Original Article

To Assess the Impact of Physical Factors on Velocity, Speed, and Accuracy of Tennis Serve

Xudong Ma[1], Azhar Yaacob[2], Tengku Fadilah Tengku Kamalden[3], Yee Guan NG[4]*

[1]Department of Sports Studies, Faculty of Educational Studies, Universiti Putra Malaysia, Serdang, Malaysia.
ORCID iD: https://orcid.org/0009-0003-9482-3066
Email: 16609409402mxd@gmail.com
[2]Department of Environmental & Occupational Health, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia Serdang, Malaysia.
ORCID iD: https://orcid.org/0000-0001-5159-1021
Email: azhar_y@upm.edu.my
3National Sports Institute (ISN),National Sports Complex, Bukit Jalil 57000 Kuala Lumpur.
ORCID iD: https://orcid.org/0000-0001-7504-1585
Email: tengku.fadilah@gmail.com
[4]Department of Environmental & Occupational Health, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia Serdang, Malaysia.
ORCID iD: https://orcid.org/0000-0001-7373-2139
Email: shah86zam@upm.edu.my

Abstract

Background: Real-world variables significantly influence the velocity of a tennis serve. Key factors include biomechanical components, anthropometrics, and strength and conditioning practices. **Objective:** This study investigates the coordination of racquet and ball speed, examining how physical attributes and training impact serve performance. **Methods:** An exhaustive review was conducted using Google Scholar, analyzing 25 key papers related to tennis serve velocity, biomechanics, and training programs. The focus was on identifying the contributions of lower and upper body strength, as well as trunk stability, to serve velocity. **Results:** The analysis revealed that Increased lean muscle mass, arm length, and body height correlate with faster serves. Maximizing isometric strength and optimizing force production at joint Am J Sports Medic chains enhance serve velocity. Only a minor portion of the force exerted on the ball (less than 50%) is generated by the trunk and lower body, yet they significantly influence the velocity. Variations in serve velocity improvements ranged from 3.0% to 29.0% across studies, with disparities potentially due to different study durations (four weeks to nine months) and methodologies. Match fatigue significantly reduces serve velocity and stroke volume (SV) over time. Shoulder injuries are primarily caused by imbalances between agonist and antagonist muscles, despite advancements in serve velocity. **Conclusion:** Efficient and effective training models are essential for improving tennis serve performance. Enhancements in isometric strength, force production, and muscle mass are crucial, alongside careful monitoring and recovery to manage the physical demands on athletes. Incorporating resistance training that focuses on both lower and upper body strength, as well as trunk stability, into a periodized strength and conditioning program, is recommended to optimize serve velocity and overall athletic performance.

Keywords: Tennis Serves, Strength, Power, Lower-body, Upper-body, Fatigue, Biomechanics, Anthropometrics.

Introduction

Rafael Nadal and Roger Federer, two very skilled tennis players, are among the most robust and fit athletes of our day. Due to advancements in racquet technology and Strength and Conditioning (S&C) training methods, the game has evolved towards a style of play that emphasises power and speed. As a result, players now frequently achieve serve speeds of 200 km/h or more.[1] The serving motion is notoriously challenging to perform due to the numerous geographical and temporal factors involved, such as stance, ball throw, racquet cocking, and hitting the ball at full extension.[2] Kovacs has provided a comprehensive explanation of the serving motion, which consists of eight distinct steps.[3]

Athletes demonstrate exceptional neuromuscular

Access this article online

Quick Response Code:

Website: www.jnsbm.org

DOI: https://doi.org/10.4103/jnsbm.JNSBM_15_1_15

Address for Correspondence: Department of Environmental & Occupational Health, Faculty of Medicine and Health Sciences,Universiti Putra Malaysia Serdang, Malaysia.
Email: shah86zam@upm.edu.my

Submitted: 21st March, 2024 **Received:** 11th April, 2024
Accepted: 24th April, 2024 **Published:** 04th May, 2024

How to cite this article: Ma X, Yaacob A, Kamalden T F T, Y N Guan. To Assess the Impact of Physical Factors on Velocity, Speed, and Accuracy of Tennis Serve. J Nat Sc Biol Med 2024;15:124-133

coordination and stability throughout a three-set match, highlighting the significant neuromuscular requirements of this activity. Neuromuscular fatigue is a frequent occurrence in intermittent sports such as tennis. As a result, modern players prioritise strength training as much as technical and tactical preparation, both on and off the court.[4,5]

The serve is a highly important shot in modern tennis.[1,6,7] This stroke has a direct impact on the score, making it one of the most often used moves in the game.[8] Consequently, SV has demonstrated improvement on the professional tour by reducing the number of double faults and increasing the number of aces.[9] Aside from technical indicators, it is crucial to assess particular anthropometric characteristics that have been proven to be positively associated with SV. Differences in correlation strengths exist between genders and skill levels. However, it appears that achieving a higher peripheral racket velocity at ball impact is crucial overall. This can potentially be accomplished by having a longer arm length or a taller torso Components.[10-13]

The ability of a player to generate speed is directly influenced by their body mass (BM), which affects stroke volume (SV) through the principle of force (mass × acceleration) and torque generation.[14,15]

Ongoing research is being conducted to examine the impact of physical abilities and neuromuscular performance parameters on SV. Peak dynamic strength.[16-18]

Furthermore, it appears that shortcomings in these crucial areas become apparent during competitive matches or after specific training intensities. A significant portion of previous research has focused on the simulation of competitions or the retrospective analysis of data. It is evident that playing tennis can have a significant impact on crucial performance characteristics,[19-23] studying the impact of factors such as overall match play loads, volume, intensity of play, calendar, and travelling on these traits would be intriguing.

The goal of this work was to identify and describe the physical factors that have a good or detrimental impact on SV, as well as to address any existing differences linked to sex, level, and age. The search terms used in this review were "Tennis Serve," "Serve Speed or Velocity," "Anthropometry," "Biomechanics," "Physical," "Strength," "Power," "Match," "Competition," and "Training." The studies examining potential correlations between physical variables and stroke volume (SV) also incorporated research that assessed alterations in SV pre- and post-training sessions or competitive matches. The participants were classified into three categories based on their eligibility: "elite" (players with ATP or WTA rankings above 1000 at the time of the study), "competition" (players over 18 years old participating in competitive events without a ranking above 1000, including collegiate players), and "junior" (players under 18 years old participating in both international and national/regional events). The exclusion criteria encompassed research with players categorised as "amateur" or "recreational". Our initial assumption was that SV, or sprint velocity, is a complex capacity that is influenced by anthropometrics (body height and mass), strength (the ability to exert force quickly), and biomechanics (the ability to rotate the legs, hips, trunk, and shoulders). In addition, the above variables would be negatively affected and performance would decrease with a large amount of match play.

Biomechanics and Movement Competency

In order to achieve an efficient serve, it is essential to develop specific technical attributes. An efficient serve is a complex motor skill that requires speed, accuracy, and a non-aggressive approach to musculoskeletal well-being. In order to achieve this objective, previous research have attempted to separate and identify the most crucial biomechanical elements.[1,5,24]

The key aspect that contributes to increasing the speed of the racquet head is the height at which the hit occurs, along with the amount of momentum and forward rotation transferred to the ball. Hence, it appears that the accurate velocity vectors of the upper arm, lower arm, and hand play a crucial role in generating this velocity. To achieve high racquet head speeds, it is essential to flex the hand and upper arm, pivot the storage compartment, rotate the torso, and internally rotate the shoulder.[25] The key to achieving a fast swing is the internal pivot action, which accelerates the upper arm and increases the swing's stylish velocity, ultimately leading to impact. The serve is a complex mechanism that involves several body movements and stages. However, its main impact occurs in the upper arm.

Anthropometric Characteristics

Table 1 demonstrates that the player's backhand (BH) and the height at which the ball makes contact during the serve are the most crucial factors that affect the ability to generate high-velocity serves. Increasing the height at which the ball is hit provides a greater amount of space within the opponent's serve box, as observed from a biomechanical perspective. Consequently, by striking the ball from a higher position, a player can enhance their trajectory and elevate their SV.[13] The most efficient biomechanical configuration for achieving faster serves differs based on the specific phase of the stroke being analysed, as the serve is a skill that encompasses multiple components. Kovacs and Ellenbecker proposed an eight-stage multi-stage examination of the serve.[1] The investigations established a connection between anthropometrics and speed. Specifically, we identified four noteworthy and statistically significant correlations for the first serve: height, upper arm length, arm circumference, and BMI. However, just one factor was shown to be associated with the second serve, which was the measurement of wrist circumference.[1,5,23]

Therefore, we may conclude that the velocity of the initial serve is more dependent on anthropometric traits in comparison to the velocity of the subsequent serve. Specifically, numerous studies have found a moderate link between the height, upper arm length, and arm circumference of female players and their first serve speed. Likewise, the body mass index (BMI) of male players exhibited a slight connection with the pace at which they executed their first serve.[24] The author disclosed that the participants' Body Mass Index (BMI) was 20.84 ± 0.86 for females and 22.51 ± 1.20 for males.[25] The study revealed a detrimental association between BMI and the velocity of the initial serve in males. Previous studies have also identified and explained a similar adverse correlation between BMI and serve speed. This relationship is associated with the potential influence of increasing muscle mass and subsequent improved strength.[5,13,25] The importance of a sideways tilt of the pelvis and shoulders during the loading period has also been acknowledged,[1] As a result of this alignment, angular momentum can be generated through sideways bending of the trunk during the forward swing.[1,5,13,24,25] A crucial aspect of the cocking phase involves lowering the racquet and positioning it behind the body. This action extends the racquet's trajectory before to contact and enables greater storage of elastic energy. Attaining complete external rotation of the shoulders and ensuring a nearly parallel alignment between the racquet and trunk seem to be essential. The subsequent stage, known as the acceleration phase, involves swiftly propelling the racquet from its current position till the moment of impact. The most precise kinematic models for aligning the contact point indicate a little abduction of the shoulder and a modest flexion of the wrist, elbow, and lead knee.[5,13,23]

Table 1: Anthropometric Features Associated with SV.

References	Description and Goal	Variable Tested	Correlation
Vaverka and Cernosek[14]	Find out if elite players' BH and SV are related during Grand Slams.	BH, cm: 179.0 (6.0) BH, cm: 173.0 (7.0)	SF: r = .50 (.05) S1: r = .49(.08) S2: r = .30 (.21) SF: r = .50 (.05) S1: r = .50 (.04) S2: r = .34 (.07)
Bonato et al [12]	Examine the connection between professional players' SV and anthropometric and functional characteristics.	BH, cm: 181.8 (4.1) BM, kg: 79.7 (4.3)	r first serve = .79* r second serve = ,81* first serve = −0.22 r second serve = −0.15
Sögut[31]	Identify potential connections between SV and BH.	BH, cm: 160.4 (11.42) BH, cm: 160.4 (0.08)	r =.40 r=.70
Palmer et al[32]	To investigate the relationship between power, SV, BH, ROM, strength, and motor control	BH, cm: 160.2 (6.25)	r = 0.50**
Hayes et al[13]	Find out if anthropometric measurements and SV in top junior tennis players are related.	BM, kg: 65.6 (11.5) r = .70* BMI, kg/m2 : 20.20 (1.6) r = .30 BH, cm: 169.2 (8.9)	r-.69** r=.30
Fett et al[15]	Find out how anthropometric traits affect SV in competitive junior tennis players.	BM, kg: 35.3 (5.10) BH, cm: 150.9 (8.5) BMI, kg/m2 : 15.3(1.4)	r =.41** r =.35
Sögut[33]	Identify different functional and anthropometric characteristics and how they relate to SV.	BMI, kg/m2 :20.5(1.9) 170.5(5.5)	r =.10 r =.330*
Fernandez Fernandez et al[34]	Examine the functional profile of the shoulder and determine how the measured variables and SV are related.	MBO MBF MBB	.550 .630* .440*

Strength, Power, and ROM

The research has given extensive emphasis to the significance of anthropometric parameters in increasing SV, but it has also given complete consideration to the understanding surrounding strength aspects that impact this stroke. Research has shown that many components of strength are SV determinants (Table 2). Studies evaluating maximal dynamic strength via bench press or overhead press have not discovered strong associations between this variable and SV. This is in line with the observation that the weight of the implement (i.e., racquet) ranges from 200 to 400 g, which suggests that the initial demands for maximal dynamic strength during strokes are low.[13,18]

Table 2: Factors That Are Bad for SV.

References	Description and Goal	Fatiguing Conditions	Findings
Davey et al[35]	Analyze how exhaustion affects particular sports skills.	High-intensity intermittent activity	SV was not decreased yet accuracy declined 30%*
Ojala and Hakkinen[40]	to look at how certain performance and physiological factors changed throughout the course of a three-day tennis competition.	3-d tennis tournament	SV was altogether lower before the third coordinate contrasted and the main match (−2.69%*)
Rota et al[37]	Analyze how fatigue affects tennis performance and upper body muscular activity.	High-intensity intermittent-specific activity	SV is diminished 4.5%* and accuracy 10.5%*
Gescheit et al[41]	Examine the effects of playing matches back-to-back on one's health, perception, and performance.	Matches on consecutive days	SV is reasonably expanded step by step. Accuracy diminishes during successive days
Maquirrain et al[42]	Examine SV and accuracy in long-duration grass-court professional matches including men.	Wimbledon 5 set matches	No huge changes were enrolled
Martin et al[43]	Analyze how shoulder ROM and SV changed during the course of a three-hour tennis match.	3-h match	1.5 m/s (−3.15%*) decreases after 3 h of play. No decreases at 90 min

FACTORS NEGATIVELY AFFECTING SV

Engaging in tennis matches can alter the aforementioned physiological parameters that are positively associated with an elevated stroke volume (SV). Weariness is considered a triggering factor that has a negative impact on the complex nature of the tennis serve, specifically on SV. The decrease in muscular strength is directly associated with metabolic fatigue, muscle weakening, discomfort, and impaired functionality,[22] Each of these factors has the capacity to adversely affect SV. Specifically, studies indicate that weariness mostly affects accuracy, leading to a decrease in performance.[30,32,33] Lactate accumulation was determined to be the cause of serve accuracy reductions (−30% and −11.7%, respectively) seen by Davey *et al.*[30] and Rota *et al.*[32]. In addition to impacts on accuracy, weariness in specific areas as well as determining strength and power characteristics appear to be the primary causes of SV declines.[30]

However, not all players are equally affected by this fatigue, as it is likely influenced by factors such as the number of matches played, level of experience, and playing style. Although there may have been obstacles in terms of strength and power levels, Terraza-Rebollo and Baiget[36] No decreases in accuracy or speed of movement were seen following an obstacle training or MBT routine. This suggests that players may rely on alternative neuromuscular characteristics to enhance their effectiveness during the serve. These evaluations indicate that following a specific level of tennis activity, there are weaknesses in shoulder strength and range of motion (ROM) in both internal and external rotation values. The authors agree and recommend the development of intervention programmes that incorporate strategies to reinstate values before engaging in practice or competition, especially for players who lack the expertise and ability to derive advantages from tactical decisions or technical proficiency to counteract declines in sports performance.

PRACTICAL APPLICATIONS

There are multiple serving models that can be utilised to optimise SV. The primary contributors to the generation of angular momentum in transferring speed to the ball and the head of the racquet are elbow extension, shoulder internal rotation, knee extension and lower leg drive, hip and trunk rotation, and hand/wrist flexion. Coaches should endorse these indications to promote technical proficiency.[27-30]

- The capacity to achieve higher ball impact locations has a significant correlation with swing velocity. Both the backhand (BH) and arm length (AL) play a critical role for tennis players in this regard. However, additional parameters that can be improved by training, such as altering body composition to have a higher proportion of lean body mass, may have a favourable effect on stroke volume. This makes the idea of goal-oriented training options quite interesting. However, it is important to consider the specific requirements of each person.
- Force-time curve parameters are observed in both sexes, and especially as age and level increase (MIS, RFD, and IMP) surrounding the shoulder joint are good indicators of SV. Coaches are recommended to incorporate strength training programmes that cover the full spectrum of the load-velocity curve. In order to achieve the desired outcomes, it is vital to carefully focus on the maximum velocity intention during programme execution.
- Consistently engaging in high-intensity matches can potentially decrease accuracy and skill level. Experienced and skilled players seem to be able to maintain their serve velocity (SV) by relying on other aspects such as range of motion (ROM), technique, or tactical choices that contribute to executing a perfect serve. However, repeated competitive matches or intensive match play will almost likely have a negative impact on SV. In order to restore initial strength and power levels, it is advisable to promptly employ efficient recovery methods, especially when dealing with younger and less experienced individuals who may be more susceptible to negative impacts.
- The complexity of tennis serves exemplifies the unique nature of the Kinetic Chain concept[37] this is evident in the majority of games that involve the act of throwing (such as baseball and cricket) and kicking (such as football and Australian Rules Football).[38,39] When an activity becomes more efficient, fluent, rhythmic, and coordinated, the ability to produce voluntary force becomes more apparent.[40] Executing the tennis serve talent effectively requires careful attention to technical and temporal factors. This skill engages the entire body, from the lower to the upper body.[41] Research has shown that motor skills developed from infancy have a considerable impact on physical fitness characteristics in maturity.[41] Motor competence is dependent on motor coordination, which is the capacity to effectively synchronise movements of different body parts when the body is in motion. It involves rapid physical movement while executing a variety of crucial skills. Tennis players are able to consistently perform strokes by effectively coordinating their body components in both spatial and temporal dimensions, allowing them to accurately manipulate their movements.[41,42] The transitions of the serving motion are illustrated in Figure 1 below. Younger players will gradually realise that the serve is a highly challenging stroke to execute due to the need for precise coordination between different muscle groups, which puts a significant load on the neuromuscular system.[18,42]

Figure 1: Changes in the Serving Motion (*A = Start phase, B = Loading/Cocking Phase, C = Acceleration/ Ball Contact Phase, D = Follow-Through/Deceleration Phase). https://www.researchgate.net/publication/234084703_Upper_limb_joint_kinetic_analysis_during_tennis_serve_Assessment_of_competitive_level_on_efficiency_and_injury_risks.*

There has been limited research conducted on the fitness qualities of elite tennis players. Ulbricht and his colleagues[43] outlined and compared the performance characteristics of U12, U14, and U16 highly skilled male and female junior tennis players who excel at both regional and national levels. As anticipated, athletes at the national level demonstrated superior performance in all fitness assessments across all age groups. Ulbricht's study provides valuable guidance for strength and conditioning coaches in assessing serving velocity among elite junior athletes. The following results from the study can be utilised for the specific objectives of this paper (table 3).

Table 3: Performance Traits of National Tennis Athletes Competing at the u16 Top Junior Level for Men and Women.

	Male	Female
CMJ(cm)	~ 35	~30
Grip strength (kg)	~40	~34
Overhead medicine Ball Throw (cm)	~970	~750
Serving Velocity(km/h)	~170	~150

Out of the ten studies that were analysed, only two revealed an improvement in serving speed. Smart implemented a two-week split training regimen that focused specifically on strengthening the core[44] on intermediate level tennis participants (~3.5 years of experience). During the initial four-week period, the workouts primarily emphasised endurance and stability with exercises such as planks and sit-ups. In the subsequent four-week period, the focus shifted to exercises like medicine ball throws and back bridges. Other biometric tests (e.g., 5RM bench press [r = 0.75] and vertical jump [r = 0.64]) demonstrated strong correlations with serving velocity, but core endurance demonstrated a negative correlation (r = <0.35), suggesting that core-training should be combined with upper- and lower-body strength and power exercises. A PAP-style training program was run by 53-year-old Terraza-Rebollo for competitive teenage tennis players (>4 years of experience). The idea behind this program was to increase serving velocity by executing 80% 1RM Bench Press and/or 80% 1RM Half Squats (3x3). The right protocol was followed in terms of the amount of time that passed before testing (0-, 5-, 10-, and 15-min after exercise), however, there was no discernible distinction observed. The study highlighted the restrictions by emphasising the need for targeted training. It suggested that future studies should incorporate power-focused workouts including as medicine ball tosses, squats, and trap bar leaps. These activities are more effective in replicating the movement speed observed in the serve.

Lower Body Contribution

Enhancing serving performance can be accomplished by providing a consistent yet adaptable foundation of support throughout the serving action. Considering that the kinetic-chain principle originates in the lower body, specifically the ankles, knees, and hips, in this case,[11] Athletes must allocate a same amount of time and effort to developing the force and power generation of their lower extremities as they do to their upper extremities. The capacity to increase the absolute velocity of the ball is mostly derived from lower body mechanics rather than upper body mechanics, contrary to the belief of many amateur tennis players.[45] Athletes lower their centre of mass (knee flexion) in order to prepare for jumping up (Figure 2B) and making contact with the ball while it is in mid-flight. This action allows them to release a significant quantity of elastic energy through the stretch-shortening cycle (SSC). This effectively increases the gap between the fixed net's height and the height at which the ball makes contact.[11] This element, which is defined as the body's vertical lift (54) (Figure 2C), Enables a greater degree of ball projection at a sharper angle, enabling athletes to strike the ball with more force and boosting the likelihood of successful serves within the designated service box.[11] Girard *et al*.[45] discovered that there was a noticeable decrease in the maximum vertical ground reaction force (~0.75 Fz) and absolute ball speed (~25 km/h) By restricting the range of motion of the knee joint, specifically in terms of flexion and extension. Consequently, the restricted mobility of the knees not only impacted the capacity to generate elastic energy for rapid knee extension, but also hindered the trunk's ability to rotate and flex sideways (Figure 2B). Previous estimates suggest that the lower body contributes to around 50% of the creation of kinetic energy force in elite athletes.[46] This underscores the need of meticulously crafted strength and conditioning (S&C) programmes.

Upper Body Contribution

Extensive research has been conducted on the mechanics of the upper body and the involvement of muscles in relation to the tennis serve, specifically focusing on the internal (IR) and external rotation (ER) of the shoulder.[3,4,47-53] This is logical because the fundamental principle of modern tennis strategy is to optimise the speed at which the racquet head moves during the serve, forehand, and backhand in order to generate greater propulsion velocities.[1] However, these movements also generate significant force and torque, which are the main factors responsible for the majority of shoulder injuries.[53] Cohen's demonstration reveals a common imbalance in the strength of internal and external shoulder rotations, with the internal rotation being more developed than the outward rotation (4:3, respectively).[1] This is explained by two factors: (a) the repetitious nature of the game, where the serve and forehand are the two most often used strokes;[54] and (b) the large eccentric pressures produced in the serving arm, which enable the SSC to produce more concentric force.[53] When paired with shoulder flexion,[47] a robust positive connection has been observed between shoulder IR and serving speed ($r = 0.67$), accounting for approximately 55% of the variance. Similarly, ER and max serve speed were shown to be positively correlated ($r = 0.63$).[12] This emphasizes how crucial it is to improve the shoulder rotator cuff muscles' agonist-antagonist interaction in order to reduce the chance of injury.[40] Therabands can be used to perform both internal and exterior rotator cuff exercises to achieve this. Incorporating shoulder IR and ER movements into the dynamic warm-up is suitable. These exercises can be carried out with the elbows at 90˚ or the shoulder flexed and abducted to 90˚. Furthermore, the eccentric phase of the action can be emphasized as a way to sufficiently prepare the athlete for both their strength and power training session and their on-court technical training.[1,12,41,52-56]

When it comes to studying the biomechanics of tennis serves, inertial measurement equipment may provide a substantial three-dimensional measuring system. In order to determine if it would be feasible to use an inertial measurement unit to record kinetic and kinematic data during a tennis serve, this case study set out to do just that. Wearing the inertial measurement gadget known as the Xsens MVN suit, two very talented and uninjured tennis players competed. Striking a 1 m2 target area at the edge of the service box on an indoor tennis court surface, they hit two sets of five flat "first" serves. Between the loading and end stages, there was no difference in the development of the joint angles (shoulder, elbow, knee), centre of mass displacements, and rotations between the male and female participants, with the exception of the rotation of the centre of gravity during the loading stage. There were consistent changes in the distribution of forces on the joints (mid-trunk, upper-trunk, shoulder, elbow, and wrist) and the contributions of the various body segments (pelvis linear, pelvis rotation, trunk, shoulder, elbow, and wrist) throughout the ball contact stage. Overall, lower, and higher energy contributions were similar for both players from the loading to completion phases, demonstrating acceptable coefficient of variances across the two trials. For the purpose of gathering biomechanical data during on-court tennis serves, this inertial measurement gadget is ideal. In the future, tennis players and coaches may be able to use the data to get personalised feedback that will aid in their motor development and serve efficiency.

Citations made by Franck Brocherie et al. During the loading, ball contact, and completion phases of the serve, male tennis players' joint angles, centre of mass displacement (in italics), and rotation are shown in the top panel (A). Panel B, located at the bottom, displays the same dimensions for female tennis players. At the second the ball makes contact, the racquet's speed is also clearly visible (Figure 2).

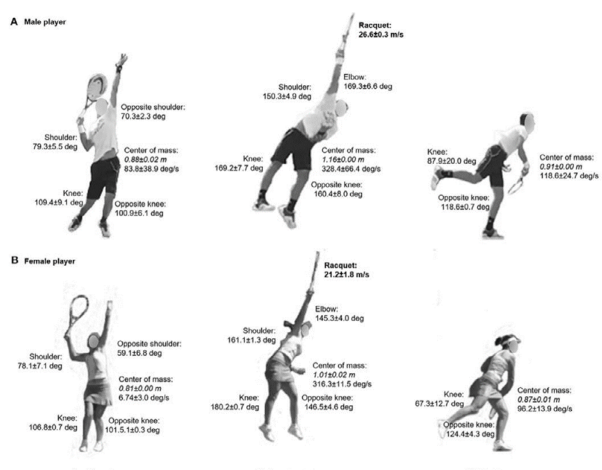

Figure 2: M ass Displacement and Rotation During Loading, Ball Contact (*Cited from: Brocherie F and Dinu D (2022) Biomechanical estimation of tennis serve using inertial sensors: A case study. Front. Sports Act. Living 4:962941. doi: 10.3389/fspor.2022.962941*)

Made in Richardson, TX, USA, the Stalker Professional Sports Radar was the radar gun that was used to assess the serve velocity. All of this method followed the recommendations made in the previous references.[5,9] To summarise, the radar gun was positioned three metres behind the server, with an aim towards the centre of the baseline. It was also pointed towards the court's middle and at a height of around 2.2 metres, which is the ball's predicted impact point. A unique and regulated warm-up regimen was developed for every participant. The warmup consisted of 5 minutes of mobility exercises for the upper body, followed by two sets of eight repetitions of first and second serves, respectively. Players then proceeded to serve three sets at maximum speed. The court's deuce side was the location for every serve. All racquets and balls used in the test were brand new Babolat Gold balls sent in from Lyon, France. The servers have to touch down within a one-meter radius of the main service line for data collection to be possible. In order to facilitate statistical analysis in the future, the fastest serve speed was used. Results showing intraclass correlation coefficients (ICCs) between 0.90 and 0.98 indicate that the test is reliable over days.

To make sure their serves were pinpoint accurate, each participant served five more times utilising their best flat or slice spin, aiming for the "advantage" service box. Figure 2 shows the scoring method that was used to determine the serve accuracy. The frequency of balls falling within a defined target area was given a score of 3, 2, 1. A score of zero was assigned to shots that failed to land inside the specified target zones, also called errors. Within the intersection of the service line and the centre line was the specified serving area measuring 1.8 m x 1.8 m. From the deuce court, players were instructed to serve their first serves flat and along the centre line, or T. These methods have been tested on male junior tennis players before and are known to be accurate predictors of serve accuracy (Figure 3).

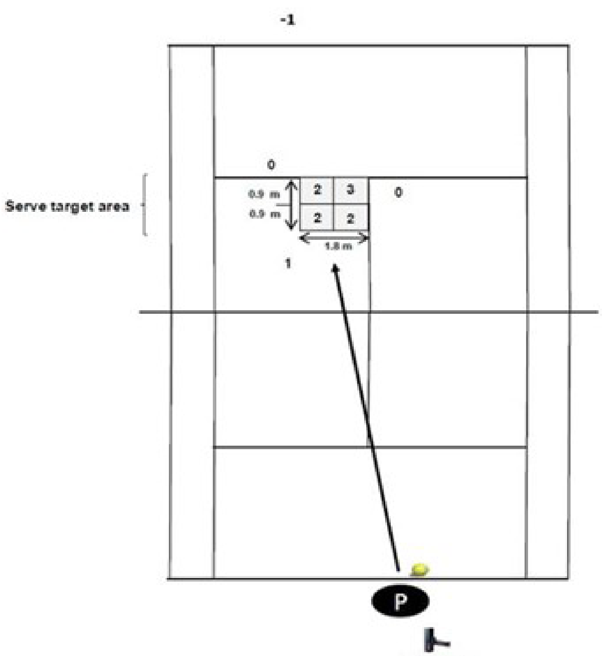

Figure 3: Illustration of the Service Performance Evaluation and Goal Area Measurements (*cited Fernandez-Fernandez, J.; Moya-Ramon, M.; Santos-Rosa, F.J.; Gantois, P.; Nakamura, F.Y.; Sanz-Rivas, D.; Granacher, U. Within-Session Sequence of the Tennis Serve Training in Youth Elite Players. Int. J. Environ. Res. Public Health 2021, 18, 244. https://doi.org/10.3390/ijerph18010244*)

Conclusion and Future Implementations

Efficient maintenance unquestionably necessitates a considerable degree of technical expertise. Coaching techniques and publications have provided specific serving models that aim to raise velocity production and improve mobility in order to achieve this goal. Nevertheless, the technological prerequisites may vary depending on the specific model employed and the current phase of the event. However, it seems that the primary elements influencing the speed of the racquet and ball are the force generated by the lower legs, the rotation of the hips and trunk, the extension of the upper arm, and the internal rotation of the body. Regarding the inclination of SV towards anthropometric traits, it appears that faster serves are enhanced by a higher impact point achieved by BH or AL, as well as a bigger body mass lean. The relationship between upper body power and strength levels, such as maximum isometric strength (MIS) and rate of force development (RFD), in the specific joint locations involved in the serve kinetic chain has been consistently linked to faster serve times in the past. Therefore, it is recommended to incorporate the development of these attributes as part of a programme aimed at improving serve velocity. Extended or repeated competitive stress can potentially damage the essential physical components mentioned earlier and negatively affect SV, especially in less experienced younger players. The tennis serve is undeniably one of the most challenging strokes to execute proficiently due to its demanding requirements of precise timing and intersegmental synchronisation. Professional athletes effectively utilise the kinetic-chain theory by employing their entire body to exert force on the ball. While the dominant arm is responsible for throwing the ball, the lower body and trunk areas contribute the majority of the force and strength, highlighting the interconnection between different body parts. Prior to commencing any strength and/or power training, it is crucial to first focus on proper technique. This is because the latter form of training has a significant role in enhancing joint stability, especially during the deceleration/follow-through phase. The difficulty of the tennis serve stems from the coordination of muscles and joints. Insufficient flexibility can hinder muscle activation and lead to joint constraints that impact serve performance. Studies have demonstrated a substantial correlation between shoulder internal rotation flexibility and the ability to generate speed.[57,58] The execution of a tennis serve necessitates the management of various physical elements, while also relying on a coordinated sequence of movements in order to generate a powerful and fast serve.[58] Based on this, we deduce the significance of coordination when serving.

Studies have demonstrated that performing uncomplicated shoulder internal rotation (IR) and external rotation (ER) exercises using resistance bands and light free weights can enhance serving velocity by around 5%. Nevertheless, to enhance athletic performance, it is crucial to consider the principle of training specialisation. The tennis serve is characterised by its unilateral aspect, and it seems that unilateral resistance training is more advantageous for improving tennis serve performance. Furthermore, medicine balls and cable pulley systems have been widely employed to imitate FH (forehand) and BH (backhand) strokes due to their ability to facilitate swift, rapid motions in several directions against a resistance that is typically greater than the weight of the racquet.

References

1. Kovacs MS, Ellenbecker TS. A Performance Evaluation of the Tennis Serve: Implications for Strength, Speed, Power, and Flexibility Training. Strength Cond J. 2011; 33(4): 22-30. doi: https://doi.org/10.1519/SSC.0b013e318225d59a.
2. Antúnez RM, Hernández FJ, García JP, Vaíllo RR, Arroyo JS. Relationship between motor variability, accuracy, and ball speed in the tennis serve. J Hum Kinet. 2012; 33: 45-53. doi: https://doi.org/10.2478/v10078-012-0043-3.
3. Kovacs M, Ellenbecker T. An 8-stage model for evaluating the tennis serve: implications for performance enhancement and injury prevention. Sports Health. 2011; 3(6): 504-13. doi: https://doi.org/10.1177/1941738111414175.
4. Gelen E, Dede M, Bingul BM, Bulgan C, Aydin M. Acute Effects of Static Stretching, Dynamic Exercises, and High Volume Upper Extremity Plyometric Activity on Tennis Serve Performance. J Sports Sci Med. 2012; 11(4): 600-5. Available from: https://www.jssm.org/hf.php?id=jssm-11-600.xml.
5. Fleisig G, Nicholls R, Elliott B, Escamilla R. Kinematics used by world class tennis players to produce high-velocity serves. Sports Biomech. 2003; 2(1): 51-64. doi: https://doi.org/10.1080/14763140308522807.
6. Fitzpatrick A, Stone JA, Choppin S, Kelley J. Important performance characteristics in elite clay and grass court tennis match-play. Int J Perform Anal Sport. 2019; 19(6): 942-52. doi: https://doi.org/10.1080/24748668.2019.1685804.
7. Sánchez-Pay A, Torres-Luque G, Fernandéz-Garcia ÁI, Sanz-Rivas D, Palao JM. Differences in game statistics between winning and losing for male wheelchair tennis players in Paralympics Games. Mot. Rev. Educ. Física. 2017; 23 doi: https:doi.org/10.1590/s1980-6574201700030011.
8. Kovalchik SA, Reid M. Comparing Matchplay Characteristics and Physical Demands of Junior and Professional Tennis Athletes in the Era of Big Data. J Sports Sci Med. 2017; 16(4): 489-97. Available from: https://www.jssm.org/hf.php?id=jssm-16-489.xml.
9. Reid M, Morgan S, Whiteside D. Matchplay Characteristics of Grand Slam Tennis: Implications for Training and Conditioning. J Sports Sci. 2016; 34(19): 1791-98. doi: https://doi.org/10.1080/02640414.2016.1139161.
10. Dossena F, Rossi C, Torre AL, Bonato M. The role of lower limbs during tennis serve. J Sports Med Phys Fitness. 2018; 58(3): 210-218. doi: https://doi.org/10.23736/S0022-4707.16.06685-8.
11. Bonato M, Maggioni MA, Rossi C, Rampichini S, La Torre A, Merati G. Relationship Between Anthropometric or Functional Characteristics and Maximal Serve Velocity in Professional Tennis Players. J Sports Med Phys Fitness. 2015; 55(10): 1157-65. Available from: https://www.minervamedica.it/en/journals/sports-med-physical-fitness/article.php?cod=R40Y2015N10A1157.
12. Hayes MJ, Spits DR, Watts DG, Kelly VG. Relationship Between Tennis Serve Velocity and Select Performance Measures. J Strength Cond Res. 2021; 35(1): 190-97. doi: https://doi.org/10.1519/jsc.0000000000002440.
13. Vaverka F, Cernosek M. Association between body height and serve speed in elite tennis players. Sports Biomech. 2013; 12(1): 30-37. doi: https://doi.org/10.1080/14763141.2012.670664.
14. Ikeda Y, Kijima K, Kawabata K, Fuchimoto T, Ito A. Relationship between side medicine-ball throw performance and physical ability for male and female athletes. Eur. J. Appl. Physiol. 2007; 99: 47-55. doi: https://doi.org/10.1007/s00421-006-0316-4.
15. Wong F, Keung JH, Lau NM, Ng DK, Chung JW, Chow DH. Effects of body mass index and full body kinematics on tennis serve speed. J Hum Kinet. 2014; 40: 21-28. doi: https://doi.org/10.2478/hukin-2014-0003.
16. Colomar J, Baiget E, Corbi F. Influence of Strength, Power, and Muscular Stiffness on Stroke Velocity in Junior Tennis Players. Front Physiol. 2020; 11: 196. doi: https://doi.org/10.3389/fphys.2020.00196.
17. Kraemer WJ, Ratamess N, Fry AC, et al. Influence of resistance training volume and periodization on physiological and performance adaptations in collegiate women tennis players. Am J Sports Med. 2000; 28(5): 626-33. doi: https://doi.org/10.1177/03635465000280050201.
18. Kraemer WJ, Hakkinen K, Triplett-Mcbride NT, et al. Physiological changes with periodized resistance training in women tennis players. Med Sci Sports Exerc. 2003; 35(1): 157-68. doi: https://doi.org/10.1097/00005768-200301000-00024.
19. Gallo-Salazar C, Del Coso J, Barbado D, et al. Impact of a competition with two consecutive matches in a day on physical performance in young tennis players. Appl Physiol Nutr Metab. 2017; 42(7): 750-56. doi: https://doi.org/10.1139/apnm-2016-0540.
20. Lertwonghattakul, T., Sriramatr, S., & Rachnavy, P. Analysis of Kinetic Chain Mechanism Affecting Energy Flow in Kick Topspin Tennis Serve in Elite and Amateur Tennis Players. Annals of Applied Sport Science, 2023 11(2). https://doi.org/10.52547/aassjournal.1133.
21. Girard O, Lattier G, Micallef JP, Millet GP. Changes in exercise characteristics, maximal voluntary contraction, and explosive strength during prolonged tennis playing. Br J Sports Med. 2006; 40(6): 521-26. doi: https://doi.org/10.1136/bjsm.2005.023754.
22. Mendez-Villanueva A, Fernandez-Fernandez J, Bishop D. Exercise-induced homeostatic perturbations provoked by singles tennis match play with reference to development of fatigue. Br J Sports Med. 2007; 41(11): 717-22. doi: https://doi.org/10.1136/bjsm.2007.037259.

23. Moreno-Pérez V, López-Samanes Á, Domínguez R, et al. Acute effects of a single tennis match on passive shoulder rotation range of motion, isometric strength and serve speed in professional tennis players. PLoS One. 2019; 14(4): e0215015. doi: https://doi.org/10.1371/journal.pone.0215015.
24. Elliott B. Biomechanics and Tennis. Br J Sports Med. 2006; 40(5): 392-96. doi: https://doi.org/10.1136/bjsm.2005.023150.
25. Delgado-García G, Vanrenterghem J, Muñoz-García A, Molina-Molina A, Soto-Hermoso VM. Does stroke performance in amateur tennis players depend on functional power generating capacity? J Sports Med Phys Fitness. 2019; 59(5): 103. doi: https://doi.org/10.23736/S0022-4707.18.08518-3
26. Söğüt M. Ball Speed during the Tennis Serve in Relation to Skill Level and Body Height. Pamukkale Journal of Sport Sciences. 2016; 7(2): 13.05.2016. Available from: https://dergipark.org.tr/en/pub/psbd/issue/20590/219435.
27. Palmer K, Jones D, Morgan C, Zeppieri G, Jr. Relationship Between Range of Motion, Strength, Motor Control, Power, and the Tennis Serve in Competitive-Level Tennis Players: A Pilot Study. Sports Health. 2018; 10(5): 462-67. doi: https://doi.org/10.1177/1941738118785348.
28. Söğüt M. Physical and morphological characteristics of Turkish national adolescent tennis players and their association with serve speed. Spor Hekimligi Dergisi. 2018; 54(1): 64–70. doi: https://doi.org/10.5152/tjsm.2019.117.
29. Maquirriain J, Baglione R. Cardey M. Male professional tennis players maintain constant serve speed and accuracy over long matches on grass courts. Eur J Sport Sci. 2016; 16(7): 845-849. doi: https://doi.org/10.1080/17461391.2016.1156163
30. Davey PR, Thorpe RD, Williams C. Fatigue Decreases Skilled Tennis Performance. J Sports Sci. 2002; 20(4): 311-18. doi: https://doi.org/10.1080/026404102753576080.
31. Bonato M, Maggioni MA, Rossi C, Rampichini S, La Torre A, Merati G. Relationship between anthropometric or functional characteristics and maximal serve velocity in professional tennis players. J Sports Med Phys Fitness. 2015; 55: 1157-1165.
32. Rota S, Morel B, Saboul D, Rogowski I, Hautier C. Influence of Fatigue on Upper Limb Muscle Activity and Performance in Tennis. J Electromyogr Kinesiol. 2014; 24(1): 90-97. doi: https://doi.org/10.1016/j.jelekin.2013.10.007.
33. Gescheit DT, Cormack SJ, Reid M, Duffield R. Consecutive days of prolonged tennis match play: performance, physical, and perceptual responses in trained players. Int J Sports Physiol Perform. 2015; 10(7): 913-20. doi: https://doi.org/10.1123/ijspp.2014-0329.
34. Maquirriain J, Baglione R, Cardey M. Male professional tennis players maintain constant serve speed and accuracy over long matches on grass courts. Eur J Sport Sci. 2016; 16(7): 845-49. doi: https://doi.org/10.1080/17461391.2016.1156163.
35. Martin C, Bideau B, Delamarche P, Kulpa R. Influence of a Prolonged Tennis Match Play on Serve Biomechanics. PLoS One. 2016; 11(8): e0159979. doi: https://doi.org/10.1371/journal.pone.0159979.
36. Yanci J, Granados C, Otero M, Badiola A, Olasagasti J, Bidaurrazaga-Letona I, Iturricastillo A, Gil SM. Sprint, agility, strength and endurance capacity in wheelchair basketball players. Biol. Sport. 2015; 32: 71-78. doi: https://doi.org/10.5604/20831862.1127285.
37. Knudson D, Elliott B. Biomechanics of Tennis Strokes. In: Hung GK, Pallis JM, Eds. Biomedical Engineering Principles in Sports. Springer; 2004:153-81. doi: https://doi.org/10.1007/978-1-4419-8887-4_7.
38. Fleisig GS. Biomechanics of Overhand Throwing: Implications for Injury and Performance. In: 1 of 1-Conference of Science, Medicine & Coaching in Cricket 2010. Cricket Australia; 2010:17-20. Available from: https://www.researchgate.net/publication/48381254.
39. Lust KR, Sandrey MA, Bulger SM, Wilder N. The effects of 6-week training programs on throwing accuracy, proprioception, and core endurance in baseball. J Sport Rehabil. 2009; 18(3): 407-26. doi: https://doi.org/10.1123/jsr.18.3.407.
40. Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power: Part 1--biological basis of maximal power production. Sports Med. 2011; 41(1): 17-38. doi: https://doi.org/10.2165/11537690-000000000-00000.
41. Butler BN, Aicher TJ, & Wieber B. Junior College or the NCAA: The Case of a U.S. Women's Tennis Team with No U.S. Players. Journal of Global Sport Management, 2020, 5(1), 83-101. doi: https://doi.org/10.1080/24704067.2019.1670089.
42. Girard O, Lattier G, Maffiuletti NA, Micallef JP, Millet GP. Neuromuscular Fatigue During a Prolonged Intermittent Exercise: Application to Tennis. J Electromyogr Kinesiol. 2008; 18(6): 1038-46. doi: https://doi.org/10.1016/j.jelekin.2007.05.005.
43. Mendez-Villanueva A, Fernandez-Fernandez J, Bishop D. Exercise-induced homeostatic perturbations provoked by singles tennis match play with reference to development of fatigue. Br J Sports Med. 2007; 41(11): 717-722. doi: https://doi.org/10.1136/bjsm.2007.037259.
44. Smart J, McCurdy K, Miller B, Pankey R. The Effect of Core Training on Tennis Serve Velocity. The Journal of Strength & Conditioning Research. 2011; 25: S103-S04. doi: https://doi.org/10.1097/01.JSC.0000395743.57804.e8.
45. Gallo-Salazar C, Del Coso J, Barbado D, et al. Impact of a competition with two consecutive matches in a day on physical performance in young tennis players. Appl Physiol Nutr Metab. 2017; 42(7): 750-756. doi: https://doi.org/10.1139/apnm-2016-0540.
46. Kibler WB. The 4000-watt tennis player: Power development for tennis. Med Sci Tennis. 2009; 14(1): 5-8. Available from: https://sponet.fi/Record/4017273.
47. Sprigings E, Marshall R, Elliott B, Jennings L. A three dimensional kinematic method for determining the effectiveness of arm segment rotations in producing racket-head speed. J Biomech. 1994; 27: 245-254.

48. Roetert EP, Ellenbecker TS, Chu DA, Bugg BS. Tennis-specific shoulder and trunk strength training. Strength Cond J. 1997; 19(3): 31-43. doi: https://doi.org/10.1519/1073-6840(1997)019<0031:TSSATS>2.3.CO;2.
49. Cohen DB, Mont MA, Campbell KR, Vogelstein BN, Loewy JW. Upper extremity physical factors affecting tennis serve velocity. Am J Sports Med. 1994; 22(6): 746-50. doi: https://doi.org/10.1177/036354659402200604.
50. Malliou P, Papadimitriou D, Malliou V, et al. The Effect of Strength Training on Tennis Service Performance of Junior Tennis Players. Exercise and Quality of Life. 2011; 3(1): 31-40. Available from: https://eqoljournal.com/wp-content/uploads/2017/06/EQOL_3_1_d.pdf.
51. Mont MA, Cohen DB, Campbell KR, Gravare K, Mathur SK. Isokinetic concentric versus eccentric training of shoulder rotators with functional evaluation of performance enhancement in elite tennis players. Am J Sports Med. 1994; 22(4): 513-17. doi: https://doi.org/10.1177/036354659402200413.
52. Niederbracht Y, Shim AL, Sloniger MA, Paternostro-Bayles M, Short TH. Effects of a shoulder injury prevention strength training program on eccentric external rotator muscle strength and glenohumeral joint imbalance in female overhead activity athletes. J Strength Cond Res. 2008; 22(1): 140-45. doi: https://doi.org/10.1519/jsc.0b013e31815f5634.
53. Treiber FA, Lott J, Duncan J, Slavens G, Davis H. Effects of Theraband and lightweight dumbbell training on shoulder rotation torque and serve performance in college tennis players. Am J Sports Med. 1998; 26(4): 510-15. doi: https://doi.org/10.1177/03635465980260040601.
54. Fernandez-Fernandez J, Ellenbecker T, Sanz-Rivas D, Ulbricht A, Ferrautia A. Effects of A 6-Week Junior Tennis Conditioning Program on Service Velocity. J Sports Sci Med. 2013; 12(2): 232-39. Available from: https://www.jssm.org/hf.php?id=jssm-12-232.xml.
55. Ochi S, Campbell MJ. The progressive physical development of a high-performance tennis player. Strength Cond J. 2009; 31(4): 59-68. doi: https://doi.org/10.1519/SSC.0b013e3181af8053.
56. Behringer M, Neuerburg S, Matthews M, Mester J. Effects of two different resistance-training programs on mean tennis-serve velocity in adolescents. Pediatr Exerc Sci. 2013; 25(3): 370-84. doi: https://doi.org/10.1123/pes.25.3.370.
57. Koçyiğit B, Akin S, Şentürk A. The Effects of Combined Trainings on Tennis Serve Speed in Tennis Players. Turkiye Klinikleri J Sports Sci. 2020; 12(2): 137-46. doi: https://doi.org/10.5336/sportsci.2019-70168.
58. Söğüt M. A Comparison of Serve Speed and Motor Coordination between Elite and Club Level Tennis Players. J Hum Kinet. 2017; 55: 171-76. doi: https://doi.org/10.1515/hukin-2017-0015.