (Table 2.2) we found significant differences between the two groups in the contributions of the shoulder (representing the contribution of the trunk and lower limbs). These differences are corroborated with the higher velocity of shoulder at impact (Table 2.1), showing that the ability to accelerate the shoulder is a key factor that could distinguish the HP of the INT players and tennis coaches should focus on this key factor. Contrary to our study, Takahashi et al. (1996) when comparing the contributions with three different forehand shots (flat, top spin and lob top spin) showed that the main contribution to the racket head velocity was mainly due to the internal rotation of the upper arm followed by the flexion and abduction of the upper arm. The same pattern was showed by Elliott et al. (1997) when comparing different grip styles forehand, contrary to the flexion of the upper arm followed by the internal rotation of the upper arm presented in our study. On another hand, a study with elite tennis players (Pedro et al., 2022) demonstrated that the horizontal flexion of the upper arm, followed by the extension of the forearm and by the internal rotation of the upper arm were the main responsible for the contribution to the racket head velocity. We consider that these differences with previous studies could be attributed to the differences due to the lab condition producing more flat forehand. Also some differences with the study of Elliott et al. (1997) when comparing the pronation contribution in players with eastern grip, presenting a negative contribution to the racket head velocity, although, the players with western grip present a minimum but positive contribution. There are different aspects that could distinguish our results, such the majority of our participants used a semi-western grip, and as it was showed by Elliott et al. (1997) these contributions could be affected by the way players hold the racket. Once more we think that the results of these study present an important feature for coaches to help their athletes to achieve a higher performance.

In conclusion we can refer that the horizontal shoulder velocity and the contributions of the trunk and lower limbs are a key factor that could distinguish the INT from the HP tennis players. Moreover, the major contribution of the upper limb rotations to the racket head velocity independent of the level of expertise was the flexion of the upper arm, followed by the internal rotation of the upper arm. Tennis coaches should focus on upper body strength training as well as to develop the trunk and shoulder rotation velocity towards the direction of the ball, whereas physiotherapists should be aware of these contributions to develop a prevention program for athletes. Future studies should try to understand if differences in the contributions are present also between other levels of players like elite players and the forehand drive performed with different stances.

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Conflict of Interest

The authors have no conflicts of interest to declare, financial, or otherwise.

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Chapter 3

Concurrent validity of an inertial measurement system in tennis forehand drive[2]

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Abstract

The kinematic analysis in tennis forehand drive plays an important assistance to understand the quality of this technique. The Inertial measurement units (IMUs) due to its portability, larger capturing area and faster set up preparation, present an alternative to the optical motion capture systems (OS) considered as gold standard, however the degree of accuracy is task specific. This study aimed to compare the concurrent validity of a IMUs (Xsens MVN system) for measuring upper and lower limb kinematics using an OS (Qualisys Track Manager) as reference. Kinematic variables were evaluated during the forehand drive acceleration phase performed by 29 participants. The results demonstrated an excellent coefficient of multiple correlation (CMC) values (CMC ≥ 0.95), for the majority of the variables with exception of shoulder in the anteroposterior plane (CMC: 0.85), and elbow in the axial plane (CMC: 0.79). Root-mean-square error (RMSE) were considered from good to tolerable with exception of the elbow joint angle in transverse plane. One dimensional (1D) statistical parametrical mapping (SPM) demonstrated good agreement between the two systems, with exception of elbow in transverse plane. The present work presents an important advancement to a more frequently use of the IMUs in tennis, as well as in other racket sports.

Keywords: tennis forehand; IMUs; 3D joint kinematics; motion capture; one-dimensional statistical parametric mapping

Introduction

Tennis forehand drive is essential in tennis (Reid et al., 2013) and, a higher performance has been associated with various kinematic variables such as the horizontal flexion/abduction that contribute for racket velocity (Elliott et al., 1997) and, increased joint angles for lower limbs that contribute for a higher ball velocity (Seeley et al., 2011). Kinematic patterns are also differentiated between players with different level (Landlinger et al., 2010a, 2010b) and between open and square stance (Knudson & Bahamonde, 1999).

Optical motion capture systems (OS) are the most popular in kinematic analysis (Chiari et al., 2005), as in forehand drive (Elliott et al., 1989; Landlinger et al., 2010b). Despite being considered the gold standard (Cuesta-Vargas et al., 2010), OS are often conducted inside the laboratories presenting a considerable effort to capture tasks outside the lab (Robert-Lachaine et al., 2017).

An alternative are the inertial measurement units (IMUs), which are lighter, portable and of low energy usage, (Vries et al., 2009), capable to estimate body segment orientation and position (Roetenberg et al., 2009) and offer an accurate method to study human motion, but the degree of accuracy and reliability is site and task specific (Cuesta-Vargas et al., 2010).

Studies found good agreement in upper limb motion during simulated swimming (Fantozzi et al., 2015 with coefficient of multiple correlation (CMC) >0.9 and root-mean-square error (RMSE) <5°), during ergonomic tasks (Robert-Lachaine et al., 2017: CMC > 0.92 and RMSE < 5°) suggesting that differences were predominantly attributed to the biomechanical models and, also with diferent calibration methods (Bouvier et al., 2015: CMC:0.80-0.97; RMSE:8.7-24.9°). Regarding the lower limbs, it was showed an accuracy ranging between acceptable (RMSE < 5°) and tolerable (RMSE < 10°) in gait Bessone et al. (2019), a high accuracy in flexion/extension Zhang et al., 2013: CMC: > 0.96) and acceptable levels of concurrent validity when measuring kicking biomechanics (Blair et al., 2018).

Despite the latter studies, until now there is no reference to the accuracy of upper limbs involving large ranges of motion in abduction/adduction and internal/external rotation, high velocities, and an impact, representing a lack of confidence for a regular use of the IMUs in a more ecological environment, particular in tennis forehand drive. Thus, the aim of this study was to analyse the concurrent validity of an IMUs system for the assessment of upper and lower limb angular kinematics during a tennis forehand drive, using an optical motion capture system as criterion.

Methods

Participants

Eighteen experienced (13 males and 5 female) and eleven male intermediate tennis players (age: 21,8 ± 6,0 years; height: 1,8 ± 0,1 cm; mass: 69,4 ± 10,1 kg), provided written informed consent to participate in this study, which was approved by the Institution's Ethics Committee (21/2018). Two male intermediate tennis players were left handed whereas the others were right handed. All participants were free from injuries, the experienced tennis players practiced regularly and competed at national competitions, had national ranking and the intermediate did not compete and had no national ranking.

Testing Protocol

After the individual warm-up participants were instructed to hit the ball as fast as they can against a hanging cotton cloth of 3X2 to cushion the ball. The participants used their own tennis rackets and, the tennis balls were thrown by an experienced tennis coach into a bounce area for the stroke with 3 seconds between each stroke (Rogowski et al., 2011). Three repetitions from each participant were collected.

Instrumentation

Kinematics variables were simultaneously recorded at 240Hz with a) a IMUs suit (Xsens MVN Link System, Xsens technologies, Enschede, Netherlands) using the Xsens MVN Analyse (version 2018.0.3, ref) software and b) an OS with fifteen infrared high-speed cameras (Oqus 300, Qualisys AB, Sweden), using the Qualisys Track Manager (version 2.17, Qualisys AB, Gothenburg, Sweden) software.

The Xsens MVNV Link system comprises 17 IMUs on each segment (Roetenberg et al., 2013; Xsens Technologies, 2018) (Figure 3.1) and calibration procedures executed as previously described (Roetenberg et al., 2009).

For the OS 43 reflective markers (Figure 3.1) were placed on the following anatomical landmarks: C7, T8, suprasternal notch, xiphoid, lateral and medial epicondyle of the humerus, acromioclavicular, lateral point of the radial styloid, medial point on ulnar styloid, base of the second and fifth metacarpal proximal phalanges, anterior and posterior superior iliac spines, lateral and medial epicondyles, lateral and medial malleoli and 1st, 2nd and 5th metatarsal heads (Wu et al., 2002, 2005). Additionally, ten rigid light weight clusters with four non-collinear tracking markers were placed in each segment.

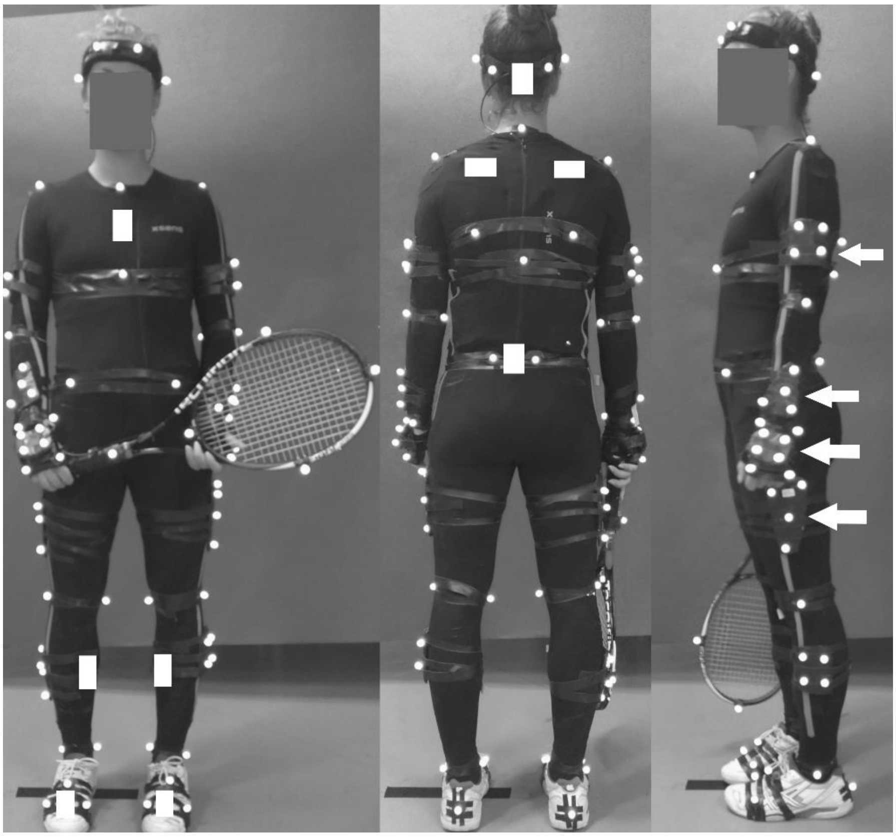

Figure 3.1- Xsens suit with 17 IMUs sensors presented with white rectangles and white arrows for the ones under the lightweights and marker set up placed on each body segment with 43 reflective markers and 10 lightweights with 4 non-collinear tracking markers.

Data processing

The segments' position and orientation (POSE) in the MVNX file were used to compute joint angles of shoulder, elbow, wrist, separation angle (difference between shoulders and pelvis in transverse plane), hip, knee and ankle from the dominant side (corresponding to the rear leg), using a ML-AP-Axial Cardan sequence (Grood & Suntay, 1983) in software Visual 3D (V6, C-motion, Inc. Germantown, USA).

The 3D marker trajectories during the standing and forehand drive trials were identified and exported to c3d format in Qualisys Track Manager, and filtered in Visual 3D using a 4th order low-pass Butterworth filter with a cut off frequency of 10 Hz (Seeley et al., 2011). A biomechanical model was built with 15 segments (head, thorax, upper-arms, forearms, hands, pelvis, thighs, shanks and foots). To minimize the differences attributed to the biomechanical model, the segments' origin, dimensions and anatomical axes definitions were equivalent to the ones used in the Xsens model (Robert-Lachaine et al., 2017). Joint angles, computed as described above, were time normalized from the first movement of the racket shaft in the direction of the shot (Figure 3.2) until the last frame before impact (Landlinger et al., 2010a).

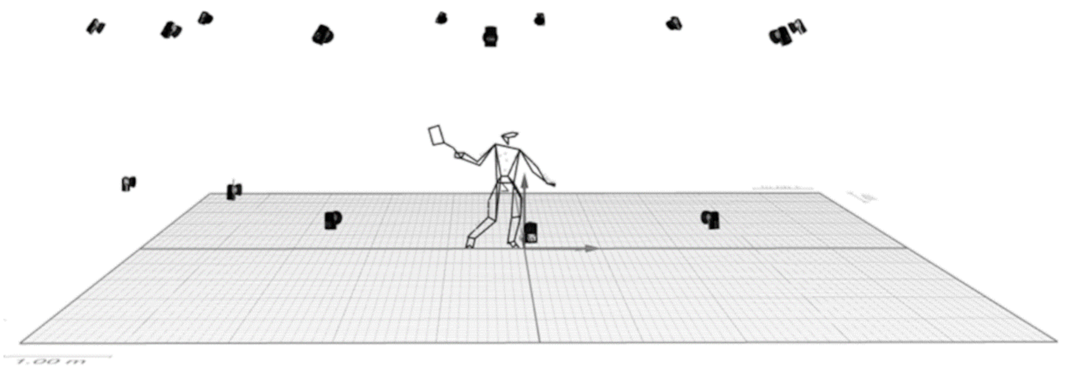

Figure 3.2 – Representation of the first movement of the racket shaft in the direction of the shot of a single participant in the Qualisys Track Manager software.

Statistical Analysis

Concurrent validity was assessed by CMC (Ferrari et al., 2010), RMSE and one dimensional (1D) statistical parametric mapping (SPM) (Friston et al., 1995; Pataky et al., 2013; Pataky, Robinson, et al., 2016) using a two-tailed paired sample t-test, differences were considered statistically significant for p-values < 0.05. All SPM analyses were performed in Python 2.7 using the open source package located at http://www.spm.1d.org/ (Pataky, Vanrenterghem, et al., 2016). The RMSE interpretation was based in McGinley et al., (2009) as good (RMSE ≤ 2°), acceptable (2° < RMSE ≤ 5°), and tolerable (5° < RMSE ≤ 10°) and unbearable accuracy (RMSE > 10°). All CMC analyses and the RMSE calculations were performed in Microsoft Office Excel 2016.

Results

The waveforms measured with the two systems demonstrated excellent CMC values (CMC ≥ 0.95) for all computed variables with the exception of the shoulder in the anteroposterior plane (CMC: 0.89) considered as very good, and elbow in the axial plane (CMC: 0.79) considered as good agreement (Table 3.1). The RMSE indicated values under 5° for most of the studied variables with the exception of the hand in sagittal and frontal plane, as well as the shoulder and ankle in sagittal plane, which presented values around 6°. Only the elbow in transverse plane showed a value of around 13°RMSE (Table 3.1). The SPM-1D analysis showed significant differences for some of the joint angles during some periods of the event, showed in Figure 3.3 and Figure 3.4 whenever SPM trajectory exceeds the threshold (grey area).

Table 3.1 - Descriptive statistics of joint angles comparing the IMUs vs OS models with mean values of the coefficient of multiple correlation (CMC) and root-means square error (RMSE).

Joint	Plane	CMC	RMSE
Shoulder	Frontal	0,89	3,5°
	Sagittal	0,95	6,1°
	Transverse	0,99	4,1°
Elbow	Sagittal	0,99	1,5°
	Transverse	0,79	13,1°
Wrist	Frontal	0,98	6,3°
	Sagittal	0,99	6°
Separation Angle	Transverse	0,99	4,4°
Hip	Frontal	0,97	2,3
	Sagittal	0,99	2,6°
	Transverse	0,99	3,5°
Knee	Sagittal	0,96	3,6°
Ankle	Sagittal	0,96	6,7°

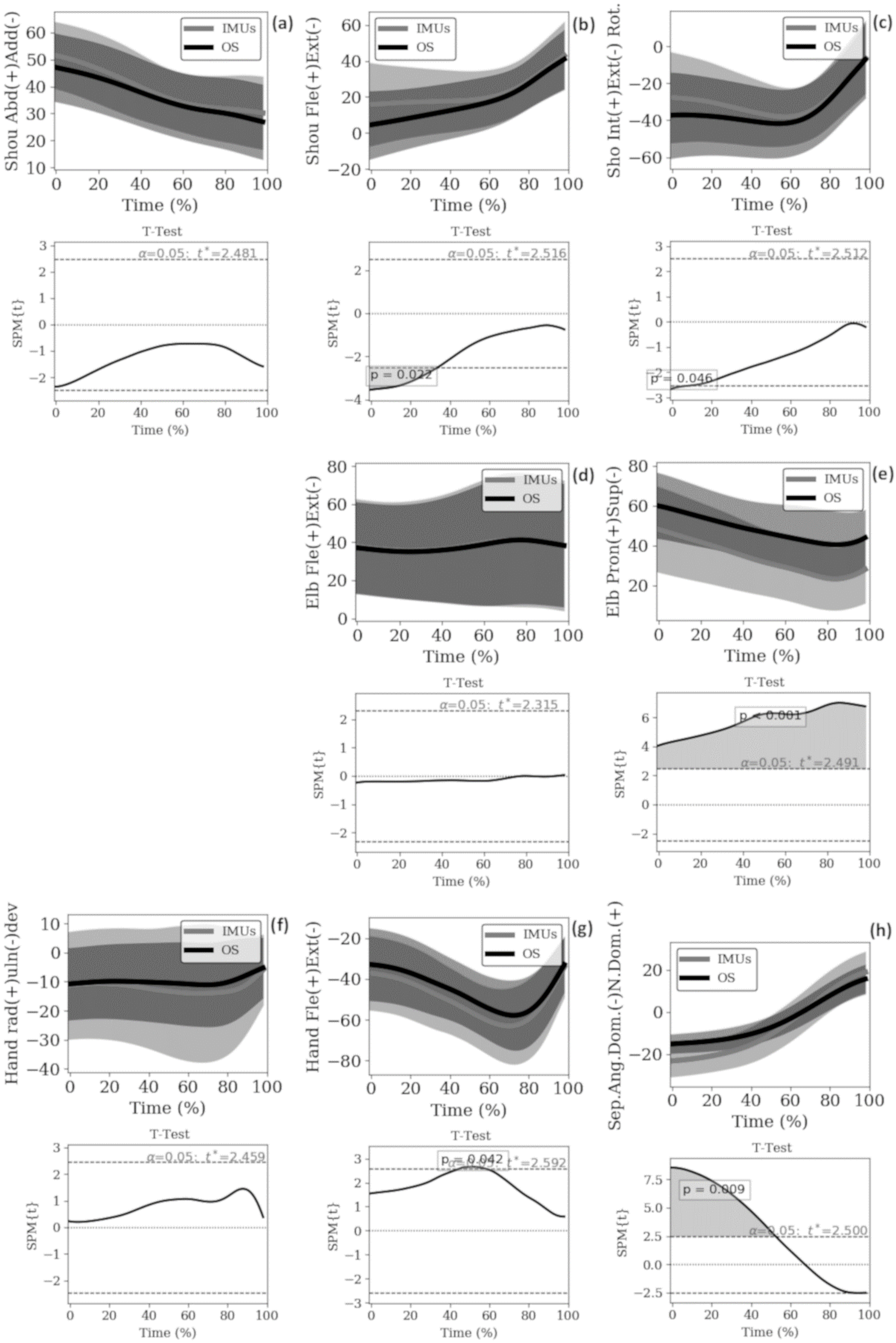

Figure 3.3 - Joint angles and the respective 1D-SPM results, during the time normalized acceleration phase, for the IMUs system (grey line) and the OS (black line). Shoulder abduction/adduction (a), shoulder flexion/extension (b), shoulder internal/external rotation (c), elbow flexion/extension (d), pronation/supination (e), hand radial/ulnar deviation (f), wrist flexion/extension (g), separation angle (h). Grey shaded regions indicate where differences were statistically significant.

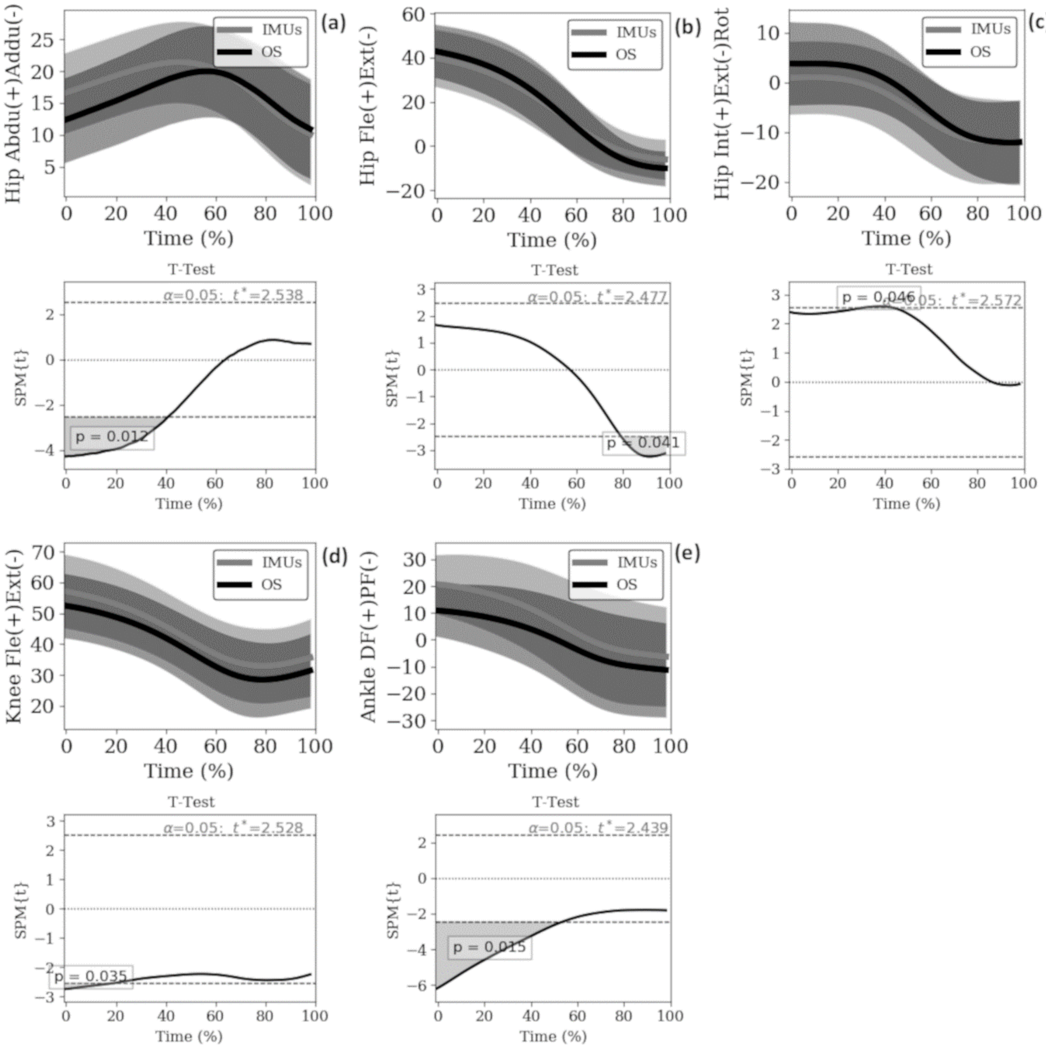

Figure 3.4 - Joint angles and the respective 1D-SPM results, during the time normalized acceleration phase, for the IMUs system (grey line) and the OS (black line). Hip abduction/adduction (a), hip flexion/extension (b), hip internal/external rotation (c), knee flexion/extension (d), ankle flexion/extension (e). Grey shaded regions indicate where differences were statistically significant.

Discussion

The purpose of this work was to analyse the concurrent validity of the angular kinematics from an IMUs system against an OS in tennis forehand drive. CMC values were excellent in the majority of the joint axis. Elbow joint angle in the transverse plane presented 13.1° of RMSE, even though with good agreement (CMC: 0.79). The RMSE were acceptable and tolerable for the remaining joint angles, whereas the SPM analysis showed a good agreement although with significant differences in some joint angles during some periods.

Limitations of the study are associated with the iron structures inside the laboratories that could interfere with electronic devices and the non-ecological environment for data collection.

Sagittal plane presented similar results in shoulder angle and hand (CMC ≥ 0.95, RMSE: 4-8°) during simulated swimming (Fantozzi et al., 2016) and ergonomic tasks (Robert-Lachaine et al., 2017: 0.9 ≤ CMC ≥ 0.98, RMSE: 2.0-3.6°). Moreover, our study presented higher agreement compared with a repetitive movement task for shoulder, elbow and hand (RMSE > 10°) (Bessone et al., (2019). Hand accuracy (Figure 3.3g) showed confident results with just some differences during 42 to 60% of the event, probably caused by the high acceleration of the movement during this phase which can also be related to the higher RMSE for the hand (Bessone et al., 2019).

As expected, the lower limb in sagittal plane presented an excellent CMC and an acceptable accuracy (Table 3.1), contrary, the higher RMSE for the ankle joint might be related to the plantarflexion (Figure 3.4e) when the foot starts to leave the ground and also, with a more rigidity area where IMU is placed compared with the markers (Bessone et al., 2019). Similar results were found during walking (Zhang et al., 2013, CMC ≥ 0.96) and ergonomics (Robert-Lachaine et al., 2017, CMC: 0.95-1, RMSE: 2.2-3.8°) in the sagittal plane for lower limbs. The SPM-1D analysis for the lower limb revealed excellent agreement (Figure 3.4b) until 80% of the entire event in the hip sagittal plane showing significant differences just before impact during hyperextension of the hip. On another hand the knee joint (Figure 3.4d) showed significant differences during the maximum flexion of the knee, which could be related with soft tissue artefact, due to the larger area taken by the cluster compared to IMUs.

Regarding the frontal plane, joint angles demonstrated excellent correlation (CMC) with the exception of the shoulder (very good correlation), acceptable to tolerable errors (Table 3.1), and the SPM-1D analysis (Figure 3.3 and Figure 3.4) showed excellent similarity during the entire event for the shoulder and hand with the exception of the hip joint angle (Figure 3.4a) during the initial period of event (0-42%). A little higher agreement values for shoulder (0.95 ≤ CMC ≥ 0.97, RMSE 4-8°) were demonstrated by Fantozzi et al., (2016). Contrarily, inferior agreement were showed by Bouvier et al., (2015) demonstrating inaccuracy (RMSE > 10°) and imprecision (coefficient of repeatability > 10°) during a wheel movement.

Concerning the transverse plane, slightly better results for elbow (0.93 ≤ CMC ≥ 0.99, RMSE: 2.5-10°) were shown by Fantozzi et al., (2016) and Robert-Lachaine et al., (2017). Contrary, our results show inferior error magnitude (Table 3.1) compared to a wheel movement for shoulder in transverse plane (RMSE: 8.0-26.2°) (Bouvier et al., 2015). We believe that this good accuracy specially in transverse plane was due the use of an equivalent model between systems Contrary, differences in the transverse plane of the elbow (Figure 3.3e) could be associated to some movement of the hand in this plane while participants held the racket between IMUs calibration and the static trial of the OS. Also, the separation angle showed significant differences until 55% of the event, during the higher rotation of the trunk towards the dominant hand, this difference could be attributed to the different technologies between systems.

Despite some studies involving upper limbs have been considered as “conflicting” (Poitras et al., 2019), other studies showed a good agreement when using equivalent biomechanical models Robert-Lachaine et al. (2017), being also corroborated with our study (Table 3.1). On the other hand and although the utility and frequency in reporting CMC values (Cuesta-Vargas et al., 2010), the SPM-1D seems to be a good tool to measure continuous time-series to quantify segment and joint co-ordination (Blair et al., 2018) and to the best of our knowledge this is the first study comparing IMUs and OS systems in tennis forehand drive.

We can conclude that the IMUs Xsens MVN can provide very good measures for the majority of joint angles during a tennis forehand. The present work presents an important advancement to a more frequently use of the IMUs in tennis, as well as in other racket sports.

Conflict of interest statement

No potential conflict of interest was reported by the authors.

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Chapter 4

Evaluation of Upper Limb Joint Contribution to Racket Head Speed in Elite Tennis Players Using IMU Sensors: Comparison Between the Cross-Court and Inside-Out Attacking Forehand Drive[3]

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Abstract

This study aimed to quantify and compare the upper limb angular kinematics and its contributions to the racket head speed between the cross-court (CC) and inside-out (IO) attacking tennis forehand of elite tennis players in a competitive environment. A new approach was used to study the forehand drive with mini-inertial sensors of motion capture to record the kinematic data. Six strokes in each direction per participant (72 shots in total) were chosen for analysis. Upper limb kinematics were calculated in the Visual 3D platform (Visual 3D Professional V5.01.21, C-motion, Germantown, MD). The method used to calculate the upper limb's contributions was performed with MATLAB software and used the segment's (upper arm, forearm, and hand) angular velocities and their respective displacement vectors obtained through the inertial sensors. Upper limb kinematics demonstrated a higher shoulder rotation in the IO direction with significant differences at the end of the backswing, which could be a key factor in distinguishing the two directions of the shot. Results also demonstrated that the horizontal flexion of the upper arm (around the shoulder joint) was primarily responsible for the racket velocity in the anteroposterior direction (48.1% CC and 45.2% IO), followed by the extension of the forearm (around the elbow joint) (17.3% CC and 20.9% IO) and the internal rotation of the upper arm (around the shoulder joint) (15.6% CC and 14.2% IO). No significant differences were shown in the contributions of upper limbs to the racket head velocity between the two directions of the shot. Tennis coaches and players should develop a specific training programme to perform higher angular velocities in these specific joint rotations.

Keywords: tennis forehand; 3D joint kinematics; upper limb contribution; racket velocity

Introduction

As the second most important stroke in tennis after the serve (Reid et al., 2013a), with which tennis players constantly try to dominate the point (Roetert et al., 2009), the cross-court (CC) and the down-the line (DL) forehand drive (Elliott et al., 1989; Landlinger et al., 2010a, 2010b) have been the focus of kinematic studies in tennis and table tennis (Malagoli Lanzoni et al., 2018). The latest studies demonstrated several kinematic differences between the CC and DL direction of the shot, such as the racket velocity, hip alignment, and shoulder alignment (Landlinger et al., 2010a), and also in the knee and elbow flexion, among others (Malagoli Lanzoni et al., 2018), presenting valuable information to tennis coaches.

Although the forehand drive is performed mostly from the forehand side of the court, advanced players are able to cover up to 85% of the court with the forehand and it can be used to produce more “winners” shots (Brabenec, 2015); thus, it can be used from both sides, and used as a tactical advantage to the shots on the left side of the court (Martin-Lorente et al., 2017). This shot, the so-called inside-out (IO) forehand, can be defined as a forehand played from the backhand side diagonally to the opponent’s backhand (Blandón, 2008). To our knowledge, kinematic studies on the forehand drive have analysed the CC and DL forehand drive, whereas no study has investigated the differences between the CC and the IO forehand.

Researchers agree that understanding the mechanics of the movement is essential to develop racket velocity and also to minimise the risk of injury for the athlete (Elliott, 2006). Thus, the speed of the racket head at impact is critical in tennis and can be varied by the players, particularly via the upper limb segments. Furthermore, the role of the angular velocity vectors of the upper arm, forearm, and hand in generating maximum racket impact speed can produce valuable information for those interested in tennis (Elliott et al., 1995). Studies have been undertaken on the contributions of the individual segments’ rotations of the upper limb to the racket head velocity in the tennis forehand between players with different grip positions (Elliott et al., 1997), in the tennis serve (Elliott et al., 1995) and in the squash forehand (Elliott et al., 1996). However, there is no reference to the contributions describing different directions of the shot. Moreover, none of these studies were performed with opposition on the other side of the court. This condition can assume particular importance in the execution of the movement because the decision to place the ball cross court or down the line depends on the perception of the opponent's position on the court.

Later studies and the majority of kinematic studies have been conducted primarily using optical systems (Elliott et al., 1995; Elliott et al., 1996; Elliott et al., 1997; Seeley et al., 2011) and, despite their accuracy (Cappozzo et al., 1995), these systems require a considerable effort to capture tasks outside a laboratory (Roetenberg et al., 2009). Alternatively, inertial measurement unit systems (IMUs) provide a lighter, portable, and easier-to-use system for capturing data outside of a laboratory (Vries et al., 2009), and an accurate and reliable method to study human movement (Cuesta-Vargas et al., 2010). In the tennis forehand drive, in particular, IMUs presented very good agreement and reliability for the majority of joint angles (Pedro et al., 2021) when compared with an optical system. Good agreement was also found for upper limbs during simulated swimming (Fantozzi et al., 2015b).

With this in mind, and considering the significant differences shown between the CC and DL in previous studies (Elliott et al., 1989; Landlinger et al., 2010a, 2010b; Malagoli Lanzoni et al., 2018), there is a lack of knowledge about the kinematic variables and the contributions of the upper limb that can distinguish the offensive tennis forehand drive when players play in the CC and the IO directions. Therefore, this study aimed to quantify and compare the kinematics and the contributions of the upper limb (upper arm, forearm, and hand) segments' rotation to the racket head velocity in a tennis forehand during an attacking situation of elite tennis players, when players performed the forehand drive in the CC and the IO directions, with opposition players creating a more representative situation. We hypothesised that the two directions of the shot (CC and IO) would present (a) different upper limb angular kinematics, and (b) different contributions of the upper limbs to the racket head velocity.

Materials and Methods

Participants

A convenience sample of six elite male right-handed tennis players (age 21 ± 4.2 years, height 178.2 ± 2.9 cm, mass 73.0 ± 1.8 kg), volunteered to participate in the study. Three had Association of Tennis Professional (ATP) rankings (630, 1156, and 1520, respectively) and the other three had national rankings in Portugal (4, 44, and 69, respectively). Two other tennis players with national rankings collaborated in the study, one male and one female (age 19.5 ± 0.7 years, height 168.5 ± 9.2 cm, mass 65 ± 8 kg) to create an opposition situation. All participants were free from injuries, practised regularly, competed at national and international level, and provided written informed consent to participate in this study, which was approved by the Institution’s Ethics Committee and meets the declaration of Helsinki.

Testing Protocol

Before testing, all the participants performed the necessary warm-up and hit as many practice shots as they wanted [4]. A ball machine (Lobster—Phenom Electric Tennis Ball Machine D641, 437, North Hollywood, CA, USA) projected new tennis balls (Dunlop All Court) with a controlled horizontal velocity (24.5 m/s) similar to that of other studies (Landlinger et al., 2010a, 2010b), to a bouncing area (Figure 4.1) where the players were able to play an offensive forehand. The opponent assumed different positions on the court and the player had to place the ball on the opposite side. Participants were encouraged to hit the ball as they would in a match when attempting to hit a winner. One Panasonic HC-V10 digital video camera (Figure 4.1, cam2) operating at 60 Hz captured the placement of the shot. The shots were considered valid, “in”, when landed inside the CC and IO target boxes (3 × 4.5 m) (Figure 4.1) (Landlinger et al., 2012). Six valid shots in each direction (CC and IO direction) inside the target area were chosen for analyses (72 forehand shots over all participants). Data were analysed during the acceleration phase, which was determined from the first forward movement of the racket shaft in the anteroposterior direction (X) (Figure 4.1) until ball impact, defined as the instant where the ball–racket contact occurred.

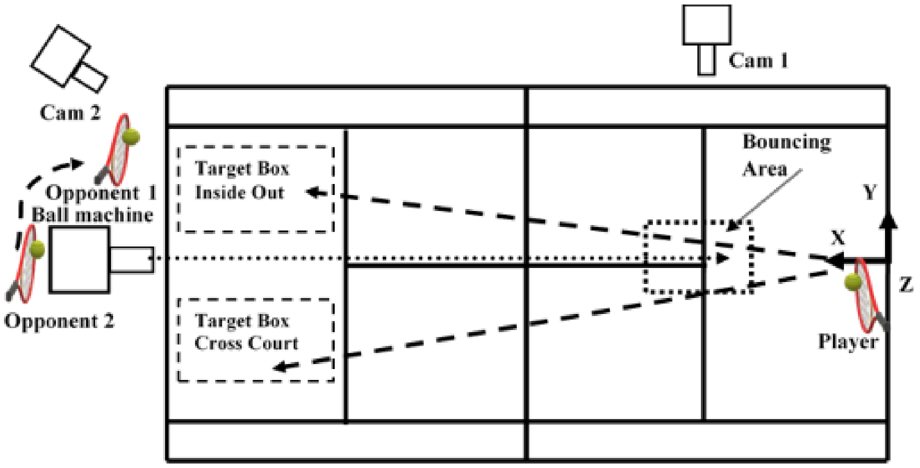

Figure 4.1 -. Testing environment. (1) One Lobster ball machine with the projection line toward the bouncing area, (2) one Qualisys Oqus 210c camera (Cam 1), (3) one Panasonic digital video camera (Cam 2), (4) coordinate system, (5) stroke direction, (6) bouncing area, (7) target boxes for the CC and IO direction forehands, (8) participant with Xsens IMUs, (9) opponents 1 and 2.

Instrumentation

The data were captured at 120 Hz with 17 IMUs sensors (Xsens MVN Technologies, Enschede, NL) (Gandy et al., 2015), using the MVN Studio Pro software, and were continuously updated using a biomechanical model of the human body (Roetenberg et al., 2009). The accuracy of these IMUs showed an excellent coefficient of multiple correlation values (CMC ≥ 0.95) for the majority of the variables of the upper limb (shoulder, elbow, and wrist) (Pedro et al., 2021). The placement of sensors in each segment was intended to be over the bones whenever possible to reduce soft tissue artefacts (Leardini et al., 2005). Calibration procedures were performed to align the sensors with the body alignment and to determine the segment's length (Xsens Technologies B.V., 2012). One Qualisys video camera, model Oqus 210c (Qualisys AB, Gothenburg, Sweden) operating at 240 Hz in Qualisys Track Manager (version 2.10., Qualisys AB, Gothenburg, Sweden), was synchronised with the IMUs to identify the instant of impact.

Data Processing

The three-dimensional coordinates of virtual markers representing bony landmarks in each segment (Figure 4.2) (created in the MVN Studio^{TM} Pro software based on the IMUs model) were exported to C3D format. In Visual 3D software (Visual 3D Professional V5.01.21, C-motion, Germantown, MD, USA), these virtual markers were used for the reconstruction of a biomechanical model with three degrees of freedom (DOF) for the shoulder, two DOF for the elbow, two DOF for the wrist, three DOF for the trunk, and three DOF for the pelvis. The rigid segments were reconstructed as follows: upper arm (projected from the shoulder joint centre to the mid-point between the lateral and medial epicondyle of the humerus); forearm (projected from the mid-point between the lateral and medial epicondyle of the humerus to the mid-point between the lateral point of the radial styloid and the medial point on the ulnar styloid); hand (projected from the mid-point between the lateral point of the radial styloid and the medial point on the ulnar styloid to the mid-point between the base of the second and fifth metacarpal proximal phalanges); trunk (projected from the mid-point between the C7 and the suprasternal notch and the medial point between T8 and PPX); and pelvis (projected from the mid-point between iliac crests and the medial point between right and left great trochanters), with a length and an imported local coordinate system from MVN Studio^{TM} Pro software. Kinematic variables of interest from the dominant upper limb during the forehand drive were as follows: shoulder alignment with the baseline (shoulders parallel with the baseline presented an angle of 0° and when perpendicular with the baseline presented an angle of 90°); separation angle (difference between shoulders and pelvis in the transverse plane); shoulder flexion/extension; shoulder abduction/adduction; shoulder internal/external rotation; elbow flexion/extension; elbow pronation/supination; wrist flexion/extension; and wrist abduction/adduction. Joint angles were calculated using a medio-lateral, anteroposterior, axial Cardan sequence (Grood & Suntay, 1983). All joint angles were time normalised to the period between the first movement of the racket shaft in the direction of the shot and the impact.

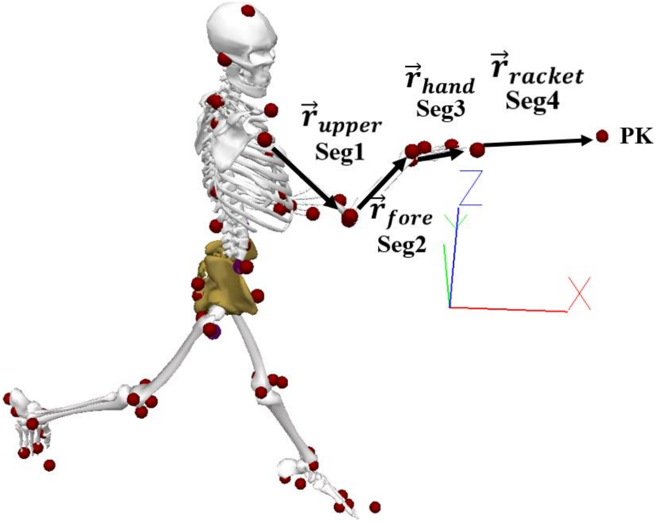

Figure 4.2. Participant's virtual markers and derived vectors. Seg1 (segment 1: upper arm), Seg 2 (segment 2: forearm), Seg 3 (segment 3: hand), Seg 4 (segment 4: racket), Pk (centre of the racket).

For the contribution of segments' rotations to the racket head velocity, the centre of the racket (PK) was determined by measuring the distance from the centre of the wrist to the centre of the racket head (Figure 4.2). The kinematic variables of the centre of the racket and angular velocity, proximal end position, and distal end position from upper limbs (upper arm, forearm, and hand) were exported from Visual 3D (Visual 3D Professional V5.01.21, C-motion, Germantown, MD, USA) to MATLAB (R2010A). The racket head velocity contribution of each of the three segments of the upper limb was determined by orthogonal unit vectors to define each of the reference frames (Sprigings et al., 1994). The contributions of the upper limb kinematics were described according to the anatomical movements as flexion/extension, abduction/adduction, and internal/external rotations for the upper arm (around the shoulder joint), although we reported the combined contribution of the upper arm flexion and abduction with respect to racket head speed, as in a previous study (Elliott et al., 1995); pronation/supination and flexion/extension for the forearm (around the elbow joint); and palmar flexion/extension and radial/ulnar flexion for the hand (around the wrist joint). Calculations of the upper limb segments for the absolute angular velocity vectors were used to calculate the relative angular velocity vectors of upper arm segments with respect to the proximal attachment. Then, the angular velocities of each joint were resolved to the scalar (dot) product between the relative angular velocity vectors and their appropriate unit vector. To define the contributions of the segments to the racket head velocity in the direction of the movement, the vector cross product between the anatomical angular velocity vectors and their respective positions vectors to the centre of the racket head was computed (Figure 4.2) (Sprigings et al., 1994). To determine the percentage contributions of each segment rotation to the racket velocity, the velocity was considered as 100%, and each rotation as a percentage of that 100%.

The velocity in the middle of the racket (V_k) (Figure 4.2) was calculated with the linear velocities of the upper limbs and expressed as:

$$\vec{V}_k = \vec{V}_g + (\overrightarrow{W}_1 \times \vec{r}_{upper}) + (\overrightarrow{W}_2 \times \vec{r}_{fore}) + (\overrightarrow{W}_3 \times \vec{r}_{hand}) \quad (1)$$

where $\vec{V}_g$ is interpreted as the linear velocity contribution that the legs and torso make to develop the racket head velocity, $\overrightarrow{W}_{1,2,3}$ are the absolute angular velocities of the three segments, and $\vec{r}_{upper,fore,hand}$ vectors define the segments' length. Knowing the relation between absolute and relative velocity:

$$W_{21} = W_2 - W_1 \quad (2)$$

$$W_{31} = W_3 - W_2 \quad (3)$$

where W_{21} are the relative velocities of the forearm segment relative to the arm and W_{31} are the relative velocities of the hand relative to the forearm, and relative velocities are expressed in the global reference system. In the algorithm presented in [27], the rotation in the y-axis (adduction and abduction) of the elbow and the rotation in the z-axis (internal and external) of the hand are equal to zero.

$$W_1 = [W_{1X}, W_{1Y}, W_{1Z}] \text{ (absolute velocity of the upper arm)}$$

$$W_{21} = [W_{21X}, 0, W_{21Z}] \text{ (relative velocity of the forearm)}$$

$$W_{31} = [W_{31X}, W_{31Y}, 0] \text{ (relative velocity of the hand)}$$

The contribution of the separate anatomical rotations (W) can be determined with the following equation:

$$\begin{gathered}\vec{\boldsymbol{V}}_{\boldsymbol{k}} = \vec{\boldsymbol{V}}_{\boldsymbol{g}} + \{(\vec{\boldsymbol{W}}_{\boldsymbol{1X}} + \vec{\boldsymbol{W}}_{\boldsymbol{1Y}} + \vec{\boldsymbol{W}}_{\boldsymbol{1Z}}) \times \vec{\boldsymbol{r}}_{\boldsymbol{upper-pk}}\} \\ +\{(\vec{W}_{21X} + \vec{W}_{21Z}) \times \vec{r}_{fore-pk}\} + \{(\vec{W}_{31X} + \vec{W}_{31Y}) \times \vec{r}_{hand-pk}\}\end{gathered} \tag{4}$$

where $\vec{V}_g$ is the linear velocity of legs and torso, $\vec{W}_{1X,21X,31X}$ are the angular velocities of flexion and extension, $\vec{W}_{1Y,31Y}$ are the angular velocities of adduction and abduction, $\vec{W}_{1Z,21Z}$ are the angular velocities of internal and external rotation of the three segments, and $\vec{r}_{upper-pk,fore-pk,hand-pk}$ are the vectors with their origin in the joint and extremity in the middle of the racket (Sprigings et al., 1994).

Statistical Analyses

The means of the six repetitions in the CC and IO directions (72 forehand shots) for each participant of the selected kinematic (Table 4.1) and contribution (Table 4.2) variables of the upper arm, forearm, hand, and racket were calculated. Data were first tested for normality using the Shapiro–Wilk test ($p < 0.05$). Differences between variables having a normal distribution were accessed with a paired samples t-test and those that deviated from a normal distribution were assessed using a Wilcoxon Matched-Pairs Signed Ranks test to identify significant differences. For the paired *t*-test, the effect size (ES) was calculated as the Cohen's d, where ≥ 0.2, ≥ 0.5, and ≥ 0.8, represent small, medium, and large effect sizes (Cohen, 1988), respectively. For the Wilcoxon Matched-Pairs Signed Ranks test, the level of significance was set at $p \leq 0.05$ and effect size (r) was defined as small for small effect ≥ 0.1, medium effect ≥ 0.3, and large effect ≥ 0.5 (Pallant, 2011). Significance was set at $p \leq 0.05$ for all tests and all data are reported as mean ± SD. All statistical analyses were performed using SPSS version 20 (SPSS Inc. Company, Chicago, IL, USA). The kinematic differences between the two shots were also assessed using the one dimensional (1D) statistical parametric mapping (SPM). This statistical procedure identifies where significant differences occur during the entire waveform. More specifically, SPM-1D using a two-tailed paired sample t-test was used to compare each joint angle curve between the two directions of the shot from each participant. The SPM-1D method uses random field theory to identify field regions that co-vary significantly with the experimental design (Friston et al., 1995; Pataky et al., 2013; Pataky, Robinson, et al., 2016). Differences were considered statistically significant for *p*-values < 0.05. All SPM analyses were performed in Python 2.7 using the open source package located at http://www.spm.1d.org/ (20/12/2021) (Pataky, Vanrenterghem, et al., 2016).

Table 4.1 -**.** Upper limb kinematic variables in cross-court and inside-out directions.

Variables	**Cross-Court**	**Inside-Out**	**Stat. Test**	***p*-Value**	**ES**
Shoulder Alignment Base line					
End of backswing (°)	−92.2 ± 8.8	−97.2 ± 8.8 *	5.966	0.000	0.99
Impact (°)	19.3 ± 9.4	8.5 ± 9.4 *	−5.153	0.000	−2.10
Separation Angle toward dominant arm					
End of backswing (°)	22.1 ± 4.6	20.9 ± 6.3	1.224	0.229	0.20
Impact (°)	−16.5 ± 5.1	−16.5 ± 7.1	−0.094	0.925	−0.04
Shoulder Flexion (+)/extension (−)					
End of backswing (°)	12.9 ± 8.3	14.1 ± 8.2	−1.432	0.161	−0.24
Impact (°)	54.7 ± 14.1	54.3 ± 14.6	0.260	0.796	0.04
Shoulder Abduction (−)/adduction (+)					
End of backswing (°)	−45.1 ± 9.1	−46.6 ± 9.0	1.572	0.125	0.26
Impact (°)	−47.9 ± 4.6	−47.3 ± 7.1	−0.534	0.593	−0.22
Shoulder int. (+)/ext. rotation (−)					
End of backswing (°)	−54.5 ± 9.5	−55.3 ± 8.5	1.112	0.274	0.19
Impact (°)	−84.9 ± 18.8	−85.5 ± 19.9	0.594	0.556	0.10
Elbow Flexion (+)/Extension (−)					
End of backswing (°)	59.7 ± 13.3	60.4 ± 13.5	−1.062	0.295	−0.18
Impact (°)	66.3 ± 18.9	66.4 ± 22.9	−0.074	0.942	−0.01
Elbow Pronation (+)/Supination (−)					
End of backswing (°)	72.8 ± 21.4	72.8 ± 21.2	0.027	0.979	0.00
Impact (°)	28.3 ± 23.0	28.3 ± 20.4	−0.011	0.991	0.00
Wrist Flexion (+)/Extension (−)					
End of backswing (°)	−18.4 ± 13.6	−19.0 ± 14.2	0.496	0.623	0.08
Impact (°)	−30.4 ± 13.3	−31.3 ± 12.7	0.724	0.474	0.12
Wrist adduction (−)/abduction (+)					
End of backswing (°)	4.8 ± 13.7	5.8 ± 13.1	−1.226	0.228	−0.20

Mean and standard deviation for joint angles of upper and trunk from the end of the backswing to impact in the two directions of the shot. Angles are reported in degrees. Zero degrees correspond to the anatomical position. * Significant differences between CC and IO.

Table 4.2 - Contribution of the upper limb rotations to the racket head velocity in cross-court and inside-out directions.

Segments	Cross Court		Inside Out				
	M (±SD) (m/s)	Contribution. (%)	M (±SD) (m/s)	Contribution (%)	*t*-Test	*p*-value	ES
Shoulder	2.3 ± 0.3	10.4	2.3 ± 0.5	10.6	0.158	0.881	0.06
Upper Arm							
Flex/Ext/Add/Abdu	10.4 ± 4.6	48.1	10.0 ± 3.4	45.2	0.522	0.624	0.21
Intl/Ext Rotation	3.3 ± 2.2	15.6	3.3 ± 2.4	14.2	0.000	1.000	0.00
Forearm							
Flex/Ext	3.7 ± 2.2	17.3	4.6 ± 3.3	20.9	−1.421	0.215	−0.58
Pron/Supi	−0.2 ± 1.4	−2.0	0.1 ± 1.1	−0.9	−0.488	0.646	−0.20
Hand							
Flex/Ext	1.0 ± 0.9	4.5	1.5 ± 1.7	5.3	−0.162	0.878	−0.07
Add/Abd	1.3 ± 1.5	6.1	1.1 ± 1.4	4.9	0.539	0.613	0.22
Centre of racket	21.8 ± 2.2		22.6 ± 1.8		−0.778	0.472	−0.32

Contributions of the shoulder (representing the contribution of the legs and trunk) and upper limb to the linear velocity of the racket in the cross-court and inside-out directions of the shot.

Results

Data revealed a normal distribution for all variables except: (a) shoulder alignment with baseline at impact; (b) separation angle at impact; (c) shoulder joint angle flexion/extension at impact; and (d) shoulder joint angle abduction/adduction at impact. Considering the kinematic variables, the only significant differences between the two directions of the shot were in the shoulder alignment to the baseline at the end of backswing, where the shot in the IO direction presented a higher rotation, and at impact, where a higher rotation was found in the CC direction (Table 4.1). For the remaining joint angles, no significant differences were found between the two directions of the shot (Table 4.1). The SPM-1D analysis showed significant differences for shoulder alignment with the baseline at the beginning and end of the event, and in shoulder axial rotation at between 32 and 47% of the event (Figure 4.3), when the SPM trajectory exceeded the threshold (grey area). There were no significant differences, and the effect sizes were small in upper limb contributions when comparing both directions (Table 4.2). In both shots, the order of importance of contributions to the racket head velocity was the flexion/abduction of the upper arm (around the shoulder joint), extension of the forearm (around the elbow joint), internal rotation of the upper arm, shoulder (around the shoulder joint and representing the contribution of the trunk and lower limbs), abduction of the hand, flexion of the hand (around the wrist joint), and the pronation of the forearm (around the elbow joint). The pronation of the forearm had a negative effect on racket head linear velocity, reducing it by up to 2% in the x-direction at impact. At the impact, the linear velocities of the centre of the racket head in the x-direction were not significantly different between the two shots.

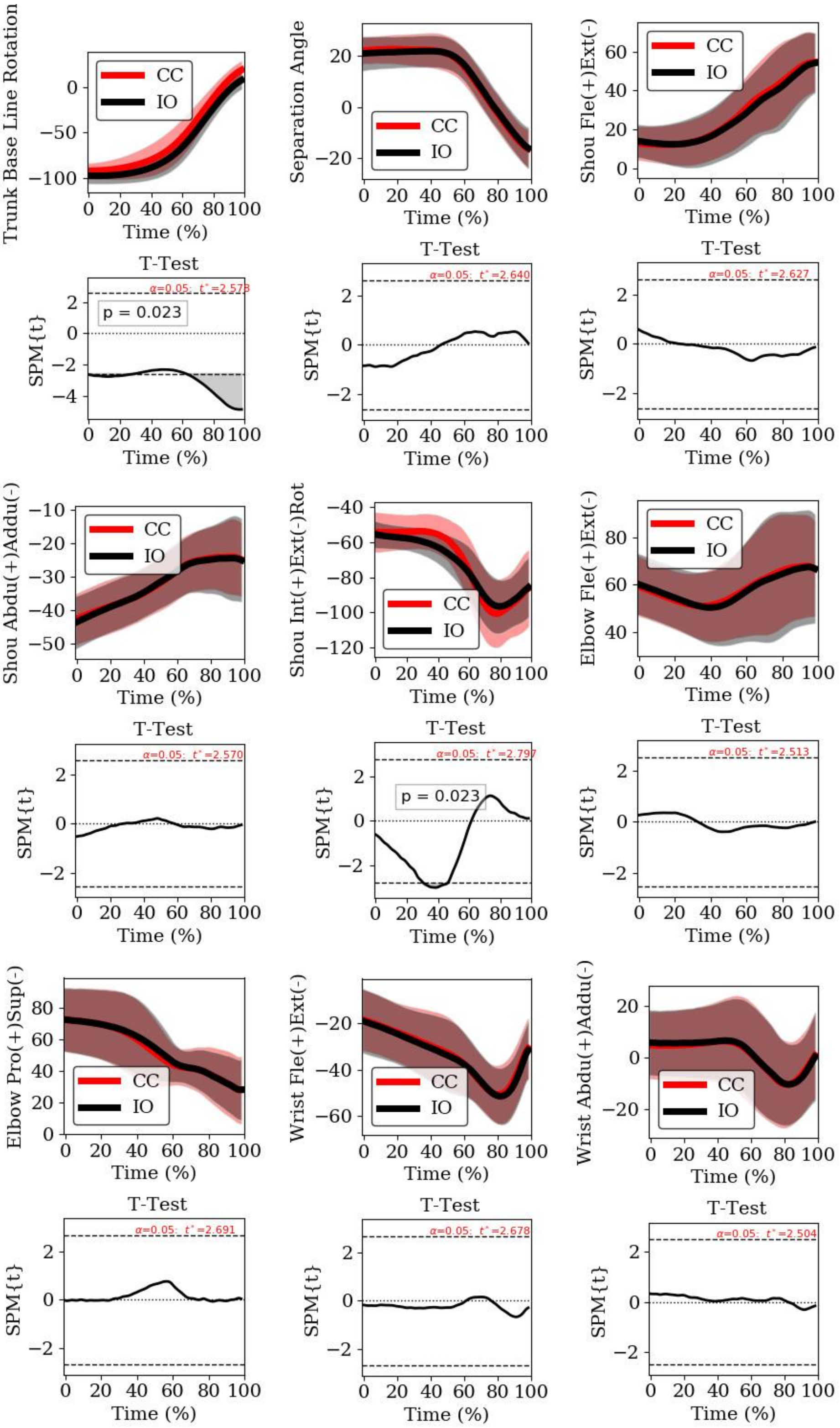

Figure 4.3 -.1D-SPM analysis. Joint angles and the respective 1D-SPM results, during the time normalised acceleration phase, between the cross-court (red line) and the inside-out (black line) directions. Trunk baseline rotation, separation angle, shoulder flexion/extension, shoulder abduction/adduction, shoulder internal/external rotation, elbow flexion/extension, elbow pronation/supination, wrist flexion/extension, wrist abduction/adduction. The horizontal positive and negative dashed lines indicate the threshold test values (t* values). Grey shaded regions indicate where differences were statistically significant.

Discussion

The present study aimed to quantify and compare the angular kinematics of the upper limb and its contributions to the racket head velocity during an attacking forehand drive played in the CC and IO directions of elite tennis players using an IMUs system. The results showed a higher rotation of shoulders to the baseline at the end of the backswing in the IO direction, which may be a key factor in distinguishing the two directions of the shot. These differences were also corroborated by the SPM analysis, which showed the differences at the end of the backswing and when the ball contact occurred. Considering the contributions of the upper limb rotations to the racket head velocity, the flexion/abduction of the upper arm (around the shoulder joint) was considered the most important contribution to the racket head velocity, followed by the extension of the forearm (around the elbow joint) and the internal rotation of the upper arm (around the shoulder joint). To the best of our knowledge, this is the first kinematic study performed using an opposition player, creating a more representative environment to study these variables.

Limitations of the study are associated with the small number of participants, although this number may be considered reasonable because the level of the participants was elite (Harrison et al., 2020). Moreover, the motion capture rate may be considered somewhat low (120 Hz); thus, higher capture rate IMUs should be considered for future studies, particularly to ensure that the ball contact is captured.

The calculated velocity of the centre of the racket in this study (Table 4.2) was somewhat superior to that of tennis players with high-performance forehand drives (≈17.0 m/s) (Bruce Elliott et al., 1997), which may reflect the difference between elite and non-elite tennis players. Similar velocities were found at the racket tip with state-ranked tennis players (Elliott et al., 1989), whereas elite tennis players presented a higher mean maximum velocity of approximately 33.1 m/s (Landlinger et al., 2010b) and approximately 31.1 m/s at impact (Landlinger et al., 2010a).

At the end of the backswing, the shoulder alignment was found to be almost perpendicular to the baseline (CC: −92.8.8 ± −8.8°, IO: −97.2 ± 8.8°); however, at impact, it was nearly parallel to the baseline (CC: 19.3 ± 9.4°, IO: 8.5 ± 9.4°), which is in accordance with other studies (Elliott et al., 1997; Landlinger et al., 2010a). Despite the similarities in the shoulders' alignment with other studies, significant differences were present between the two directions of the shot (Table 4.1). Moreover, these significant differences were present during the first phase of the event between 0 and 30% of the forward swing (Figure 4.3). We consider that these differences at the end of backswing may be associated with the necessary adjustments to a more comfortable alignment to the direction of the shot and may present an important key factor if noted by players to anticipate the opponent's shot direction. Regarding the separation angle (CC: 22.1 ± 4.6°, IO: 20.9 ± 6.3°), which is considered an important key factor in stretching appropriate muscles (Elliott, 2006) and taking advantage of the stretch-shortening cycle of muscles (Roetert et al., 2009) to support the acceleration phase, it was slightly inferior compared to a fast forehand drive (Seeley et al., 2011), with high-performance tennis players (Elliott et al., 1997) showing approximately 30° between the shoulders and the pelvis. Moreover, higher separation angles were shown in a badminton smash (King et al., 2020). Nonetheless, our study produced similar results to those from elite tennis players (Landlinger et al., 2010a), with values between approximately 20 and 25°. The similar separation angles of both directions (Table 4.1 and Figure 4.3) indicate that the necessary adjustments are performed by both feet, which maintain a similar separation angle for the different directions of the shot, contrary to the shoulder alignment with the baseline. Regarding the shoulder contribution to the racket head velocity, which represents the contribution of the lower limbs and trunk (CC: 10.4%, IO: 10.6%), there were no significant differences between the two directions of the shot (Table 4.2), and a similar contribution of approximately 10% was shown with a flat forehand for players with eastern and western grips (Elliott et al., 1997), and in the power serve in tennis (Elliott et al., 1995).

The shoulder joint angle flexion/extension was found to be almost aligned with the trunk at the end of the backswing (CC:12.9 ± 8.3°, IO: 14.1 ± 8.2°), similar to high-performance tennis players holding the racket with a western grip (Elliott et al., 1997), moreover, the flexion angle at impact (CC: 54.7 ± 14.1°, IO: 54.3 ± 14.6°) is also similar to that of the latter study. The shoulder abduction maintained a similar value between the end of the backswing and the impact (Table 4.1). The contribution of the flexion/abduction of the upper arm (CC: 48.1%, IO: 45.2%) was considerably superior (Table 4.2) when compared with players using an eastern grip (34.1%) and even more compared with players using a western grip (20.8%) (Elliott et al., 1997). One considerable difference between the participants is the fact that the majority used a semi-Western grip, although we do not think this could be related to such a difference. The internal/external rotation of the upper arm presented similar values (CC: −84.9 ± 18.8°, IO: −85.5 ± 19.9°) as those of highly skilled male tennis players (Seeley et al., 2011) for peak external rotation and impact joint angles. By comparison, the 1D_SPM analysis showed significant differences between 33 and 47% of the event (Figure 4.3), showing an inferior external rotation of the upper arm in the CC direction. The contribution of the internal/external rotation presented inferior importance (CC: 15.6%, IO: 14.2%) compared with a previous study (Elliott et al., 1997), where the authors showed a contribution of approximately 40%. One consideration for this difference may be related to the ball impact height due to the specificity of the stroke inside the tennis court, where a more horizontal movement may be present in our study.

The forearm flexion joint angle showed similar values (Table 4.2) as those of highly skilled tennis players (Seeley et al., 2011) at the end of the backswing (CC: 59.7 ± 13.3°, IO: 60.4 ± 13.5°) and at the impact (CC: 66.3 ± 18.9°, IO: 66.4 ± 22.9°), whereas the contribution of the extension of the forearm segment (CC: 17.3%, IO: 20.9%) (Table 4.2) was higher compared with tennis players with eastern or western grips, with a contribution between 2.4 and 0.6% for a flat forehand

(Elliott et al., 1997). The axial rotation of the forearm showed a pattern of supination during the acceleration phase, thus showing a negative contribution to the racket head velocity (CC: −2.0%, IO: −0.9%). This is in line with the results of a previous study (Elliott et al., 1997).

The hand segment showed slightly inferior extension values at the end of the backswing (CC: −18.4 ± 13.6°, IO: −19.0 ± 14.2°) and at impact (CC: −30.4 ± 13.3°, IO: −31.3 ± 12.7°) (Table 4.1) in relation to other studies (Elliott et al., 1997; Seeley et al., 2011), although the contribution of this rotation (CC: 4.5%, IO: 5.3%) is in accordance with a study using high-performance forehand players (Elliott et al., 1997). For the abduction, the contribution in the present study (CC: 6.1%, IO: 4.9%) (Table 4.2) was slightly higher compared with participants with an Eastern grip, and inferior to those with a Western grip, during a flat forehand (Elliott et al., 1997).

Although some of the present results were in line with those from the only previous study (Elliott et al., 1997) using this method to calculate the contributions to the racket head velocity in the forehand drive, there were also some discrepancies. Some differences between the two studies should be considered, such as the impact location. In our study, impact occurred inside the court, with players hitting the ball as soon as possible, and in some cases the impact occurred in a position above the net. This may represent a more horizontal movement in comparison with the same stroke performed near the baseline, which may, therefore, present some kinematic differences.

The present findings on the shoulders' alignment to the baseline may be useful to players and coaches for predicting the direction of the opponent's forehand, as also seen in table tennis (Malagoli Lanzoni et al., 2018), and to identify strategies to disguise their own shot. Moreover, this study showed that these differences can occur within the initial 30% period of the forward swing, thus providing additional important information for tennis coaches and players. Considering the similarities of the contributions to the racket head velocity in both directions of the shot we recommend to coaches and athletes specific strength training to develop high angular velocities in the most important racket head velocity contributions. We also highlight the importance of a physiotherapy program to prevent injury (Elliott, 2006) to the external rotators of the shoulder and back muscles, and to compensate for the multiple repetitions of flexion/abduction in the forehand stroke.

Conclusions

The consistency in joint angles when players hit the ball in the CC and IO directions suggests that highly skilled players have greater motor control consistency and show differences only in their shoulder alignment with the baseline. This may represent important information for players and coaches, either to anticipate the opponent's shot or to disguise their own shot. The horizontal flexion of the upper arm (around the shoulder joint) and the extension of the forearm (around the elbow joint) are the most important contributors to the racket head velocity in the forehand drive during an attack situation. Thus, tennis coaches and players should develop a specific training program to develop higher angular velocities in these specific joint rotations. The absence of significant differences in the segment contributions in the two directions of the shot (CC and IO), in terms of most of the joint angles of the upper arm and trunk, demonstrate that an adjustment is made to the feet and the whole body according to the tactical option. Future studies should try to understand the differences in the contributions for different impact locations and levels of expertise.

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Chapter 5

Upper extremity kinetic differences between a quasi-static stance and a dynamic stance in the tennis forehand drive: relationship to racket velocity[4]

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Pedro, B., Cabral, S., & Veloso, A. P. Upper extremity kinetic differences between a quasi-static stance and a dynamic stance in the tennis forehand drive: relationship to racket velocity. Submitted to the *Journal of Biomechanics.*

Abstract

The purpose of this study was to compare the joint moments of force of the upper limb between one forehand drive performed in quasi-static stance (QSS) (with both feet on the ground at the impact) and one forehand performed in dynamic stance (DS) with frontal weight transfer (with both feet off the ground at the impact). Six high-performance tennis players were recorded with an optical system with a frequency of 240Hz during both techniques. Three forehands in QSS and three in DS of each participant were selected for analysis. Results demonstrated that the forehand performed with QSS present higher moments of force, in the shoulder, elbow and wrist joint, although no significant differences were present in racket velocity between both stances. The results of this study could present an important information for tennis coaches as for their players in order to understand which forehand technique creates higher joint loads, and therefore adapt their practice for each situation.

Keywords: upper limb, kinetics, forehand, racket velocity.

Introduction

Tennis is a complex and demanding sport where upper limb injuries can occur during the great amount of repetitions and respective overloading of the joints (Chung & Lark, 2017). The tennis forehand drive is considered the most important technique in tennis after the serve (Reid et al., 2013) and, players try to be as aggressive as they can to win the point (Roetert et al., 2009). Biomechanical research in the tennis forehand drive has focused mostly in kinematic studies such as, the key factors between different levels of expertise (Landlinger et al., 2010b), differences between flat and topspin forehand (Genevois et al., 2020), differences in the forehand kinematics as post-impact ball speed increased (Seeley et al., 2011) and also, it was demonstrated that the most important rotations of the upper limb to the racket head velocity in the forehand drive were the horizontal flexion/abduction and internal rotation of the upper arm (Elliott et al., 1997) and also the extension of the forearm (Pedro et al., 2022). Regarding the kinetic studies focusing the upper limb in the forehand drive there are not many studies as in kinematics. Nevertheless, Bahamonde & Knudson, (2003) compared the kinetics of the upper limbs between the close and open stance and demonstrated that the close stance produced higher torques resulting in higher loads at the upper limb joints.

Most of the studies addressing the tennis forehand have no reference to the stance used by the players (Landlinger et al., 2010a, 2010b; Seeley et al., 2011). Those that defined the stance used by the participants referred mainly the close and the open stance (Bahamonde & Knudson, 2003; Genevois et al., 2020). Nevertheless, in modern tennis there are many variations used by top players in the stance adopted in relation to the ball. A particularly interesting variation when attacking the ball is that the players can hit the ball with their feet off the ground, transferring all their body weight to the ball. This technique used by the players should have implications in their performance as well as on the mechanical load placed upon the upper limb joints. To the best of our knowledge, no study has compared these different forehand drive stances to understand what differentiates quasi-static stance (when the player hit the ball with their feet on the ground) with a more dynamic stance with frontal weight transfer (when the players contact the ball with their feet off the ground). Thus, the aim of this work was to compare (1) the joint kinematics of the upper limb, (2) the joint kinetics of the shoulder, elbow, and wrist, as well as (3) the racket velocity between the tennis forehand drive performed in a quasi-static stance (QSS) and a dynamic stance (DS) with frontal weight transfer.

Methods

Participants

Six male right-handed experienced tennis players (age: 27.2 ± 10.2 years; height: 177.6 ± 3.9 cm; mass: 69,4 ± 5.2 kg), provided written informed consent to participate in this study, which was approved by the Institution’s Ethics Committee (21/2018). All participants were free from injuries, the tennis players practiced regularly between 4h and 10h hours per week, competed at national competitions and had national ranking.

Testing Protocol

The testing session was conducted in a motion analysis laboratory. Participants had 15 min for an individual warm-up, and they could hit as many strokes as they wanted to become familiar with the test environment. Before data collection, participants observed a demonstration of the experimental procedure, and they used their own tennis rackets to ensure they felt as comfortable as possible during the data collection. Each participant was instructed to hit the ball as fast as they could just like in a real match. Each participant performed three forehand drives in QSS (with their feet on the ground at impact) and three forehand drives in DS (with their feet of the ground at the impact) (Figure 5.1) against a hanging cotton cloth of 3X2 m to cushion the ball (Pedro et al., 2021). The tennis balls were thrown by an experienced tennis coach placing the ball into a bounce area for the stroke with 3 seconds between each stroke as in a previous study (Rogowski et al., 2011).

Figure 5.1 - Participant performing the forehand with a quasi-static stance with their feet on the ground at impact (left) and a dynamic stance with frontal weight transfer with their feet off the ground at impact (middle), from the beginning of the acceleration phase until the impact. Racket with four tracking markers (right).

Instrumentation

Full body kinematics were recorded at 240Hz with an optical system (OS) with fifteen infrared high-speed cameras (Oqus 300, Qualisys AB, Sweden) and one video camera (Oqus 210c) to identify the ball contact with the racket, using the Qualisys Track Manager (version 2.17, Qualisys AB, Gothenburg, Sweden) software. The kinematic data were obtained using 43 reflective markers (Figure 5.2) with a 25 mm diameter, placed on the following anatomical landmarks: C7, T8, suprasternal notch, xiphoid, lateral and medial epicondyle of the humerus, acromioclavicular, lateral point of the radial styloid, medial point on ulnar styloid, base of the second and fifth metacarpal proximal phalanges, anterior and posterior superior iliac spines, lateral and medial epicondyles, lateral and medial malleoli and 1st, 2nd and 5th metatarsal heads (Wu et al., 2002, 2005). Additionally, ten rigid light weight clusters with four non-colinear tracking markers were placed laterally on both upper arms, forearms, hands, thighs, and shanks. Five additional tracking markers were placed on the tennis racket of each participant (Figure 5.*1*) (Landlinger et al., 2010b). The standing trial used to create the model was captured with an “n-pose” (with the hands facing medial).

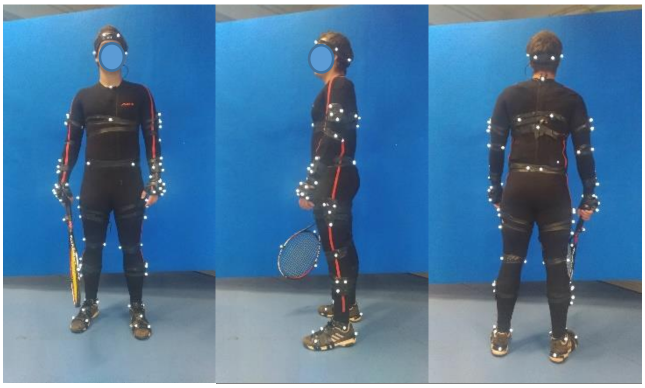

Figure 5.2 – Marker set-up. 43 reflective markers and 10 lightweights with 4 non-collinear tracking markers.

Data Processing

The 3D marker trajectories during the standing and forehand drive trials were identified in Qualisys Track Manager software and exported to c3d format, and filtered in Visual 3D using a 4th order low-pass Butterworth filter with a cut off frequency of 15 Hz (Martin et al., 2014). Using the markers' coordinates during the standing trial, a biomechanical model was built with 16 segments (head, thorax, upper-arms, forearms, hands, racket, pelvis, thighs, shanks, and feet). The segments' POSE was computed from the trajectories of the tracking markers using a segment optimization (Spoor & Veldpaus, 1980). The inertial parameters of the participants' segments were computed based on Hanavan (1964), while segment masses were determined according to Dempster, (1955). The moment of inertia of the racket about its medial-lateral axis was computed using the parallel axis theorem and published racket "swingweight" data (USRSA, 2010, as suggested by Elliott et. al. (2003). Racket moment of inertia about the long-axis was calculated as reported in the literature (Brody, 1985):

$$\text{Moment of inertia } (\text{kg/m}^2) = (\text{mass} \times \text{head width}^2) / 17.75$$

Racket moment of inertia about its anterior-posterior axis was the sum of the racket's other two principal moments of inertia (Brody, 1985). The separation angle (difference between shoulders and pelvis in transverse plane) and the angles for the shoulder, elbow, wrist, hip, knee and ankle joints from the dominant side were calculated using a ML-AP-Axial Cardan sequence (Grood & Suntay, 1983). All angles were time normalized to the period between the first movement of the racket shaft in the direction of the shot until the last frame before impact (Landlinger et al., 2010a). The Netwton-Euler inverse dynamics approach (Robertson et al., 2014) was used to calculate the joint moments of force. All modelling and variable calculations were performed in Visual 3D software (Visual 3D Professional V5.01.21, C-motion, Germantown, MD).

Statistical Analyses

All statistical analyses were performed using SPSS version 20 (SPSS Inc. Company, Chicago). Means and standard deviation of the upper arm, forearm, hand, and racket variables were calculated. Data were first tested for normality using the Shapiro-Wilk test ($p < 0.05$). The presence of statistical differences in peak joint moments of force (Nm) and racket head velocity at impact between QSS forehand and DS forehand was accessed with a paired t-test, for variables with normal distribution, and with a Wilcoxon Matched-Pairs Signed Ranks test, for those that deviated from a normal distribution. The level of significance was set at $p \leq 0.05$. For the paired t-test, the effect size (ES) was calculated as the Cohen's d, where = 0.2, = 0.5, and = 0.8, represent small, medium, and large effect sizes (Cohen, 1988), respectively. For the Wilcoxon Matched-Pairs Signed Ranks test, the level of significance was set at $p \leq 0.05$ and effect size (r) was defined as small ($r =0.1$), medium ($r = 0.3$), and large ($r = 0.5$) (Pallant, 2011). The 3 shots with QSS and the 3 shots with DS of each participant (36 shots in total) were chosen for analyses from the beginning of the racket movement in the direction of the ball until ball contact.

Differences in joint angles and angular velocities between the stances were tested with the one dimensional (1D) statistical parametric mapping (SPM) to shows where significant differences occur during the entire waveform over the entire curve. More specifically, SPM-1D using a paired sample t-test was used to compare each joint angle curve between the QSS and the DS. The SPM-1D method uses random field theory to identify field regions which co-vary significantly with the experimental design (Friston et al., 1995; Pataky et al., 2013; Pataky, Robinson, et al., 2016). Differences were considered statistically significant for p-values < 0.05. All SPM analyses were performed in Python 2.7 using the open source package located at http://www.spm.1d.org/ (Pataky, Vanrenterghem, et al., 2016).

Results

The SPM-1D analysis comparing joint angles (Figure 5.3) of the upper limb showed significant differences in the wrist frontal and sagittal plane between 77-85% and 0-10% of the event, respectively. The SPM-1D analysis comparing the upper limb angle velocities (Figure 5.4) showed significant differences for shoulder angle velocities in frontal plane between 55-70% of the event and in the sagittal plane between 5-23% and between 70-80% of the event. The elbow angle velocity showed significant differences in the sagittal plane between 40 and 55% of the event. The wrist angle velocities showed significant differences in the frontal plane between 65-74% and at the end of the event (80-100%). Table 5.1 show the peak joint moment of force during the acceleration phase between both stances and the maximal racket tip velocity in both techniques. Moments of force were significantly different in shoulder extension and internal rotation, in the elbow varus and supination and in the wrist radial deviation and flexion.

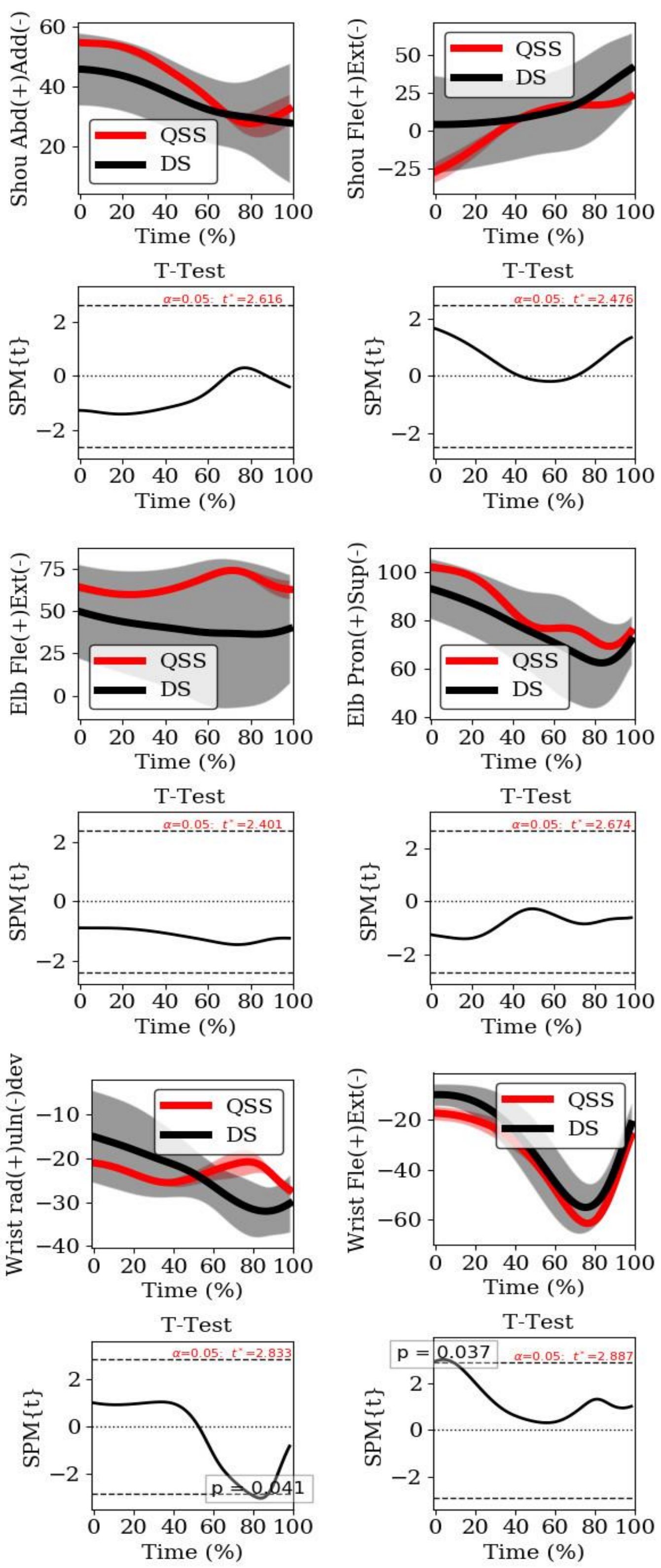

Figure 5.3 - Joint angles and the respective 1D-SPM results, during the time normalized acceleration phase, between the QSS (red line) and the DS (black line). Shoulder abduction/adduction, shoulder flexion/extension, shoulder pronation/supination, elbow flexion/extension, elbow pronation/supination, wrist abduction/adduction and wrist flexion/extension. The horizontal positive and negative dashed lines indicate the threshold test values (t* values). Grey shaded regions indicate where differences were statistically significant.

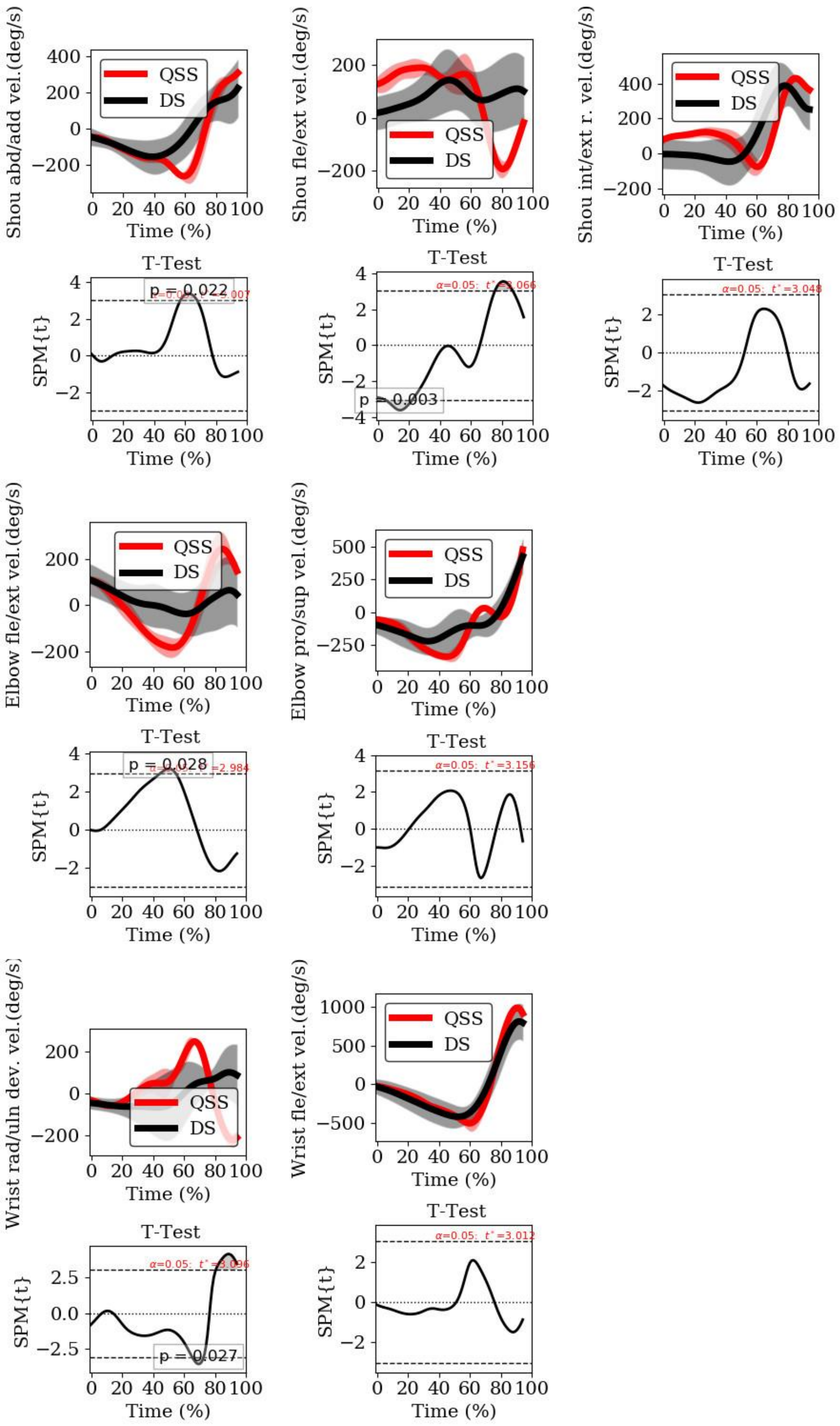

Figure 5.4 - Joint angular velocity and the respective 1D-SPM results, during the time normalized acceleration phase, between the QSS (red line) and the DS (black line). Shoulder abduction/adduction, shoulder flexion/extension, shoulder pronation/supination, elbow flexion/extension, elbow pronation/supination, wrist abduction/adduction and wrist flexion/extension. The horizontal positive and negative dashed lines indicate the threshold test values (t* values). Grey shaded regions indicate where differences were statistically significant.

Table 5.1 **-** Mean and standard deviation of peak joint moments of force (Nm) performed during the acceleration phase of the forehand drive in quasi-static stance (QSS) and in dynamic stance (DS).

Variables	QSS - Mean ± SD or Md (n)	DS - Mean ± SD Or Md (n)	Stat. Test	p-value	ES
Shoulder					
Abduction (+)	31,1 ± 14,6	32,4 ± 12,2	-0,472	0,643	-0,11
Adduction (-)	-10,4 ± 7,3	-11,9 ± 7,0	0,867	0,398	0,20
Flexion (+)	35,9 ± 17,5	37 ± 12,2	-0,337	0,740	-0,08
Extension (-)	-20,1 ± 3,5	-16,5 ± 4,1	-3,333	0,004+	-0,79
Internal rotation (+)	35,4 ± 5,5	29,2 ± 9,3	3,128	0,006+	0,74
External rotation (-)	-38,1 (18)	-23,7 (18)	-1,938	0,053	-0,32
Elbow					
Varus (+)	7,5 ± 2,7	6,3 ± 2,3	2,787	0,013+	0,66
Valgus (-)	-12 ± 4,9	-10,8 ± 4,9	-1,287	0,215	-0,30
Flexion (+)	5,2 ± 6,0	3,6 ± 3,2	1,582	0,132	0,37
Extension (-)	-8,4 (18)	-8,0 (18)	-0,196	0,845	-0,03
Pronation (+)	12,8 ± 4,2	12,4 ± 3,3	0,564	0,580	0,13
Supination (-)	-6,4 (18)	-3,8 (18)	-2,373	0,018+	-0,40
Wrist					
Flexion (+)	4,6 ± 1,7	4,0 ± 1,6	2,926	0,009+	0,63
Extension (-)	-0,9 ± 0,4	-1,0 ± 0,4	0,430	0,672	0,69
Radial (+)	2,9 ± 0,6	2,6 ± 0,5	2,674	0,016+	0,10
Ulnar (-)	-1,0 (18)	-0,9 (18)	-0,065	0,948	-0,11
Racket Tip Vel. at impact	27.9 ± 3.4	27.7 ± 3.5	0,479	0,638	0,11

To better interpret the findings, we defined: negative shoulder joint moments indicate adduction, extension, and external rotation; negative elbow joint moments indicate valgus, extension, and supination; negative wrist joint moments indicate extension and ulnar deviation.

Discussion

The purpose of this study was to compare the kinematics and kinetics of the upper limb between two different forehand drives, one in a QSS (with both feet on the ground at the impact) and one with DS (with both feet off the ground at the impact) and to identify if the DS presented a higher racket velocity. The results showed similar racket velocity and upper limb joint angles between both stances except for the wrist flexion in the beginning of the event and in the wrist radial deviation just before the end of the event. The joint angular velocities presented higher peak velocities when the players hit the ball with their feet on the ground in all the three joints (Figure 5.4). In the same way, the peak joint moments with significant differences presented higher values in the three joints of the upper arm when the players hit the ball with their feet on the ground (QSS).

The racket velocity was similar between both stances (QSS: 27.9 ± 3.4 vs DS: 27.7 ± 3.5 m/s) demonstrating that we could not associate a higher racket velocity to any of the stances. The racket velocity of our study was similar to high-performance tennis players when playing down the line and in the cross court direction with 27.8 and 30.4 m/s respectively (Landlinger et al., 2010a), and superior to (Elliott et al., 1997) with 17.0 and 16.6 m/s in the center of the racket in a flat and top spin forehand respectively. Although the study was performed in the laboratory, the players were able to achieve similar velocities to those observed in previous studies in a real environment.

Shoulder joint angles showed a higher abduction, extension, and external rotation at the beginning of the acceleration phase in the QSS (Figure 5.3). This higher range of motion in the beginning of the acceleration phase in the three axes of the shoulder, could be a distinguish factor between the two stances. Previous study showed higher shoulder external rotation values at impact in a fast forehand performed by highly skilled tennis players (Seeley et al., 2011), on another hand, similar elbow flexion values were presented by elite and high-performance tennis players (Landlinger et al., 2010a) at impact. Considering the wrist joint angle, the QSS showed an inferior ulnar pattern just before the impact, although a higher flexion of the wrist in the beginning of the acceleration phase (Figure 5.3). Similar extension wrist values were demonstrated by (Seeley et al., 2011).

Considering the angular velocities, the higher peak velocities shown in the QSS (Figure 5.4) could be explained by the higher range of motion presented in the shoulder joint angle in the beginning of the acceleration phase (Figure 5.3). More specifically, significant differences were shown in shoulder angular velocity in sagittal plane in the beginning of the forward swing where the QSS demonstrated a higher angular velocity and in the anterior-posterior plane in the middle of the event. Similar internal rotation angular velocities were described in previous studies with highly skilled tennis players (Seeley et al., 2011) although, inferior to elite and high-performance tennis players (Landlinger et al., 2010b). The peak elbow flexion angular velocity in QSS were similar to elite tennis players (Landlinger et al., 2010a). Similar wrist flexion angular velocities were observed by highly skilled tennis players (Seeley et al., 2011).

The peak joint moments of force presented the largest magnitudes in the shoulder, followed by the elbow and the wrist as shown in a previous study with teaching professionals and intermediate tennis players (Bahamonde & Knudson, 2003). The QSS showed higher peak joint moments of force in the majority of the three joints of the upper limb with the exception of the shoulder abduction and adduction, shoulder flexion, and wrist extension, although, significant differences were only noticed at the shoulder extension, internal rotation, elbow varus and supination and wrist flexion and radial deviation (Table 5.1). We believe that the inferior magnitude of joint moments of force presented in the DS could be related to the higher momentum created throughout all body during the acceleration phase, consequently hitting with the feet off the ground.

The shoulder peak joint moment of force (QSS: 35,4 ± 5,5 vs DS: 29,2 ± 9,3) obtained in internal rotation were similar to intermediate tennis players (Bahamonde & Knudson 2003) in the square and open stance, although, inferior when compared with professional players in square stance. Our results presented inferior peak joint moments, in comparison with the ones from the same study, for the flexion of the shoulder (Bahamonde & Knudson 2003). These differences could be explained by individual differences in the forehand technique. Moreover, our study was developed inside the laboratory which could have some influence in the performance of the participant. On the other hand, in the abduction of the shoulder, we have observed higher values compared to intermediates tennis players during the open and the square stance (Bahamonde & Knudson, 2003), which can be explained by a considerable abduction at the beginning of the acceleration phase. On the other hand, and despite a different technique, Creveaux et al. (2013) showed higher joint moments in shoulder during the tennis serve, during the upward acceleration in all three axis of rotation. The higher peak joint moments of force of the shoulder are in line with Elliott et al. (1997) that considered that the higher contributions to the racket head velocity were related to the flexion/abduction of the upper arm and the internal rotation of the upper arm regardless of the grip used by the players. The shoulder joint presented the large peak moment of forces values, followed by the elbow and the wrist, the same pattern was shown during the tennis serve (Martin et al., 2014).

The elbow peak joint moments were superior for the pronation, inferior for varus and inferior for flexion of the elbow compared with teaching professionals tennis players (Bahamonde & Knudson, 2003).The wrist peak moments for flexion were similar to teaching professionals in square stance and inferior to intermediate players (Bahamonde & Knudson, 2003).

Limitations of the study are related to the small number of participants, although, as the level of the participants was high-performance it can be acceptable (Harrison et al., 2020). Furthermore, this study was a non-ecological study performed inside the laboratory, thus, a more ecological study in a real tennis court should be considered for future studies.

Conclusion

This study identified the peak joint torque between one forehand in quasi-static stance and one forehand in dynamic stance with weight transfer both in close stance. Our results suggest that the players create higher loads when they hit the ball with their feet on the ground, moreover, the racket velocity between both techniques were similar. These results could present a valuable information for coaches and players to make better decisions concerning the practice and to select the better technique in different game situations, also to physiotherapists to understand which technique create higher loads and their associations to upper limb injuries.

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Chapter 6

General Discussion

Discussion

The aim of this thesis was to provide a better understanding of the determinant factors in tennis forehand drive between different levels of expertise, different directions of the shot, and different stances to perform this technique. Our methodological approach incorporated two different systems to collect the data, one optical system that was used inside the laboratory and one inertial measurement system that was validated and used outside of the laboratory. This chapter will summarise and discuss the main findings of each of the studies of this thesis.

Main Findings

Study 1 - Upper limb kinematics and their contribution to racket head velocity during a tennis forehand: differences between intermediate and high-performance tennis players

Understanding what could differentiate a tennis forehand drive of an intermediate from a high-performance tennis player could present an important information to tennis coaches to focus on the key factors that could lead an intermediate tennis player to achieve a higher performance. Therefore, the aim of the first study (Chapter 2) was to investigate the differences of the kinematic and the contributions of the upper limb rotations to the racket head velocity between intermediate and high-performance tennis players. Contrary to what we could expect, the racket velocity between both levels in this study presented similar values. These velocities were in line with a previous study with advanced tennis players (Knudson & Blackwell, 2005), although, higher velocities were observed in elite and high-performance tennis players (Landlinger et al., 2010a) (31.1 ± 2.1 m/s and 29.1 ± 1.7 m/s). The separation angle, a key factor to accumulate elastic energy at the end of the backswing (Elliott, 2006), presented inferior values when compared with a previous study by Takahashi et al. (1996). This could be explained by the close stance performed by participants during the trials. On another hand, at the impact, we corroborate our results with previous studies for the elbow joint angles (Landlinger et al., 2010a). The more experienced tennis players presented higher linear shoulder velocity, these differences were previously demonstrated between elite and high-performance tennis players (Landlinger et al., 2010a). These differences should be considered by tennis coaches to develop higher linear shoulder velocities to develop intermediate tennis players. The method used to calculate the contributions of upper limb rotations to the racket head velocity (Sprigings et al.,1994) was already used to compare different grip styles to hold the racket (Elliott et al., 1997), although, and to the best of our knowledge, this was the first study using this method to compare the contributions between different level of expertise in the tennis forehand drive. Our study showed that what differentiates intermediates form the high-performance tennis players was the higher contribution of the shoulder to the racket head velocity.

Study 2 - Concurrent validity of an inertial measurement system in tennis forehand drive

After understanding what differentiates the intermediate from the high-performance tennis players, we follow the purpose of recording kinematic data with elite athletes in an ecological environment to understand the contributions of the upper limb rotations to the racket head velocity. However, before achieving that goal, we needed an easier, faster, and reliable system to record kinematic data outside of the laboratory. Thus, before we could use it with confidence, we needed to validate the system with a reference system in the specific task. Thus, the aim of the second study (Chapter 3) was to analyse the concurrent validity of an IMUs system for the assessment of upper and lower limb angular kinematics during a tennis forehand drive, using an optical motion capture system as criterion. Results of our study showed excellent correlation (CMC) for most of the joint angles, the RMSE varied from acceptable to tolerable and the SPM analysis demonstrated agreement during 70 to 100% of the forward swing for most of the joint axes.

Similar results were demonstrated during simulated swimming (Fantozzi et al., 2016) and in handling tasks for the sagittal plane of the shoulder and hand. On another hand, our study presented higher agreement in sagittal plane compared with a repetitive movement task for shoulder, elbow and hand (RMSE > 10°) (Bessone et al., 2019) as well as for elbow (CMC: 0.95, RMSE: 12-17°) during an ergonomic task (Robert-Lachaine et al., 2017). For the lower limbs, similar results were shown in previous studies where the lower limbs presented excellent CMC and RMSE in other activities, such as walking, stair ascent and stair descent (Zhang et al., 2013, CMC ≥ 0.96) and ergonomics (Robert-Lachaine et al., 2017, CMC: 0.95-1, RMSE: 2.2-3.8°) in the sagittal plane for all three joints of the lower limbs. The transverse plane showed inferior error magnitude compared to a wheel movement for shoulder (Bouvier et al., 2015). This good accuracy in this plane could be associated to the equivalent model used between systems. On another hand, differences in elbow transverse plane could be associated to some movement in the hand while the participants held the racket between IMUs calibration and the static trial of the OS. Overall, these findings of this study represent a significant contribution to a more frequent use of IMUs in tennis, as in other rackets sports as padel and badminton.

Study 3 - Evaluation of Upper Limb Joint Contribution to Racket Head Speed in Elite Tennis Players Using IMU Sensors: Comparison Between the Cross-Court and Inside-Out Attacking Forehand Drive

After we finish our validation study with the IMUs system, we had the confidence to collect data with elite athletes in real environment in the tennis court. Therefore, this study aimed to quantify and compare the kinematics and the contributions of the upper limb (upper arm, forearm, and hand) segments' rotation to the racket head velocity in a tennis forehand during an attacking situation of elite tennis players, when players performed the forehand drive in the cross-court and the inside-out directions. We hypothesized that the two directions of the shot (CC and IO) would present (a) different upper limb angular kinematics, and (b) different contributions of the upper limbs to the racket head velocity. Our study showed similar racket velocities to previous studies with state ranking tennis players (Elliott et al., 1989) and somewhat superior racket velocities compared to high-performance tennis players (Elliott et al., 1997). Shoulder alignment with the baseline showed similarities with previous studies (Elliott et al., 1997; Landlinger et al., 2010a), although, significant differences in shoulder alignment were found between the two directions of the shot. These differences occurred in the beginning of the forward swing, between 0 and 30% of the event, showed in SPM analysis. Furthermore, these differences may present an important key factor if noted by players to anticipate the opponent's shot direction. On another hand, it was shown that the flexion/abduction of the upper arm (around the shoulder joint) was considered the most important contribution to the racket head velocity, followed by the extension of the forearm (around the elbow joint) and the internal rotation of the upper arm (around the shoulder joint). Previous studies (Elliott et al., 1997) using the same method (Sprigings et al., 1994) to calculate these contributions presented the internal rotation of the upper arm as the most important rotation to the racket head velocity. These considerable differences could be associated to the ball impact height due to the specificity of the stroke inside the tennis court, where a more horizontal movement may be present in our study. Overall results could give an important contribute to tennis coaches, to anticipate the direction of the shot of the opponent's forehand and helping to develop a specific training program to develop higher angular velocities in these specific joint rotations.

Study 4 - Kinetics of upper extremity between a quasi-static stance and a dynamic stance in the tennis forehand drive: relationship to racket velocity and risk injury

After providing an extensive description of the tennis forehand kinematics our goal was also to describe the kinetics of the upper limb associated to different stances. Thus, the aim of the fourth study was to compare the joint kinetics of the shoulder, elbow, and wrist, between the tennis forehand drive performed in a quasi-static stance and a dynamic stance with frontal weight transfer and the racket velocity between both stances. Contrary to what we expected, the results showed similar racket velocities between both stances, thus, we could not associate a more dynamic stance to a higher racket velocity. To the best of our knowledge, this was the first study to compare these two different stances. Previous studies have compared open and close stance forehand racket velocities (Knudson & Bahamonde, 1999) and also with no significant differences between stances. The upper limb joint angle patterns did not differ between both stances except for the wrist joint. We corroborate the upper limb joint angles with previous studies (Landlinger et al., 2010a; Seeley et al., 2011). On another hand, the angular velocities presented higher values when the players hit the ball with their feet on the ground in all three joints of the upper limb. Similar internal rotation angular velocity were described in previous studies with highly skilled tennis players (Seeley et al., 2011) although, inferior to elite and high-performance tennis players (Landlinger et al., 2010b). The upper limb peak joint moments of force presented the largest magnitude in the shoulder, followed by the elbow and the wrist as shown in a previous study with teaching professionals and intermediate tennis players (Bahamonde & Knudson, 2003). The quasi-static stance presented higher moments of force in the majority of joint axis of the upper limb. The higher magnitude presented when players hit the ball with their feet on the ground in contrast to when they hit the ball with the feet off the ground, is perhaps because a more effective use of the linear displacement of the body is presented when hit the ball with their feet off the ground. The results suggest that players should jump to the ball with the aim of anticipate and not with the purpose of gain some ball velocity.

Conclusion

The work of this thesis consists in a detailed studied of biomechanical determinant factors in the tennis forehand drive. More specially, between different levels of expertise, between different shot directions of elite tennis players, the kinetics between two different stances and a validation of an IMUs for the tennis forehand drive.

Methodological considerations

Although the materials and methods present a detailed description (chapter 2 to 6), there are still some methodological considerations that justify a more comprehensive description which will be focused on the following paragraphs.

Motion Capture and 3D modelling reconstruction study 1 and 4

To record the kinematic data, an optoelectronic stereophotogrammetry system was used, which is the most used system to record human movement. It is composed by a set of cameras defining the measurement volume and the system provides the location (Cartesian coordinates) of point markers either emitting or retro-reflecting light, located on the skin surface relative to a global coordinate system. This procedure is performed by mathematical operations throughout the received 2-D coordinates of each marker that should be captured at least by two cameras during each instant.(Müller & Wolf, 2018).

The frame rate used to capture the desire movement should be adequate to ensure that the maximum and minimum displacement of each joint and limbs, and other key events as ball impact are recorded. Although a higher capture rate will therefore improve the precision and accuracy of the date during the selected movements. Thus, higher capture rates are specially important during activities like tennis, which studies have been using the suggested capture rates between 200-500Hz (Payton & Barlett, 2008). In our case we used 240Hz because we were able to detect the ball contact instant.

In the second study the use of 120Hz to capture the data could be questioned. Indeed, a higher capture rate could give us a more valuable information about the kinematic and more importantly, with 240Hz we ensure the contact ball contact instant which it’s not always possible with 120Hz, because the impact has a quite short duration. In activities with high velocities like tennis, some studies used motion capture rate of 240Hz (Seeley et al. 2011) or even higher (400Hz) (Landlinger et al., 2010). It is suggested that activities as tennis, the captures rate should be between 200-500Hz. Although, at the time of the study the IMUs available was of 120Hz that’s why we used this frame rate. Moreover, in this study we defined the ball contact with a video camera Oqus 210c (Qualisys AB, Gothenburg, Sweden) operating at 240 Hz in Qualisys Track Manager (version 2.10., Qualisys AB, Gothenburg, Sweden).

Marker set

The marker set used for movement analysis captures with the optoelectronic system was based on the on the ISB recommendations for shoulder, elbow, wrist and hand (Wu et al., 2005) following the standard local axis system for each articulation segment. Markers were placed on the following anatomical landmarks: C7, T8, suprasternal notch, xiphoid process, lateral and medial epicondyle of the humerus, acromioclavicular joint, lateral point of the radial styloid, medial point on ulnar styloid, base of the second and fifth metacarpal proximal phalanges, anterior and posterior superior iliac spines, lateral and medial femoral epicondyles, lateral and medial malleoli and 1st, 2nd and 5th metatarsal heads (Wu et al., 2002, 2005). Moreover, ten rigid light-weight clusters with four non-collinear tracking markers were placed laterally on both upper arms, forearms, hands, thighs, and shanks.

To compute the position and orientation (POSE) of each rigid body there are three classes of algorithms: a direct method, a segment optimization method, and a global optimization method. One limitation about the direct pose estimation is the lack of redundancy in the markers and require that all the markers appear in every frame which could present some problems during the dynamic trials. The segment optimization method also known as the six degrees of freedom (six DOF) where each segment has at least three tracking markers and all six variables that describes its pose are estimated. One limitation about this method it's the lack of explicit linkage connection between segments. The global optimization method is referred as the search for an optimal pose of the multisegment model that minimizes the differences between the measured and the model-determined marker coordinates across all body segments (Robertson et al., 2014). Thus, considering the advantages and limitations of each of the methods we used the segment optimization method whenever the optical system was present.

Filter cut-off frequency

For the biomechanical recordings, the signal and noise will significantly overlap the frequency domain. The selection of an appropriate cut-off frequency is needed to remove the noise maintaining however as much signal as possible. The kinematic data are relative contain a higher error associated due to skin movement artifacts and marker vibration compared with the force platform measures, thus, researchers usually use a relatively low cut-off frequency (e.g. 10-20Hz) while the data from force platform are presented raw or with somewhat high cut-off frequency (50-100Hz) (Müller & Wolf, 2018) Thus, the choice of 10 Hz for filtering the kinematic signals of our studies were based in the previous literature and also in other studies focusing the tennis forehand (Seeley et al., 2011). On the other hand the fourth study we use a 15Hz low pass filter as (Martin et al., 2014) in upper limb joint kinetic analysis during tennis serve (Martin et al., 2014).

IMU 3D orientation

Accordingly, to Vries et al. (2009) the magnitude of distortion of the earth magnetic field depends on the material used in the surrounded area and should be considered on the effect of the disturbances on the accuracy of the orientation estimation with IMUs. Thus, to obtain a valid data it is recommended to “map” the laboratory on ferromagnetic characteristics before validating, and when calibrating against a reference system, the recordings should start at the same location, ensuring a constant offset and offset correction. It is referred that the Kalman filter is less sensitive to magnetic (Vries et al., 2009), which is what was used by the IMUs used in this study. Moreover, every measurement of our study had started at the same location in a safe area where the calibration took place.

Recommendations for future research

Future studies should try to understand if differences in the contributions are present also between other levels of players like elite players and also the forehand drive performed with different stances.

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Thesis related outcomes

First author papers in scientific journal

Published

Pedro, B.; João, F.; Lara, J.P.R.; Cabral, S.; Carvalho, J.; Veloso, A.P. Evaluation of Upper Limb Joint Contribution to Racket Head Speed in Elite Tennis Players Using IMU Sensors: Comparison between the Cross-Court and Inside-Out Attacking Forehand Drive. Sensors 2022, 22, 1283.

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Bruno M. M. Pedro, Sílvia A. R. Cabral, Jerusa P. R. Lara, António P. Veloso. Upper limb kinematics and their contribution to racket head velocity during a tennis forehand: differences between intermediate and high-performance tennis players. Scandinavian Journal of Medicine & Science in Sports.

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