DOCTORAL THESIS

Biomechanical, force-time curve and neuromuscular training impact on serve performance in high level tennis players

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UNIVERSITAT DE VIC
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Escola de Doctorat

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Dedicat a la Roser, a la Mireia i a l’Alba.

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LIST OF PUBLICATIONS

This thesis is based on the following publications:

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STUDY IV

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Quartile: Q1 (20/87)

Category: Sport Sciences

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ABSTRACT

Tennis serve is considered the most complex, powerful and determinant stroke in high level tennis competition. Specifically, serve velocity (SV) alongside serve accuracy (SA) plays a preponderant role in elite competitions. Considering that serve performance is influenced by different kind of parameters, the presented doctoral thesis was planned in order to provide a multifactorial approach of the topic of the study. The influence of disparate nature of variables on SV and SA in real match (**study I**), laboratory (**study II**) and training (**study III and IV**) conditions were analyzed. To begin, we determined the influence of anthropometric, ball impact and landing location parameters in elite tennis competition (**study I**). Then, we analysed the associations between SV and various single-joint upper limb isometric force-time curve parameters (Isometric force [IF], rate of force development [RFD] and impulse [IMP]) in competition tennis players (**study II**). Finally, we observed if joint-specific post-activation potentiation enhancement (PAPE) and isometric strength training (IST) training methods improves SV in young tennis players (**study III and IV**). We conclude that anthropometric, ball impact and bounce landing location parameters influence SV during a professional competition. We demonstrate that force-time parameters (IF, RFD and IMP) at different time frames in upper limb joints involved in the serve kinetic chain moderate to very largely influence SV in competitive players. Concretely, the capability to develop force in short periods of time (< 250 ms) in the shoulder joint was shown to be relevant to develop high SV. Lastly, we proved that performing two short upper-limb tennis-specific joint isometric exercises elicits PAPE increasing SV without SA impairment. In addition, combining 6-week of IST with the habitual tennis workouts results in significant increases in SV without SA detriment in young competitive players.

RESUM

El servei de tenis es considera el cop més complex, potent i determinant en el tennis d'alt nivell. En concret, la velocitat (SV) conjuntament amb la precisió (SA) de servei juga un paper preponderant en competicions d'elit. Considerant que el rendiment del servei està influenciat per diferents tipus de paràmetres, la tesi doctoral es va organitzar per abordar la temàtica d'estudi des d'un enfocament multifactorial. Es va analitzar la influència de variables de naturalesa dispar en la SV i SA en condicions de partit real (**estudi I**), laboratori (**estudi II**) i entrenament (**estudi III i IV**). Per començar, vam determinar la influència de paràmetres antropomètrics, d'impacte i de la ubicació d'aterratge de la pilota en una competició de tennis d'elit (**estudi I**). Després, vam analitzar les associacions entre SV i diversos paràmetres de la corba força-temps de les extremitats superiors (força isomètrica [IF], taxa de desenvolupament de força [RFD] i impuls [IMP]) en tennistes de competició (**estudi II**). Finalment, vàrem observar si els mètodes d'entrenament de força isomètrica màxima (IST) i de potenciació postactivació (PAPE) milloren la SV en jugadors de tennis joves (**estudi III i IV**). Concloem que els paràmetres antopometrics, d'impacte i la ubicació d'aterratge de la pilota influeixen la SV durant una competició professional. Es demostra que els paràmetres de força-temps (IF, RFD i IMP) de les articulacions de les extremitats superiors involucrades en la cadena cinètica de servei influeixen de manera moderada a gran la SV en jugadors de tennis de competició. En concret, la capacitat de desenvolupar força en períodes curts de temps (<250 ms) de l'articulació de l'espatlla es va demostrar que era rellevant per desenvolupar una elevada SV. Finalment, demostrem que la realització d'exercicis basats en la IF de l'articulació de l'espatlla provoca el fenomen de PAPE augmentant el SV sense deteriorament SA. A més, la combinació de 6 setmanes de IST amb els entrenaments habituals produeix augments significatius en la SV sense perjudici de la SA.

RESUMEN

El servicio de tenis se considera el golpe más complejo, potente y determinante en el tenis de alto nivel. En concreto, la velocidad (SV) juntamente con la precisión (SA) de servicio juegan un papel preponderante en competiciones de élite. Considerando que el rendimiento del servicio está influenciado por diferentes tipos de parámetros, la tesis doctoral se organizó para abordar la temática de estudio desde un enfoque multifactorial. Se analizó la influencia de variables de naturaleza dispar en la SV y SA en condiciones de partido real (**estudio I**), laboratorio (**estudio II**) y entrenamiento (**estudio III y IV**). Para empezar, determinamos la influencia de parámetros antropométricos, de impacto y de ubicación de aterrizaje de pelota en una competición de tenis de élite (**estudio I**). Después, analizamos las asociaciones entre SV y parámetros de la curva fuerza-tiempo de las extremidades superiores (fuerza isométrica [IF], tasa de desarrollo de fuerza [RFD] e impulso [IMP]) (**estudio II**). Finalmente, observamos si los métodos de entrenamiento de fuerza isométrica máxima (IST) y de potenciación postactivación (PAPE) mejoran la SV (**estudio III y IV**). Concluimos que los parámetros antropométricos, de impacto y ubicación de aterrizaje de pelota influyen la SV durante una competición profesional. Se demuestra que los parámetros de fuerza-tiempo (IF, RFD e IMP) de las articulaciones de las extremidades superiores involucradas en la cadena cinética de servicio influyen de manera moderada a grande la SV. En concreto, la capacidad de desarrollar fuerza en periodos cortos de tiempo (<250 ms) de la articulación del hombro fue relevante para desarrollar una elevada SV. Finalmente, se demuestra que la realización de ejercicios basados en la IF de la articulación del hombro provoca el fenómeno de PAPE aumentando la SV sin deterioro de la SA. Además, la combinación de 6 semanas de IST con los entrenamientos de tenis habituales produce aumentos significativos en la SV sin perjuicio de la SA.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ANOVA – Analysis of variance

ATP – Association of Professional Tennis Players

BH – Body height

BM – Body mass

BMI – Body mass index

CA – Conditioning activities

CSL – Centre service line

CV – Coefficient of variation

DB - Double fault

DCSL – Distance from the centre service line (with)

DSL – Distance from the bounce to the service line (depth)

EE – Elbow extension

EF – Elbow flexion

ES – Effect size

Fps – Frames per second

FS – Fastest serves

FS1 – Fastest first serve

FS2 – Fastest second serve

FSV – Fastest serve velocity

FSV1 – Fastest first serve velocity

FSV2 – Fastest second serve velocity

GHz – Gigahertz

HSV – High serve velocity

Hz – Hertz

ICC – Intraclass correlation coefficient

IF – Isometric force

IH – Impact height

IMP – Impulse

IPA – Impact projection angle

IPF – Isometric peak force

IST – Isometric strength training

ITF – International Tennis Federation

ITN – International Tennis Number

LSV – Low serve velocity

MBT – Medicine ball throws

MVIC – Maximal isometric voluntary contractions

PAP – Post-activation potentiation

PAPE – Post-activation performance enhancement

PRFD – Peak rate of force development

RFD – Rate of force development

RIH – Relative impact height

ROM – Range of movement

S1 – First serve

S2 – Second serve

SA – Serve accuracy

SD – Standard deviation

SEE – Standard error of estimate

SHE – Shoulder extension

SHER – Shoulder external rotation

SHF – Shoulder flexion

SHIR – Shoulder internal rotation

Sig. – Significance value

SL – Service line

SSC - Stretch-shortening cycle

SV – Serve velocity

SV1 – First serve velocity

SV2 – Second serve velocity

TS – Total serves

TS1 – Total first serves performed

TS2 – Total second serves performed

TSV – Total performed serves velocity

TSV1 – Total first serve performed velocity

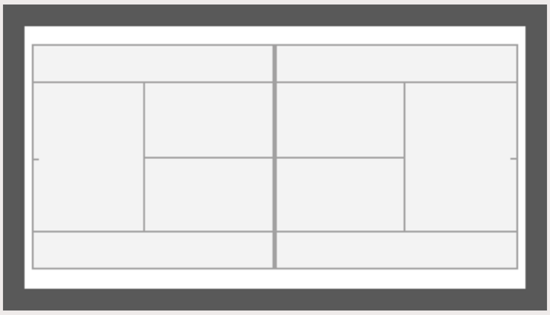
TSV2 – Total second serves performed velocity

WE – Wrist extension

WF – Wrist flexion

WTA – Women’s Tennis Association

1 INTRODUCTION



1.1 Tennis serve

In all tennis matches and points, players start the game with the serve and it is one of the most repeated strokes in high level competition (Whiteside & Reid, 2017b). Moreover, the tennis serve is the unique stroke in a tennis match in which players have an entire control over the ball trajectory. Serve is a high-speed movement currently considered the most important, powerful and determinant shot in professional tennis (Fitzpatrick et al., 2019) and also in young tennis players (Ulbricht et al., 2016). From a technical and biomechanical perspective, tennis serve could be contemplated as the most complex tennis stroke (Kovacs & Ellenbecker, 2011b).

Alongside the recent evolution of tennis performance, the serve velocity (SV) has played a preponderant role in elite tennis competitions (Gillet et al., 2009). It could be said that being capable of serving at high velocities is a prerequisite to reach a high performance tennis level (Fitzpatrick et al., 2019; Ulbricht et al., 2016). An increasing SV diminishes the time for the opponent to return the ball properly and increment the probability of the server's dominance in the following play or of achieving a direct point (Vaverka & Cernosek, 2016). The importance of the tennis serve is especially remarkable if we take into consideration that about 60% of rallies in the whole match in both genders finishes within the first four shots (Carboch et al., 2018) (Figure 1). All these aspects considered, tennis coaches are trying to emphasize training strategies aimed to increase serve performance.

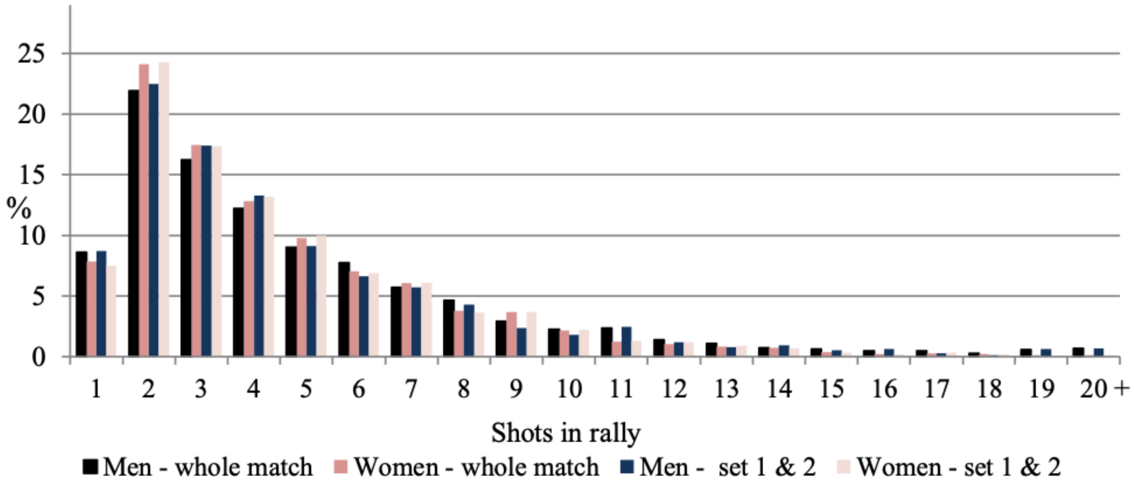


Figure 1. Frequency analyses of rally shots in men's and women's matches (Reproduced from Open Access Carboch et al., 2018).

1.2 Tactical and strategic serve relevance

Tennis performance is characterized by a complex interaction between physical, psychological, tactical, strategical, and technical abilities (Kovacs, 2006). When analyzing world-class tennis players, different player profiles can be observed. However, from a tactical and strategic perspective, a broad consensus exist considering that serve performance is a key factor in world-class modern tennis (Fett et al., 2020; Gillet et al., 2009). Serve performance is determined by an interaction of ball velocity, spin and accuracy. SV and accuracy (SA) determine decisive strategic aspects such as the percentage of points won on serve, the number of serves games won, or the number of points won directly or with short rallies (i.e., < 4 shots) (Fitzpatrick et al., 2019). This is especially relevant in males who get twice more aces per serve game, win 14% more points on first serve (S1) and achieve 20% more unreturned S1 than female players (Reid et al., 2016).

In particular, SV has been considered the greatest contributor to serve performance (Vaverka & Cernosek, 2013), and there is a significant effect of SV on the probability of winning the point (Gillet et al., 2009; Mecheri et al., 2016) (Figure 2).

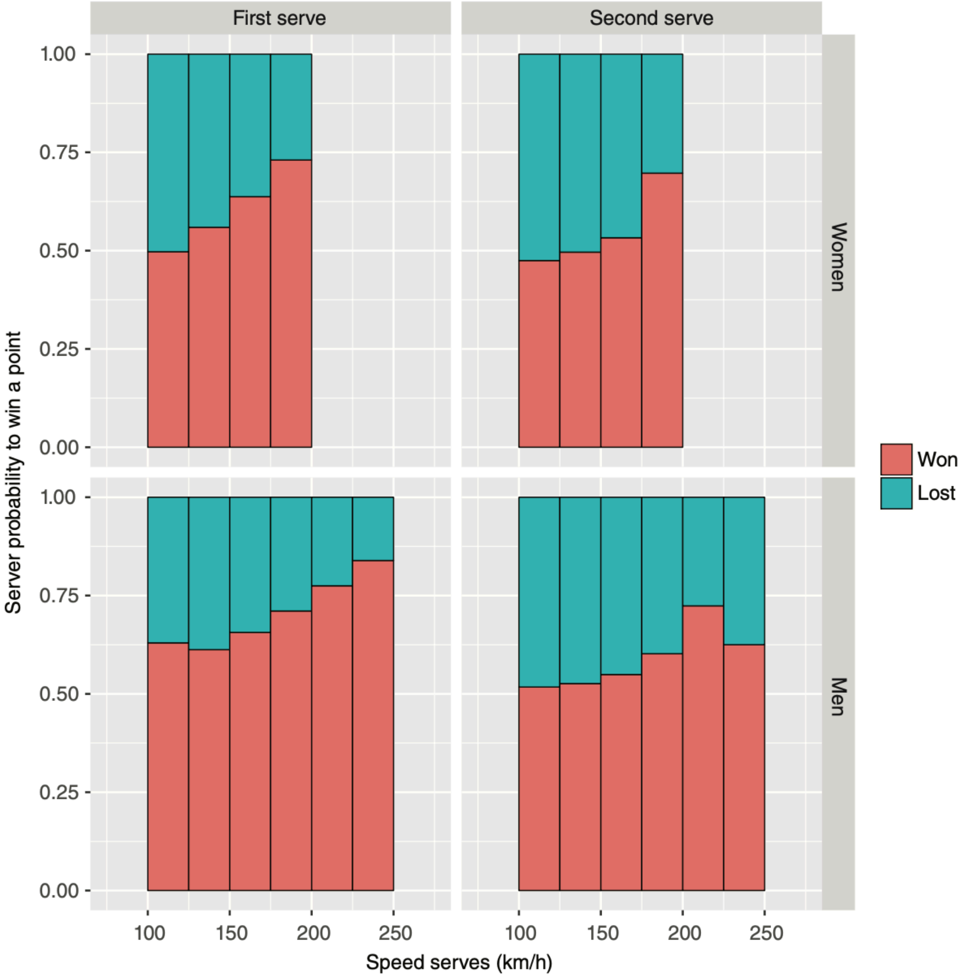


Figure 2. Probability of winning a point as a function of the serve speed and rank (Reproduced with permission from Mecheri et al. (2016).

Nowadays, it is usual to see several SV up to 200 km·h^{-1}, and although the Association of Professional Tennis Players (ATP) and Women Tennis Association (WTA) does not officially recognize SV records, a 263 (Figure 3A; Samuel Groth, Busan Open, South Korea) and 220 km·h^{-1} (Figure 3B; Georgina Garcia, Hungarian ladies Open, Hungary) serves have previously been registered in a men's and women's official tennis matches, respectively.

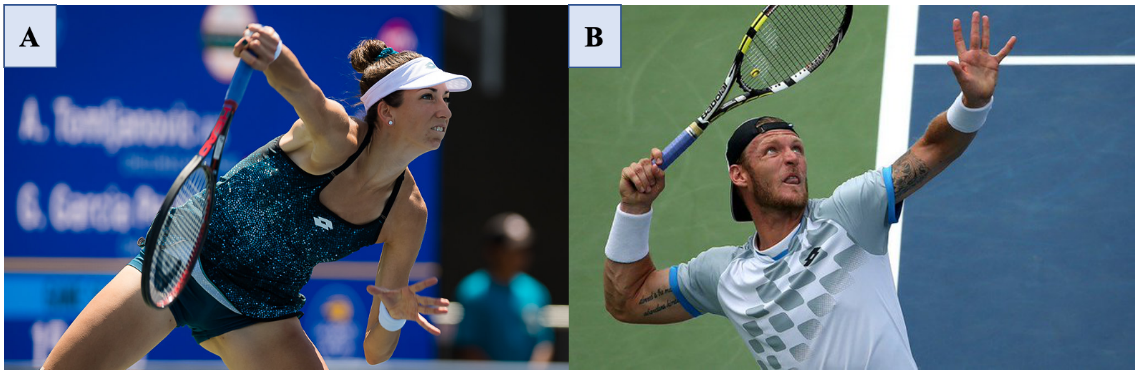


Figure 3. WTA (A) and ATP (B) tennis players with fastest serve registered in official matches. Retrieved from WTB Gallery (Jimmie48 Photography, Tennis Dunyasi, July 30, 2018) and Teddy Tennis London (@TeddyTennisLDN; May 19, 2017).

The proportion of S1 points won was significantly correlated with competition performance on all surfaces (Fitzpatrick et al., 2019). During the 2022 season, the 10-world class best servers won about 90% of serve games and the 80% of the points played with the S1 performing on average around 13 aces with only about 3 doubles faults per match. By contrast, and showing the relevance of SV, the same players only won around 50% of the points played with their second serve (S2). On the other hand, it should be noted that the best servers, although their high-speed serves, show a high level of accuracy with about 65% of S1 in (Table 1).

Table 1. Top 10 best-performing serve ATP players for 52 weeks on all surfaces (ATP, 2022). Data retrieved from ATP web site (https://www.atptour.com/en).

Player	S1 in (%)	S1 points won (%)	S2 points won (%)	Service games won (%)	Aces / match (x̄)	DB / match (x̄)
John Isner	67.6	80.7	53.8	91.5	21.4	2.9
Reilly Opelka	65.4	78.4	56.4	89.1	15.9	2.1
Nick Kyrgios	66.3	78.7	56.1	92.0	13.1	3.1
Hubert Hurkacz	63.7	77.2	54.8	88.5	12.0	1.5
Matteo Berrettini	65.0	77.5	51.1	88.9	12.7	2.2
Maxime Cressy	70.3	76.1	50.9	86.8	9.4	3.2

Alexander Zverev	62.2	78.3	54.0	88.4	15.1	8.3
Daniil Medvedev	63.5	76.7	53.0	86.9	8.8	3.8
Stefanos Tsitsipas	61.7	75.6	54.9	85.2	8.3	2.4
Arthur Rinderknech	63.7	77.1	48.6	85.0	10.0	1.9
Mean ± DS	**64.9 ± 2.6**	**77.6 ± 1.5**	**53.4 ± 2.5**	**88.2 ± 2.3**	**12.7 ± 4.0**	**3.1 ± 1.9**

S1 = first serve; S2 = second serve; DB = double fault

Regarding serve performance and tactical and strategic gender differences, Reid et al. (2016) collated serve performance data for 102 males and 95 female players during 2012-14 Australian Open tournament. It was noted that both men and women hit about six serves in play per service game, but males reach significantly more aces and a high proportion of unreturned S1. Moreover, males serve at a high peak and mean SV and are able to win a significantly greater proportion of points on their S1 and S2 than female players (Table 2) (Reid et al., 2016).

Table 2. Serve performance characteristics of Australian Open Grand Slam tennis. Adapted from Reid et al. (2016).

	Men	**Women**	**Sig.**	***d***
Serves per service game	6.1 ± 0.6	6.4 ± 0.9	0.006	0.40
Aces per service game	0.48 ± 0.30	0.23 ± 0.25	< 0.001*	0.91
DB per service game	0.25 ± 0.18	0.42 ± 0.29	< 0.001*	0.71
S1 in (%)	61.0 ± 7.5	60.2 ± 8.4	0.501	0.10
S1 points won (%)	69.1 ± 9.15	60.8 ± 12.6	< 0.001*	0.76
S2 points won (%)	48.7 ± 9.4	41.9 ± 14.0	< 0.001*	0.58
S1 unreturned (%)	22.7 ± 6.9	18.9 ± 9.2	< 0.001*	0.47
S2 unreturned (%) Peak	15.1 ± 7.5	12.2 ± 7.9	0.006	0.37
Peak SV ($km \cdot h^{-1}$)	206.3 ± 11.8	171.8 ± 10.5	< 0.001*	3.07
Mean SV1 ($km \cdot h^{-1}$)	184.3 ± 9.2	155.5 ± 9.8	< 0.001*	3.02
Mean SV2 ($km \cdot h^{-1}$)	152.1 ± 9.6	131.2 ± 8.5	< 0.001*	2.29

DB = double fault; S1 = first serve; S2 = second serve; SV = serve velocity; SV1 = first serve velocity; SV2 = second serve velocity; Sig. = Significance value; d = Cohen's *d* effect size; * Significant difference (Alpha was set at 0.001).

1.3 Determinant tennis serve velocity (SV) factors

Considering the importance of SV on professional male and female tennis competition performance, the recognition of factors that influence SV is currently relevant for researchers and coaches and therefore it has been widely explored. A broad consensus exist in considering that the tennis SV are characterized by its multifactional performance nature, consequently, when examining the factors that influence SV, different kind of parameters (i.e., neuromuscular, anthropometric, biomechanical, technical, tactical and strategic) seem to all contribute to some extent to build fast serves (Bonato et al., 2015; Gillet et al., 2009; Kovacs & Ellenbecker, 2011b) (Figure 4). Among them, body height (BH) and body mass (BM), and the activation and coordination of the trunk, upper and lower limb joints throughout the whole kinetic chain while relying on elastic energy and muscle preload are a paramount factors (Reid et al., 2008). Specifically, the shoulder joint and the ability to develop high velocity rotational movements to accelerate the tennis racket prior to ball impact have been identified as a key parameter to develop fast serves (Baiget et al., 2016; Elliott, 2006; Reid & Schneiker, 2008). On this matter, it could be hypothesized that the neuromuscular function and explosiveness of shoulder joint positions included in the serve kinetic chain exert a significant influence on SV in competition tennis players.

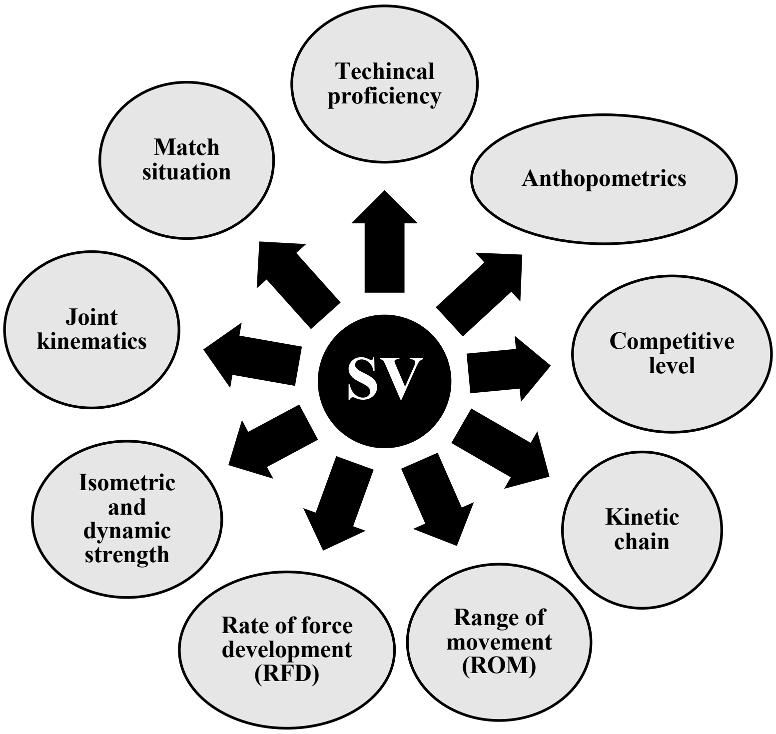


Figure 4. Determinant factors of tennis serve velocity (SV).

Summarizing, the most outstanding parameters analyzed by the current scientific literature are as follows:

- Technical proficiency: Range of acceptability level for specific movement (Fleisig et al., 2003).
- Whole kinetic chain: Efficient activation and coordination of trunk and upper and lower limbs joints (Elliott, 2006).
- Anthropometrics: Body height, arm length and body mass (Bonato et al., 2015; Fett et al., 2020; Söğüt, 2018; Vaverka & Cernosek, 2013; Wong et al., 2014).
- Competitive level: Players with higher tennis level tend to serve faster. The relevance of strength and power on SV could become more important as age and level increase (Colomar et al., 2020).

- Range of movement (ROM): Appropriate ROM of joints involved in the tennis serve (Palmer et al., 2018).
- Rate of force development (RFD): Ability to develop force in short-time periods (<250 ms) (Canós et al., 2022; Colomar, Corbi, & Baiget, 2022a, 2022c; Hayes et al., 2021).
- Isometric (Baiget et al., 2016; Fett et al., 2020; Hayes et al., 2021) and dynamic (Bonato et al., 2015; Dossena et al., 2018; Fett et al., 2020; Hayes et al., 2021; Palmer et al., 2018; Pugh et al., 2003; Signorile et al., 2005) strength.
- Lower and upper limbs joint kinematics and muscle activity (Chow et al., 2009; Gordon & Dapena, 2006; Hernández-Davó et al., 2019; Martin, Kulpa, Ropars, et al., 2013; Reid et al., 2007, 2008; Wong et al., 2014).
- Match situation: On first serve, professional tennis players serve faster when facing break point (i.e., score that gives the returning player the opportunity to win a game) whereas on second serve they decelerate their serve (Meffert et al., 2018).

1.4 Phases and stages of tennis serve kinetic chain

As previously mentioned, a broad consensus exists in considering that to apply an optimal force production, it is necessary to activate and coordinate multiple segments in the whole kinetic chain including lower limbs, trunk and upper limbs. Specifically, it is necessary to add the forces from the ground up through the kinetic chain, to the upper limbs and finally to the racket (Kovacs & Ellenbecker, 2011a), being necessary the use of elastic energy and muscle preload (Girard et al., 2007). In fact, the complication in the tennis serve movement relies on the summation of forces from the ground up through the kinetic chain and out into the ball (Kovacs & Ellenbecker, 2011a). This summation of force is also needed in groundstrokes, as an example, Figure 5 shows the successive inclusion of body segments into action during a forehand. An optimal body segments participation would have to start from the ground and impulse is transferring via ankle – knee – hip to shoulder – elbow – wrist – racquet (Zuša et al., 2015). Regarding the main joints involved, the tennis serve primarily imposes high requirements on the shoulder joint throughout substantial rotational velocities and forces, (Kibler et al., 2007) mainly in the racquet acceleration phase previous to the ball impact (Elliott, 2006).

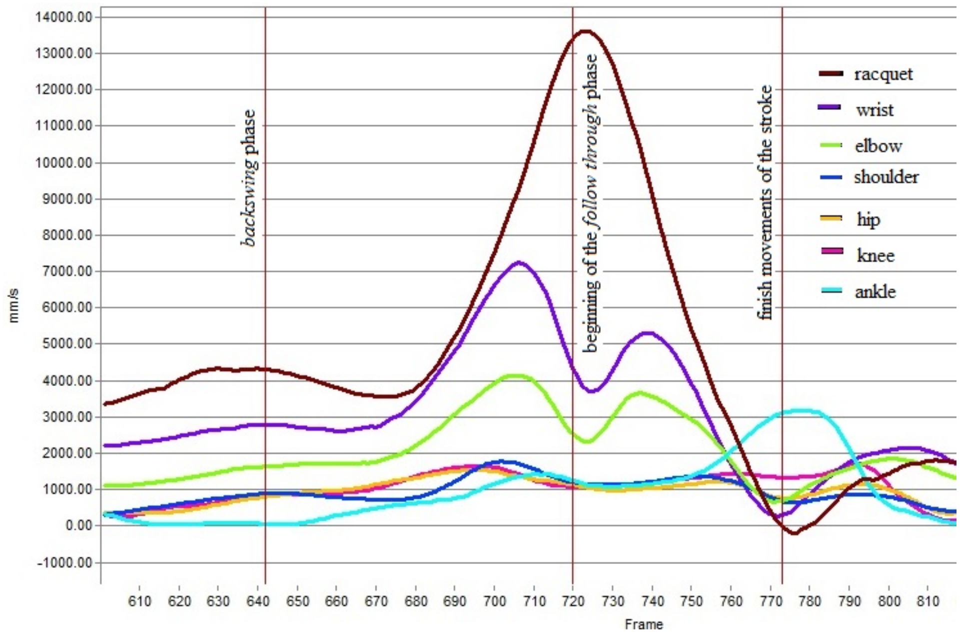


Figure 5 . Absolute velocities of the racquet and body segments during a forehand stroke production of young tennis player. Retrieved from Open Acces Zusa et al. (2015).

To describe the tennis serve's temporary movement sequence an 8-stage model with 3 phases as shown in Figure 6 (Kovacs & Ellenbecker, 2011a, 2011b) has been proposed. The preparation phase starts with the first sign of movement until maximal shoulder external rotation (SHER). The acceleration phase initiates from maximal SHER until the ball contact finishes. Finally, the follow-through phase initiates immediately post ball impact and advances until the service movement finishes (Figure 6).

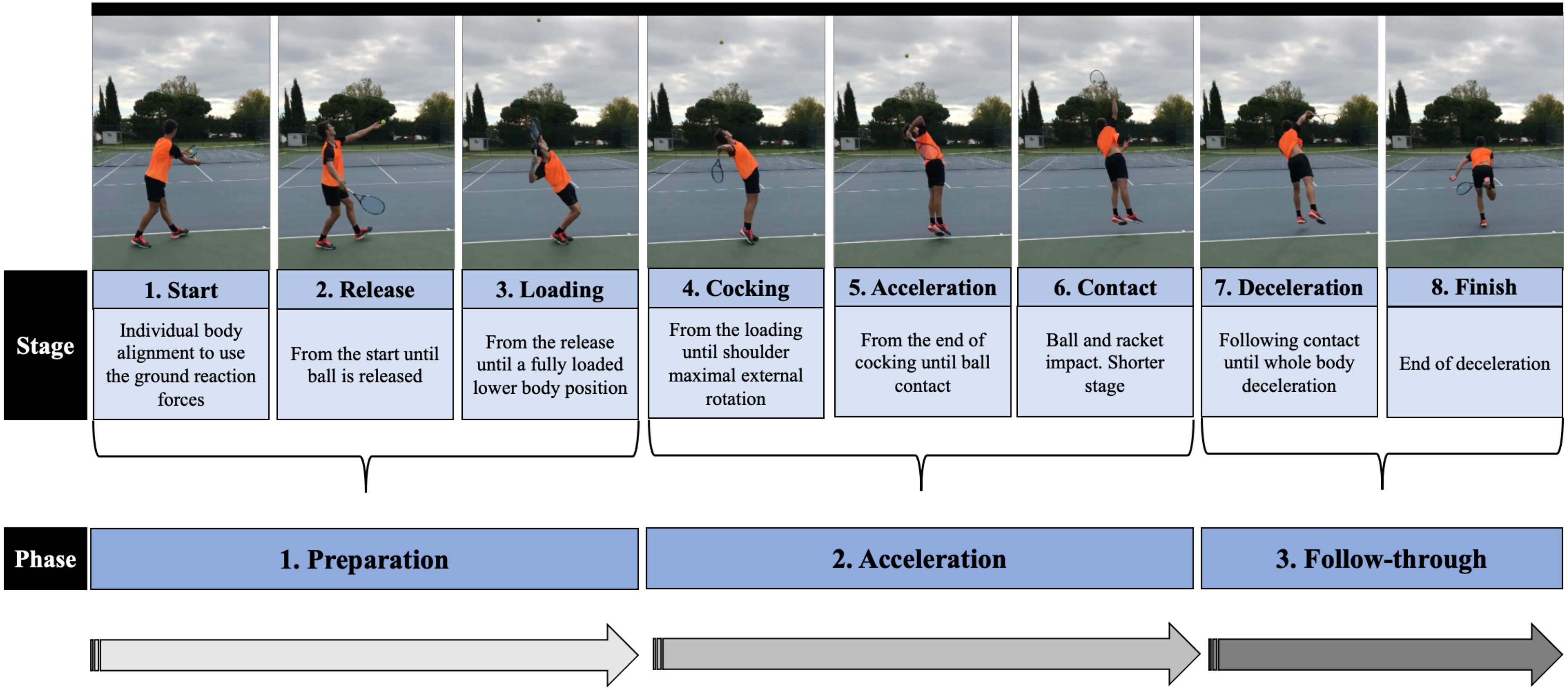


Figure 6. Time sequence of stages and phases of the tennis serve kinetic chain.

1.5 Force-time curve characteristics

Explosive strength is known as the capability of the neuromuscular system to increment contractile force or torque as quickly as possible during rapid voluntary contractions executed from low or resting level. RFD is derived from the force- or torque- time curves registered over explosive voluntary contractions and is widely used to characterize explosive strength of athletes (Maffiuletti et al., 2016). Because of this, RFD is a paramount parameter in rapid movements where a short contraction time may not allow maximal muscle force to be reached (Rodríguez-Rosell et al., 2018).

Alternative quantification approach for RFD consists of calculating the force impulse (IMP), as force or torque integrated with respect to time (Rodríguez-Rosell et al., 2018). Figure 7 shows the differences between RFD and IMP, while RFD is calculated by the linearly increasing force between designated time points, IMP is the area under the curve.

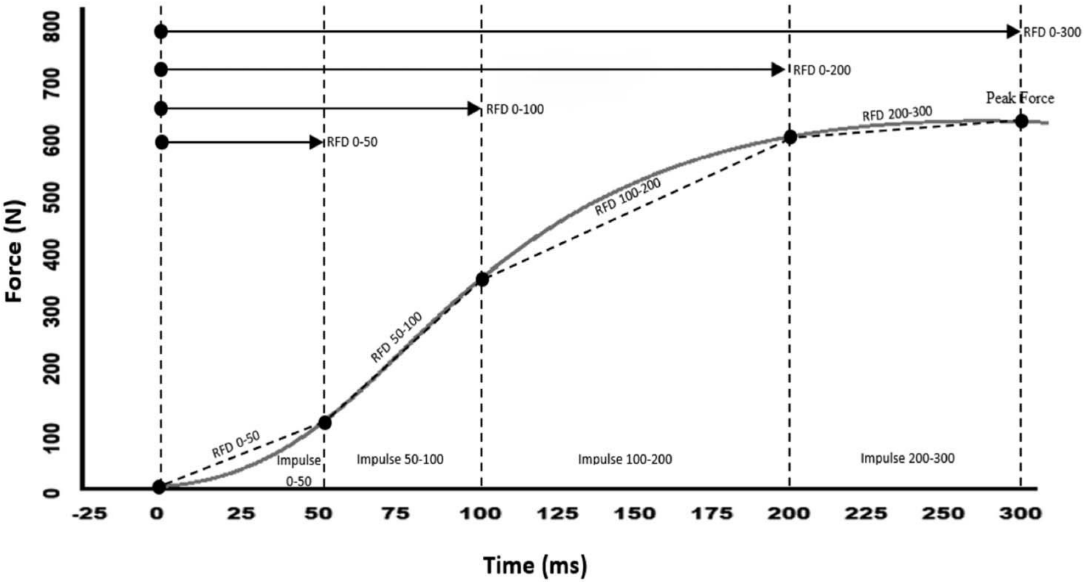


Figure 7. Rate of force development (RFD) and impulse across typical epochs. Reproduced with permission from Turner et al. (2020).

Although the whole tennis serve (i.e., preparation, acceleration and follow-through phases) lasts about 650 ms (i.e., from -326 ms before to +325 ms after ball impact), the acceleration phase corresponding to the concentric muscle activation lasts about 80 ms (Kibler et al., 2007). Consequently, explosive rotational movements to accelerate the racket towards the ball are paramount to produce maximal SV (Myers et al., 2015; Reid & Schneiker, 2008). In this scenario, the short time contraction available may not elicit maximal force production (i.e., time frame > 300 ms needed) and it seems that the ability to apply force over the time constraints of the acceleration phase of serve (i.e., time frame 0 to <200ms) is determinant for SV. From this perspective, force-time characteristics such as the RFD, impulse (IMP) or isometric force (IF) at different time frames are considered relevant key neuromuscular function parameters (Kawamori et al., 2006), and especially RFD has been considered a key factor in fast and forceful movements in trained athletes (Aagaard et al., 2002; Rodríguez-Rosell et al., 2018). According to this, RFD has been shown as a good predictor of sport performance in swimming (Beretić et al., 2013), sprint running (Seitz, Reyes, et al., 2014), cycling (Stone et al., 2004), weightlifting (Haff et al., 2005), gymnastics (Moeskops et al., 2020), basketball (Townsend et al., 2019) or rugby (Wang et al., 2016) and also recently in tennis (Colomar, Corbi, & Baiget, 2022c).

1.6 Isometric strength training and testing

The assessment of RFD has commonly been performed by isometric testing, because it can be objectively measured form the force-time or torque-time curve obtained during isometric contractions (Rodríguez-Rosell et al., 2018). Moreover, isometric monitoring has been proved as a valid and effective method to follow strength-training adaptations (Peltonen et al., 2018), it is time efficient, induces minimal fatigue (Dos'Santos et al.,

2017) and is advantageous to implement assessment tools to evaluate and control SV (Colomar, Corbi, & Baiget, 2022b).

It has been recommended that the isometric test to assess the force-time parameters of athletic populations should be executed near or at the joint angle where the peak force is applied throughout the specific dynamic movement of interest (Lum et al., 2020). In this sense, the isometric monitoring characteristics allows to easily implement exercises biomechanically comparable to subsequent sport actions, and allows to replicate positions and angles involved in the serve kinetic chain (Baiget et al., 2016). Previous investigations have positively correlated maximum isometric force (IF) and SV (Baiget et al., 2016; Bonato et al., 2015) and recently various isometric upper limb force-time parameters (i.e., RFD or IMP) and the majority of joints and positions involved in the tennis serve motion (i.e., wrist, elbow and shoulder) have been included in testing.

Considerable information is currently available concerning different dynamic strength training methods to increase SV in competition tennis players (Colomar, Corbi, & Baiget, 2022a). Several studies have shown how strength methods such as plyometrics (i.e., medicine ball throws [MBT]) (Terraza-Rebollo et al., 2017), flywheel (Canós et al., 2022), elastic tubing (Terraza-Rebollo et al., 2017; Treiber et al., 1998), machine-based (Canós et al., 2022) or free weights (Terraza-Rebollo et al., 2017; Treiber et al., 1998) positively affect SV. Isometric strength training (IST) comprises the contraction of the skeletal muscles with no external movement. Although the transferability of IST to dynamic performance has been controversial, it has been also shown as an effective strength training method to increase performance of dynamic high-velocity sports actions (Lum & Barbosa, 2019). IST allows to obtain modifications in physiological qualities including muscle architecture, tendon stiffness, joint angle-specific torque and metabolic functions (Oranchuk et al., 2019). In this regard, it could be hypothesized that IST in combination with dynamic strength methods might be an effective strategy to increase SV and neuromuscular performance in competition tennis players.

1.7 Postactivation performance enhancement (PAPE)

Due to the relevance of being able to serve at high velocities, tennis coaches have a growing interest on specific strength training aiming at increasing players' maximal force and power production (Gale-Watts & Nevill, 2016). Postactivation potentiation (PAP) is a muscular phenomenon that is expressed by an acute increase in strength and power performances as a result of the recent voluntary contractile history (Boullosa et al., 2020). Agreement exists in considering phosphorylation of myosin regulatory light chains and the recruitment of higher-order motor units as critical aspects determining PAP (Baudry & Duchateau, 2007; Beato & Stiff, 2021; Skurvydas et al., 2019). A temporary enhancement appears in sports performance following high-intensity voluntary conditioning activities (CA), influenced by several neuromuscular, biomechanical or physiological parameters (Seitz & Haff, 2016; Tillin & Bishop, 2009). One of the main parameters affecting PAP is the adequate intracomplex recovery. The CA could produce both PAP and fatigue coexisting at the same time, the balance between these two variables determines the subsequent performance response (i.e., enhance, reduce or unchanged performance) (Lim & Barley, 2016) (Figure 8). Thus, identifying the optimal rest interval between the CA and the subsequent sport action is crucial to achieve performance enhancements. In this matter, there is not a unique optimal intracomplex recovery and studies shows a wide spectrum of times ranging from 0 to 10 minutes. Lim & Barley (2016) suggest how PAP can be accomplished earlier after low-volume CA (window 1 – Figure 8) or after a high-volume CA (window 2 – Figure 8).

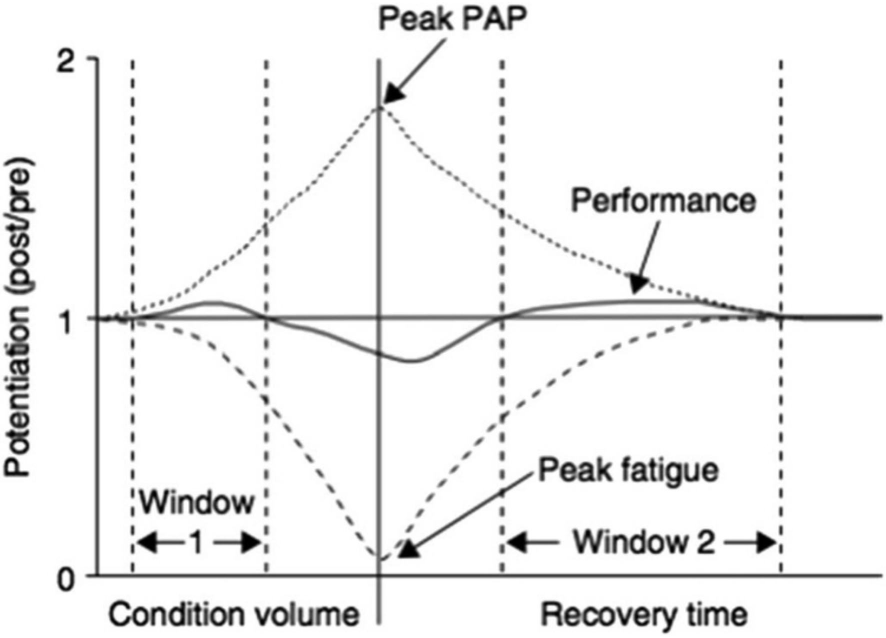
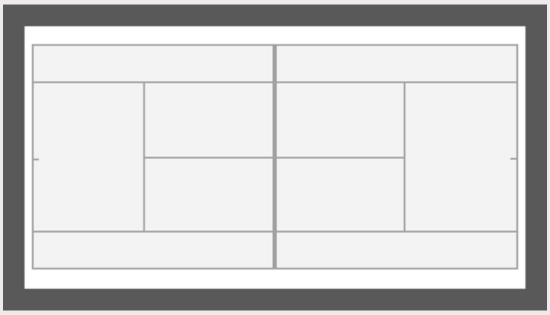


Figure 8. A model of the relationship between postactivation potentiation (PAP) and fatigue after previous conditioning stimulus. Retrieved with permission from Lim & Barley (2016).

Albeit PAP has been proved to produce physiological improvements, these are not always accompanied by functional performance enhancements (Hodgson et al., 2005). The postactivation performance enhancement (PAPE) refers to an increase in voluntary performance associated to a potentiation effect independent of the potentiation parameters involved (Boullosa et al., 2020; Zimmermann et al., 2020). The effects of PAPE have been proved to be higher for rapid ballistic than slow movements or isometric contractions (Vandenboom, 2017). Thus, PAPE has shown small to moderate effects on explosive sport actions such as jumping, throwing, sprinting or upper-body ballistic movements (Seitz, Reyes, et al., 2014), mainly by improving RFD and power (Tillin & Bishop, 2009). A large amount of PAPE research has focused on selected CA exercises (i.e., resistance, ballistic, plyometric, elastic bands, blood flow restriction or flywheel) and contractions (i.e., isometric, concentric and eccentric) to increase performance in high-speed sport-specific actions, with the concentric multi-joint traditional resistance exercises the most used (Boullosa, 2021; Seitz & Haff, 2016). Regarding tennis serve PAPE, literature suggests that using heavy load traditional resistance CA (i.e., bench press and half squat) does not enhance SV in young tennis players (Terraza-Rebollo & Baiget, 2020). However, no information exists related to the hypothetic benefits of PAPE effect using tennis specific joint MVIC.

2 AIMS AND HYPOTHESIS



2.1 General objective

The general aim of this doctoral thesis was to determine how neuromuscular training, anthropometric, ball impact and landing location, and force-time curve parameters influence serve performance in high-level and junior tennis players.

2.2 Specific objectives

The general objective has been divided into specific objectives, which are addressed in specific papers:

Study I. Influence of anthropometric, ball impact and landing location parameters on serve velocity in elite tennis competition:

- To analyse the associations between SV and anthropometric, ball impact and landing location parameters in total performed serves velocity (TSV) and fastest serve velocity (FSV) in professional tennis players during an ATP Tour event
- To observe differences between S1 and S2 and to determine a SV prediction model based on the relationship between the observed variables.

Study II. Upper limb force-time characteristics determines serve velocity in competition tennis players:

- To analyse the associations between SV and various single-joint upper limb isometric force-time curve parameters (IF, RFD and IMP) in competition tennis players.
- To develop a prediction model based on the relationship between these variables.

- To determine whether selected IF, RFD and IMP parameters in different upper limb joints are capable of discriminating between tennis players with different SV performances.

Study III. Joint-specific post-activation potentiation enhances serve velocity in young tennis players:

- To analyze the effects of PAP induced by upper-limb tennis-specific joint maximal isometric voluntary contractions (MVIC) on SV and SA in young tennis players.
- To compare the PAP effects on SV and SA using two different MVIC CA protocols.
- To explore if changes in SV would be related to tennis player's neuromuscular performance.

Study IV. 6-Week joint-specific isometric strength training improves serve velocity in young tennis players:

- To evaluate the effects of adding a short time specific-joint IST on serve performance (SV and SA) and force-time curve parameters (RFD, IMP and MVIC) in young tennis players.

2.3 Hypothesis

In accordance with the general and specific objectives, the following hypothesis were established:

Study I:

- SV would be highly influenced by anthropometric (i.e., BH, BM and body mass index [BMI]) and ball impact (impact height [IH] and impact projection angle [IA]) during an ATP competition, especially in the S1.
- There would be significant differences between S1 and S2 in SV, IH, IPA and bounce landing location parameters (width and depth).

Study II:

- SV would be significantly determined by single-joint upper limb isometric force-time curve parameters (IF, RFD and IMP) in competition tennis players.
- The upper limb isometric force-time curve parameters (IF, RFD and IMP) would be able to discriminate between tennis players with different SV performances.

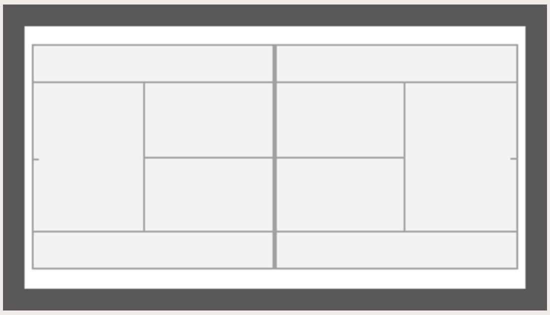
Study III:

- Implementing serve upper body specific-joint CA exercises would be appropriate to promote PAPE responses.
- The PAPE responses would be influenced by tennis player's neuromuscular performance.

Study IV:

- Implementing upper-limb joint-specific IST biomechanically comparable to the tennis serve would increase the neuromuscular function and the ability to produce force rapidly associated with SV enhancement without SA detriment.

3 METHODS



Four studies were conducted trying to address the general and specific objectives and test the raised hypothesis. The general design of the doctoral thesis was planned in order to provide a multifactorial approach of the topic of the study (Figure 9). Seventy competition male (n = 57) and female (n = 13) tennis players were recruited for the different studies. The general selection criteria were that all the subjects had an International Tennis Number (ITN) ranging from 1 (professional level) to 3 (advanced level), a minimum of 5-years of tennis training and competition and did not practice another competitive sport. The specific participant characteristics and inclusion criteria of each study are presented in each section. Study I was a cross-sectional observational study that analyzed 945 serves (630 S1 and 315 S2) performed during an official ATP 500 outdoor red clay tournament (Barcelona Open Banc Sabadell). For each serve, IH, IPA, relative impact height [RIH] and ball bounce location were computed. All data in this study were recorded by Foxtenn's technology (Foxtenn Bgreen, SL, Spain) currently used in ATP, WTA and ITF professional tennis events. Study II was a single-cohort, cross-sectional study conducted to investigate the relationships between SV and force-time parameters in 8 tests of upper-limb muscle function joints involved in the serve kinetic chain in high-performance tennis players. Finally, studies III and IV were crossover-randomized designs used to evaluate the acute and delayed effects induced by different upper-limb tennis-specific joint MVIC CA and training protocols on serve performance in young competition tennis players. The specific methodological designs are presented in each section of the included papers.

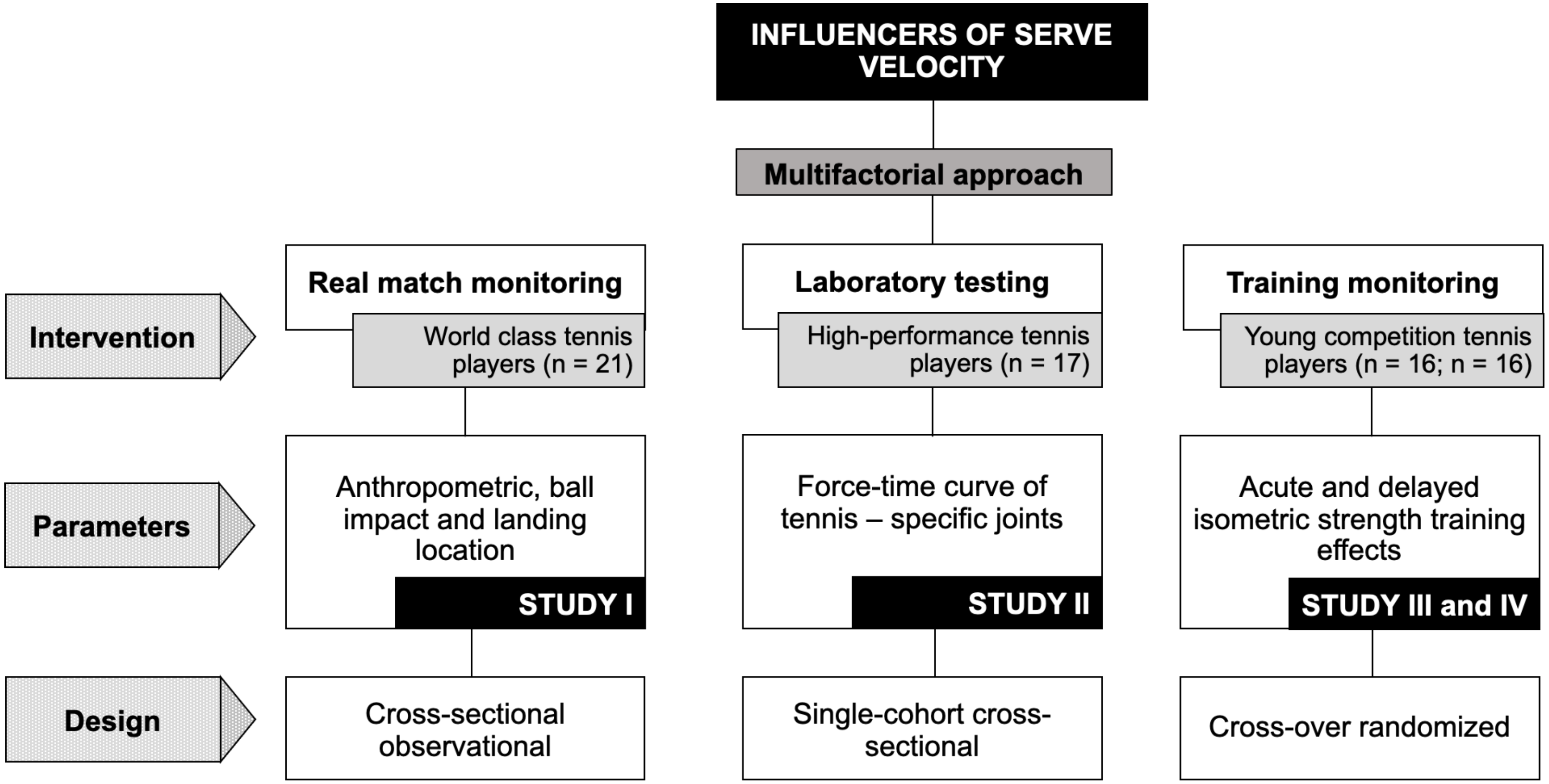
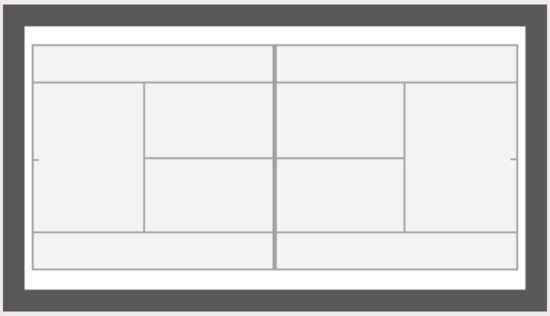


Figure 9. General study design.

4 RESULTS



4.1 Study I

Influence of anthropometric, ball impact and landing location parameters on serve velocity in elite tennis competition

by

Baiget E, Corbi, F, López JL

4.1.1 ABSTRACT

This study aimed (i) to analyse the associations between serve velocity (SV) and anthropometric, ball impact and landing location parameters in total serves (TS) and fastest serves (FS) performed during an ATP Tour event; (ii) to observe differences between first (S1) and second (S2) serves, and (iii) to determine a SV prediction model based on the relationship between the observed variables. Using Foxtenn technology, 30 S1 and 15 S2 were registered in 14 matches in twenty-one male professional tennis players. Ball impact (impact height [IH], impact projection angle [IPA] and relative impact height [RIH]), bounce landing (width and depth) location parameters, S1 and S2 SV in TS (TSV1 and TSV2) and FS (FSV1 and FSV2) alongside anthropometric characteristics of tennis players (body height [BH], body mass [BM] and body mass index [BMI]) were analysed. Significant moderate to large associations were found between BH and BM and TSV1, FSV1 and FSV2 ($r = 0.315$ to 0.593; $p < 0.001$), and between IH and IPA and TSV1 and TSV2 ($r = 0.294$ to -0.409; $p < 0.001$). BH and BM were the unique significant contributors of FS explaining 22 to 35% of FSV1 and FSV2. Only BM appears in the model to predict FSV1 and FSV2 ($r^2 = 0.48$ and 0.21). We concluded that all three anthropometric, ball impact and bounce landing location parameters small to moderately influence TSV. Anthropometric parameters show an impact on SV when tennis players serve at or near maximal speed, highlighting the influence of BM above BH.

Keywords: body mass, body height, impact height, impact projection angle, tennis serve

4.1.2 INTRODUCTION

Tennis serve (S) is a multifactorial nature stroke influenced by several neuromuscular, anthropometric, biomechanical, technical and tactical parameters. From a technical and biomechanical perspective, S has been considered as the most complex tennis stroke (Kovacs & Ellenbecker, 2011b). A broad consensus exists in considering that to apply an optimal force production, it is necessary to activate and coordinate multiple segments in the whole kinetic chain including lower limbs, trunk and upper limbs (Reid et al., 2008). Specifically, it is necessary to add the forces from the ground up through the kinetic chain, to the upper limbs and finally to the racket (Kovacs & Ellenbecker, 2011a), being necessary the use of elastic energy and muscle preload (Girard et al., 2007).

From a tactical and strategic perspective, a high S velocity (SV) and accuracy are a key factor in world-class modern tennis (Fett et al., 2020; Gillet et al., 2009). SV has been considered the greatest contributor to S performance (Vaverka & Cernosek, 2013), and there is a significant relationship between SV and the probability of winning the point (Gillet et al., 2009). Nowadays, it is usual to see several SV up to 200 km·h^{-1}, and although the Association of Professional Tennis Players (ATP) does not officially recognize SV records, a 263 km·h^{-1} S has previously been registered in a men's official tennis match. In 2020, the top 10 ATP tennis players won 78.1 ± 7.2 % of S games, there were 34 with up to an 80% and 3 players with up to 90% of S games won (https://www.atptour.com/en). The proportion of first S (S1) points won was significantly correlated with competition performance on all surfaces (Fitzpatrick et al., 2019). SV and accuracy determine decisive strategic aspects such as the percentage of points won on S, the number of S games won, or the number of points won directly or with short rallies (i.e., < 4 shots) (Fitzpatrick et al., 2019). This is especially relevant in males who get twice more aces per S game, win 14% more points on S1 and achieve 20% more unreturned S1 than female players (Reid et al., 2016). Despite this, tennis performance is characterized by a complex interaction between physical, psychological, tactical, and technical abilities. When analyzing world-class athletes, different player profiles can be observed. Therefore, on which of the aforementioned aspects participants rely on more specifically to develop their game may vary significantly between individuals.

Given the importance of SV on success in professional male tennis competition, the recognition of factors that influence SV is currently relevant for researchers and coaches and therefore it has been widely explored. The influence of different nature parameters of tennis players SV such as anthropometric characteristics (Bonato et al., 2015; Fett et al., 2020; Söğüt, 2018; Wong et al., 2014), competitive level (Colomar et al., 2020), isometric (Baiget et al., 2016; Fett et al., 2020; Hayes et al., 2021) and dynamic (Bonato et al., 2015; Dossena et al., 2018; Fett et al., 2020; Hayes et al., 2021; Palmer et al., 2018; Pugh et al., 2003; Signorile et al., 2005) strength, rate of force development (RFD) (Hayes et al., 2021), muscle stiffness (Colomar et al., 2020), isokinetic speed (Signorile et al., 2005), range of motion (ROM) (Girard et al., 2007; Palmer et al., 2018), lower and upper limbs joint kinematics and muscle activity (Chow et al., 2009; Gordon & Dapena, 2006; Hernández-Davó et al., 2019; Martin, Kulpa, Ropars, et al., 2013; Reid et al., 2007, 2008; Wong et al., 2014), the match situation (Meffert et al., 2018) or the resistance training (Myers et al., 2015) have been measured. However most of these investigations were conducted mainly in laboratory/court simulated conditions with absence of a returner (Allen et al., 2016). Based on the uncertain nature of the game, tennis players constantly make decisions on ball landing location of their shots (Gillet et al., 2009, 2010). It has been suggested that to appropriately register the S performance the representativeness of S and return is needed (Krause et al., 2019). The S without a returner and real match conditions does not allow the server to decide direction, velocity and angle of S depending on the tactical situation.

Although modern technological advances allow to monitor and capture different performance parameters of strokes directly applying video-footage, there are few investigations carried out under real professional tennis events that reflect the influence of parameters related to the ball impact and bounce landing location. Furthermore, the influence of the anthropometric, ball impact and landing location parameters on total (TS) and fastest (FS) S performed during a real match have not been established. To the best of our knowledge, this is the first study that explores the influence of anthropometric, ball impact and bounce landing location parameters on first and second (S2) SV in total (TS) and fastest (FS) serves during an ATP competition, comparing differences between S1 and S2. Thus, the aims of the study were (a) to analyse the associations between SV and anthropometric, ball impact and landing location parameters in TSV and FSV in professional tennis players during an ATP Tour event; b) to observe differences between S1 and S2 and (c) to determine a SV prediction model based on the relationship between the observed variables.

4.1.3 METHODS

Participants

The inclusion criteria for the study were world-class male professional tennis players who participated in the singles main draw of the 2019 Barcelona Open Banc Sabadell and played in the central court of the tournament. The data of twenty-one male professional tennis players (mean ± SD; age, 26.4 ± 5.4 years; height, 186.9 ± 7.4 cm; BM, 81.6 ± 7.1 kg; body mass index [BMI], 23.4 ± 1.1 $kg \cdot m^{-2}$) were used for the performance analysis. The mean ATP ranking of the players was 42.2 ± 37.9 ranging from 2 to 155 and 81% were right-handed. Permission to use the data and the installations was granted by Reial Club de Tennis Barcelona·1899. The study was performed in accordance with current ethical standards, established in the Declaration of Helsinki of the AMM (2013) and approved by the Clinical Research Ethics Committee of the Catalan Sports Administration (08_2020_CEICGC).

Experimental Design

The collection of data took place during an official ATP 500 outdoor red clay tournament (22-28 April 2019). The main draw of the tournament included a total of 48 elite tennis players of which 43.8% were analysed (http://www.protennislive.com/posting/2019/425/mds.pdf). For data analysis and in order to match the number of S evaluated in each player, the first 45 S per player (30 S1 and 15 S2) that landed in the service box (no foot fault or net cord) were registered in 14 matches between the second and fourth round, resulting in a total of 945 S (630 S1 and 315 S2) analysed. Data collection approximates to the professional S profile, the proportion of S1 and S2 in elite tennis are around 60 and 40% (Fitzpatrick et al., 2019) and competition tennis players hit around 50 and 150 S during a match (Martin et al., 2014). Matches were played approximately from 11 am to 20 pm. Parameters related to the ball impact point (impact height [IH], impact projection angle [IPA] and relative impact height [RIH]), ball bounce landing location (width and depth) and S1 and S2 velocities (SV1 and SV2) were registered for players in TS and FS. Moreover, anthropometric characteristics of professional tennis players (body height [BH], body mass [BM] and body mass index [BMI]) were registered. This procedure was used to determine to what extent anthropometric (BH, BM and BMI), ball impact (IH, IPA and RIH) and bounce landing location (depth and width) related to SV1 and SV2. On the other hand, multiple regression analyses were used to develop models that were most effective at predicting SV1 and SV2.

Measurements

Peak SV and ball impact and landing location parameters were recorded in real time by Foxtenn's technology (Foxtenn Bgreen, SL, Spain) currently used in ATP, WTA and ITF professional tennis events. Foxtenn's analysis technology system allows to capture ball trajectories through an automatic tracking of the ball that includes instantaneous ball position and ball velocities are also provided. Ball trajectories tracking is based on capturing images by multiple high-speed cameras of the real ball bounce in combination with high-frequency laser scanners fixed around the court (https://www.itftennis.com/media/1435/foxtenn-diamond-player-pro-perfromance-court-report.pdf). Specifically, the ball impact and bounce location parameters were determined by a high-speed camera (300 fps) positioned in the center of the baseline at a height of 8 m and 10 synchronized laser scanners (100 Hz each one) situated close to the ending lines at ground level and using as reference parameter the centre service line and the service line. Peak SV was determined using two radar guns (Stalker ATS II, United States, frequency: 34.7 GHz (Ka-Band) ± 50 MHz) positioned in the center of the baseline at a height of 2 m. The cameras, laser scanners and radar guns were wired to a server and a designated operator controlled the system via software running on a second server (connected to the first server). The system meets International Tennis Federation (ITF) criteria (https://www.itftennis.com/media/2715/evaluation-paper-revision-25.pdf) of accuracy and reliability (https://www.itftennis.com/media/2172/line-calling.pdf) and is approved by the Women´s Tennis Association (WTA) and ATP. Depth of service landing location was determined by the distance from the bounce to the service line (DSL) and width lateral bounce location by the distance from the centre service line (DCSL) (Figure 10B). IPA was determined by the ball impact projection angle from the horizontal (vertical projection angle) and IH by the distance in cm from the ball at the impact moment to the ground (Figure 10A). Figure 10A shows the three phases of specific serve model (Kovacs & Ellenbecker, 2011b) and the ball impact parameters (IH and IPA) are located in the acceleration phase (second phase). Anthropometric characteristics of professional tennis players (BH and BM) were obtained from publicly available information listed in the official ATP website as in previous studies conducted in elite tennis players (Söğüt, 2018; Vaverka & Cernosek, 2016). RIH was determined by the relationship between IH and BH: (IH/BH)*100.

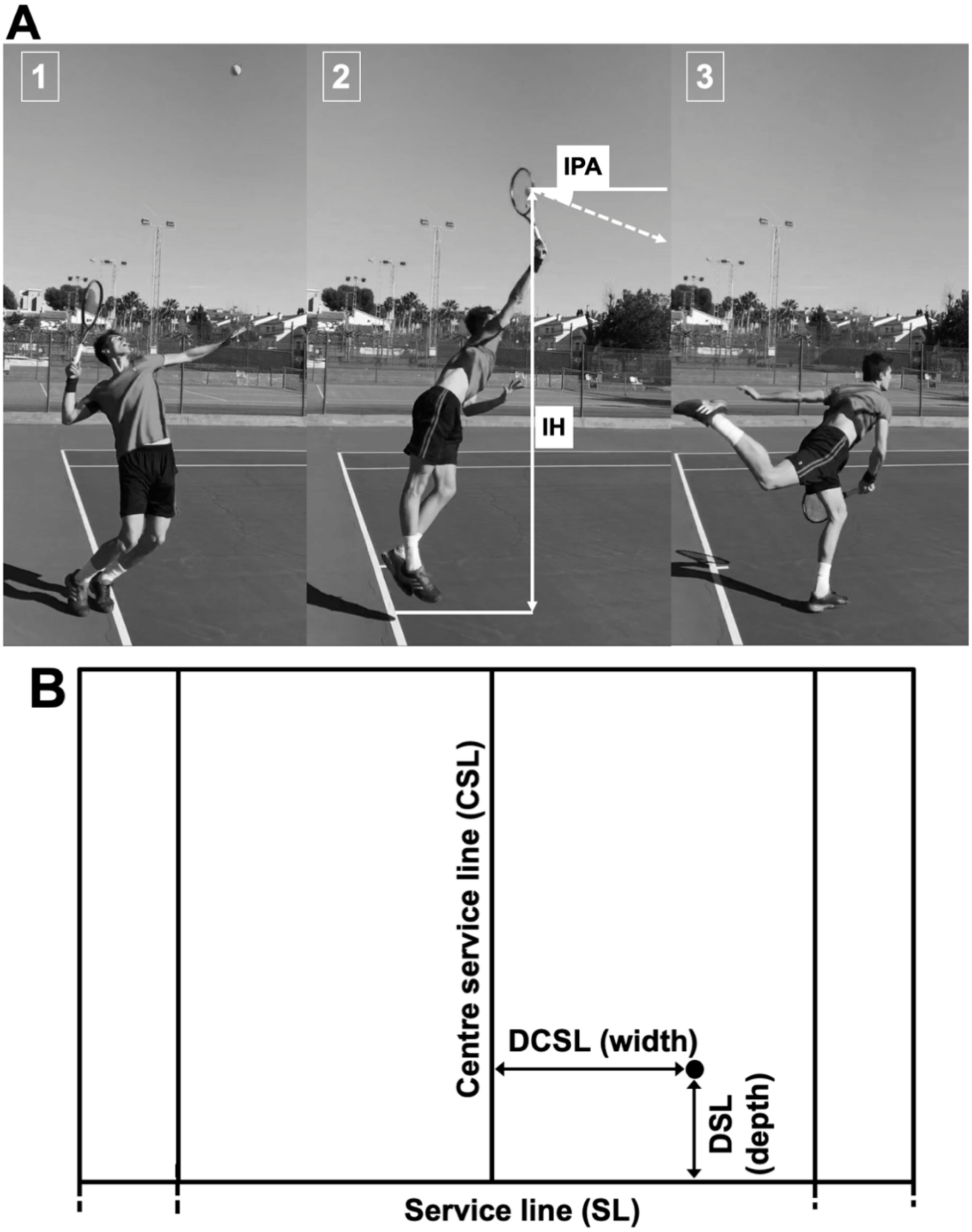


Figure 10. Methods used to calculate ball impact (A) and landing location (B) parameters of tennis serve. Impact angle (IPA), impact height (IH), depth (distance to the service line; DSL) and width (distnace to the centre service line, DCSL) are shown. Selected images of preparation phase (1, loading stage), acceleration phase (2, contact stage) and follow-through phase (3, finish stage).

Statistical Analyses

Descriptive data are expressed as mean ± standard deviation (SD) and 95% confidence intervals (95% CI). The normality of variables distribution was assessed with the Shapiro-Wilk test. Most of parameters at TS1 (SV, IH, RIH and DCSL), TS2 (IH, RIH and IPA), FS1 (IPA and DCSL) and FS2 (RIH, IPA and DCSL) did not have a Gaussian distribution, so nonparametric test were used. Friedman's test was used to discern any significant differences between S1 and S2. Wilcoxon's test was used to identify those differences. Mean percent differences values were also used. The magnitude of the differences in mean was quantified as effect size (ES) and interpreted according to the criteria used by Cohen (Cohen, 1988) <0.2 = trivial, 0.2–0.4 = small, 0.5– 0.7 = moderate, >0.7 = large. Spearman rank order correlation coefficients for non-parametric data were used to examine the relations between SV and anthropometric, ball impact and bounce variables, while coefficient of determination were used to explain the common variance between these variables and SV. Correlations were classified as trivial (0–0.1), small (0.1–0.3), moderate (0.3–0.5), large (0.5–0.7), very large (0.7–0.9), nearly perfect (0.9), and perfect (1.0) (Hopkins et al., 2009). As DSL, and SV at FS1 and FS2 were normally distributed, parametric statistical analysis were conducted. Paired t-test was used to discern any significant differences between S1 and S2 and Pearson correlation coefficient was used to quantify the relationship between FS1, FS2 and DSL. TSV1, TSV2, FSV1 and FSV2 were used as the dependent variables in the stepwise multiple regression analysis, whereas anthropometric data (BH, BM, BMI) and ball impact variables (IH, IPA, RIH) operated as independent predictors. Ball landing location parameters (width and depth) were not used as independent predictors because it was considered that they depend on SV rather than the opposite. Statistical significance was accepted at an alpha level of $p \leq 0.05$. All statistical analyses were performed using IBM SPSS Statistics 26.0 (SPSS, Inc., Chicago, IL.).

4.1.4 RESULTS

TS1 and TS2 bounce landing locations are shown in Figure 11. TS2 and FS2 showed a large and a moderate to large reduction of SV (ES = 1.30 and 2.61, -16.7 and -18.6%; $p < 0.001$) and depth (increase in DSL: ES = -0.63 and -1.08, 53.9 and 53.1%; $p < 0.001$ and < 0.01) and a small to large increase in IPA (ES = -0.42 and -0.75, 20.1% and 16.5%; $p < 0.001$ and < 0.01) compared to the TS1 and FS1. No differences ($p > 0.05$) and small to trivial ES were found between IH, RIH and width at S1 compared to S2 (Table 3).

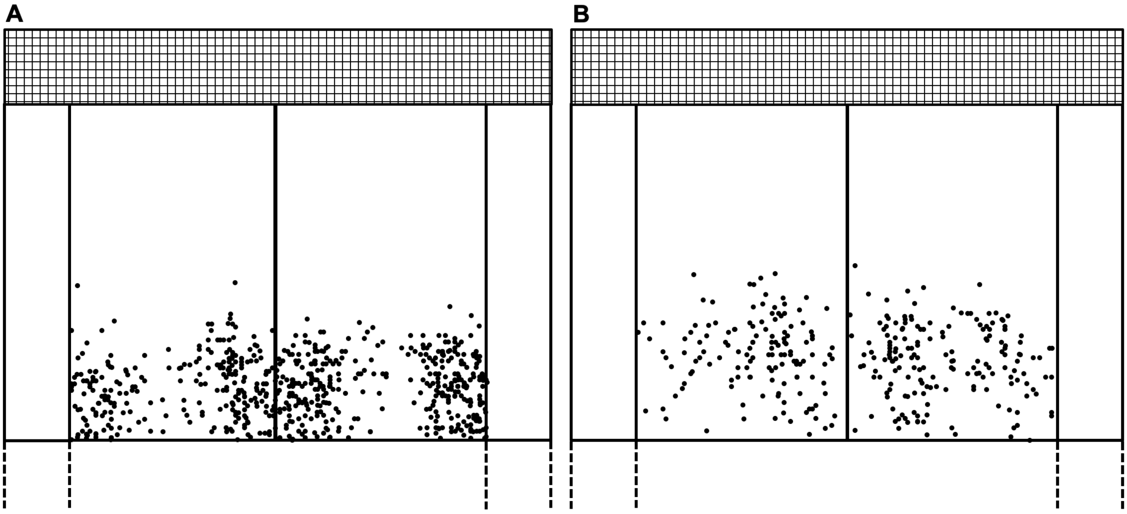


Figure 11. First (A) and second (B) total serves (TS1 and TS2) bounce landing locations.

Table 3. Serve velocity (SV), impact (IH, IPA and RIH) and landing location (DCSL and DSL) parameters and differences between first and second total (TS1 and TS2) and fastest (FS1 and FS2) serves.

	TS (n = 945)						**FS (n = 42)**					
	TS1 (n = 630)	**TS2 (n = 315)**	**Difference**				**FS1 (n = 21)**	**FS2 (n = 21)**	**Difference**			
			p	***ES***	**Descriptor**	**%**			***p***	***ES***	**Descriptor**	**%**
SV (km·h^{-1})	173.6 ± 18.0 (172.4 – 175.1)	144.7 ± 13.1* (143.2 – 146.1)	<0.001	1.30	Large	-16.7	201.3 ± 9.9 (196.8 – 205.8)	163.8 ± 9.2* (159.6 – 168.0)	<0.001	2.61	Large	-18.6
Ball impact location parameters												
IH (cm)	303.4 ± 11.9 (302.4 – 304.3)	303.3 ± 12.1 (302.0 – 304.7)	0.416	0.04	Trivial	-0.03	302.1 ± 11.3 (296.9 – 307.2)	304.3 ± 11.3 (299.1 – 309.4)	0.297	-0.25	Small	0.73
RIH (%)	162.5 ± 2.2 (162.2 – 162.6)	162.4 ± 3.0 (162.0 – 162.7)	0.321	0.04	Trivial	-0.1	161.7 ± 2.3. (160.7 – 162.7)	163.0 ± 5.5. (160.5 – 165.5)	0.309	-0.27	Small	0.80
IPA (°)	-4.37 ± 1.19 (-4.47 – -4.29)	-3.49 ± 1.35* (-3.63 – -3.34)	<0.001	-0.42	Small	20.1	-4.62 ± 0.67 (-4.31 – -4.57)	-3.86 ± 0.96* (-3.41 – -4.30)	0.003	-0.75	Large	16.5
Ball landing location parameters												
Width - DCSL (cm)	219.3 ± 138.0 (208.5 – 230.1)	209.1 ± 102.9 (197.7 – 220.5)	0.848	0.01	Trivial	-4.7	202.6 ± 149.0 (134.8 – 270.4)	155.9 ± 107.6 (106.0 – 204.9)	0.339	0.25	Small	-33.0
Depth - DSL (cm)	101.6 ± 57.1 (97.2 – 106.1)	156.4 ± 73.7* (148.3 – 164.6)	<0.001	-0.63	Moderate	53.9	70.8 ± 54.8 (45.8 – 95.8)	146.6 ± 62.5* (118.2 – 175.0)	<0.001	-1.08	Large	53.1

Data are mean ± SD (95% confidence interval). TS = total serves performed; TS1 = total first serves performed; TS2 = total second serves performed; FS = fastest serves; FS1 = fastest first serve; FS2 = fastest second serve; SV = serve velocity; IH = impact height; IPA = impact projection angle; RIH: relative impact height; DCSL = distance to the centre service line; DSL = distance to the service line; ES = effect size;. Note: Magnitudes of ESs were assessed using the following criteria: <0.2 = trivial, 0.2–0.4 = small, 0.5–0.7 = moderate, >0.7 = large. *Significantly different from first serve.

The correlation coefficients between the measured variables and TSV and FSV are presented in Table 4. Significant moderate and large positive correlations were found between anthropometric parameters (BH and BM) and TSV1, FSV1 and FSV2. The coefficient of determination between BH and BM and FSV1 and FSV2 ranged from 22 to 35%. Significant moderate positive (IH) and small to moderate negative (IPA, DCSL and DSL) correlations were found between ball impact and bounce landing location and TSV1 and TSV2. No significant correlations were found between ball impact and bounce landing location parameters and FSV.

Table 4. Correlation coefficients (r) between anthropometric (PH, BM and BMI), ball impact (IH, IPA and RIH) and landing location (DCSL and DSL) parameters and first and second total (TSV1 and TSV2) and fastest (FSV1 and FSV2) serves velocities.

	TSV (n = 945)						**FSV (n = 42)**					
	TSV1 (km·h^{-1})			**TSV2** (km·h^{-1})			**FSV1** (km·h^{-1})			**FSV2** (km·h^{-1})		
	r	***p***	***r*²**	***r***	***p***	***r*²**	***r***	***p***	***r*²**	***r***	***p***	***r*²**
Anthropometric parameters												
BH (cm)	0.318	<0.001	0.101	0.016	0.772	0.000	0.503	0.020	0.253	0.486	0.025	0.236
BM (kg)	0.315	<0.001	0.099	0.075	0.186	0.006	0.593	0.005	0.352	0.466	0.033	0.217
BMI (kg·m^{-2})	0.128	0.001	0.016	0.073	0.195	0.005	0.264	0.247	0.070	0.125	0.588	0.016
Ball impact location parameters												
IH (cm)	0.294	<0.001	0.086	0.329	<0.001	0.108	0.419	0.059	0.176	0.135	0.560	0.016
RIH (%)	-0.062	0.118	0.004	-0.050	0.379	0.003	-0.212	0.357	0.045	-0.397	0.075	0.158
IPA (°)	-0.391	<0.001	0.153	-0.409	<0.001	0.167	-0.177	0.443	0.031	-0.143	0.536	0.020
Ball bounce landing location parameters												
Width-DCSL (cm)	-0.173	<0.001	0.030	-0.190	0.001	0.036	-0.127	0.585	0.016	0.039	0.867	0.001
Depth-DSL (cm)	-0.169	<0.001	0.029	-0.179	0.001	0.032	-0.196	0.394	0.038	0.043	0.855	0.002

TSV = total performed serves velocity (all serves included); TSV1 = total first serve performed velocity; TSV2 = total second serves performed velocity; FSV = fastest serve velocity; FSV1 = fastest first serve velocity; FSV2 = fastest second serve velocity; BH = body height; BM= body mass; BMI = body mass index; IH = impact height; IPA = impact projection angle; RIH = relative impact height; DCSL = distance to the centre service line*;* DSL = distance to the service line*; r* = correlation coefficients; r^2 = determination coefficient

Results of the stepwise multiple regression analysis to explore how the anthropometric and ball impact location values predicted the TSV and FSV are summarized in Table 5. BM and IPA analysed together explained 16% of the variation observed in the TSV1 (adj $r^2 = 0.158$; $p < 0.001$) and IPA, IH, BH and RIH explained 20% of the variation in the TSV2 (adj $r^2 = 0.197$; $p < 0.001$). Only the BM appeared in the predictive models of the FSV1 and FSV2 and explained 48 and 21% of the variation respectively (adj r^2 = 0.480 and 0.208; $p < 0.001$ and $p = 0.022$, respectively).

Table 5. Anthropometric and ball impact variables included in the stepwise multiple regression analysis to explain the variance on first and second total (TSV1 and TSV2) and fastest (FSV1 and FSV2) serves velocities.

Dependent variables	Step	Independent variables entered	Correlations			SEE	*p*
			r	r^2	Adj. r^2		
TSV1 (n = 945)	1	BM	0.340	0.115	0.114	16.9	<0.001
	2	BM and IPA	0.401	0.161	0.158	16.2	<0.001
TSV2 (n = 315)	1	IPA	0.390	0.152	0.150	12.1	<0.001
	2	IPA and IH	0.422	0.178	0.173	12.0	<0.001
	3	IPA, IH and BH	0.441	0.194	0.187	11.9	<0.001
	4	IPA, IH, BH and RIH	0.455	0.207	0.197	11.8	<0.001
FSV1 (n = 21)	1	BM	0.712	0.506	0.480	7.1	<0.001
FSV2 (n = 21)	1	BM	0.498	0.248	0.208	8.2	0.022

TSV1 = total first serves velocity; TSV2 = total second serves velocity; FSV1 = fastest first serve velocity; FSV2 = fastest second serve velocity; BM = body mass; IPA = impact projection angle; RIH = relative impact height; Adj. r^2 = adjusted coefficient of determination; SEE = standard error of estimate.

4.1.5 DISCUSSION

The main purpose of this study was to analyse the associations between SV and anthropometric, ball impact and landing location parameters in professional tennis players during an ATP Tour event and to observe differences between S1 and S2. Among the variables registered, anthropometric (greater BM and BH), ball impact (higher IH and IPA) and bounce landing (minor width and larger depth) location parameters small to moderately influence TSV. However, the present findings reinforce the influence of anthropometric parameters (BH, BM) in SV when tennis player try to maximize ball velocity (i.e., TSV1, FSV1 and FSV2), but not when S are more conservative (i.e., TSV2). When tennis players serve at maximal SV (FSV1 and FSV2), the anthropometric parameters were the unique significant contributors of SV explaining 22 to 35% of SV. Moreover, the prediction model highlights the importance of BM above BH on FSV. S1 shows a large increase of SV in combination with moderate to large increases in depth and IPA compared to S2.

Regarding BH, it clearly seems that the tallest tennis players have a better disposition to serve fast, as its influence was large in FSV1 ($r = 0.503$), moderate on TSV1 and FSV2 ($r = 0.318$ and 0.486) and no influence was found in TSV2. This fact involves that as more powerful a S is, the influence of BH on SV is increased, emphasizing the importance of the principle of force production above the influence of longer connecting body segments. These results are somehow expected in agreement with studies registered in professional tennis tournaments such as the four Grand Slams ($r = 0.31 - 0.57$) (Vaverka & Cernosek, 2016) and Wimbledon (SV1, $r = 0.640$, $p < 0.001$) (Wong et al., 2014). Greater BH allows a biomechanical benefit to SV over lower BH, as longer limbs allow to obtain higher peripheral head racket velocity at ball impact getting greater hand-racket angular momentum with the equal angular speed of upper body segments (Hayes et al., 2021; Martin, Kulpa, Delamarche, et al., 2013; Vaverka & Cernosek, 2016). This association seems to be higher when S is tested in laboratory-court simulated conditions in professional tennis players for both S1 ($r = 0.78$, $p < 0.05$) and S2 ($r = 0.80$; $p < 0.05$) (Bonato et al., 2015). Possibly, the increase of the effect of BH in closed situations is because there is no decision making and decisive tactical factors of S performance involved (i.e., depth, directions or accuracy). Players can focus only on SV execution, and this fact supports the hypothesis of the relevance to analyze the S influencing parameters during real competition.

In the same way as BH, BM demonstrated large associations with FSV1 ($r = 0.593$), moderate with TSV1 and FSV2 ($r = 0.315$ and 0.466) and no associations were found with TSV2. Moreover, BM explained 35% of the variability of FSV1. In line with this, moderate and large associations have been found in junior tennis players ($r = 0.44 – 0.57$; $r = 0.68$) (Fett et al., 2020; Hayes et al., 2021), but on the contrary, no associations have been found in S performed in a closed situation ($r = -0.22$ and -0.15; $p > 0.05$) (Bonato et al., 2015). Interestingly, the unique step in FSV1 (adj. $r^2 = 0.48$) and FSV2 (adj. $r^2 = 0.21$) and the first step in TSV1 (adj. $r^2 = 0.11$) included in the multiple regression analysis demonstrate the relevance of BM when players serve at or near maximal SV. The potential biomechanical factors that may cause the clear influence of BM on maximal SV are related to the principle of force (mass x acceleration) and torque production (Fett et al., 2020; Wong et al., 2014). Based on allometry assumption, BM is associated with torque production and an increased torque would reinforce SV (Wong et al., 2014). In this sense, Gale-Wats & Nevill (2016) established that the body structure (i.e., body composition) in world-class tennis players has been changing in recent times increasing their muscle mass and experiencing a transformation from endurance to power athletes. The same researchers suggested that a greater muscle mass and the ability to generate power production in all strokes in professional tennis players is associated with greater tennis performance, while taller but less muscled players (i.e., more linear body shape) would perform worse. However, although in professional tennis players we could assume that a high BMI is related to a greater muscle mass, we observed only a small influence of BMI in TSV1 ($r = 0.128$), but not in FSV. Contrary, in competition but not ATP level tennis players, BMI was largely associated ($r = 0.577$; $p < 0.05$) with SV (Wong et al., 2014) and moderate significant ($r = 0.32$ to 0.40; $p < 0.001$) and no significant ($r = 0.31$, $p > 0.05$) associations have been found in junior tennis players (Fett et al., 2020; Hayes et al., 2021). Considering that BMI represents an interaction of two parameters (i.e., BM and BH), it is possible that a single increase in BM does not generate a significantly increase in SV and an optimal relationship probably exist between BM and BH to optimize SV.

Regarding ball impact location parameters (IH and IPA), they show a comparable influence to anthropometrics on TSV1 ($r = 0.294$ and -0.391), but contrary to BH and BM, a higher influence on TSV2 ($r = 0.329$ and -0.409) and no significant association with FSV. It seems that the benefit of ball impact location parameters on SV was lower when players try to maximize SV, however, we could speculate that they have a major impact on S accuracy. In addition to BH, there were diverse factors that could affect IH, such as vertical jump height, the vertical height of the hitting shoulder, the impact point on the string and the sum of arm and racquet length (Bonato et al., 2015; Vaverka & Cernosek, 2013, 2016). Also, it has been argued that IH could affect the precision of S. It has been stated that a higher IH contributes to a larger accessible area in the service box (Vaverka & Cernosek, 2013) and allows a greater SV with the equal probability of the ball landing inside the service box (Vaverka & Cernosek, 2016). RIH was introduced in the analysis as an IH and BH ratio, as it has been found that IH represents the 160% of

BH showing the repercussion on IH of the factors that accompany BH (i.e., vertical jump height and vertical height of the hitting shoulder). RIH did not show any influence in SV, thus we could speculate that even if BH has a large influence on SV, the factors that accompany BH to determine IH does not affect SV. No differences in IH and RIH were found between S1 and S2, showing that these parameters are relatively stable in different tennis S (i.e., flat or topspin S). In this same line, no significant differences have been observed between S1 and S2 jump height (Dossena et al., 2018). It has been stated that in the S there is a higher biomechanical consistency of impact conditions than groundstrokes or volleys as a result of the initially stationary location on the court (Allen et al., 2016) and that players are able to dominate the main ball impact positions and to reproduce systematically the S performance (Tubez et al., 2019).

Regarding IPA and in the same way that IH, a moderate influence on TSV was found, showing that a large IPA favours TSV but not FSV. However, moderate and large differences have been found between IPA in S1 and S2. In this same line, Chow et al. (Chow et al., 2003) observed greater IPA in the S1 than in S2 (6.3 ± 1.8° vs 3.1 ± 2.0°). We consider that IPA interpretation should be done alongside the analysis of depth (DSL) and ball velocity. The large differences found between S1 and S2 in depth (~50%) and ball velocity (~17-18%) together with the large differences in IPA (20 and 16.5 %), shows that the S1 are significantly faster, deeper and with a major IPA than S2. Probably IPA may vary between flat and spin S and the less IPA and depth in S2 can be attributed to the slower SV and greater topspin. In S related with more speed and aggressive action (i.e., power S) players used flat S (i.e., minimum amount of spin on the ball) (Chow et al., 2009), contrary the S2 are conservative using topspin or slice which reduces SV (Gillet et al., 2009). A minor spin and higher SV are characterized by straighter ball trajectories over flight than slower S, and consequently, with a reduced clearance over the net to land in the service box. Contrary, on topspin S with greater ball spin rate and less ball velocity (i.e., S2) the Magnus force provokes further curved ball trajectory and lower forward velocity and depth (Chow et al., 2003; Sheets et al., 2011). Therefore, the straight ball trajectory of fastest S needs a large IPA and allows it to reach a greater depth. From a tactical perspective, the greater SV and deeper landing location in S1 compared to S2 leads to a smaller margin of error, however it has been established that a greater SV offers a higher probability to win the S (Mecheri et al., 2016). In agreement with this, the top 10 ATP tennis players until April 2020 won the 71.3 ± 4.0% of points played with the S1 and 49.7 ± 7.2% with S2 (https://www.atptour.com/en).

Visual inspection shows that S1 ball bounces (Figure 11A) are located closer to service centre line (i.e., T location) and singles sideline (wide location) and less into the centre service box (i.e., body location) than S2 (Figure 11B). Alongside a higher SV1 than SV2, the differences between S1 and S2 landing location probably occurs because tennis players try to optimize the tactical advantage, number of aces or points directly won with S to a greater extent in the S1 than S2. In this same line, it has been shown that S1 are more effectively near to T location or near to the singles sideline (wide location) and body serves occur to a lesser extent (Whiteside & Reid, 2017a). Nevertheless, the negative moderate and small associations found between width and TSV1 and TSV2 ($r = -0.173$ and -0.190) shows a trend that fastest TS were closer to the centre service line (i.e., T location), especially in TSV1. An explanation for this could be that when players seek wide S, they tend to focus on accuracy of S to move the opponent off the court and achieve a positional advantage. Instead, when serving near the T location they seek to maximise S speed and diminish the time reaction of the opponent.

From a practical standpoint, our data emphasizes the influence of selected anthropometric (BM and BH) parameters on SV in professional tennis players during an

ATP Tour event and reinforces the BM as an important influencing factor when players serve at or near maximal SV. In this regard, because BH can't be modified in adult tennis players, it can be postulated that neuromuscular strength training interventions aimed at increasing lean BM can be helpful for improving SV, especially in not very tall professional tennis players (i.e., < 185 cm). However, this assumption should be taken with caution since the ability to accelerate, decelerate and change of direction over short distances is paramount in tennis performance. A greater BM will produce a greater inertia demanding higher force production to produce a given change in velocity or direction (Sheppard & Young, 2006), so an optimal interaction between increasing BM and COD performance should be found.

There are some limitations that need to be considered when interpreting the results of the present study. First, anthropometric characteristics of tennis players (i.e., BH and BM) were obtained from publicly available information listed in the official ATP website, assuming that the provided data may differ minimally from real data. Second, previously discussed, S is a highly complex stroke determined by different nature parameters (Kovacs & Ellenbecker, 2011a, 2011b), however the presented SV prediction model is based on a partial spectrum of serve performance (i.e., some anthropometric [BH and BM], ball impact and bounce variables). The model would be more accurate considering other determinant factors such as technical (Mecheri et al., 2016), strategical (Gillet et al., 2009), range of motion (Hernández-Davó et al., 2019; Palmer et al., 2018) or muscle power performance (Baiget et al., 2016; Fett et al., 2020; Hayes et al., 2021; Palmer et al., 2018) parameters.

4.1.6 CONCLUSIONS

In conclusion, the results of the present study have shown that anthropometric (greater BM and BH), ball impact (higher IH and IPA) and bounce landing (minor width and larger depth) location parameters small to moderately influence SV during an ATP Tour event. However, when tennis players serve at or near maximal SV, the influence of anthropometric parameters are increased being the major contributors to SV. The prediction model constructed highlights the influence of BM above BH on the fastest serves, suggesting its importance to generate power production at the professional tennis level. Moreover, S1 are deeper and show a greater IPA compared to the S2.

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4.2 Study II

Upper limb force-time characteristics determines serve velocity in competition tennis players

by

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4.2.1 ABSTRACT

Purpose: (a) To analyse the associations between serve velocity (SV) and various single-joint upper limb isometric force-time curve parameters; (b) to develop a prediction model based on the relationship between these variables and (c) to determine whether these factors are capable of discriminating between tennis players with different SV performances. **Method**: Seventeen high-performance tennis players performed 8 isometric tests of joints and movements included in the serve kinetic chain (wrist and elbow flexion [WF and EF] and extension [WE and EE]; shoulder flexion [SHF] and extension [SHE], internal and external rotation [SHIR and SHER]). Isometric force (IF), rate of force development (RFD) and impulse (IMP) at different time intervals (0 – 250 ms) were obtained for analysis. **Results**: Significant ($p < 0.05$ to $p < 0.01$) and moderate to very large correlations were found between SV and IF, RFD and IMP at different time intervals in all joint positions tested (except for the EF). Stepwise multiple regression analysis highlighted the importance of RFD in the SHIR from 0-50 ms and IF in the SHF at 250 ms on SV performance. Moreover, the discriminant analyses established SHIR RFD from 0 to 30 ms as the most important factor discriminating players with different serve performances. **Conclusions**: Force-time parameters in upper limb joints involved in the serve moderate to very largely influence SV. Findings suggest that the capability

to develop force in short periods of time (< 250 ms), especially in the shoulder joint, seems relevant to develop high SV in competition tennis players.

Keywords: power, rate of force development, strength, force production, impuls

4.2.2 INTRODUCTION

The tennis serve is a high-speed movement currently considered the most important, powerful and determinant shot in high level tennis (Fitzpatrick et al., 2019). In particular, serve velocity (SV) has become one of the major performance parameters in competition tennis players (Fitzpatrick et al., 2019; Gillet et al., 2009). Tennis serve is a hugely complex stroke and when examining the factors that influence SV, different nature parameters (i.e., neuromuscular, anthropometric, biomechanical, technical, tactical and strategic) seem to all contribute to some extent to build fast serves (Bonato et al., 2015; Gillet et al., 2009; Kovacs & Ellenbecker, 2011b).

High speed rotational movements to accelerate the racket towards the ball seem necessary to produce maximal SV (Myers et al., 2015; Reid & Schneiker, 2008). In addition, activating and coordinating efficiently diverse segments in the whole kinetic chain, involving lower limbs, trunk and upper limbs (Roetert et al., 2009) is paramount in parallel with the use of elastic energy and muscle preload (Elliott, 2006). Although all phases of the tennis serve (i.e., cocking, acceleration and deceleration phases) last around 650 ms, the acceleration phase corresponding to concentric muscle activation lasts about 80 ms (Kibler et al., 2007) From this perspective, force-time characteristics such as the rate of force development (RFD), impulse (IMP) or isometric force (IF) at different time frames are considered key neuromuscular function parameters (Taber et al., 2016) and especially RFD has been considered a determinant factor in fast and forceful movements in trained athletes (Aagaard et al., 2002). According to this, RFD is considered as a good predictor of performance in individual (Seitz, Reyes, et al., 2014; Stone et al., 2004) or team (Townsend et al., 2019; Wang et al., 2016) sports. However, limited research has examined the functional relevance of force-time parameters to SV in competition tennis players.

It has been recommended that the isometric test to assess the force-time parameters of athletic populations should be executed near or at the joint angle where the peak force is applied throughout the specific dynamic movement of interest (Lum et al., 2020). Although previous investigations have positively correlated maximum IF and SV (Baiget et al., 2016; Bonato et al., 2015), few studies have included various isometric upper limb force-time parameters (i.e., RFD or IMP) or the majority of joints and positions involved in the tennis serve motion (i.e., wrist, elbow and shoulder), limiting the possibility to evaluate the relationship between these variables and SV. Therefore, grouping and assessing those upper body joints and positions mostly involved in the serve kinetic chain could be useful to provide insights on the influence of force-time characteristics on SV. Moreover, isometric testing is time efficient, induces minimal fatigue (Dos'Santos et al., 2017) and therefore could result advantageous to implement assessment tools to evaluate and control SV more resourcefully in competition players. Thus, the aims of the study were (a) to analyse the associations between SV and various single-joint upper limb isometric force-time curve parameters (IF, RFD and IMP) in competition tennis players; (b) to develop a prediction model based on the relationship between these variables and (c) to determine whether selected IF, RFD and IMP parameters in different upper limb joints are capable of discriminating between tennis players with different SV performances.

4.2.3 METHODS

Subjects

Seventeen high-performance tennis players, 12 male and 5 female (mean ± SD; age 16.8 ± 1.1 years; body mass 68.8 ± 7.8 kg, body height 176.7 ± 8.6 cm) with an International Tennis Number (ITN) ranging from 1 (elite) to 2 (advanced) participated in this study. Their weekly training volume ranged from 20 to 25 hours, which focused on tennis-specific training (i.e., technical and tactical skills), aerobic and anaerobic training (i.e., on- and off-court exercises). Inclusion criteria for all subjects required each participant to have a minimum of 2 year experience in strength training and a minimum of 5 years of tennis training and competition. Exclusion criteria was to have a previous history of upper extremity surgery, shoulder, back or knee pain or rehabilitation in the past 12 months. All players were right-handed. Scientific Committee of the Research and Health Education Foundation of Osona approved the study (CEIC 2015882), and all subjects gave written informed consent after being informed of the risks and benefits of participation. Parental written informed consent was obtained for subjects under 18 years of age. The study was conducted following the ethical principles for medical research with human beings, established in the Declaration of Helsinki of the AMM (2013).

Design

A single-cohort, cross-sectional study was conducted to investigate the relationships between SV and force-time parameters in 8 tests of upper-limb muscle function joints involved in the serve kinetic chain. The whole cohort of subjects was included in the correlational analysis. On the one hand, this procedure was used to determine to what extent upper-limb force-time parameters were related to SV. On the other hand, multiple regression analyses were used to develop models that were most effective at predicting

SV. Moreover, tennis players were retrospectively allocated into 2 groups according to their SV, and stepwise discriminant analysis was used in order to determine the isometric time-force curve variables that best distinguished SV.

Methodology

The study was divided into two testing sessions performed on the same day, with 30 min rest periods between them. All participants performed first the maximum SV test followed by the force-time assessment. No vigorous physical activity was performed in the 24 hours before testing. No caffeine ingestion was allowed in the 24 hours before testing and meal ingestion was avoided at least three hours before the scheduled test time.

Serve velocity testing

Maximum SV was recorded on a hard-surface tennis court (GreenSet surface, worldwide SL, Barcelona, Spain) under stable weather conditions (air velocity < 2 $m \cdot s^{-1}$), with new tennis balls (Head ATP, Spain). A hand-held radar gun [Stalker ATS II, United States, frequency: 34.7 GHz (Ka-Band) ± 50 MHz] was used for recording peak velocity. Prior to the assessment of each subject, the radar was calibrated with a Ka-Band verification fork, following the manufacturer's recommendations. The radar was positioned in the center of the baseline, 2 m behind the line and player and at an approximate height of 2 m, following the trajectory of the ball during the serve. Before the test, participants performed a warm-up protocol that included mobility exercises, 5 min of free rallies and 10 progressive serves. After, each player was instructed to hit two sets of six flat serves (i.e., with minimum amount of spin) on each side of the court hitting as hard and precise as possible to the “T”, with 60 s rest periods between sets. Only the serves that were “in” were registered and mean SV was used for analysis. We assumed that the direction and service target (T, body and wide) significantly affected the execution of the serve (Reid et al., 2011), influencing test reliability. Subjects were verbally encouraged to hit the ball as hard as possible. Immediate feedback was provided to the subjects to encourage maximum effort.

Isometric Force-Time Curve Assessment

Eight maximum isometric tests of joints and movements included as a part of the service kinetic chain (Elliott, 2006) were performed (wrist and elbow flexion [WF and EF] and extension [WE and EE]; shoulder flexion and extension [SHF and SHE], internal and external rotation [SHIR and SHER]) (Figure 12) with the dominant arm using a strain gauge (MuscleLab4000e; BoscosystemLab, Rome, Italy) (Baiget et al., 2016). The amplified and calibrated force signal was sampled at 200 Hz. The specific position for each isometric pull was established before each trial with the use of a validated goniometer (Easyangle; Meloq AB, Stockholm, Sweden). After 5 min of standardized dynamic warm-up, participants completed a sub maximal isometric contraction of 50% of perceived maximal voluntary contraction in each of tested positions. Every subject performed three maximal voluntary contractions of 3-5 s durations separated by 1 min (between sets) and 5 min (between joints) of rest. The subjects were instructed to perform every test “as fast and as hard as possible” and to avoid any pretension and countermovement. Strong verbal encouragement was given during every contraction. Upper limb positions were tested in a cable jungle machine (Technogym®, Italy). Similar racket grip diameter was selected with the aim of increasing specificity, and special attention was placed on grip comfort during tests to avoid strength feedback inhibition. In the upper limb tests, participants sat in an upright position with 90° of hip flexion, with the thighs supported and the medial borders of the knees placed together. Participants were restrained by a waist band and two thoracic straps crossing over at the sternum, which together acted to prevent any extraneous movement. SHF and SHE positions were recorded with the upper extremity flexed to 90° and the elbow extended, while SHIR and SHER was performed with the shoulder abducted and the elbow flexed to 90°. The apparatus seat height was adjusted so that the trunk-thigh angle was 90° and the shank-thigh angle was 90°. Elbow and wrist tests were performed in a seated position, with the elbow bent at 90°. In both cases, subjects were asked to hold a U-shaped handle linked to the strain gauge in a prone position. Trials with an initial counter movement were discarded and an extra trial was recorded (Maffiuletti et al., 2016).

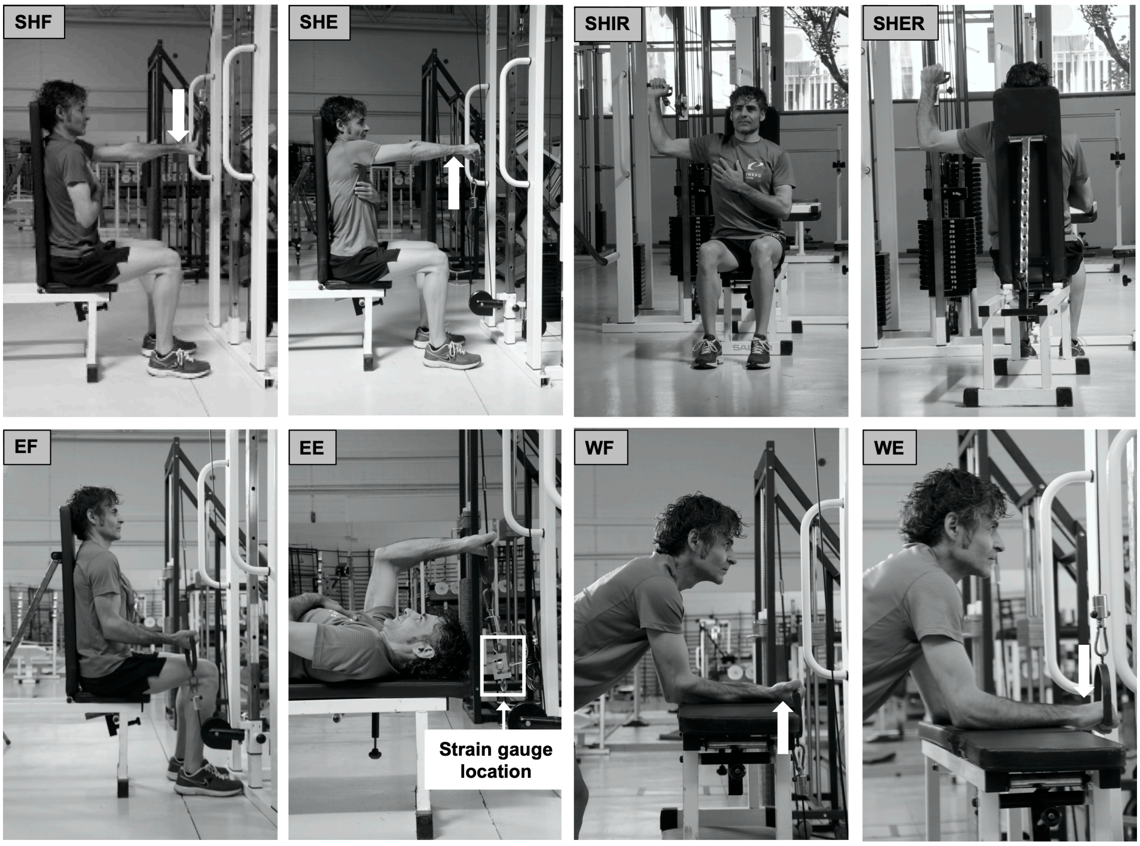

Figure 12. Maximum isometric single-joint upper limb tests performed. Abbreviations: SHF, shoulder flexion; SHE, shoulder extension; SHIR, shoulder internal rotation; SHER, shoulder external rotation; EF, elbow flexion; EE, elbow extension; WF, wrist flexion; WE, wrist extension.

Isometric Force-Time Curve Analyses

Once the force time curves were obtained, the on-set of effort was determined through visual inspection and a manual section of each force-time curve. The same researcher determined on-set of effort by visually detecting the last point before force deflected above the range of the baseline noise. RFD and IMP were calculated based on the manual onset of effort detection (Maffiuletti et al., 2016). Peak of force at 0, 30, 50, 90, 100, 150, 200 and 250 ms from the start of the contractions were obtained. In the same way, maximum force from the entire interval time evaluated was also reported. The RFD between 0-30, 0-50, 0-90, 0-100, 0-150, 0-200 and 0-250 ms was calculated as the slope of segment between time moments (Figure 13), in accordance with previous studies,(Haff et al., 2015) and with the equation:

$$\text{RFD} = \Delta\ \text{Force} / \Delta\ \text{Time}$$

Contractile isometric accumulated IMP (integral of torque and time) was also calculated in the same time intervals from RFD with the parallelogram method from the area under the force-time curve between selected time intervals as follows:

$$\int_{t_0}^{t_n} \text{Force} \times \text{d Time}$$

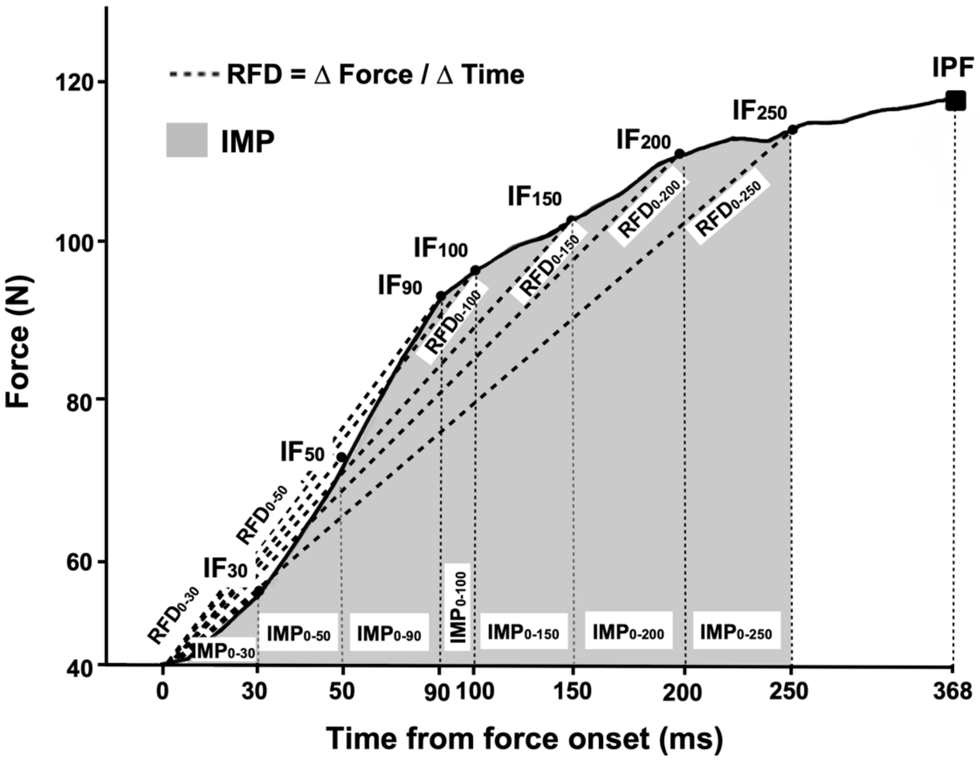

Figure 13. Example of isometric force-time curve, data from a representative subject of the wrist extension (WE). Isometric force (IF), rate of force development (RFD) and impulse (IMP) at different times frames (0, 30, 50, 90, 100, 150, 200 and 250 ms) and isometric peak force (IPF) are shown.

Force-time curve parameters (Table 6) analysed reached an acceptable level of reliability with excellent intraclass correlation coefficients (mean ICCs ≥ 0.896; range: 0.823 to 0.994) and coefficients of variation (CVs) of less than 20% (mean CVs ≤ 16.8; range: 6.3 to 19.2%). SV showed excellent consistency (ICC = 0.970; CV = 3.7%).

Table 6. Reliability of force-time curve measurements.

	ICC[†]	**ICC range**	**CV**[†] **(%)**	**CV range (%)**
IF$_{30}$	0.963 ± 0.01	0.953 – 0.974	10.9 ± 3.7	6.3 – 14.6
IF$_{50}$	0.966 ± 0.02	0.939 – 0.986	10.8 ± 2.5	7.9 – 13.4
IF$_{90}$	0.950 ± 0.04	0.892 – 0.980	14.1 ± 2.5	10.8 – 16.9
IF$_{100}$	0.950 ± 0.06	0.865 – 0.994	15.4 ± 3.2	12.0 – 19.0
IF$_{150}$	0.957 ± 0.04	0.907 – 0.993	13.5 ± 2.3	10.5 – 15.8
IF$_{200}$	0.970 ± 0.02	0.949 – 0.993	13.0 ± 3.1	9.7 – 16.8
IF$_{250}$	0.982 ± 0.01	0.974 – 0.992	10.8 ± 2.5	7.8 – 13.5
IPF	0.948 ± 0.05	0.897 – 0.990	7.8 ± 3.1	6.0 – 11.1
RFD$_{0\text{-}30}$	0.911 ± 0.06	0.823 – 0.967	16.8 ± 6.4	14.1 – 18.7
RFD$_{0\text{-}50}$	0.945 ± 0.03	0.904 – 0.984	15.8 ± 5.5	11.3 – 19.2
RFD$_{0\text{-}90}$	0.928 ± 0.06	0.857 – 0.986	13.0 ± 4.0	10.7 – 15.4
RFD$_{0\text{-}100}$	0.967 ± 0.01	0.957 – 0.987	11.8 ± 4.3	7.8 – 14.1
RFD$_{0\text{-}150}$	0.908 ± 0.05	0.860 – 0.973	13.7 ± 4.3	12.4 – 14.8
RFD$_{0\text{-}200}$	0.896 ± 0.02	0.872 – 0.920	14.9 ± 5.7	11.8 – 16.6
RFD$_{0\text{-}250}$	0.926 ± 0.04	0.882 – 0.966	14.2 ± 5.1	12.3 – 17.9
IMP$_{30}$	0.962 ± 0.01	0.952 – 0.976	13.4 ± 4.6	9.1 – 18.8
IMP$_{50}$	0.963 ± 0.01	0.961 – 0.965	12.9 ± 3.8	9.6 – 17.8
IMP$_{90}$	0.969 ± 0.01	0.963 – 0.974	13.8 ± 2.6	11.7 – 17.6
IMP$_{100}$	0.970 ± 0.01	0.959 – 0.977	14.3 ± 2.1	12.9 – 17.3
IMP$_{150}$	0.968 ± 0.02	0.947 – 0.982	16.3 ± 1.9	13.5 – 17.9
IMP$_{200}$	0.969 ± 0.01	0.952 – 0.981	14.7 ± 1.6	12.9 – 16.2
IMP$_{250}$	0.967 ± 0.03	0.930 – 0.985	13.3 ± 1.6	11.8 – 15.3

[†] Values are mean ± SD. ICC, intraclass correlation coefficient; CV, coefficient of variation; IF$_{30}$, isometric force at 30 ms; IF$_{50}$, isometric force at 50 ms; IF$_{90}$, isometric force at 90 ms; IF$_{100}$, isometric force at 100 ms; IF$_{150}$, isometric force at 150 ms; IF$_{200}$, isometric force at 200 ms; IF$_{250}$, isometric force at 250 ms; IPF, isometric peak force; RFD$_{0-30}$, rate of force development from 0 to 30 ms; RFD$_{0-50}$, rate of force development from 0 to 50 ms; RFD$_{0-90}$, rate of force development from 0 to 90 ms; RFD$_{0-100}$, rate of force development from 0 to 100 ms; RFD$_{0-150}$, rate of force development from 0 to 150 ms; RFD$_{0-200}$, rate of force development from 0 to 200 ms; RFD$_{0-250}$, rate of force development from 0 to 250 ms; IMP$_{30}$, impulse at 30 ms; IMP$_{50}$, impulse at 50 ms; IMP$_{90}$, impulse at 90 ms; IMP$_{100}$, impulse at 100 ms; IMP$_{150}$, impulse at 150 ms; IMP$_{200}$, impulse at 200 ms; IMP$_{250}$, impulse at 250 ms.

Statistical Analyses

Descriptive data are expressed as mean ± standard deviation (SD). The normality of variables distribution was assessed with the Shapiro-Wilk test. Intrasession reliability of measures was determined using a two-way average measure of the intraclass correlation coefficient (ICC). Pearson correlation coefficient was used to examine the relations between mean SV and isometric time-force curve variables, while coefficient of determination was used to explain the common variance between these variables and SV. Correlations were classified as trivial (0–0.1), small (0.1–0.3), moderate (0.3–0.5), large (0.5–0.7), very large (0.7–0.9), nearly perfect (0.9), and perfect (1.0) (Hopkins et al., 2009). Mean SV was used as the dependent variable in the stepwise multiple regression analysis, whereas isometric time-force curve variables at different time points (IF, RFD and IMP) operated as independent predictors. The subjects were also split into two groups based on their SV; low SV (LSV; SV < 165 km·h-1) and high SV (HSV; SV ≥ 165 km·h-1), respectively. SV ≥ 165 km·h-1 was used as the criterion to determine groups as the mean SV of the total serves was 166.6 ± 14.6 Km·h-1. The LSV included 7 tennis players (age 16.5 ± 1.4 years; body mass 65.0 ± 8.9 kg, height 171.9 ± 8.9 cm; SV= 153.3 ± 10.2 km·h-1) and the HSV 10 players (age 17.0 ± 0.9 years; body mass 71.4 ± 6.0 kg, height 180.1 ± 6.9 cm; SV = 176.1 ± 8.1 km·h-1). Stepwise discriminant analysis was used for selected isometric time-force curve variables, with SV as the dependent variable (LSV vs. HSV). After checking for equality of the variances (Levene's test), differences between the 2 groups' mean values of the variables included in the discriminant analysis were assessed using the unpaired Student's t-test (equal variances) or by Welch's test (unequal variances). Statistical significance was accepted at an alpha level of $p \leq 0.05$. All statistical analyses were performed using IBM SPSS Statistics 26.0 (SPSS, Inc., Chicago, IL.).

4.2.4 RESULTS

Players hit a total of 204 flat serves (102 each side), 50.5% of serves were considered good (52.9 ± 23.0 % left and 48.0 ± 19.4 % right side) and the average SV was 166.6 ± 14.6 Km·h-1 (167.4 ± 14.4 Km·h^{-1} left and 165.7 ± 14.8 Km·h^{-1} right side).

Isometric time-force curve variables are shown in Figure 14. Significant large-to-very large (r = 0.52 to 0.72) correlations were found between SV and IF at 100 to 250 ms in WE, WF, SHF and SHIR, IF at 200 to 250 ms in EE and SHE and IPF in all positions. Additionally, moderate-to-large (r = 0.49 to 0.59) significant correlations between SV and IF at 90 ms in WE, WF and SHF, IF at 50 ms in WF and IF at 150 ms in SHE. The coefficients of determination ranged from 24 to 52% (Table 7).

Similarly to IF, RFD parameters demonstrated significant moderate-to-very large (r = 0.49 to 0.71) correlations between SV and RFD from 0 to 100, 150, 200 and 250 ms in all extension (WE, EE, SHE), SHF and SHIR positions. There were also significant large (r = 0.50 to 0.58) correlations between SV and RFD from 0 to 150, 200 and 250 ms in WF, RFD0-50 and RFD0-90 in WE, SHE and SHIR, RFD0-30 in WE, RFD0-90 in SHF and RFD0-250 in SHER. The coefficients of determination ranged from 25 to 50% (Table 7).

Regarding IMP, significant moderate-to-large (r = 0.53 to 0.66) correlations were found between mean SV and IMP at 150 to 250 ms in WE, SHE, WF, SHF and SHIR, IMP at 200 and 250 ms in EE and IMP at 50 to 100 ms in WF. The coefficients of determination ranged from 25 to 44% (Table 7).

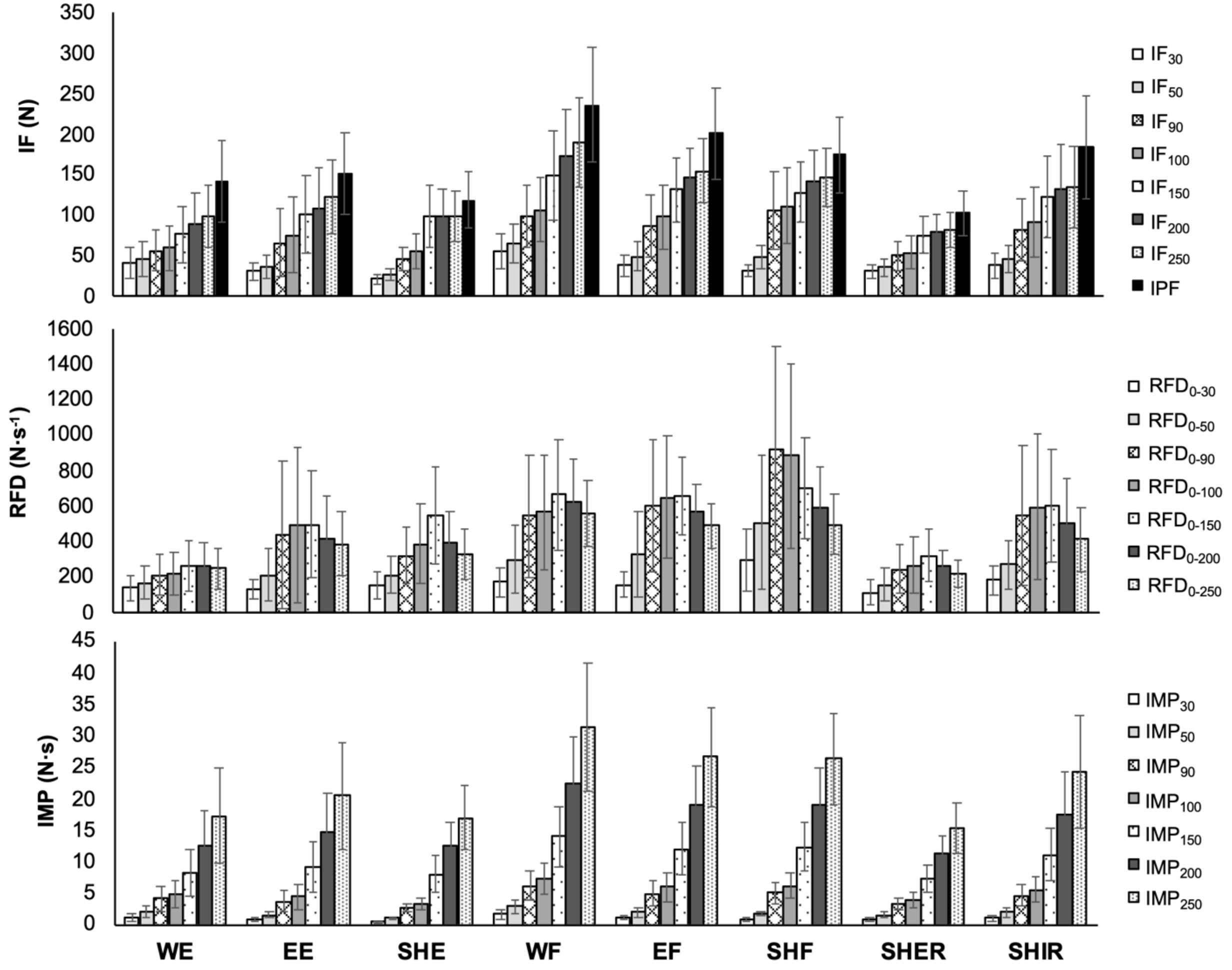

Figure 14. Isometric force-time curve results. Data are Mean ± SD. Abbreviations: IMP, impulse; RFD, rate of force development; IF, isometric force; WE, wrist extension; EE, elbow extension; SHE, shoulder extension; WF, wrist flexion; EF, elbow flexion; SHF; shoulder flexion; SHER, shoulder external rotation; SHIR, shoulder internal rotation; IF30, isometric force at 30 ms; IF50, isometric force at 50 ms; IF90, isometric force at 90 ms; IF100, isometric force at 100 ms; IF150, isometric force at 150 ms; IF200, isometric force at 200 ms; IF250, isometric force at 250 ms; IPF, isometric peak force; RFD0 – 30, rate of force development from 0 to 30 ms; RFD0 – 50, rate of force development from 0 to 50 ms; RFD0 – 90, rate of force development from 0 to 90 ms; RFD0 – 100, rate of force development from 0 to 100 ms; RFD0 – 150, rate of force development from 0 to 150 ms; RFD0 – 200, rate of force development from 0 to 200 ms; RFD0 – 250, rate of force development from 0 to 250 ms; IMP30, impulse at 30 ms; IMP50, impulse at 50 ms; IMP90, impulse at 90 ms; IMP100, impulse at 100 ms; IMP150, impulse at 150 ms; IMP200, impulse at 200 ms; IMP250, impulse at 250 ms.

Table 7. Correlation coefficients (r) between serve velocity and isometric force-time curve variables.

Variable	**SV ($Km \cdot h^{-1}$)**															
	Extension						**Flexion**						**Rotation**			
	WE		**EE**		**SHE**		**WF**		**EF**		**SHF**		**SHER**		**SHIR**	
	r	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**
Isometric force (IF)																
IF_{30} (N)	0.40	0.16	-0.12	0.01	-0.43	0.18	0.49	0.24	0.04	0.00	-0.16	0.03	-0.18	0.03	-0.01	0.00
IF_{50} (N)	0.46	0.21	-0.08	0.01	-0.14	0.02	0.54*	0.29	0.20	0.04	0.28	0.08	-0.09	0.01	0.14	0.02
IF_{90} (N)	0.54*	0.29	0.115	0.01	0.35	0.12	0.56*	0.31	0.19	0.04	0.49*	0.24	0.09	0.01	0.48	0.23
IF_{100} (N)	0.56*	0.31	0.38	0.14	0.34	0.12	0.58*	0.34	0.17	0.04	0.52*	0.27	0.17	0.03	0.58*	0.34
IF_{150} (N)	0.61*	0.37	0.48	0.23	0.50*	0.25	0.65†	0.42	0.19	0.04	0.67†	0.45	0.34	0.12	0.63*	0.40
IF_{200} (N)	0.63*	0.40	0.51*	0.26	0.57*	0.14	0.65†	0.32	0.30	0.09	0.70†	0.49	0.30	0.09	0.62*	0.38
IF_{250} (N)	0.65†	0.42	0.50*	0.25	0.59*	0.19	0.60*	0.36	0.36	0.13	0.72†	0.52	0.35	0.12	0.54*	0.29
IPF (N)	0.67*	0.45	0.59*	0.35	0.72†	0.52	0.64†	0.41	0.63*	0.40	0.70†	0.49	0.45	0.20	0.54*	0.29
Rate of force development (RFD)																
RFD_{0-30} ($N \cdot s^{-1}$)	0.66†	0.44	0.27	0.07	0.48	0.23	0.42	0.18	0.29	0.08	0.44	0.19	0.23	0.05	0.45	0.20
RFD_{0-50} ($N \cdot s^{-1}$)	0.69†	0.48	0.39	0.15	0.52*	0.27	0.30	0.09	0.32	0.10	0.42	0.18	0.25	0.06	0.53*	0.28
RFD_{0-90} ($N \cdot s^{-1}$)	0.69†	0.48	0.45	0.20	0.59*	0.35	0.37	0.14	0.22	0.05	0.50*	0.25	0.29	0.08	0.55*	0.30
RFD_{0-100} ($N \cdot s^{-1}$)	0.69†	0.48	0.54*	0.29	0.49*	0.24	0.41	0.17	0.19	0.04	0.53*	0.28	0.33	0.11	0.63*	0.40

RFD$_{0-150}$ (N·s^{-1})	0.67†	0.45	0.55*	0.30	0.55*	0.30	0.50*	0.30	0.22	0.05	0.67†	0.45	0.45	0.20	0.71†	0.50
RFD$_{0-200}$ (N·s^{-1})	0.67†	0.45	0.64*	0.41	0.60*	0.19	0.58*	0.20	0.37	0.14	0.69†	0.48	0.44	0.19	0.69†	0.48
RFD$_{0-250}$ (N·s^{-1})	0.69*	0.48	0.53*	0.28	0.63†	0.27	0.50*	0.25	0.44	0.19	0.71†	0.50	0.50*	0.25	0.63*	0.40
Impuls (IMP)																
IMP$_{30}$ (N·s)	0.36	0.13	-0.09	0.00	-0.31	0.10	0.48	0.23	0.05	0.00	-0.30	0.09	-0.21	0.04	-0.05	0.00
IMP$_{50}$ (N·s)	0.40	0.16	-0.01	0.00	-0.11	0.01	0.50*	0.25	0.11	0.01	-0.05	0.00	-0.17	0.03	0.01	0.00
IMP$_{90}$ (N·s)	0.46	0.21	0.26	0.07	-0.02	0.00	0.58*	0.34	0.20	0.04	0.38	0.14	-0.07	0.00	0.25	0.06
IMP$_{100}$ (N·s)	0.47	0.22	0.31	0.10	0.07	0.00	0.59*	0.35	0.20	0.04	0.42	0.18	-0.03	0.00	0.33	0.11
IMP$_{150}$ (N·s)	0.53*	0.28	0.47	0.22	0.52*	0.27	0.64†	0.41	0.19	0.04	0.55*	0.30	0.16	0.03	0.54*	0.29
IMP$_{200}$ (N·s)	0.56*	0.31	0.50*	0.25	0.56*	0.31	0.66†	0.44	0.22	0.05	0.60*	0.36	0.23	0.05	0.60*	0.36
IMP$_{250}$ (N·s)	0.59*	0.35	0.52*	0.27	0.56*	0.31	0.66†	0.44	0.25	0.06	0.66†	0.44	0.26	0.07	0.59*	0.35

SV, serve velocity; WE, wrist extension; EE, elbow extension; SHE, shoulder extension; WF, wrist flexion; EF, elbow flexion; SHF, shoulder flexion; SHER, shoulder external rotation; SHIR, shoulder internal rotation; IF$_{30}$, isometric force at 30 ms; IF$_{50}$, isometric force at 50 ms; IF$_{90}$, isometric force at 90 ms; IF$_{100}$, isometric force at 100 ms; IF$_{150}$, isometric force at 150 ms; IF$_{200}$, isometric force at 200 ms; IF$_{250}$, isometric force at 250 ms; IPF, isometric peak force; RFD$_{0-30}$, rate of force development from 0 to 30 ms; RFD$_{0-50}$, rate of force development from 0 to 50 ms; RFD$_{0-90}$, rate of force development from 0 to 90 ms; RFD$_{0-100}$, rate of force development from 0 to 100 ms; RFD$_{0-150}$, rate of force development from 0 to 150 ms; RFD$_{0-200}$, rate of force development from 0 to 200 ms; RFD$_{0-250}$, rate of force development from 0 to 250 ms; IMP$_{30}$, impulse at 30 ms; IMP$_{50}$, impulse at 50 ms; IMP$_{90}$, impulse at 90 ms; IMP$_{100}$, impulse at 100 ms; IMP$_{150}$, impulse at 150 ms; IMP$_{200}$, impulse at 200 ms; IMP$_{250}$, impulse at 250 ms.

*$p < 0.05$; †$p < 0.01$.

A stepwise multiple regression analysis was used to select the most promising isometric time-force curve variables for determination of SV (Table 8). The model reached its best fit after 2 steps and SHIR RFD from 0 to 50 ms was entered first into the model, explaining 48% of the variance in SV. SHF IF at 250 ms was the second-best predictor, contributing a further 19% to the model, which allowed the combined model to account for 67% of the overall variance for SV.

Table 8. Isometric force-time curve variables included in the stepwise multiple regression analysis to explain the variance on mean SV.

Step	**Independent variables entered**	**Correlations**			**SEE**	***p***	**Regression equation**
		r	**r^2**	**Adj. r^2**			
1	$SHIR\_RFD_{0\text{-}50}$	0.73	0.54	0.48	8.3	<0.001	y = 147.82 + (0.054 x $SHIR\_RFD_{0\text{-}50}$)
2	SHF_IF_{250}	0.86	0.75	0.67	6.5	<0.001	y = 118.54 + (0.051 x $SHIR\_RFD_{0\text{-}50}$) + (0.219 x SHF_F_{250})

Abbreviations: $SHIR\_RFD_{0\text{-}50}$, shoulder internal rotation rate of force development from 0 to 50 ms; SHF_IF_{250}, shoulder flexion isometric force at 250 ms; Adj. r^2, adjusted coefficient of determination; SEE, standard error of estimate.

The predictive model that best discriminated players who were able to serve above or below 165 km·h-1 included 5 isometric time-force curve variables, and correctly classified 91.7 % of the players. The most discriminating factor was the SHIR RFD from 0 to 30 ms and the following four most discriminating factors included RFD related to SHIR, WF, EF and SHE RFD at different times (SHIR_RFD0-30, WF_RFD0-150, EF_RFD0-30, SHE_RFD0-200). Last, SHE IF at 150 ms was the fifth most important factor (Table 9). Table 9A shows the differences between the isometric time-force variables included in the discriminant analysis. Differences ranged to small in SHE RFD from 0 to 200 ms and SHE IF at 150 ms (ES = -0.43; 18.6 to 22.8%), to moderate in SHIR

RFD from 0 to 30 ms, WF RFD from 0 to 150 ms and EF RFD from 0 to 30 ms (ES = -0.71 to -1.10; 41.0 to 58.5%).

Table 9. Variables included in the stepwise discriminant analysis procedure (B) and force-time comparisons between the groups of different tennis serve velocity performances (A).

Step*	Entered variables	A. Time-force curve comparison between the two groups (LSV vs. HSV)					B. Discriminant analysis procedure					
				Difference			Wilk's lambda					
		LSV (n = 7)	HSV (n = 10)	Change (%)	ES (95% CI)	Descriptor	Statistic	df1	df2	df3	Statistic	p-value
1	SHIR_RFD$_{0-30}$	140.0 ± 38.7	219.1 ± 94.9	56.6	-1.06 (-2.14 – 0.05)	Moderate	0.378	1	1	8.000	13.145	0.007
2	WF_RFD$_{0-150}$	528.4 ± 295.5	745.1 ± 311.7	41.0	-0.71 (-1.74 – 0.35)	Moderate	0.191	2	1	8.000	14.842	0.003
3	EF_RFD$_{0-30}$	117.7 ± 28.9	186.6 ± 80.8	58.5	-1.10 (-2.18 – 0.01)	Moderate	0.093	3	1	8.000	19.602	0.002
4	SHE_RFD$_{0-200}$	342.3 ± 184.3	420.3 ± 176.7	22.8	-0.43 (-1.41 – 0.55)	Small	0.039	4	1	8.000	31.039	0.001
5	SHE_IF$_{150}$	88.8 ± 39.7	105.3 ± 37.9	18.6	-0.43 (-1.40 – 0.56)	Small	0.004	5	1	8.000	220.832	<0.001

Data are Mean ± SD. Abbreviations: SHIR_RFD$_{0-30}$, shoulder internal rotation rate of force development from 0 to 30 ms; WF_RFD$_{0-150}$, wrist flexion rate of force development from 0 to 150 ms; EF_RFD$_{0-30}$, elbow flexion rate of force development from 0 to 30 ms; SHE_RFD$_{0-200}$, shoulder extension rate of force development from 0 to 200 ms; SHE_IF$_{150}$, shoulder extension isometric force at 150 ms. At each step, the variable that minimizes the overall Wilk's lambda is entered. *Maximum number of steps is 352; minimum partial F to enter is 3.84; maximum partial F to remove is 2.71. Magnitudes of Cohen's ESs were assessed using the following criteria: < 0.2, trivial; 0.2–0.6, small; 0.6–1.2, moderate; 1.2–2.0, large; > 2.0, very large.

4.2.5 DISCUSSION

To our knowledge, the present study is the first to investigate whether force-time curve parameters in different upper limb joints involved in the serve kinetic chain determine SV in competition tennis players. IF, RFD and IMP at different time intervals in all joint positions tested (except for the EF) moderate to very largely influence SV in competition tennis players. Moreover, the prediction model and the stepwise discriminant analyses highlight the importance of RFD, especially in the SHIR, due to the relevance of the involved joint and action in the serve kinetic chain.

Significant associations were found between time-force characteristics at different time intervals and SV, showing that the capability to develop force in shorter periods (i.e., <250ms) would be an important factor in the SV in competition tennis players. This finding reinforces the assumption that, although SV relies on different nature parameters such as technique, strength, anthropometric characteristics or range of movement (Kovacs & Ellenbecker, 2011b), the neuromuscular function and the explosiveness of the dominant upper limb joints involved in the kinetic chain are relevant parameters to develop faster serves. The associations ranged between moderate to very large in IF in all positions except SHER, between large to very large in RFD in all positions except EF and was large regarding IMP in all positions except EF and SHER. Added, 50% of the variability of SV is predictable from the SHIR RFD from 0 to 50 ms. These associations showed a higher degree in the wrist (WE and WF) and shoulder (SHF and SHIR) joints, and the multiple regression analysis highlighted the contribution of shoulder positions (i.e., SHF and especially SHIR) above others, due to the high influence of this joint in the serve kinetic chain.(Elliott, 2006) From a functional perspective, in the same way as the majority of overhead athletes (Myers et al., 2015), SHIR plays a decisive role in the requirements of explosive rotational movements in the upper arm acceleration during the swing to impact (Elliott, 2006). By contrast to this, and stated in previous investigations, it would appear that if the RFD assessment does not include specific angle contribution of upper limb joints involved in the serve kinetic chain, the relevance of RFD would be questionable (Hayes et al., 2021). In this same line, force-time parameters in the EF and SHER positions were not significantly correlated with SV, possibly because they may not have a significant contribution in the explosive rotational movements in the swing to impact (Elliott, 2006; Kibler et al., 2007).

Regarding RFD, all positions except EF showed moderate to large associations with SV. The prediction model constructed, and the stepwise discriminant analyses appear to highlight the importance of RFD above IF or IMP specially in the SHIR, showing that the ability to develop force rapidly in rotational movements is determinant to generate high SV. The multivariate model for predicting SV showed that approximately 50% of the variance of SV could be accounted by the SHIR RFD from 0 to 50. In this same line, SHIR RFD from 0 to 30 ms was included as the first step by the discriminant analyses. RFD could be defined as early (<100 ms) and late (>100 ms) phases from the onset of muscle contraction (Andersen & Aagaard, 2006). From this point of view, significant correlations between SV and early RFD in WE, SHE, SHF and SHIR (0.52 to 0.69; $p < 0.05$ to $p < 0.01$) and late RFD in all positions except EF ($r = 0.49$ to 0.71; $p < 0.05$ to $p < 0.01$) were found, showing that the ability to apply force rapidly at time frames from 0 to 250 ms (both early and late RFD) are necessary to serve fast. In accordance with this, although the results of multiple regression analysis highlight early phases of RFD (SHIR RFD 0 to 50 ms), the predictive model that best discriminated players who were able to serve above or below to 165 $km \cdot h^{-1}$ included both early (SHIR and EF RFD 0 to 30 ms) and late (WF and SHE RFD 0 to 150 and 250 ms) phases of contraction. Taking into consideration that early phases are determined more clearly by neural drive and intrinsic muscle properties and what could be considered as late phases are more influenced by maximal muscle strength and peripheral muscle properties (Andersen et al., 2010; de Oliveira et al., 2013), it could be argued that both neural and contractile muscle characteristics in the upper joints involved in the serve kinetic chain exert a positive influence on SV.

Concerning IMP, it was measured in addition to RFD as an indicator of the accumulation of force applied over a given period. Applied force in a great deal of sport actions is not constant throughout the time period and integration should be implemented to determine IMP (Taber et al., 2016). As in RFD, similar associations were found regarding IMP, mostly in late phases of the time frames assessed (i.e., from 150 to 250 ms). As previously stated, the tennis serve promotes high velocities through explosive rotational movements (Myers et al., 2015), and the amount of contractile IMP at each time point determines the rotational angular velocity of the distal segment at the measured time (Aagaard et al., 2002), thus a higher IMP facilitating a greater momentum may contribute to generate high-speed racquet movement and consequently higher SV.

Some study limitations should be considered when interpreting our results. First, the sample includes around 70% of male and 30% female participants, which could result in different SV and force-time profiles. In further studies it would be interesting to test associations between these variables and SV in female and male populations separately alongside a wide range of competitive levels. Second, the force signal used was sampled at 200 Hz, which could result slightly low for contraction times around 0-30 ms. Nevertheless, the reliability values obtained were adequate and this system seems accessible for practitioners that could be aiming at evaluating players performance efficiently.

4.2.6 PRACTICAL APPLICATIONS

The data presented seems to demonstrate that both early and late RFD are relevant factors of SV, especially in the shoulder joint (i.e., SHIR). Improvements in RFD can be elicited following different resistance training methods such as high-speed and low-load (i.e., < 60% 1RM) movements (i.e., plyometrics or weightlifting) or low-speed and high-load resistance training (i.e., 70-85% 1RM), especially when exercises are performed involving explosive-type muscle contractions (i.e., maximal intended velocity execution) (Blazevich et al., 2020; Maffiuletti et al., 2016). Consequently, resistance training programs aiming at increasing SV, would thoroughly benefit if instructions given while performing strength exercises included advice and feedback towards "executing as hard and as fast as possible". On the other hand, taking into account that improvements in RFD are benefited when the movement pattern used in training (i.e., body position or laterality) is comparable to that performed in testing (Blazevich et al., 2020), the use of strength exercises that integrate explosive rotational upper arm movements would be beneficial to improve SV. In this regard, the utilization of medicine ball throws (Earp & Kraemer, 2010; Reid & Schneiker, 2008; Roetert et al., 2009) or cable pulley machines (Earp & Kraemer, 2010; Kovacs & Ellenbecker, 2011a; Roetert et al., 2009) seem valid training options, as they allow to include the SHIR of the dominant upper arm present in the kinetic chain (Baiget et al., 2016). In short, programs including medicine ball throws or cable pulley machines that emphasize rotational movements executed at maximum velocity most likely improve RFD at different stages of contraction and therefore positively influence SV. Moreover, joint positions and isometric testing used here are relatively easy to include in SV assessments and could therefore be considered as valid options to evaluate and control training periodically.

4.2.7 CONCLUSIONS

In conclusion, the results of the present study have shown that force-time parameters (IF, RFD and IMP) at different time frames in upper limb joints involved in the serve kinetic chain moderate to very largely influence SV in competition tennis players. Furthermore, the prediction model constructed, and the discriminant analysis highlight the influence of RFD above IF and IMP, especially in the SHIR. Therefore, findings suggest that the capability to develop force in short periods of time (< 250 ms), especially in the shoulder joint (SHIR), seems relevant to develop high SV in competition tennis players.

4.2.8 ACKNOWLEDGEMENTS

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4.3 Study III

Joint-specific post-activation potentiation enhances serve velocity in young tennis players

by

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4.3.1 ABSTRACT

This study aimed (a) to analyze the influence of sport-specific post-activation potentiation (PAP) on serve velocity (SV) and serve accuracy (SA) in young tennis players, (b) to compare the PAP effects of two different conditioning activities (CA) on SV and SA, (c) to explore if changes in SV would be related to tennis player's neuromuscular performance. Sixteen competition young tennis players performed three testing sessions in a randomized order. In the control session, participants performed a warm-up protocol followed by the SV and SA tests. The experimental sessions involved one (shoulder internal rotation [SHIR]) or two (SHIR + shoulder flexion [SHF]) repetitions of a 5 s maximal isometric voluntary contraction (MVIC) executed prior to the SV and SA tests. Results showed a moderate significant (p = 0.037) difference between SV at control session and following the SHIR + SHF CA protocol at minute 0 (3.4 ± 4.6%; 4.6 km·h^{-1}; ES = 0.711). SA did not differ between CA protocols and control session at any time point. No significant relations were found between force-time curve parameters and SV percent changes at different recovery times. Performing two short (5 s) upper-limb tennis joint-specific MVIC seems to enhance SV without negatively affecting SA in young competition tennis players. On the contrary, performing one MVIC does not seem to obtain the same effects. Moreover, tennis players with improved neuromuscular performance do not seem to exhibit a better predisposition to PAPE.

Keywords: isometric strength, stroke velocity, shoulder, rate of force development

4.3.2 INTRODUCTION

Tennis serve is a high-demanding coordinative technical action influenced by several biomechanical, anthropometric or neuromuscular parameters (Baiget et al., 2022; Elliott, 2006; Reid & Schneiker, 2008). Alongside the recent evolution of tennis performance, the tennis serve has been considered the most powerful and important stroke in competition tennis players, with the serve velocity (SV) playing a preponderant role in elite tennis competitions (Gillet et al., 2009) and also in young tennis players (Ulbricht et al., 2016). In parallel, coaches have a growing interest on specific strength training aiming at increasing players' maximal force and power production (Gale-Watts & Nevill, 2016).

From a biomechanical standpoint, the serve is determined by diverse neuromuscular (e.g., rate of force development [RFD]), anthropometric (e.g., body mass and body height) or technical (e.g., ball impact angle and height) variables (Baiget et al., 2022; Kovacs & Ellenbecker, 2011b). Moreover, the activation and coordination of the trunk, upper and lower limb joints throughout the whole kinetic chain while relying on elastic energy and muscle preload is a paramount factor (Reid et al., 2008). Specifically, the shoulder joint and the ability to develop high velocity rotational movements to accelerate the tennis racket prior to ball impact have been identified as a key parameter to develop fast serves (Baiget et al., 2016, 2022; Elliott, 2006; Reid & Schneiker, 2008). On this matter, the neuromuscular function and explosiveness (i.e., RFD, impulse, and isometric force at different time points) of shoulder joint positions included in the serve kinetic chain (e.g., shoulder internal rotation [SHIR] and flexion [SHF]) have been proved to largely influence SV in competition tennis players (Baiget et al., 2022).

Postactivation potentiation (PAP) as a temporary enhancement in sports performance following high-intensity voluntary conditioning activities (CA) is influenced by several neuromuscular, biomechanical or physiological parameters (Seitz & Haff, 2016; Tillin & Bishop, 2009). Agreement exists in considering phosphorylation of myosin regulatory light chains and the recruitment of higher-order motor units as critical aspects determining PAP (Baudry & Duchateau, 2007; Beato & Stiff, 2021; Skurvydas et al., 2019). However, albeit PAP has been proved to produce physiological improvements, these are not always accompanied by functional performance enhancements (Hodgson et al., 2005). The postactivation performance enhancement (PAPE) refers to an increase in voluntary performance associated to a potentiation effect independent of the potentiation parameters involved (Boullosa et al., 2020; Zimmermann et al., 2020).

Considering that the effect of PAPE seems higher for rapid ballistic than slow movements or isometric contractions (Vandenboom, 2017), SV could benefit from its beneficial effects. PAPE has previously shown small to moderate effects on explosive sport actions such as jumping, throwing, sprinting or upper-body ballistic movements (Seitz, Reyes, et al., 2014), mainly by improving rate of force development (RFD) and power (Tillin & Bishop, 2009). However, it remains unclear if PAPE would elicit similar outcomes in a highly complex, coordinative, and explosive action such as the tennis serve. Moreover, considering that serve performance is determined by a combination of two different kind of variables (i.e., SV and serve accuracy [SA]). A large amount of PAPE research has focused on selected CA exercises (i.e., resistance, ballistic, plyometric, elastic bands, blood flow restriction or flywheel) and contractions (i.e., isometric, concentric and eccentric) to increase performance in high-speed sport-specific actions, with the concentric multi-joint traditional resistance exercises the most used (Boullosa, 2021; Seitz & Haff, 2016). Regarding serve PAPE, literature suggests that using heavy load traditional resistance CA (i.e., bench press and half squat) does not enhance SV in young tennis players (Terraza-Rebollo & Baiget, 2020).

In order to benefit PAPE, exercises biomechanically comparable to subsequent sport actions expected to increase performance are recommended as CA (Beato et al., 2020). Therefore, it could be hypothesized that implementing serve upper body specific-joint CA exercises would be appropriate to promote PAPE responses; however, to date, there is no clear evidence supporting this hypothesis. Moreover, no data available exists regarding the influence of tennis player's neuromuscular performance on their PAPE responses and the optimal PAPE time windows. Thus, the aims of the study were (a) to analyze the effects of PAP induced by upper-limb tennis-specific joint maximal isometric voluntary contractions (MVIC) on SV and SA in young tennis players, (b) to compare the PAP effects on SV and SA using two different MVIC CA protocols, and (c) to explore if changes in SV would be related to tennis player's neuromuscular performance.

4.3.3 METHODS

Experimental Approach to the Problem

The study used a crossover-randomized design to evaluate the acute effects induced by two upper-limb tennis-specific joint MVIC CA protocols on serve performance. Each subject attended 4 sessions (1 familiarization, 1 control and 2 experimental sessions) on different days (Figure 15). The participants performed the experimental and control trials in a randomized order separated by 48 hours. MVIC of 2 shoulder joint positions (shoulder internal rotation [SHIR] and shoulder flexion [SHF]) involved in the serve kinetic chain (Elliott, 2006) were used as a CA exercises. The independent variable (CA protocols) was manipulated to evaluate its effect on the dependent variable (SV and SA) to determine its efficacy for using it as a performance enhancer. The two CA protocols were: a) standardized warm-up + 1 x 5 s SHIR MVIC or b) standardized warm-up + 1 x 5 s SHIR MVIC + 1 x 5 s SHF MVIC with 10 s rest between each position. The control session only included the standardized warm-up. SV and SA were measured at 0, 5, 10 and 15 minutes after each protocol (Figure 15).

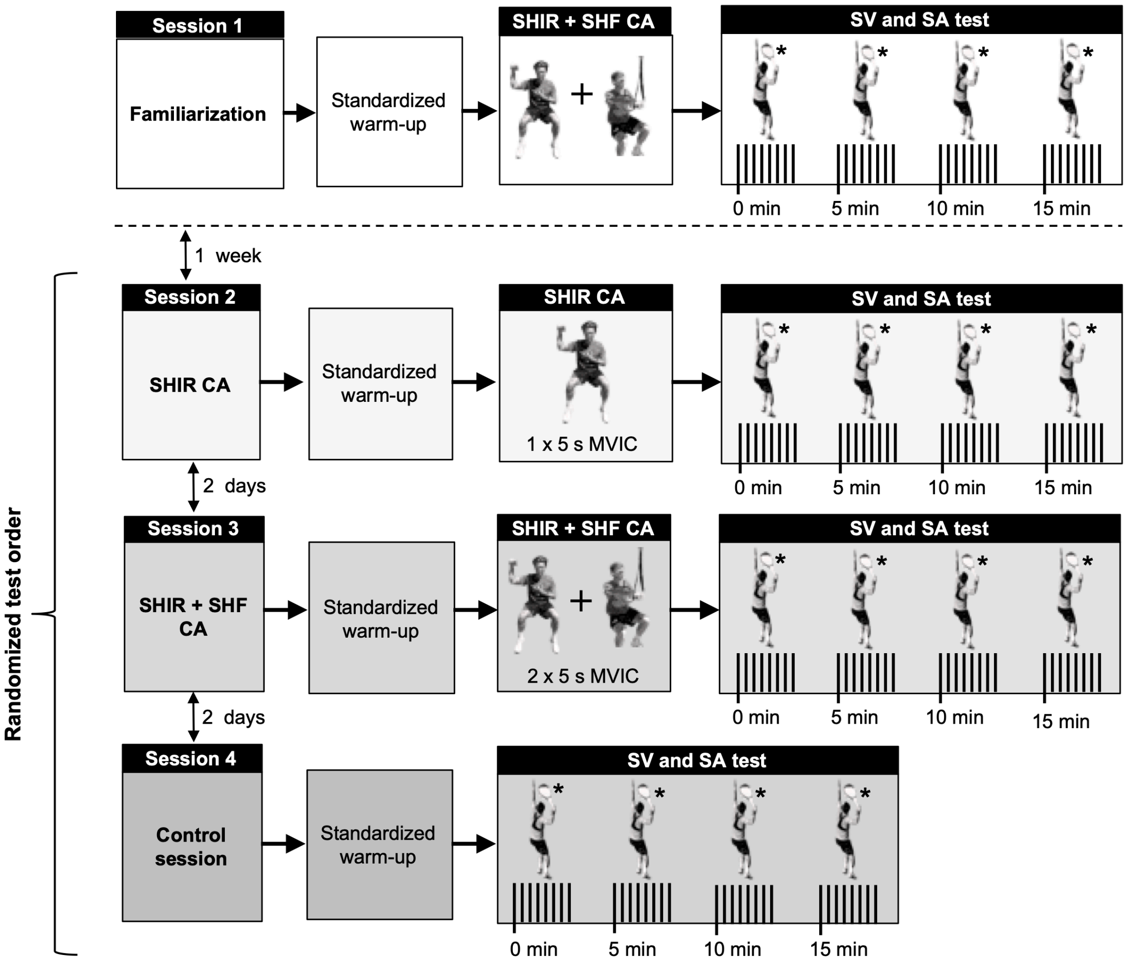

Figure 15. Study design chronology. Abbreviations: SHIR = shoulder internal rotation; SHF = shoulder flexion; CA = conditioning activity; MVIC = maximal voluntary isometric contraction; SV = serve velocity; SA = serve accuracy. *20 seconds rest between serves.

Subjects

Sixteen competition young tennis players, 8 male and 8 female (mean ± SD: age 16.9 ± 1.1 years, body height 1.76 ± 0.08 m, body mass 65.5 ± 7.8 kg; IMC 21.1 ± 1.9) were recruited for this study. The mean tennis training background of the players was 8.9 ± 1.6 years and 87.5% were right-handed. The sample size was justified by a priori power analysis (using GPower Version 3.1.9.5, University of Dusseldorf, Dusseldorf, Germany) for a repeated measures (within-between interaction) introducing the following parameters: effect size index (0.40) assuming a large partial eta-squared (0.14), α error probability (0.05), power (0.90), number of groups (3) and measurements (4), and correlation among repeated measurements (0.6) which resulted in a sample size of 15 subjects. The inclusion criteria were male and female competition tennis players. This was selected since responses to PAPE CA do not seem to be modified among sexes (Evetovich et al., 2015; Wilson et al., 2013) and an adequate strength level has been suggested necessary (Seitz, Villarreal, et al., 2014). The inclusion criteria characteristics were as follows: i) An International Tennis Number (ITN) ranging from 2 to 3 (advanced level), ii) A weekly training volume between 15 - 25 h·week^{-1}, iii) Minimum of 3-year experience in strength training and 5-years of tennis training and competition. Participants who had any upper body or back pain as well as having surgery or participated in a rehabilitation process in the last 6 months were excluded. Before their participation, subjects, or their legal tutors, in the case of being underage, voluntarily signed an informed consent. The study was conducted following the ethical principles for biomedical research with human beings, established in the Declaration of Helsinki of the AMM (2013) and approved by the Catalan Sports Council Institutional Review Board (025_CEICGC_2021).

Procedures

In the control session, the participants only performed the warm-up protocol followed by the SV and SA test. During the experimental sessions, the participants completed the warm-up protocol followed by one of the CA protocols (SHIR MVIC or SHIR + SHF MVIC) and the SV and SA test (Figure 15). One week prior to the beginning of the intervention, participants were asked to attend a familiarization session where they handed in the informed consent. In all sessions, the subjects began performing the warm-up protocol that included 10 minutes of general warm-up activities (jogging, skipping, dynamic mobility and dynamic stretching) and 10 minutes of specific warm-up for serve (exercises with elastic tubing for upper body, 10 dynamic serve imitations and 10 warm-up serves). After, in the control session the serve test was performed and in the experimental sessions the CA protocols were performed followed by the serve test. No vigorous physical activity was performed in the 24 hours before testing. No caffeine ingestion was allowed in the 24 hours before testing and meal ingestion was avoided at least three hours before the scheduled test time. The study was conducted in preparatory non-competitive microcycles.

Maximal voluntary isometric contractions (MVIC)

Two MVIC of movements included as a part of the serve kinetic chain (Elliott, 2006) were performed similarly to Baiget et al. (Baiget et al., 2016, 2022) (Figure 16). One (SHIR) or two (SHIR + SHF) repetitions of a 5 s MVIC in each position were applied as it has been shown to be the most effective duration for PAPE response (Skurvydas et al., 2019). SHIR position was performed with the shoulder abducted and the elbow flexed to 90°. SHF position was recorded with the upper extremity flexed to 90° and the elbow extended. The subjects were instructed to perform every CA exercise "as fast and as hard as possible” and to avoid any pretension and countermovement. Strong verbal encouragement was given to exert and maintain maximal force during 5 s maximal voluntary contractions. Only the dominant extremity was measured. The specific position for each isometric pull was established before each trial with the use of a validated goniometer (Easyangle; Meloq AB, Stockholm, Sweden). Similar racket grip diameter was selected with the aim of increasing specificity, and special attention was placed on grip comfort during tests to avoid strength feedback inhibition. The force-time curve for each trial was recorded using a strain gauge sampling at 80 Hz and the subsequent analysis software (Chronojump, Boscosystem, Barcelona, Spain). MVIC and peak rate of force development (PRFD) were defined as the highest value achieved during 5 s. Additionally, force outputs at 50, 100, 150 and 200 ms from the start of the pull were determined for each trial. Rate of force development (RFD) was then calculated with the following equation: $RFD = \Delta Force / \Delta Time$. All force-time registered variables reached an acceptable level of reliability with excellent intraclass correlation coefficients for SHIR (ICC = 0.897 to 0.973) and SHF (ICC = 0.860 to 0.987) and coefficients of variation of less than 20% for SHIR (CV = 11.1 to 19.2%) and SHF (CV = 6.3 to 18.3%).

Figure 16. Frontal (A), lateral (B) and back (C) views of maximum voluntary isometric contraction (MVIC) conditioning activities (CA). Abbreviations: SHIR = shoulder internal rotation; SHF = shoulder flexion; SG = strain gauge.

Serve velocity (SV) and accuracy (SA) testing

The test consisted of assessing the peak ball velocity of 32 flat S, divided into 4 sets of 8 serves (4 each side). For SV, only the serves "in" were considered and the mean values of the ball speed recorded were used for the final analysis. SA was determined as a percentage on nonerror strokes (i.e., success rate) (Vergauwen et al., 2004) The participants were constantly encouraged to hit the ball at maximum speed. Immediate feedback was provided to the subjects to encourage maximum effort. No further information about the movement was given. The participants had 20 s rest between serves and 2 min and 40 s between sets, with the purpose of avoiding fatigue. To reduce any error due to the cosine effect, the radar was placed in the line of the ball's displacement, changing it depending on the serving side. A hand-held radar gun (Stalker ATS II, United States, frequency: 34.7 GHz (Ka-Band) +/- 50 MHz) was used. International Tennis Federation (ITF) approved balls were used for the serve tests. In order to maintain uniform internal ball pressure, the balls were new in each testing session. The test was carried out with stable wind conditions. SV and SA measures showed excellent (ICC = 0.978; CV = 3.4%) and moderate (ICC = 0.457; CV = 19.9%) levels of reliability respectively.

Statistical Analysis

Descriptive data were reported as mean ± standard deviation (SD). The normality of the distributions and homogeneity of variances were assessed with the Shapiro-Wilk test. Intrasession reliability of test measures was assessed using a two-way average measure of the intraclass correlation coefficient (ICC) and the coefficient of variation (CV) for each variable. Effects of each CA protocol (SHIR, and SHIR + SHF or control) on SV at different times (0, 5, 10, 15 min) were assessed using 2-way analysis of variance (ANOVA) for repeated measurements (3 CA protocols x 4 time points) with pair-wise Bonferroni-corrected post hoc analysis. Where the data violated Mauchly's test of sphericity, the Greenhouse–Geisser correction was established. Mean differences in absolute and percent values were also used. The magnitude of the differences in mean was quantified as effect size (ES) using the Cohen's *d* (Cohen, 1988) and interpreted according to the criteria used by Hopkins et al. as small (>0.2 and <0.6), moderate (≥0.6

and <1.2) and large (≥1.2 and <2) or very large (≥2.0) (Hopkins et al., 2009). Because SA data were not normally distributed, Friedman's test was used to examine the differences in various times during recovery and between CA protocols. When a difference was revealed, Wilcoxon's test was used to identify those differences. Percent changes (Δ%) at different times recovery (0, 5, 10 and 15 min) from control values of two CA protocols were calculated. SV percentage changes differences between CA protocols were compared by 2-way analysis of variance (ANOVA) for repeated measurements (2 CA protocols x 4 time points) with pair-wise Bonferroni-corrected post hoc analysis. Because SA percentage changes data were not normally distributed, Friedman's test was used to examine the differences in various times during recovery and between CA protocols. Pearson product-moment correlation coefficients were used to analyze the relationship between SV SHIR + SHF CA protocol percent changes and force-time curve values. The level of significance was set at $p < 0.05$. All statistical analyses were performed using SPSS 23.0 software (SPSS Inc., Chicago, IL, USA).

4.3.4 RESULTS

A repeated measures ANOVA revealed statistically significant differences for the main effect of time ($F[2.1,32.2] = 5.815$; $p = 0.006$; $\eta^2 = 0.28$) and protocol ($F[2,30] = 4.479$; $p = 0.02$; $\eta^2 = 0.23$). No protocol x time interaction was found ($F[6,90] = 1.596$; $p = 0.096$; η^2 0.10). Pairwise comparison showed moderate significant SV differences between control session (140.2 ± 16.4 $km \cdot h^{-1}$) and SHIR + SHF CA protocol (144.8 ± 15.3 $km \cdot h^{-1}$) at minute 0 ($p = 0.037$; 3.4 ± 4.6%; 4.6 $km \cdot h^{-1}$; ES = 0.711). Moreover, moderate significant differences were found between SHIR CA protocol at minute 15 (139.2 ± 15.2 $km \cdot h^{-1}$) and at minute 5 (142.2 ± 14.3 $km \cdot h^{-1}$) ($p = 0.025$; 3.1 $km \cdot h^{-1}$; 2.3 ± 2.8%; ES = 0.843) and minute 10 (142.5 ± 15.5 $km \cdot h^{-1}$) ($p = 0.014$; 3.3 $km \cdot h^{-1}$; 2.4 ±

2.8%; ES = 0.915) and between the SHIR + SHF CA protocol at minute 15 (140.9 ± 14.7 km·h^{-1}) and minute 0 (144.8 ± 15.3 km·h^{-1}) (p = 0.021; 3.9 km·h^{-1}; 2.8 ± 3.1%; ES = 0.864) (Figure 17).

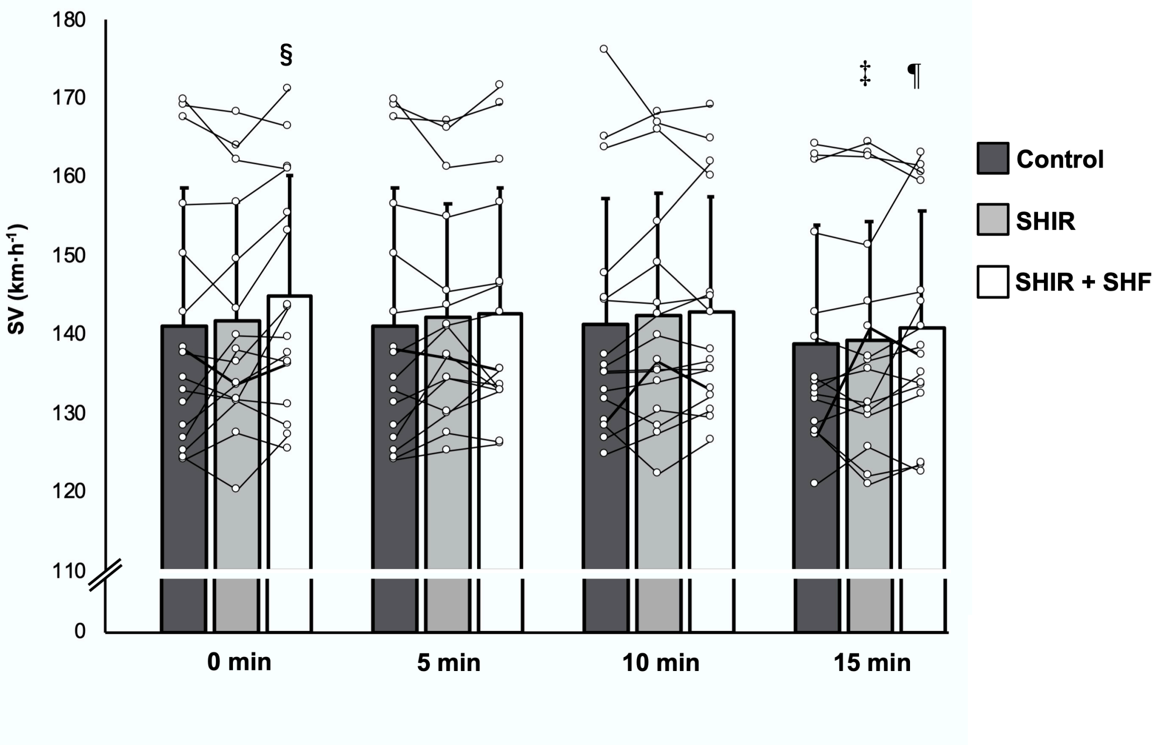

Figure 17. Comparison of serve velocity (SV) from control session after 2 different conditioning activity (CA) protocols (SHIR: shoulder internal rotation; SHIR + SHF: shoulder internal rotation plus shoulder flexion) across 4 time points (0, 5, 10 and 15 min). Values are mean ± SD; Abbreviations: SHIR = shoulder internal rotation; SHF = shoulder flexion; SV = serve velocity. §Significant serve velocity differences between control session ($p < 0.05$); ‡Significant serve velocity differences between minute 5 and 10 ($p < 0.05$); ¶Significant serve velocity differences between minute 0 ($p < 0.05$).

No significant associations were found between force-time curve parameters (MVC, PRFD and RFD from 0 to 200 ms) and SV percent changes at different recovery times (Table 10).

Table 10. Isometric force-time curve variables for each conditioning activity (CA) exercise (SHIR and SHF) and correlations coefficients (r) between serve velocity (SV) percent changes (Δ%) at different recovery times (0 to 15 min).

	SHIR					**SHF**				
		Δ%	**Δ%**	**Δ%**	**Δ%**		**Δ%**	**Δ%**	**Δ%**	**Δ%**
	Mean ± SD	**min 0**	**min 5**	**min 10**	**min 15**	**Mean ± SD**	**min 0**	**min 5**	**min 10**	**min 15**
		r	**r**	**r**	**r**		**r**	**r**	**r**	**r**
MVIC (N)	147.0 ± 57.4	-0.02	-0.15	-0.14	-0.11	197.3 ± 80.7	-0.08	-0.26	-0.10	-0.10
PRFD (N·s^{-1})	577.1 ± 284.6	0.07	0.02	-0.15	0.20	722.9 ± 231.1	-0.21	-0.41	-0.06	-0.10
RFD$_{0-50}$ (N·s^{-1})	425.8 ± 217.5	0.12	0.01	-0.14	0.23	583.0 ± 146.7	-0.23	-0.28	-0.05	-0.22
RFD$_{0-100}$ (N·s^{-1})	331.6 ± 185.4	0.11	-0.01	-0.23	0.13	428.1 ± 126.6	-0.36	-0.26	-0.18	-0.28
RFD$_{0-150}$ (N·s^{-1})	246.1 ± 134.9	0.16	0.05	-0.33	0.03	317.1 ± 128.8	-0.41	-0.24	-0.19	-0.27
RFD$_{0-200}$ (N·s^{-1})	196.9 ± 114.4	0.16	0.05	-0.42	-0.04	240.5 ± 125.8	-0.35	-0.24	-0.17	-0.23

Abbreviations: SHIR = shoulder internal rotation; SHF = shoulder flexion; MVIC = maximal voluntary isometric contraction; PRFD = peak rate of force development; RFD$_{0-50}$ = rate of force development from 0 to 50 ms; RFD$_{0-100}$ = rate of force development from 0 to 100 ms; RFD$_{0-150}$ = rate of force development from 0 to 150 ms; RFD$_{0-200}$ = rate of force development from 0 to 200 ms.

Friedman's test showed that SA did not differ between CA protocols and control session at any time point (minute 0: *p* = 0.513; minute 5: *p* = 0.739; minute 10: *p* = 0.856; minute15: *p* = 0.690). No differences were revealed between SA across different times points in control session (*p* = 0.824), SHIR (*p* = 0.723) and SHIR + SHF CA protocols (*p* = 0.838) (Figure 18).

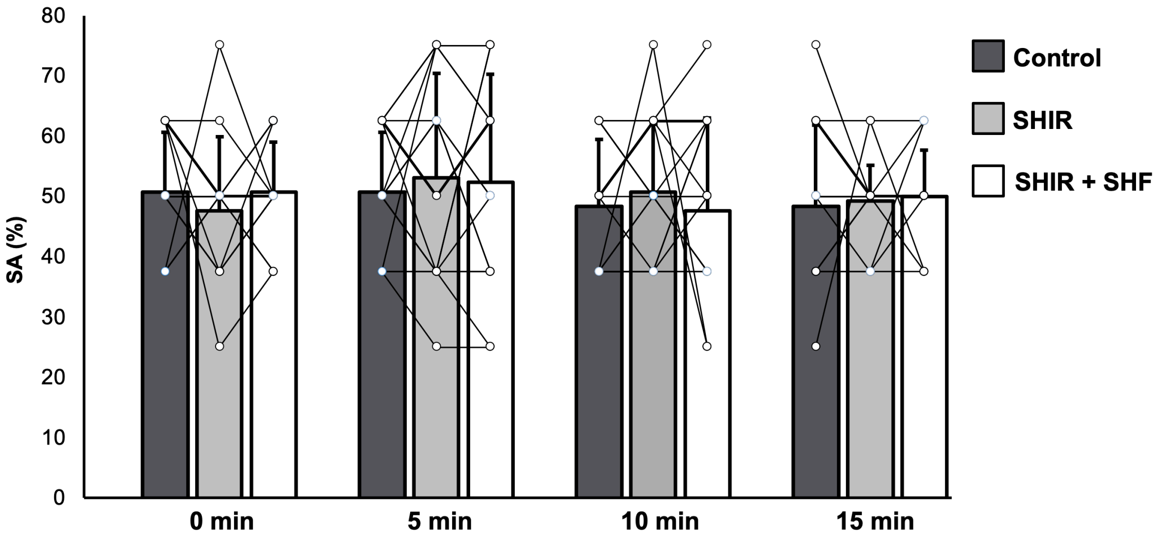

Figure 18. Comparison of serve accuracy (SA) from control session after 2 different conditioning activity (CA) protocols (SHIR: shoulder internal rotation; SHIR + SHF: shoulder internal rotation plus shoulder flexion) across 4 time points (0, 5, 10 and 15 min). Values are mean ± SD. Abbreviations: SHIR = shoulder internal rotation; SHF = shoulder flexion; SV = serve velocity.

Figure 19 shows the evolution of percentage changes in SV (A) and SA (B) from control session in two CA protocols. A repeated measures ANOVA revealed statistically significant differences in percentage changes in SV for the main effect protocol (*F*[1,15] = 7.455; p = 0.02; η^2 = 0.33). Pairwise comparison showed moderate significant percentage changes in SV differences between SHIR (1.2 ± 4.9 %) and SHIR + SHF CA (3.4 ± 4.7 %) protocols at minute 0 (*p* = 0.022; 2.2%; ES = 0.640). Friedman's test showed that percentage changes in SA did not differ between CA protocols at any time point (minute 0: $p = 0.222$; minute 5: $p = 0.422$; minute 10: $p = 0.964$; minute15: $p = 0.734$).

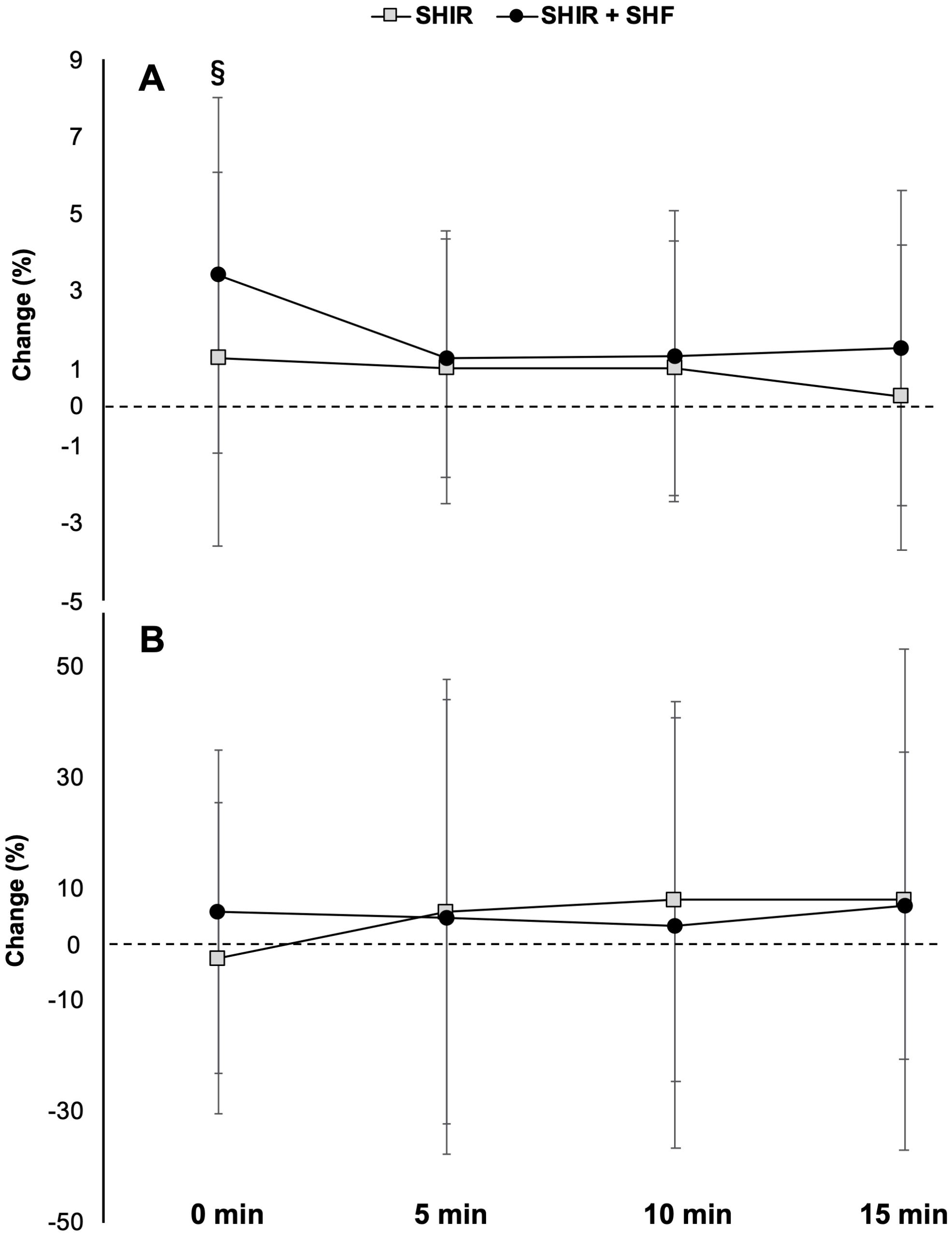

Figure 19. Comparison of percentage changes in serve velocity (A) and accuracy (B) from control session after the 2 different conditioning activity (CA) protocols (SHIR: shoulder internal rotation; SHIR + SHF: shoulder internal rotation plus shoulder flexion) across 4 time points (0, 5, 10 and 15 min). Percentage changes values are mean ± SD. Abbreviations: SHIR = shoulder internal rotation; SHF = shoulder flexion. §Significant percentages changes differences between the two conditioning activity protocols ($p < 0.05$).

4.3.5 DISCUSSION

The main finding of this study was that two short tennis-specific upper-limb joint MVIC exercises involved in the serve kinetic chain immediately induces PAPE, increasing SV without SA detriment in young competition tennis players. Moreover, no PAPE was observed following only one MVIC exercise. Furthermore, tennis players with better neuromuscular performance do not show better predisposition to PAPE.

To our knowledge, this is the first study reporting SV enhancements following joint-specific CA. The results showed that PAPE moderately increased SV (3.4 ± 4.6%; 4.6 $km \cdot h^{-1}$) without SA detriment following two MVIC CA exercises (1 x 5 s SHIR MVIC + 1 x 5 s SHF MVIC / 10 rest). We could hypothesize that the observed PAPE may benefit from the effect of the tennis specific MVIC exercises used. SHIR and SHF are involved in the serve kinetic chain being one of the main contributors to accelerate the tennis racket towards the ball. Moreover, the SHIR and SHF strength positions were performed near the joint angle where the serve ball impact happens (Elliott, 2006). In this line, the kinematic similarity between the CA and the athletic movement intended to improve the high neuromuscular recruitment of the main muscles involved in the specific sport action. This, alongside the suited direction of the resistance force vector related to the body throughout CA has previously been reported as a relevant to develop potentiation effects (Boullosa et al., 2020; Dello Iacono & Seitz, 2018). On the other hand, considering that the capacity to develop force in short periods of time (<250 ms) is highly associated with SV (Baiget et al., 2022), performing MVIC CA exercises explosively (as fast as possible) could be also beneficial to promote PAPE. Contrary to our findings, when the CA exercises were performed throughout high-intensity (3 x 3 repetitions at 80% of the 1 repetition maximum (1RM)) traditional resistance exercises (half squat and bench press), no PAPE on SV was observed (Terraza-Rebollo & Baiget, 2020). Moreover, despite the fact that ballistic exercises (i.e., weighted jumps or weightlifting variations) have been shown to induce PAPE (Maloney et al., 2014), no PAPE was observed using light load (200 and 600 g balls) throws as a CA in young tennis players (Ferrauti & Bastiaens, 2007). Of note, while serve involves stretch-shortening cycle (SSC) muscle actions (reactive strength) (Reid & Schneiker, 2008) and the used CA protocols involved isometric contractions, immediate PAPE responses seem to optimize the SSC. Previous research also found positive PAPE effects of MVIC prior SSC exercises (e.g., jumps or sprints) (French et al., 2003).

This study also compared the effect of using two different CA protocols (SHIR or SHIR + SHF), showing that PAPE effects are benefited following the summation of two CA exercises (SHIR + SHF). The preponderance of PAPE, among other parameters, relies on the contraction mode, intensity, duration or rest intervals of the CA (Skurvydas et al., 2019). Considering that the two CA protocols were conducted throughout the same contraction regime and intensity magnitude, the better PAPE enhancement of SHIR + SHF could be explained depending on two factors. On one hand, the higher total isometric contraction duration (volume) of SHIR + SHF compared to SHIR (10 s vs. 5 s) could be favorable to elicit PAPE. Likewise, is it possible that two 5 s repetitions of SHIR (2 x 5 s SHIR MVIC/ 10 rest) would have the same positive results. In agreement with this, MVIC volumes between 5 and 15 s generated immediate potentiation in jump height, maximal force, acceleration impulse in drop jump and knee extension torque (French et al., 2003; Skurvydas et al., 2019). On the other hand, the better PAPE enhancement of SHIR + SHF could be explained by the summation effect of the inclusion of another position involved in the serve kinetic chain.

There is a general consensus suggesting that PAPE is related to time-dependent factors, thus it has been recommended to find an optimal recovery time to reduce fatigue and favour PAPE responses (Seitz & Haff, 2016; Tillin & Bishop, 2009). In this study, PAPE effect was observed immediately following the MVIC SHIR + SHF CA (0 min), and no positive effects persisted throughout the time ranges from 5 to 15 min. Contrary, when CA are conducted using high intensity dynamic contractions, the better PAPE effect is mainly achieved after medium recovery durations (5-7 min) (Seitz & Haff, 2016) and the effects are reported to persist up to 10 min.(Tillin & Bishop, 2009; Wilson et al., 2013) In agreement with our results, no PAPE responses were observed following a 4-minute rest after short (3 to 7 s) MVIC CA (Pearson & Hussain, 2014) on diverse sports actions (i.e., jumps and sprints). Similarly, twitch potentiation was found immediately following short MVIC (Baudry & Duchateau, 2007; French et al., 2003; Vandenboom, 2017) while the positive effects diminished practically exponentially over time (Baudry & Duchateau, 2007).

The present study also aimed at analysing if the percentage changes in SV were related to tennis player's neuromuscular performance (MVIC, PRFD and RFD from 0 to 200 ms). We did not observe any associations between force-time curve variables and SV, meaning that individuals with higher neuromuscular performance are not able to exhibit better PAPE responses. Taking into account that strength levels or training background have been proved to affect PAPE response (Boullosa et al., 2020; Seitz & Haff, 2016; Tillin & Bishop, 2009; Wilson et al., 2013), and male and female tennis players could have shown different neuromuscular performances, the reason for the non-existent strength level and PAPE relationship could be the homogeneous background and high-volume weekly training of the participants involved (8.9 ± 1.6 years of tennis training background, minimum of 3-year in strength training; weekly training volume between 15 - 25 h·week^{-1}).

Regarding the SA, no detriments were observed in any CA protocol and recovery time point, so we may expect that 5 to 10 s MVIC CA do not elicit significative fatigue and therefore do not provoke intermuscular coordination impairments. In this line, previous studies have showed that short-duration (10 ≤ s) MVIC CA elicit PAPE without a significant fatigue, while long-duration protocols (60 ≥ s) possibly do (Skurvydas et al., 2019; Wallace et al., 2019). Although isometric and dynamic contractions generate disparate fatigue and recovery responses (Tillin & Bishop, 2009), no impairments in SA were observed using general dynamic high-intensity traditional resistance exercises as CA (Terraza-Rebollo & Baiget, 2020).

4.3.6 CONCLUSIONS

In summary, performing two short upper-limb tennis-specific joint MVIC favours the immediate appearance of SV enhancement without SA impairment in young competition tennis players, while only one MVIC does not elicit PAPE. Furthermore, tennis players with better neuromuscular performance do not seem to demonstrate a better predisposition to PAPE.

4.3.7 PRACTICAL APPLICATIONS

Based on the results of the present study, incorporating two upper-limb tennis-specific joint MVIC exercises (i.e., SHIR and SHF) acutely improves SV without a detriment in SA. Moreover, no recovery period is required to induce PAPE. The easy application of the proposed exercises (i.e., no special equipment or heavy loads needed) alongside its time-efficient characteristics (10 s work) and the minimal fatigue induced without SA detriment facilitates its implementation in the tennis court in combination with technical-tactical training sessions. Moreover, the biomechanical similarity between SHIR and SHF

MVIC positions (heavy load performed before serves) and the serve (lighter load) permits this specific layout to be implemented as a complex training resource and could be used as a neuromuscular warm-up routine.

4.3.8 ACKNOWLEDGEMENTS

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4.4 Study IV

6-Week joint-specific isometric strength training improves serve velocity in young tennis players

by

Baiget E, Colomar J, Corbi F

4.4.1 ABSTRACT

Purpose: Evaluate the effects of 6-weeks of specific-joint isometric training (IST) on serve velocity (SV), serve accuracy (SA) and force-time curve variables. **Methods:** 16 young competition tennis players were divided into an intervention (ITG; n = 10) or control group (CG; n= 6). SV, SA, maximal voluntary isometric contraction (MVIC), peak rate of force development (PRFD), rate of force development (RFD) and impulse (IMP) at different time frames while performing a shoulder internal rotation (SHIR) or flexion (SHF) were tested at week 0, week 3 and week 6. Specifically **Results:** The ITG showed significant increases in SV from pre- to posttest (7.0%, ES = 0.87) and no variations in SA. Moreover, the ITG showed significant increases from pre- to posttest in SHF RFD at 150 (30.4%, ES = 2.44), 200 (36.5%, ES = 1.26), 250 ms (43.7%, ES = 1.67) and in SHIR IMP at 150 (35.7%, ES = 1.18), 200 (33.4%, ES = 1.19) and 250 ms (35.6%, ES = 1.08). Also, in SHF RFD from inter- to posttest at 150 ms (24.5%, ES = 1.07) and in SHIR IMP at 150 (13.5%, ES = 0.90), 200 (19.1%, ES = 0.98) and 250 ms (27.2%, ES = 1.16). SHIR IMP changes from pre- to intertest were found at 150 ms (25.6%, ES = 1.04). The CG did not show changes in any of the tested variables.

Conclusions: 6-weeks of upper-limb specific-joint IST alongside habitual technical-tactical workouts results in significant increases in SV without SA detriment in young tennis players.

Keywords: rate of force development, maximal voluntary isometric contraction, impuls, tennis performance, force production

4.4.2 INTRODUCTION

Albeit tennis performance relies on multifactorial aspects, being capable of serving at high velocities is believed to be an important prerequisite to be an elite tennis player (Fitzpatrick et al., 2019; Ulbricht et al., 2016). Therefore, the transitioning phase from junior competitor to professional level should emphasize training strategies aimed to increase this performance parameter. Key multifactorial serve velocity (SV) requirements such as technical proficiency (Fleisig et al., 2003), the efficient activation of the whole kinetic chain (i.e., coordination of trunk and upper and lower limbs joints) (Elliott, 2006), anthropometrics (i.e., body height, arm length or lean body mass) (Baiget et al., 2023; Vaverka & Cernosek, 2013), range of movement (ROM) of joints involved in the tennis serve (Palmer et al., 2018) and neuromuscular parameters (Colomar et al., 2020; Fett et al., 2020; Hayes et al., 2021; Ulbricht et al., 2016) have been established as markers of fast serves. Among them, neuromuscular function and the ability to develop force in short-time periods (<250 ms) have recently been also highlighted as highly relevant (Baiget et al., 2022; Canós et al., 2022; Colomar, Corbi, & Baiget, 2022a, 2022c; Colomar, Corbi, Brich, et al., 2022).

The tennis serve primarily imposes high requirements on the shoulder joint throughout substantial rotational velocities and forces (Kibler et al., 2007), mainly in the racquet acceleration phase previous to the ball impact (Elliott, 2006). On that matter, shoulder joint (internal rotation [SHIR] and flexion [SHF]) force-time curve parameters (rate of force development [RFD] and impulse [IMP]) have been shown to be strongly associated with SV in high-performance (Baiget et al., 2016, 2022) and young tennis players as well (Colomar, Corbi, & Baiget, 2022c). In this line, SHIR and SHF maximal voluntary isometric contraction (MVIC) have been also recently proved to acutely increase SV without serve accuracy (SA) impairments, due to a postactivation performance enhancement (PAPE) (Baiget et al., in press).

Considerable information is available concerning dynamic strength training methods to increase SV in competition young tennis players (Colomar, Corbi, & Baiget, 2022a). Plyometric (i.e., medicine ball throws [MBT]) (Terraza-Rebollo et al., 2017), flywheel (Canós et al., 2022), elastic tubing (Terraza-Rebollo et al., 2017; Treiber et al., 1998), machine-based (Canós et al., 2022) or free weights (Terraza-Rebollo et al., 2017; Treiber et al., 1998) resistance training methods have been proved to positively affect SV. In contrast, although isometric strength training (IST) has been shown as an effective strength training method to increase performance of dynamic high-velocity sports actions (Lum & Barbosa, 2019; Oranchuk et al., 2019) its applicability in competition tennis players remains unknown. IST comprises the contraction of the skeletal muscles with no external movement (Lum & Barbosa, 2019) and its characteristics allows to easily implement exercises biomechanically comparable to subsequent tennis actions, replicating positions and angles involved in the serve kinetic chain (Baiget et al., 2022). Moreover, isometric monitoring has been proved as a valid and effective method to follow strength-training adaptations (Peltonen et al., 2018).

Therefore, it could be hypothesized that implementing upper-limb joint-specific IST biomechanically comparable to the tennis serve would increase the neuromuscular function and the ability to produce force rapidly associated with SV enhancement without SA detriment. Thus, the aims of the study were to evaluate the effects of adding a short time specific-joint IST on serve performance (SV and SA) and force-time curve parameters (RFD, IMP and MVIC) in young tennis players.

4.4.3 METHODS

Subjects

Sixteen competition young male tennis players from the same competition tennis academy were recruited for this study (Table 11). Due to the lower tennis academy female athlete's availability and to ensure the homogeneity of the participants characteristics, only male tennis players were included in the study. It has been suggested that albeit the adaptations to strength training in hypertrophy and lower-body strength were similar between sexes, there was a significant effect in favour of females for upper-body strength (Roberts et al., 2020). The sample size was justified by a priori power analysis (using GPower Version 3.1.9.5, University of Dusseldorf, Dusseldorf, Germany) for a repeated measures (within-between interaction) introducing the following parameters: effect size index (0.40) assuming a large partial eta-squared (0.14), α error probability (0.05), power (0.90), number of groups (2) and measurements (3), and correlation among repeated measurements (0.5) which resulted in a sample size of 16 subjects. Participants had training volume of 20 $h \cdot week^{-1}$ comprising 3 h of technical and tactical tennis practice and 1 h of physical conditioning per day from Monday to Friday. 87.5% of tennis players were right-handed. The inclusion criteria characteristics were as follows: i) Male junior tennis players with advanced tennis level (International Tennis Number (ITN) ranging from 2 to 3), ii) Minimum of 3-year experience in strength training and 5-years of tennis training and competition, iii) Not having any upper body or back pain as well as having surgery or participated in a rehabilitation process in the last 6 months. The participants were informed about the study design and discomforts related to the measurements.

Before their participation, subjects, or their legal tutors, in the case of being underage, voluntarily signed an informed consent. The study was conducted following the ethical principles for biomedical research with human beings, established in the Declaration of Helsinki of the AMM (2013) and approved by the Catalan Sports Council Institutional Review Board (002_CEICGC_2022).

Table 11. Participant characteristics.

	ITG (n = 10)	**CG (n = 6)**	***p-value***
Age (years)	15.6 ± 1.1	15.5 ± 0.6	0.113
Height (m)	1.73 ± 0.05	1.77 ± 0.04	0.108
Body mass (kg)	68.4 ± 5.2	67.7 ± 6.2	0.507
Body-mass index (kg·m^2)	22.8 ± 0.8	21.6 ± 1.1	0.734
Training background (years)	7.5 ± 1.0	7.7 ± 0.5	0.471
Competitive level (ITN)	2.7 ± 0.5	2.8 ± 0.4	0.564

Abbreviations: ITN, international tennis number; ITG, isometric training group; CG, control group. Values are presented as mean (SD) and *p-value* of the differences between ITG and CG.

Design

A longitudinal and controlled experimental design was used to investigate the effect of a short time (6 week) joint-specific (SHIR and SHF) IST intervention on serve performance (SV and SA) and SHIR and SHF force – time curve parameters. A 2-group, repeated measures (pretest, intertest and posttest) design was used. After 2 weeks without any regular resistance and tennis training (Christmas vacation), subjects were randomly allocated into the 2 groups using stratified block randomization. One group was the intervention group performing specific-joint IST (ITG; n = 10) and one was the control group (CG; n = 6). There were no significant differences in the groups competition level, biometric and training characteristics (Table 11), isometric force–time curve parameters and serve performance before training intervention. During the intervention program, both groups completed their usual physical and technical - tactical training due to the restrictions placed on the timetable by the tennis academy. In addition to that routine, the ITG completed a short time (5 to 10 minutes per session) IST before the academy planned physical sessions. CG were allocated to different physical training timetable and did not perform the IST before the sessions. Participants were blinded for group allocation during the intervention but not the investigators. Participants were told that they were all involved in a normal academy strength training program and SV and force-time curve assessment but had no accurate information about the differences between training groups. All players participated in ≥ 80% of the IST and the physical and technical-tactical training prescribed. Along the study, players were not allowed to modify the style or technique of their strokes, nor the string tension and racket they used. During the intervention no training-related injuries occurred.

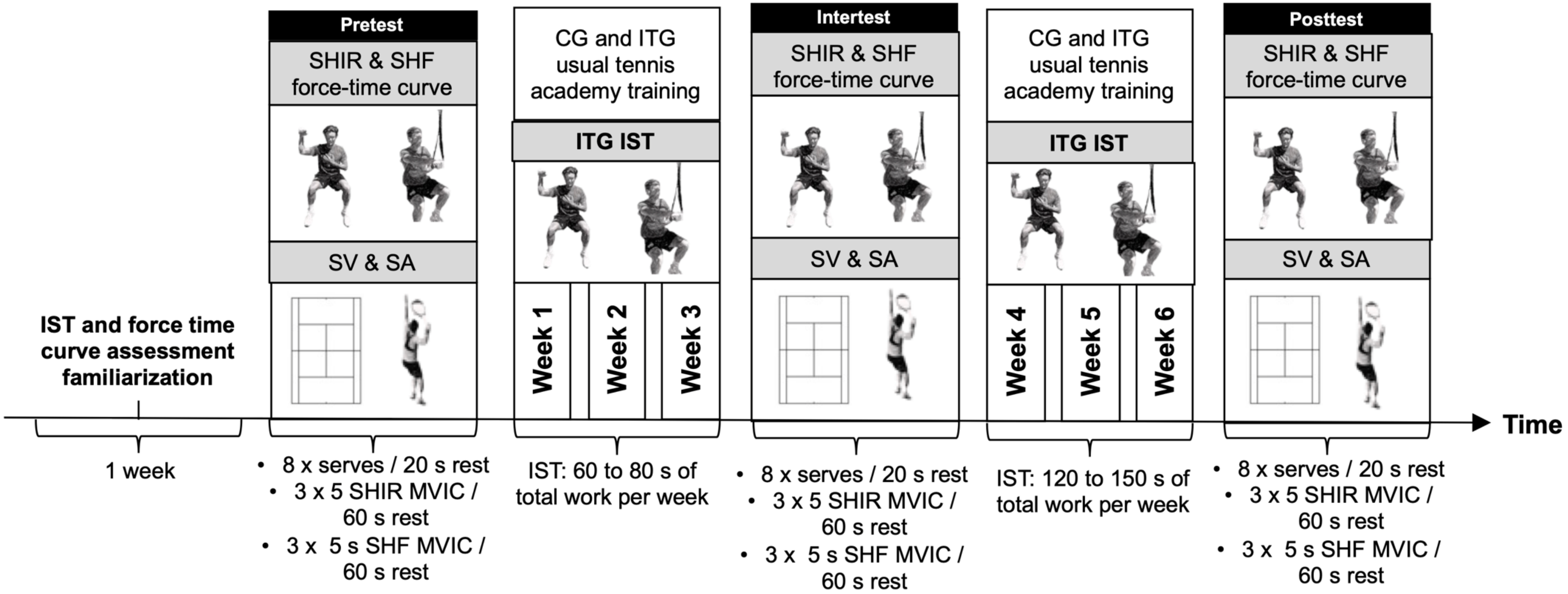

Figure 20. Study design chronology. SHIR indicates shoulder internal rotation; SHF, shoulder flexion; CG, control group; ITG, isometric training group; IST, isometric strength training; MVIC, maximal voluntary isometric contraction; SV, serve velocity; SA, serve accuracy.

Methodology

The experimental design was conducted as summarised in Figure 20. Prior to the start of the program and over a period of 1 week (three sessions), all participants were required to perform a familiarization aiming to prepare for the tests and IST. During test sessions, participants performed the SV and SA testing followed by the force-time curve assessment. In all training and test sessions, the subjects began performing the general warm-up protocol that included 10 minutes of general warm-up activities (jogging, skipping, dynamic mobility and dynamic stretching) and 10 minutes of specific warm-up for serve (exercises with elastic tubing for upper body, free rallies, 10 dynamic serve imitations and 10 progressive serves). Due to academy restrictions, participants did not exercise for at least 18 hours before the protocol took place. No vigorous physical activity was performed in the 24 hours before testing. The study was conducted in preparatory non-competitive microcycles and all measurements were performed in the morning, approximately from 7:30 am to 8:30 am.

Serve Velocity (SV) and Accuracy (SA)Testing

The test consisted of assessing the peak ball velocity of 8 flat serves (4 each side). For SV, only the serves "in" were considered and the mean values of the ball speed recorded were used for the final analysis. SA was determined as a percentage on nonerror strokes (i.e., success rate) (Vergauwen et al., 2004). The participants were constantly encouraged to hit the ball at maximum speed. Immediate feedback was provided to the subjects to encourage maximum effort. No further information about the movement was given. The participants had 20 s rest between serves. To reduce any error due to the cosine effect, the radar was placed in the line of the ball's displacement, changing it depending on the serving side. A hand-held radar gun (Stalker ATS II, United States, frequency: 34.7 GHz

(Ka-Band) +/- 50 MHz) was used. International Tennis Federation (ITF) approved balls were used for the serve tests. In order to maintain uniform internal ball pressure, the balls were new in each testing session. All results were collected on an outdoor clay court by the same researchers. The test was carried out with stable wind conditions (air velocity <2 $m \cdot s^{-1}$). SV and SA measures showed excellent (ICC = 0.889; CV = 4.9%) and moderate (ICC = 0.457; CV = 19.9%) levels of reliability respectively.

Isometric Force–Time Curve Assessment

A total of two upper-limb MVIC tests of joints and movements included as a part of the service kinetic chain (SHIR and SHF) (Elliott, 2006) were performed (Figure 21) similarly to Baiget et al. (Baiget et al., 2016, 2022). SHIR position was performed with the shoulder abducted and the elbow flexed to 90°. SHF position was recorded with the upper extremity flexed to 90° and the elbow extended. The subjects were instructed to perform every exercise "as fast and as hard as possible" and to avoid any pretension and countermovement. Only the dominant extremity was measured. The specific position for each isometric pull was established before each trial with the use of a validated goniometer (Easyangle; Meloq AB, Stockholm, Sweden). After the standardized dynamic warm-up, participants completed a submaximal isometric contraction of 50% of perceived MVIC in each of tested positions. Every subject performed 3 MVIC of 5-seconds duration separated by 1 (between sets) and 5 minutes (between positions) of rest. Similar racket grip diameter was selected with the aim of increasing specificity, and special attention was placed on grip comfort during tests to avoid strength feedback inhibition. The force-time curve for each trial was recorded using a strain gauge sampling at 80 Hz and the subsequent analysis software (Chronojump, Boscosystem, Barcelona, Spain). MVIC and peak rate of force development (PRFD) were defined as the highest value achieved during 5 s. RFD between 0 and 30, 0 and 50, 0 and 100, 0 and 150, 0 and 200, and 0 and 250 milliseconds was then calculated with the following equation: RFD = ΔForce / ΔTime. Contractile isometric accumulated IMP (integral of torque and time) was also calculated in the same time intervals as RFD with the parallelogram method from the area under the force–time curve between selected time intervals as follows:

$$\int_{t_0}^{t_n} Force \times dTime$$

All force-time registered variables reached an acceptable level of reliability with excellent intraclass correlation coefficients for SHIR (ICC = 0.897 to 0.973) and SHF (ICC = 0.860 to 0.987) and coefficients of variation of less than 20% for SHIR (CV = 11.1 to 19.2%) and SHF (CV = 6.3 to 18.3%).

Figure 21. Maximum voluntary isometric contraction (MVIC) training exercises. SHIR indicates shoulder internal rotation; SHF, shoulder flexion; SG, strain gauge.

Isometric Strength Training Intervention

The IST intervention is shown in Table 12, the training load was progressively increased throughout the 6 training weeks. Two maximal contraction (100% MVIC) isometric exercises (SHIR and SHF) were performed in the same manner as the force–time curve assessment described previously. The shoulder positions were selected as they have a representative influence in the explosive rotational movements in the swing to impact, are largely associated with SV (Baiget et al., 2022) and induce PAPE in the tennis serve (Baiget et al., in press). The IST follows the general recommended criteria that 80–100% MVIC, 1–5 s contraction with total of 30– 90 s per sessions executed explosively is recommended to improve explosive strength (Lum & Barbosa, 2019). The subjects were instructed to perform every exercise “as fast and as hard as possible”. The IST was only executed with the dominant extremity.

Table 12. Specific-joint isometric strength training intervention program.

Week	Exercise	Intensity (% MVIC)	Contraction time (s)	Reps (no.)	Sets (no.)	Days per week	Volume per session		Volume per week		Rest between reps (s)	Rest between exercises (s)
							Exercise (s)	Total (s)	Exercise (s)	Total (s)		
1	SHIR	100	5	3	1	2	15	30	30	60	15	60
	SHF	100	5	3	1		15		30		15	
2	SHIR	100	5	3	1	3	15	30	45	90	15	60
	SHF	100	5	3	1		15		45		15	
3	SHIR	100	5	4	1	2	20	40	40	80	15	60
	SHF	100	5	4	1		20		40		15	
4	SHIR	100	5	4	1	3	20	40	60	120	15	60
	SHF	100	5	4	1		20		60		15	
5	SHIR	100	5	5	1	2	25	50	50	100	15	60
	SHF	100	5	5	1		25		50		15	
6	SHIR	100	5	5	1	3	25	50	75	150	15	60
	SHF	100	5	5	1		25		75		15	

Abbreviations: SHIR, shoulder internal rotation; SHF, shoulder flexion; MVIC, maximal voluntary isometric contraction.

Statistical Analyses

The values presented are expressed as mean ± SD. The normality of the distributions and homogeneity of variances were assessed with the Shapiro-Wilk test. Independent *t*-test in biometric, training characteristics, isometric force–time curve parameters and serve performance and Mann-Whitney U test for the competition level were used to assess differences before training intervention (week 0) among the 2 groups. Correction for multiple comparisons was undertaken for isometric force-time curve parameters using the Bonferroni method with a resulting operational alpha level of 0.0018 ($p = 0.05/28$). Independent variables were defined in terms of the different strength training interventions (control vs. IST) and the 3 measurement time points (pretest vs. intertest vs. posttest). The dependent variables were the serve performance (SV and SA), the MVIC and the isometric force–time curve parameters (PRFD, RFD from 0 to 30, 50, 100, 150, 200, and 250 milliseconds and IMP at 30, 50, 100, 150, 200, and 250 milliseconds). Two-way repeated-measures ANOVA (2 groups [CG vs ITG] x time [pre-inter-posttest]) to test for global differences between pre- mid and post-intervention, the two training groups and the interaction effect between two factors was applied. Homogeneity of variance was evaluated using Mauchly's test of sphericity, and when violated, the Greenhouse-Geisser adjustment was used. When a significant difference was found for either main effect, a Bonferroni post hoc analysis was performed. The partial eta-square (η^2) effect size (ES) was calculated to evaluate the main and interaction effects of the ANOVA. The η^2 values of 0.01–0.05, 0.06–0.13, and >0.14 indicate a small, medium and large effect sizes, respectively. To determine the magnitude of within-group change in variables, a Cohen's d ES was performed on pairwise comparisons. The criteria to interpret the magnitude of the ES were 0.0–0.2 trivial, 0.2–0.6 small, 0.6–1.2 moderate, 1.2–2.0 large, and >2.0 very large. Intrasession reliability of measures was determined using a 2-way average measure of the intraclass correlation coefficient (ICC) and coefficient of variation (CV). The ICC values were interpreted as follows: excellent (> 0.85), high (0.75-0.85), moderate (0.40-0.75) and poor (< 0.40). Statistical significance was accepted at an alpha level of $p < 0.05$. All statistical analyses were performed using IBM SPSS Statistics 23.0 software (SPSS, Inc., Chicago, IL).

4.4.4 RESULTS

Serve Velocity and Accuracy (SV and SA)

A large main effect of time ($F = 4.935$, $p = 0.032$, $\eta^2 = 0.275$) were found in SV (Figure 22). The post-hoc test showed significant moderate increases in SV in the ITG from pre- to posttest (10.5 $km \cdot h^{-1}$, 7.0%, $p = 0.023$, ES = 0.87), whereas no changes from pre- to inter and from inter- to posttest were observed. The CG did not show any changes. Non-significant main effect of time ($F = 1.267$, $p = 0.299$, $\eta^2 = 0.089$) and group-by-time interaction ($F = 2.067$, $p = 0.147$, $\eta^2 = 0.137$) were found in SA.

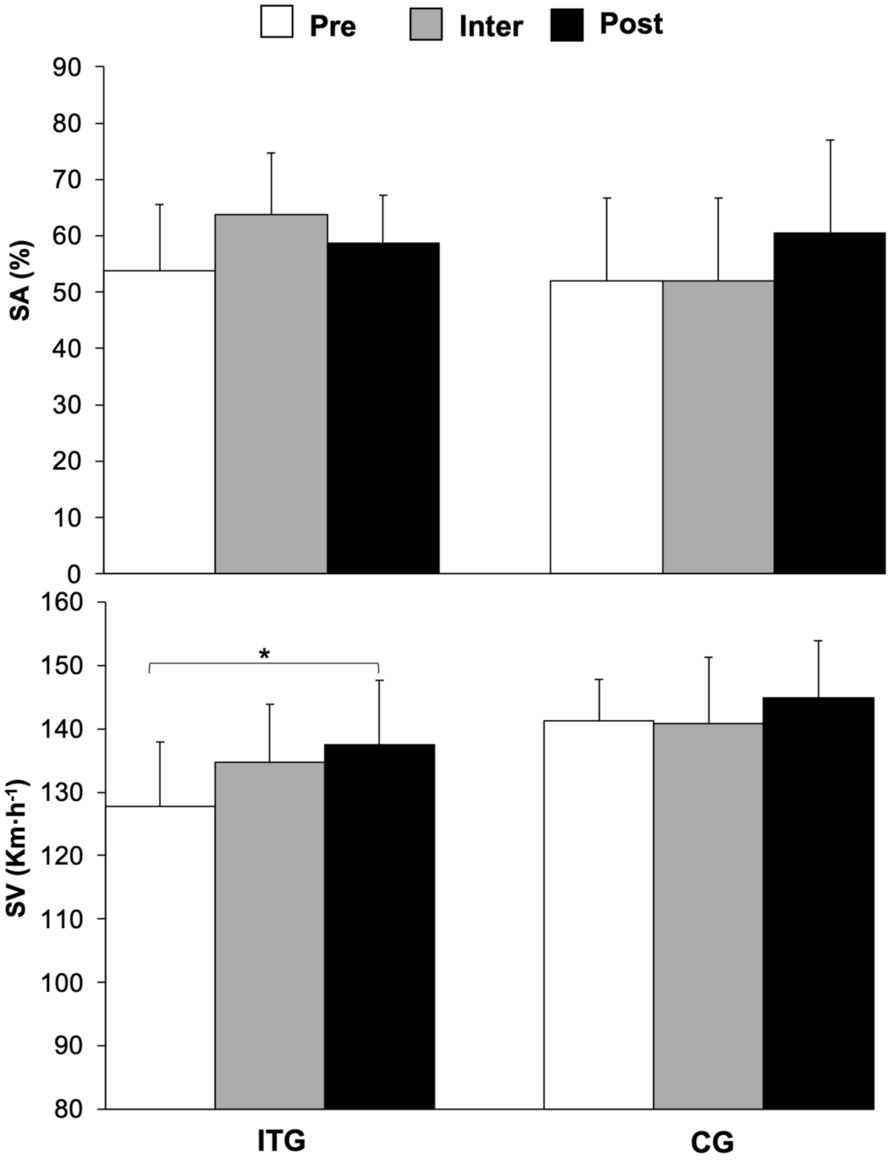

Figure 22. Comparison of serve velocity (SV) and accuracy (SA) measurements at week 0 (Pre), 3 (Inter) and 6 (Post) of training intervention for experimental (EG) and control (CG) groups. Values are presented as mean (SD). SV indicates serve velocity; SA, serve accuracy; ITG, isometric training group; CG, control group. *Significant serve velocity differences between pre to posttest ($p < 0.05$).

Maximum Voluntary Isometric Contraction (MVIC)

Non-significant group-by-time interaction (F = 0.595, p = 0.487, $\eta^2 = 0.044$) and main effect of time (F = 1.523, p = 0.241, $\eta^2 = 0.105$) were found in the SHIR and SHF MVIC (Figure 23).

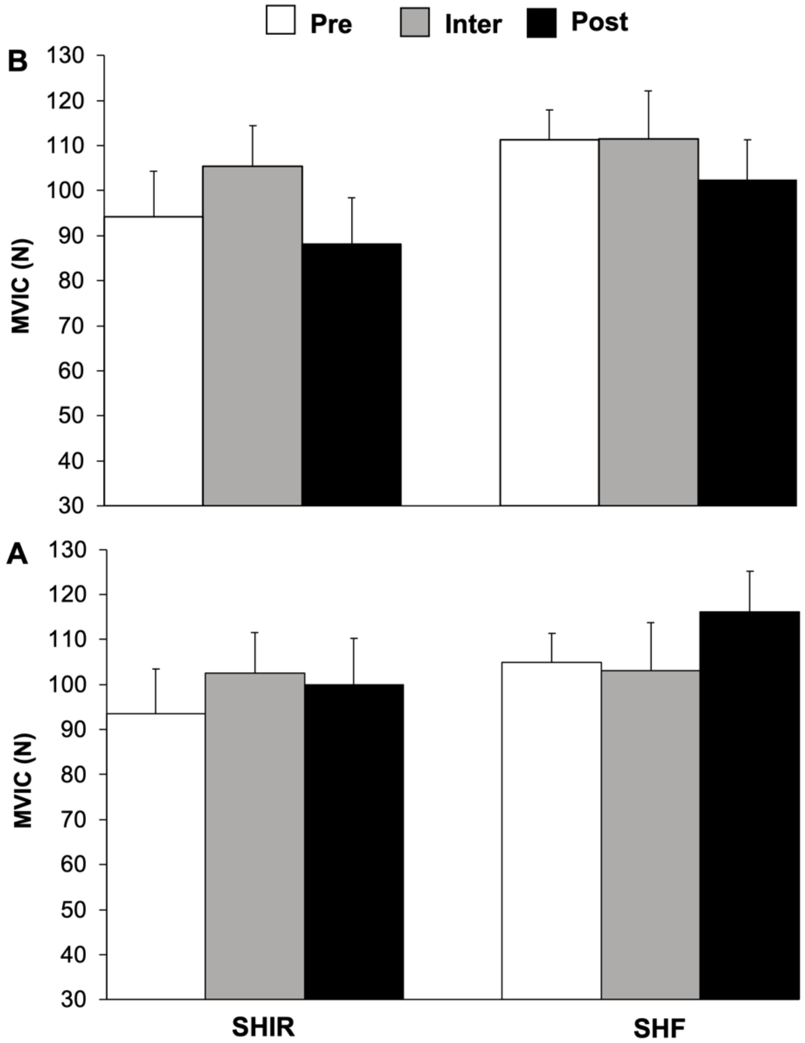

Figure 23. Comparison of maximum voluntary isometric contraction (MVIC) of shoulder internal rotation (SHIR) and flexion (SHF) at week 0 (Pre), 3 (Inter) and 6 (Post) of training intervention for the isometric training (ITG, A) and control (CG, B) groups. Values are presented as mean (SD). MVIC indicates maximum voluntary isometric contractions; SHIR, shoulder internal rotation; SHF, shoulder flexion.

Rate of Force Development (RFD)

A large group-by-time interaction ($F = 6.326$, $p = 0.015$, $\eta^2 = 0.329$) was found in SHIR PRFD (Figure 24A). The post-hoc test showed significant moderate increases in the SHIR PRFD in the ITG from pre- to posttest (504.7 N, 44.8%, $p = 0.005$, ES = 1.19) and from inter- to posttest (449.7 N, 40.6%, $p = 0.014$, ES = 1.03). A large main effect of time in SHF RFD from 0 to 150 ($F = 7.107$, $p = 0.003$, $\eta^2 = 0.353$), 0 to 200 ($F = 4.450$, $p = 0.022$, $\eta^2 = 0.255$) and 0 to 250 ms ($F = 7.278$, $p = 0.003$, $\eta^2 = 0.359$) were found (Figure 25A). The post-hoc test showed significant very large increases in the ITG from pre- to posttest in the SHF RFD from 0 to 150 (82.0 $N \cdot s^{-1}$, 30.4%, $p = 0.002$, ES = 2.44), and large increases from 0 to 200 (69.0 $N \cdot s^{-1}$, 36.5%, $p < 0.001$, ES = 1.26) and from 0 to 250 ms (58.9 $N \cdot s^{-1}$, 43.7%, $p < 0.001$, ES = 1.67). Moreover, moderate changes from inter- to posttest were observed in SHF RFD from 0 to 150 ms (66.3 $N \cdot s^{-1}$, 24.5%, $p = 0.037$, ES = 1.07) (Figure 25). The CG did not show any changes.

Impulse (IMP)

A large group-by-time interaction in SHIR IMP at 150 ($F = 6.942$, $p = 0.012$, $\eta^2 = 0.348$), 200 ($F = 6.292$, $p = 0.006$, $\eta^2 = 0.326$) and 250 ms ($F = 5.484$, $p = 0.022$, $\eta^2 = 0.297$) were found (Figure 24A). The post-hoc test showed significant moderate increases in the ITG from pre- to posttest in SHIR IMP at 150 (2.9 $N \cdot s$, 35.7%, $p = 0.003$, ES = 1.18), 200 (4.0 $N \cdot s$, 33.4%, $p = 0.003$, ES = 1.19) and 250 ms (6.0 $N \cdot s$, 35.6%, $p = 0.005$, ES = 1.08), from inter- to posttest at 150 (1.1 $N \cdot s$, 13.5%, $p = 0.03$, ES = 0.90), 200 (2.3 $N \cdot s$, 19.1%, $p = 0.01$, ES = 0.98) and 250 ms (4.6 $N \cdot s$, 27.2%, $p = 0.003$, ES = 1.16). Moderate changes from pre- to intertest were also found from in SHIR IMP at 150 ms (1.8 $N \cdot s$, 25.6%, $p = 0.009$, ES = 1.04). The CG did not show any changes.

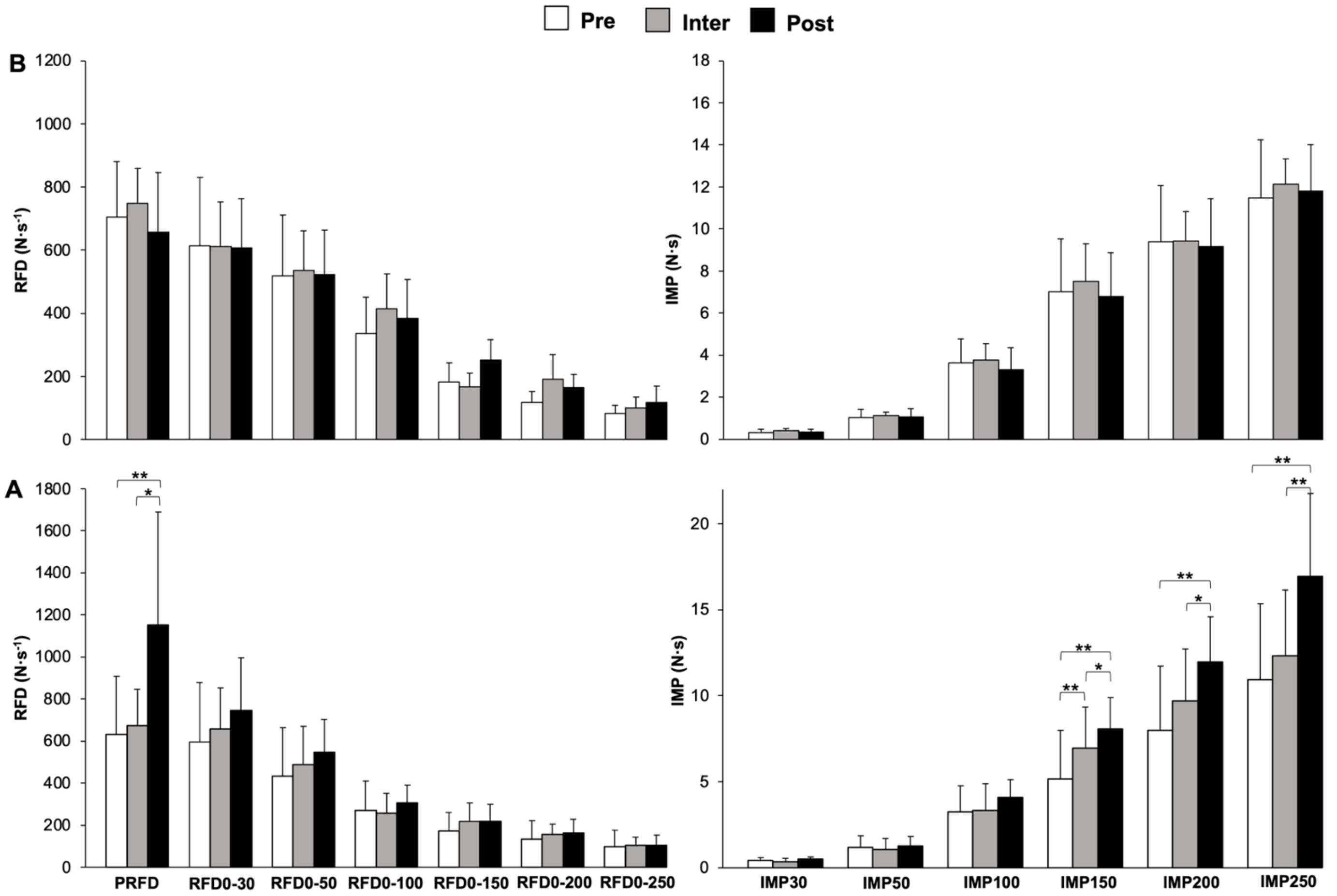

Figure 24. Comparison of shoulder internal rotation (SHIR) isometric force – time curve parameters at week 0 (Pre), 3 (Inter) and 6 (Post) of training intervention for the isometric training (ITG, A) and control (CG, B) groups. Values are presented as mean (SD). RFD indicates rate of force development; PRFD, peak rate of force development; RFD0–30, RFD from 0 to 30 milliseconds; RFD0–50, RFD from 0 to 50 milliseconds; etc.; IMP indicates impulse; IMP30, IMP at 30 milliseconds; IMP50, IMP at 50 milliseconds; etc. *p < 0.05, **p < 0.01, significantly different between the two times points.

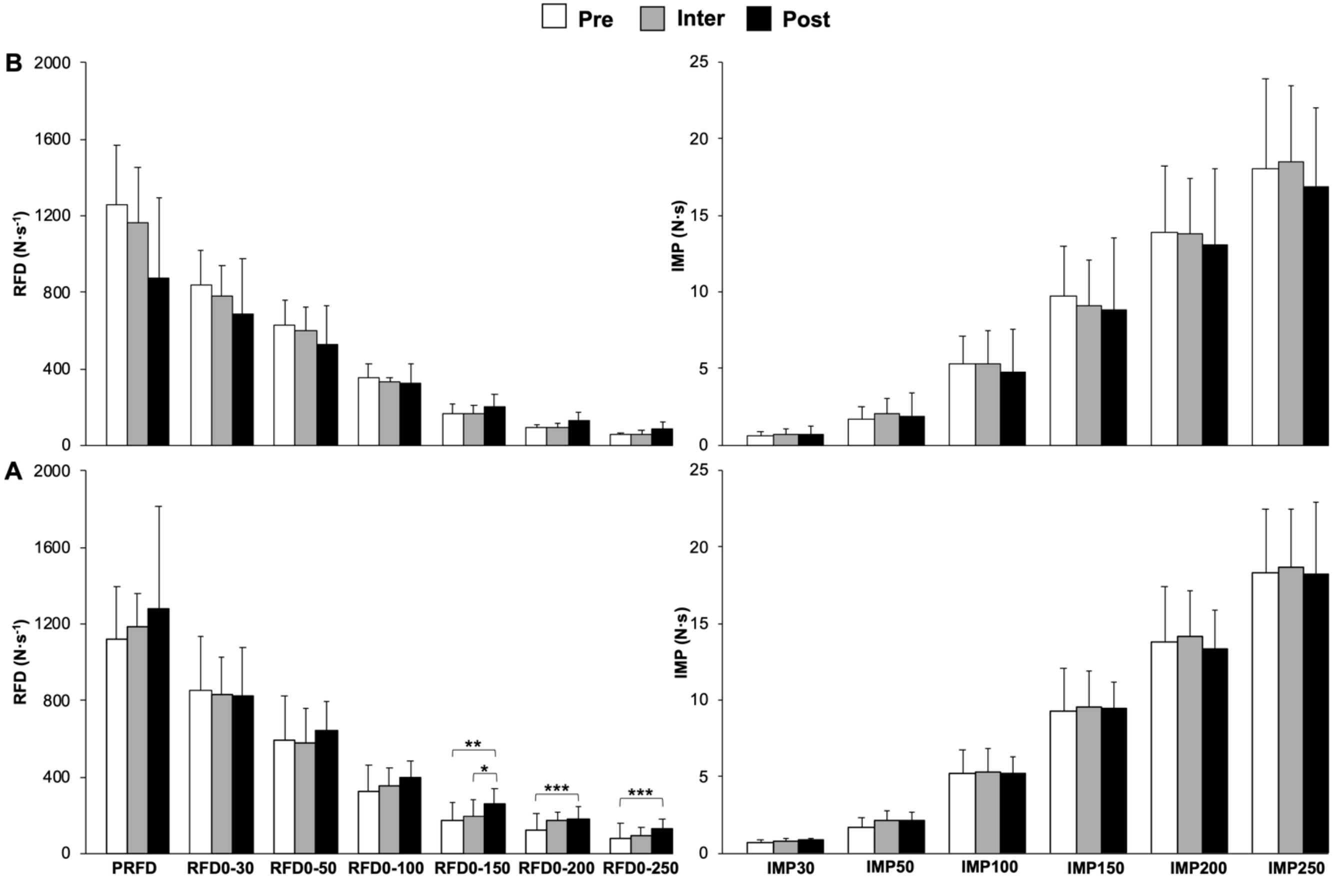

Figure 25. Comparison of shoulder flexion (SHF) isometric force – time curve parameters at week 0 (Pre), 3 (Inter) and 6 (Post) of training intervention for the isometric (ITG, A) and control (CG, B) groups. Values are presented as mean (SD). RFD indicates rate of force development; PRFD, peak rate of force development; RFD0–30, RFD from 0 to 30 milliseconds; RFD0–50, RFD from 0 to 50 milliseconds; etc.; IMP indicates impulse; IMP30, IMP at 30 milliseconds; IMP50, IMP at 50 milliseconds; etc. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, significantly different between the two times points.

4.4.5 DISCUSSION

The present study has shown that adding a 6-week upper-limb specific-joint IST to the habitual workouts results in significant increases in the ability to produce force in short time accompanied with increments in SV in young tennis players. In addition, the SA was not negatively affected by the IST.

To our knowledge, this is the first study reporting the effects of IST on functional (SV and SA) and neuromuscular (MVIC, RFD and IMP) performance on competition tennis players. Despite the tennis serve involves high-speed stretch-shortening cycle (SSC) muscle actions (Elliott, 2006), and the transferability of the IST to dynamic sport performance has been controversial (Oranchuk et al., 2019), the ITG significantly improved the force-time curve parameters in both SHIR and SHF exercises accompanied with SV enhancements. It seems reasonable that the increased SV was a result of the shoulder joint force-time curve optimization. The ability to apply force in short time periods (<250 ms) is one of the key criterion to serve fast, and specifically SHIR and SHF RFD and IMP parameters exert a clear influence on SV (Baiget et al., 2016, 2022; Colomar, Corbi, & Baiget, 2022c). Probably, some IST characteristics benefited from the direct transfer of IST to SV. Firstly, it is well known that IST exercises executed as fast and hard as possible show positive effects on explosive strength and sport performance (Oranchuk et al., 2019). Secondly, the kinematic analogy between the upper-limb specific-joint exercises used and the tennis serve allow to specifically address the direction of the resistance force vector and mainly recruit the muscles implicated in the motion (Baiget et al., in press). Finally, the greater increases in neuromuscular function take place at the trained angle (Kitai & Sale, 1989; Oranchuk et al., 2019) and the IST exercises were performed near the joint angle of the tennis serve impact phase (Elliott, 2006).

Some remarkable specific shoulder joint neuromuscular adaptations occurred following IST. On the one hand, while SHIR increased PRFD and IMP, SHF increased RFD. These disparities could be because of the different shoulder joint angle positions and resistance force vector between the two exercises (e.g., SHIR had elbow flexed and SHF extended). On the other hand, as seen in previous studies analysing the response of strength training on the early (<100ms) and late (>100ms) phases of RFD (Andersen et al., 2010), both capabilities IMP and RFD changes were found in the late phases from the onset of muscle contraction. It has been suggested that the early phases of RFD are largely determined by intrinsic muscle properties and the late-phases of RFD are more influenced by adaptative mechanisms (Rodríguez-Rosell et al., 2018). Finally, contrary to RFD and IMP, no positive effects were found in the MVIC. Probably, the short contraction time (5 s) and the fact that the IST exercises were performed explosively may have only affected the first 250 ms of the isometric contraction. It has been shown that IST adaptations are specific to the training stimulus. While explosive IST would generate more positive effects on explosive strength, sustained submaximal contraction would do so on MVIC (Oranchuk et al., 2019; Tillin & Folland, 2014). Along with the described factors, the effect of the interaction of the IST with the technical and tactical usual academy training (15 h·week^{-1}) might also exert an effect on most of the adaptation differences.

Although some minor changes were observed between week 0 and 3, the essential neuromuscular (SHIR PRFD and IMP and SHF RFD) and functional (SV) improvements occur following 6 weeks of IST. These results support the criteria that the minimum effective IST duration to achieve significant performance and physiological adaptations is about 6 weeks (Lum & Barbosa, 2019). In that case, as the intensity of the IST remained stable (100% MVIC), we could suggest that a minimum of accumulated training volume is necessary (i.e., 15 sessions and 600 s). In this sense, it has been suggested that the total

IST volume increased is more determinant than the intensity to improve force production (Oranchuk et al., 2019).

One of the key advantages of the IST is that generates minor amount of neuromuscular fatigue than dynamic strength training (Lum & Barbosa, 2019). As no impairments have been shown in the SA, we could assume that the implemented IST did not exert any negative technical effects or intermuscular coordination prejudices. This is in accordance with previous investigations that have investigated the acute and delayed effects of strength training on the accuracy of shots (Terraza-Rebollo & Baiget, 2020, 2021).

4.4.6 PRACTICAL APPLICATIONS

Shoulder IST (i.e., SHIR and SHF) could be a feasible method aimed to improve SV in young competition tennis players in combination with dynamic strength methods. Considering that competition tennis players don't have so much time and material to focus on strength training due to the travels and the extensive competition calendar, the shoulder IST could be a time-efficient and accessible alternative to generate neuromuscular and functional adaptations by improving explosiveness with limited equipment needed. Moreover, as IST is proved to generate low amounts of neuromuscular fatigue (Lum & Barbosa, 2019), it could be implemented nearby the competitions without technical impairments. SHIR and SHF exercises should be executed as hard (100% MVIC) and fast as possible, with short contraction times (≈ 5 s) and low volumes per session (30 to 50 s). Nevertheless, the proposed IST refers to a brief training program duration and therefore short-time adaptations achieved. Towards achieving long-term adaptations, probably programs of greater duration that include volume, intensity and exercise variations are needed.

4.4.7 CONCLUSIONS

To combine 6-week of upper-limb specific-joint IST with the habitual tennis workouts results in significant increases in SV without SA detriment in young competition tennis players. The SV enhancement was produced because of the shoulder joint force-time curve increases, showing the relevance of producing force in short times on SV performance.

4.4.8 ACKNOWLEDGEMENTS

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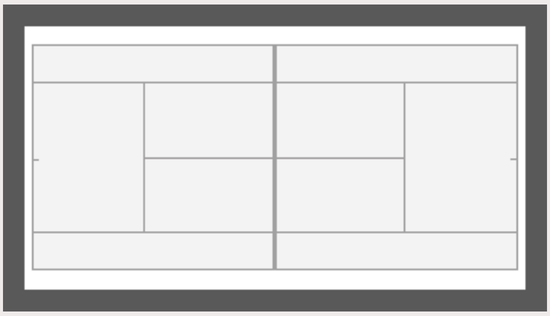
5 DISCUSSION



As previously stated, the main aim of this doctoral thesis was to determine how neuromuscular training, anthropometric, ball impact and landing location, and force-time curve parameters influence serve performance in high-level and junior tennis players. Accordingly, the discussion will be organized based on these parameters and will try to summarize the main topics of discussion of the presented studies.

5.1 Anthropometric parameters

The results obtained during an ATP Tour event revealed that anthropometric parameters exert a significant influence on SV in professional tennis players. Both BH and BM demonstrated large associations with FSV1 (BH: r = 0.503; BM: r = 0.593) and moderate with TSV1 and FSV2 (BH: r = 0.318 and 0.486; BM: r = 0.315 and 0.466) and no influence was found in TSV2. Consequently, it seems that the influence of BH and BM on SV is enlarged when professional tennis players tried to serve fast, but not when their serves are more cautious (i.e., TSV2). In this same line, when tennis players serve at maximal SV (FSV1 and FSV2), anthropometric parameters were the unique significant contributors of SV explaining 22 to 35% of SV.

Plausibly, the relevance of BH on SV is due to the importance of the principle of force production above the influence of longer connecting body segments, as longer limbs allow to obtain higher peripheral head racket velocity at ball impact getting greater hand-racket angular momentum with the equal angular speed of upper body segments (Hayes et al., 2021; Martin, Kulpa, Delamarche, et al., 2013; Vaverka & Cernosek, 2016). On the other hand, the relevance of BM on SV is related to the principle of force (mass x acceleration) and torque production (Fett et al., 2020; Wong et al., 2014). Based on allometry assumption, BM is associated with torque production and an increased torque would reinforce SV (Wong et al., 2014). Surprisingly, BM explained more of the variability (35%) of FSV1 than BH (25%) and the multiple regression analysis demonstrated the relevance of BM above BH in FSV1 and FSV2. On that matter, it has been stated that world-class tennis players have been increasing their muscle mass experiencing a transformation from endurance to power athletes. It has been suggested that a greater muscle mass and the ability to generate power production in all strokes is associated with greater tennis performance, while taller but less muscled players (i.e., more linear body shape) would perform worse (Gale-Watts & Nevill, 2016). Contrary, although in professional tennis players we could assume that a high BMI is related to a greater muscle mass, we observed only a small influence of BMI in TSV1 (r = 0.128), but not in FSV. This may be due to BMI representing an interaction of BM with BH, and it is possible that a single increase in BM does not generate a significantly increase in SV and an optimal relationship probably exist between BM and BH to optimize SV. Further research is needed to clarify the most advantageous interaction.

5.2 Ball impact and landing location parameters

Ball impact location parameters (IH, IPA and RIH), did not show significant associations with FSV, but IH and IPA showed a comparable influence on anthropometrics parameters on TSV1 (r = 0.294 and -0.391), and a higher influence on TSV2 (r = 0.329 and -0.409). Therefore, it seems that the benefit of ball impact location parameters on SV was lower when players try to maximize SV. Regarding RIH, no influence on SV appeared, thus we could speculate that even if BH has a large influence on SV, the factors that accompany BH (i.e., the vertical jump height, the vertical height of the hitting shoulder or the impact point on the string and the sum of arm and racquet length) to determine IH do not affect SV. In addition to their influence on SV, it is important to consider that ball impact parameters could be a relevant aspect of SA. It has been stated that a higher IH contributes to a larger accessible area in the service box (Vaverka & Cernosek, 2013) and allows a greater SV with the equal probability of the ball landing inside the service box (Vaverka & Cernosek, 2016).

Small to large differences have been found between S1 and S2 in SV, IPA and depth. The large differences found in depth (~50%) and ball velocity (~17-18%) together with the large differences in IPA (20 and 16.5 %), show that S1 are significantly faster, deeper and with a major IPA than S2. This is probably because the straight ball trajectory of fastest serves needs a large IPA and allows it to reach a greater depth. Presumably IPA may vary between flat, and spin serves and the less IPA and depth in S2 can be attributed to the slower SV and greater topspin. A minor spin and higher SV are characterized by straighter ball trajectories over flight than slower serves, and consequently, with a reduced clearance over the net to land in the service box. Contrary, on topspin S with greater ball spin rate and less ball velocity (i.e., S2) the Magnus force provokes further curved ball trajectory and lower forward velocity and depth (Chow et al., 2003; Sheets et al., 2011).

Visual inspection of Figure 11 shows that S1 ball bounces (Figure 11A) are located closer to the service center line (i.e., T location) and singles sideline (wide location) and less into the center service box (i.e., body location) than S2 (Figure 11B). Probably these differences are caused because tennis players try to optimize the tactical advantage, number of aces or points directly won with serve to a greater extent in the S1 than S2. Nevertheless, the negative moderate and small associations found between width and TSV1 and TSV2 ($r = -0.173$ and -0.190) shows a trend that fastest TS were closer to the center service line (i.e., T location), especially in TSV1. This may be because when players are trying to perform a wide serve, they tend to focus on accuracy of serve to move the opponent off the court and achieve a positional advantage. Instead, when serving near the T location they seek to maximize serve speed and diminish the time reaction of the opponent.

5.3 Force-time curve parameters

All force-time curve parameters registered (i.e., IF, RFD and IMP) at different time intervals (30, 50, 90, 100, 150, 200 and 250 ms) in all joint positions tested (except for the EF) moderate to very largely influence SV in competition tennis players. We could assume that, although SV relies on different nature parameters (e.g., technique, anthropometrics or ROM), the capability to develop force in shorter periods (i.e., <250ms) would be an important factor in the resulting SV. Consequently, it could be stated that the neuromuscular function and the explosiveness of the dominant upper limb joints involved in the kinetic chain are relevant parameters to develop faster serves.

The associations ranged between moderate to very large in IF in all positions except SHER, between large to very large in RFD in all positions except EF and was large regarding IMP in all positions except EF and SHER. However, the contribution of shoulder positions (i.e., SHF and SHIR) should be highlighted above others. In that sense, 50% of the variability of SV is predictable from the SHIR RFD from 0 to 50 ms, and the multiple regression analysis noted the contribution of SHF and especially SHIR. The relevance of SHIR force-time curve parameters is due to the high influence of this joint in the serve kinetic chain. SHIR plays a crucial role in the requirements of explosive rotational movements in the upper arm acceleration during the swing to impact (Elliott, 2006). Contrary, force-time parameters in the EF and SHER positions were not significantly correlated with SV, possibly because they may not have a significant contribution in the explosive rotational movements in the swing to impact (Elliott, 2006; Kibler et al., 2007).

RFD seems to exert more influence on SV than IF and IMP, showing that the ability to develop force rapidly in rotational movements is determinant to generate high SV. The multivariate model for predicting SV showed that approximately 50% of the variance of

SV could be accounted by the SHIR RFD from 0 to 50 ms. In this same line, SHIR RFD from 0 to 30 ms was included as the first step by the discriminant analyses. Both early (<100 ms) and late (>100 ms) phases from the onset of muscle contraction showed significant correlations with SV, showing that the ability to apply force rapidly at time frames from 0 to 250 ms (both early and late RFD) are necessary to serve fast. In this line, the results of multiple regression analysis highlight early phases of RFD (SHIR RFD 0 to 50 ms), while the predictive model that best discriminated players who were able to serve above or below to 165 km·h^{-1} included both early (SHIR and EF RFD 0 to 30 ms) and late (WF and SHE RFD 0 to 150 and 250 ms) phases of contraction.

IMP could be considered as an indicator of the accumulation of force applied over a given period. The relevance of this parameter could be argued because applied force in a great deal of sport actions is not constant throughout the time period and integration should be implemented (Taber et al., 2016). As RFD and IMP are related variables, comparable with RFD associations were found between SV and IMP, mostly in late phases of the time frames assessed (i.e., from 150 to 250 ms). The tennis serve generates high velocities through explosive rotational movements (Myers et al., 2015), and the amount of contractile IMP at each time point determines the rotational angular velocity of the distal segment at the measured time (Aagaard et al., 2002), thus a higher IMP facilitating a greater momentum may contribute to generate high-speed racquet movement and consequently higher SV.

5.4 Neuromuscular training

5.4.1 Postactivation performance enhancement (PAPE)

Two short tennis-specific upper-limb joint MVIC exercises (1 x 5 s SHIR MVIC + 1 x 5 s SHF MVIC / 10 rest) involved in the serve kinetic chain immediately induces PAPE, increasing SV (3.4 ± 4.6%; 4.6 km·h^{-1}) without SA detriment in young competition tennis players. Contrary, when the CA exercises were performed throughout high-intensity (3 x 3 repetitions at 80% of the 1 repetition maximum (1RM)) traditional resistance exercises (half squat and bench press), no PAPE on SV was observed (Terraza-Rebollo & Baiget, 2020). Although the used CA protocols involved MVIC, the immediate PAPE responses shown seem to optimize the SSC muscle action (reactive strength) of tennis serve. Probably, the observed PAPE may benefit from the following different specific characteristics of the exercises performed:

- SHIR and SHF strength positions are involved in the serve kinetic chain being one of the main contributors to accelerate the tennis racket towards the ball (Elliott, 2006).
- SHIR and SHF strength positions were performed near the joint angle where the serve ball impact happens (Elliott, 2006).
- The suited direction of the resistance force vector related to the body throughout CA has previously been reported as relevant to develop potentiation effects (Boullosa et al., 2020; Dello Iacono & Seitz, 2018).
- Performing MVIC CA exercises explosively (as fast as possible) could be also beneficial to promote PAPE, as the capacity to develop force in short periods of time (<250 ms) is highly associated with SV (Baiget et al., 2022).

Regarding the effect of using one or two different CA protocols (SHIR or SHIR + SHF), the results showed that PAPE effects are benefited following the summation of two CA exercises (SHIR + SHF). Considering that the two CA protocols were conducted throughout the same contraction regime and intensity magnitude, the better PAPE enhancement of SHIR + SHF could be explained depending on two factors:

- The higher total isometric contraction duration (volume) of SHIR + SHF compared to SHIR (10 s vs. 5 s) could be favorable to elicit PAPE.
- The summation effect of the inclusion of another position involved in the serve kinetic chain.

In connection with the optimal recovery time to reduce fatigue and favour PAPE response, PAPE effect was observed immediately following the MVIC SHIR + SHF CA (0 min), and no positive effects persisted throughout the time ranges from 5 to 15 min. Contrary, when CA are conducted using high intensity dynamic contractions, the better PAPE effect is mainly achieved after medium recovery durations (5-7 min) (Seitz & Haff, 2016) and the effects are reported to persist up to 10 min (Tillin & Bishop, 2009; Wilson et al., 2013).

Although strength levels or training background have been previously proved to affect PAPE (Boullosa et al., 2020; Seitz & Haff, 2016; Tillin & Bishop, 2009; Wilson et al., 2013), tennis players with higher neuromuscular performance were not able to exhibit better PAPE responses. Probably these could be due to the homogeneous background and high-volume weekly training of the participants involved (8.9 ± 1.6 years of tennis training background, minimum of 3-year in strength training; weekly training volume between 15 - 25 $h \cdot week^{-1}$).

With respect to SA, no detriments were observed in any CA protocol and recovery time point. This evidence leads us to consider that 5 to 10 s MVIC CA do not elicit significative fatigue and therefore do not provoke intermuscular coordination impairments. In agreement, previous studies have shown that short-duration ($10 \leq$ s) MVIC CA elicit PAPE without a significant fatigue, while long-duration protocols ($60 \geq$ s) do (Skurvydas et al., 2019; Wallace et al., 2019).

5.4.2 Isometric strength training

The effects of adding a 6-week upper-limb specific-joint IST to the habitual physical training workouts was analysed in competition young tennis players. The results showed increases in functional (SV) and neuromuscular (MVIC, RFD and IMP) performances without SA detriments. Although the transferability of the IST to dynamic sport performance has been controversial (Oranchuk et al., 2019) and the tennis serve involves high-speed SSC muscle actions (Elliott, 2006), the obtained results allows to state that the capability to produce force in short time (<250 ms) in both exercises used (SHIR and SHF) accompanied with SV could be optimized by an IST. These findings are in line with those obtained in study II and III showing the relevance of SHIR and SHF force-time curve parameters on SV (Baiget et al., s. f., 2022). The main neuromuscular (SHIR PRFD and IMP and SHF RFD) and functional (SV) improvements occur following 6 weeks of IST, with some minor changes observed between week 0 and 3. Therefore it seems that a minimum effective IST duration (i.e., 15 sessions) and accumulated training volume (i.e., 600 s) are needed to achieve significant performance and physiological adaptations. Moreover, both capabilities IMP and RFD changes were found in the late phases from the onset of muscle contraction (>100ms). It has been suggested that the early phases of RFD are largely determined by intrinsic muscle properties and the late-phases of RFD are more influenced by adaptative mechanisms (Rodríguez-Rosell et al., 2018). Regarding of the no positive effects in the MVIC, the short contraction time (5 s) and the fact that the IST exercises were performed explosively may have only affected the first 250 ms of the isometric contraction.

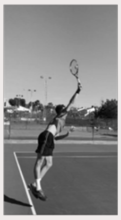
Similarly to study III, there is likely to be an optimization of the direct transfer of IST to SV due to the specific characteristics of IST. Some of them are as follows:

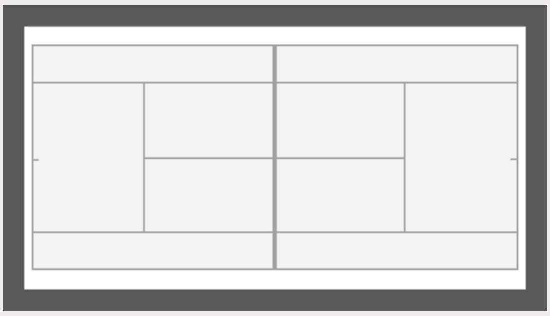
- IST exercises executed as fast and hard as possible show positive effects on explosive strength and sport performance (Oranchuk et al., 2019).
- The kinematic analogy between the upper-limb specific-joint exercises used and the tennis serve allow to specifically address the direction of the resistance force vector and mainly recruit the muscles implicated in the motion (Baiget et al., in press).
- The IST exercises were performed near the joint angle of the tennis serve impact phase (Baiget et al., s. f.; Elliott, 2006) and it has been demonstrated that the greater increases in neuromuscular function take place at the trained angle (Kitai & Sale, 1989; Oranchuk et al., 2019).
- IST generates minor amount of neuromuscular fatigue than dynamic strength training (Lum & Barbosa, 2019) and the implemented IST did not exerted any negative technical effects or intermuscular coordination prejudices.

It should be noted that some differences were found in the IST shoulder specific neuromuscular adaptations. In particular, SHIR increased PRFD and IMP whereas SHF increased RFD while no positive effects were found in the MVIC on both exercises. The following reasons are proposed to justify these adjustments disparities:

- The effect of the interaction of the IST with the technical and tactical academy training (15 h·week^{-1}) might also exert an effect on most of the adaptation differences.
- The two exercises used (SHIR and SHF) had different shoulder joint angle positions and resistance force vector (e.g., SHIR had elbow flexed and SHF extended).

6 CONCLUSIONS





In the following section, each of the specific objectives for this doctoral thesis will be answered in order to provide the outcome of the project.

Objective I: To analyse the associations between SV and anthropometric, ball impact and landing location parameters in TSV and FSV in professional tennis players during an ATP Tour event.

- Anthropometric (greater BM and BH), ball impact (higher IH and IPA) and bounce landing (minor width and larger depth) location parameters small to moderately influence SV during an ATP Tour event.
- When professional tennis players serve at or near maximal SV, the influence of anthropometric parameters are increased being the major contributors to SV.

Objective II: To observe differences between S1 and S2 and to determine a SV prediction model based on the relationship between the observed variables.

- S1 are deeper and show a greater IPA compared to the S2.
- The prediction model constructed highlights the influence of BM above BH on the fastest serves, suggesting its importance to generate power production at the professional tennis level.

Objective III: To analyse the associations between SV and various single-joint upper limb isometric force-time curve parameters (IF, RFD and IMP) in competition tennis players.

- Force-time parameters (IF, RFD and IMP) at different time frames in upper limb joints involved in the serve kinetic chain moderate to very largely influence SV in competition tennis players.

- The capability to develop force in short periods of time (< 250 ms), especially in the shoulder joint (SHIR), seems relevant to develop high SV in competition tennis players.

Objective IV and V: To develop a prediction model based on the relationship between SV and various single-joint upper limb isometric force-time curve parameters (IF, RFD and IMP). To determine whether selected IF, RFD and IMP parameters in different upper limb joints are capable of discriminating between tennis players with different SV performances.

- The prediction model constructed, and the discriminant analysis highlight the influence of RFD above IF and IMP, especially in the SHIR.

Objective VI and VII: To analyze the effects of PAP induced by upper-limb tennis-specific joint maximal isometric voluntary contractions (MVIC) on SV and SA in young tennis players. To compare the PAP effects on SV and SA using two different MVIC CA protocols.

- Performing two short upper-limb tennis-specific joint MVIC favours the immediate appearance of SV enhancement without SA impairment in young competition tennis players, while only one MVIC does not elicit PAPE.

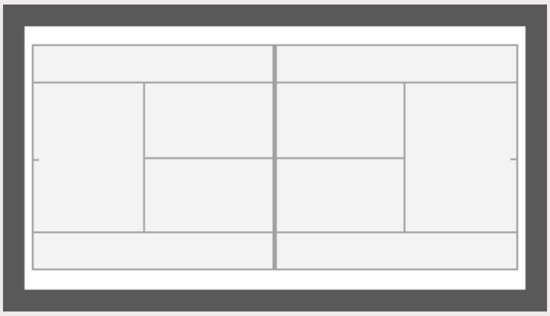
Objective VIII: To explore if changes in SV would be related to tennis player's neuromuscular performance.

- Tennis players with better neuromuscular performance do not seem to demonstrate a better predisposition to PAPE.

Objective IX: To evaluate the effects of adding a short time specific-joint IST on serve performance (SV and SA) and force-time curve parameters (RFD, IMP and MVIC) in young tennis players.

- To combine 6-week of upper-limb specific-joint IST with the habitual tennis workouts results in significant increases in SV without SA detriment in young competition tennis players.
- The SV enhancement was produced because of the shoulder joint force-time curve increases, showing the relevance of producing force in short times on SV performance.

7 PRACTICAL APPLICATIONS



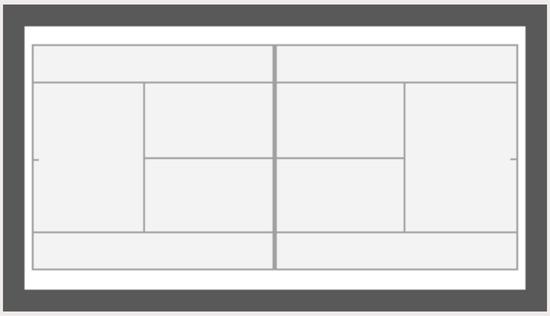
The practical applications of the project would be summarized as follows:

- Because BH can’t be modified in adult tennis players and BM has been shown as an important influencing factor when players serve at or near maximal, it can be postulated that neuromuscular strength training interventions aimed at increasing lean BM could be helpful for improving SV, especially in not very tall professional tennis players (i.e., < 185 cm).
- Due to a greater BM producing a greater inertia demanding higher force production to produce a given change in velocity or direction (Sheppard & Young, 2006), the strength training interventions aimed at increasing lean BM should be taken with caution. An optimal interaction should be found between increasing BM and COD performance.
- Strength training aiming to improve SV should consider both early and late shoulder joint RFD.
- Shoulder IST, in combination with dynamic strength methods, could be a feasible, time-efficient, accessible, and alternative method aimed to improve SV and to generate neuromuscular adaptations by improving shoulder explosiveness.
- In order to improve explosiveness and the force-time curve, SHIR and SHF exercises should be executed as hard (100% MVIC) and fast as possible, with short contraction times (≈ 5 s) and low volumes per session (30 to 50 s).
- The easy application of SHIR and SHF MVIC exercises to induce PAPE (i.e., no special equipment or heavy loads needed) beside its time-efficient characteristics (10 s work) and the minimal fatigue induced, facilitates its implementation in the tennis court in combination with technical-tactical training sessions.
- The biomechanical similarity between SHIR and SHF MVIC positions (heavy load performed before serves) and the serve (lighter load) permits this specific

layout to be implemented as a complex training resource and could be used as a neuromuscular warm-up routine.

- Due to the constant travels as a consequence of the competition, tennis players don’t have so much time and material to focus on strength training. The shoulder IST could be a time-efficient and accessible alternative to generate neuromuscular and functional adaptations with limited equipment needed.
- Considering that IST generates low amounts of neuromuscular fatigue (Lum & Barbosa, 2019), it could be implemented nearby the competitions without technical impairments.
- Shoulder joint (i.e., SHIR and SHF) force-time curve isometric testing (i.e., RFD, IMP and IF) could be considered as valid options to evaluate and control training periodically in competition tennis players.

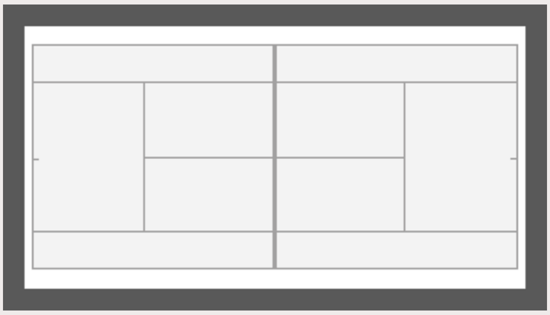
8 LIMITATIONS OF THE STUDY



There are some constraints that need to be considered when interpreting the results of the doctoral thesis. Summarizing, the main study limitations are as follows:

- Serve is a highly complex sport action determined by different nature parameters (Kovacs & Ellenbecker, 2011a, 2011b), however, the presented SV analysis is based on a partial spectrum of serve performance (i.e., some anthropometric, ball impact and bounce, force-time curve and neuromuscular training parameters). The global analysis would be more accurate considering other determinant factors such as technical (Mecheri et al., 2016), strategical (Gillet et al., 2009) or range of motion (Hernández-Davó et al., 2019; Palmer et al., 2018) parameters.
- The global sample includes around 80% of male and 20% female participants. As different SV influencers and force-time profiles could exist between genders, further studies are needed to explore them.
- The anthropometric characteristics of tennis players (i.e., BH and BM) registered in study I were obtained from publicly available information listed in the official ATP website, assuming that the provided data may differ minimally from real data.
- The force signal used in studies II, III and IV was sampled at 200 (Study II) and 80 (Study III and IV) Hz, which could result slightly low for contraction times around 0-30ms. Nevertheless, the reliability values obtained were adequate and this system seems accessible for practitioners that could be aiming at evaluating players performance efficiently.

9 REFERENCES



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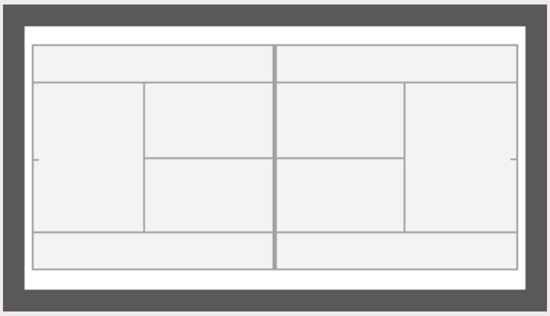
10 ANNEXES



10.1 Annex 1: Publication I

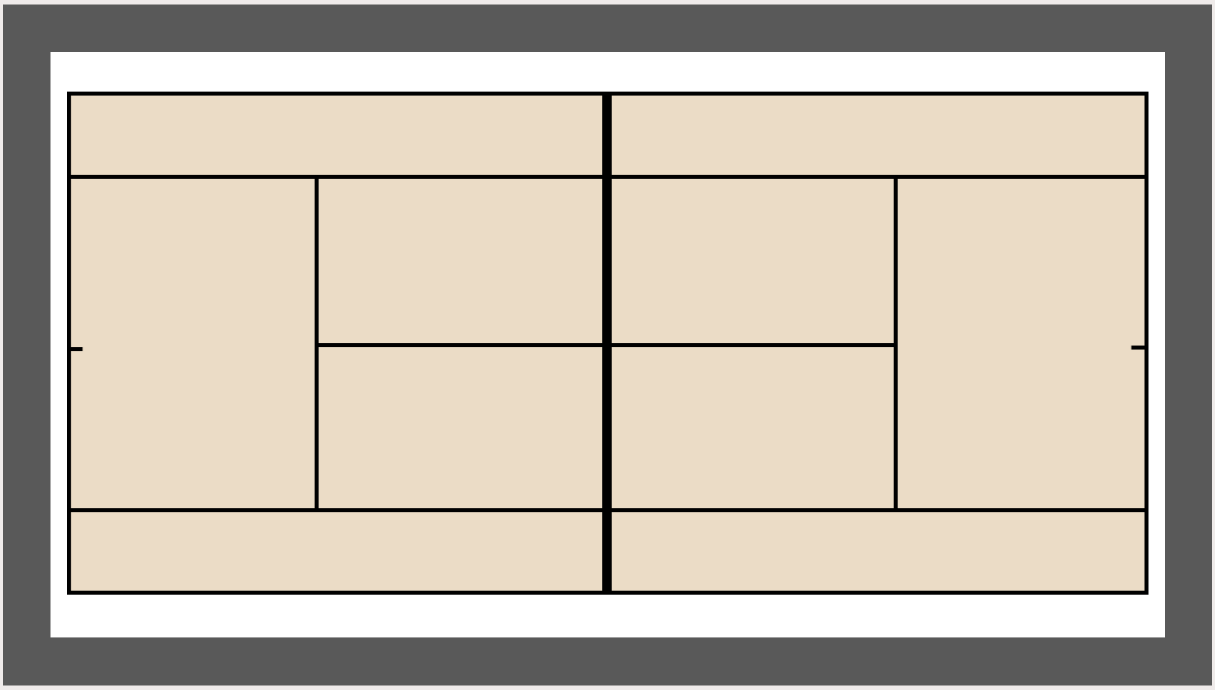
10.2 Annex 2: Publication II

10.3 Annex 3: Publication III

10.4 Annex 4: Publication IV

DOCTORAL THESIS

Ernest Baiget Vidal



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