Relationships Between Force-Time Curve Variables and Tennis Serve Performance in Competitive Tennis Players

Loïc Fourel, Pierre Touzard, Maxime Fadier, Louis Arles, Kaies Deghaies, Simon Ozan, Caroline Martin

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Running head: Force time curve variables and tennis serve performance

Laboratory: Movement, Sport Science (M2S) Laboratory

*Authors: Loic Fourel[1], Pierre Touzard[1], Maxime Fadier[1], Louis Arles[1], Kaies Deghaies[1 2], Simon Ozan[1], Caroline Martin[1]**

Institutions:

[1]M2S Laboratory, Rennes 2 University, École Normale Supérieure de Rennes, Campus de Ker Lann, Avenue Robert Schuman, 35170 Bruz, France

[2]Research and Development Department, Volodalen, 39134 Chavéria, France

* Corresponding author:

Caroline Martin

M2S Laboratory, Rennes 2 University, École Normale Supérieure de Rennes, Campus de Ker Lann, Avenue Robert Schuman, 35170 Bruz, France

02 90 09 15 80

caroline.martin@univ-rennes2.fr

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ABSTRACT

Practitioners consider the role of the legs in the game of tennis as fundamental to achieve high performance. But, the exact link between leg actions and high speed and accurate serves still lacks understanding. Here, we investigate the correlation between force-time curve variables during serve leg drive and serve performance indicators. Thirty-six competitive players performed fast serves, on two force plates, to measure ground reaction forces. Correlation coefficients describe the relationships between maximal racket head velocity, impact height and force-time curve variables. Among all the variables tested, the elapsed time between the instants of maximal vertical and maximal anteroposterior ground reaction forces ($r=-0.519$, $p<0.001$) and the elapsed time between the instant of maximal anteroposterior ground reaction force and ball impact ($r=-0.522$, $p<0.001$) are the best predictors of maximal racket velocity. Maximal racket head velocity is not significantly correlated with the mean or maximal vertical ground reaction forces, nor with the mean or maximum rate of vertical force development. The best predictor for impact height is the relative net vertical impulse during the concentric phase ($r=0.772$, $p<0.001$). This work contributes to a better understanding of the mechanical demands of tennis serve motion and gives guidelines to improve players preparation and performance. Trainers should encourage their players to better synchronize their upward and forward pushing action during the serve to increase maximal racket head velocity. Players should also aim to improve their relative net vertical impulse to increase impact height via strength training and technical instructions.

Key-words: impulse, power, biomechanics, ground reaction forces, racket velocity, impact height

INTRODUCTION

In competitive tennis, the serve is commonly described as the most important stroke (21). For high-level players, the ability to produce the highest maximal racket velocity (V_R^{max}) to reach high ball speed at impact is a key element of successful play. The ball impact height (h_{impact}) is also considered as a crucial factor affecting tennis serve performance, since the higher the impact, the greater the margin for error at the net. According to Brody (2006), only a small extra height above the ground is needed to increase the window of acceptance for the serve, that is the chance that it will go in (5). The capacity of reaching higher h_{impact} also correlates strongly with ball speed (46).

The tennis serve motion is characterized by forceful flexion and extension of both legs that generate ground reaction forces (GRF) and initiate the proximodistal kinetic chain allowing the transfer of energy and linear and angular momentum from the ground to the racket (31,34). Consequently, the interaction between the body and the ground through the leg drive is considered fundamental to good serve mechanics (16,17). Although numerous studies have investigated the relationships between upper body kinematics/kinetics and racket velocity or ball speed (31,33,34,42), not much research has focused on the effects of the lower body ground reaction forces (GRF) on serve performance parameters (16,17).

Previous studies instead described the shape of GRF curves during the serve (13,16), measured maximal vertical and anteroposterior values (F_z^{max} and F_y^{max}, respectively) (44,45), and compared these values between foot-up and foot-back serve techniques (2,13). During the serve, the largest maximal GRF were systematically recorded in the vertical direction (F_z^{max} = 1.68 - 2.12 bodyweight - BW: body mass x 9.81 m.s^{-2}) while F_y^{max} approximated 0.2 BW in the forward direction and lateral GRF (F_x) were negligible. A few studies analyzed the relationship between serve performance parameters (serve speed and h_{impact}) and the vertical GRF created by both legs, but with conflicting results. For example, Girard et al. (2007) reported that increases in F_z^{max} were significantly correlated with increases in serve speed for expert players only (17). However, in another study, the same authors showed no significant relationship between F_z^{max} and ball speed in beginners, intermediate and elite tennis players (16) but only obtained a positive significant correlation between F_z^{max} and h_{impact} in elite players. During a three-hour-long tennis match between expert players, Martin et al. (2016) found no association between F_z^{max}, ball speed and h_{impact} since F_z^{max} remained constant over the entire duration of the match while ball speed and h_{impact} significantly decreased (32). All these studies focused only on F_z^{max} as an independent variable.

The relationship between anteroposterior GRF and serve performance has never been investigated in tennis. Yet, in other sports literature, countermovement jumps analysis and/or reports on overhead sport motions (baseball pitch, volleyball spike or handball throwing) showed that much more valuable information can be extracted from the vertical and anteroposterior force-time curves such as time variables (timing of F_z^{max} and F_y^{max}), force variables (F_z^{mean}, F_y^{mean}, F_z^{max} and F_y^{max}), and variables linking both components (the mean and maximal rates of force development (RFD_z, RFD_z^{max} respectively), the mean impulse, the maximal power or the maximal center of mass (CoM) velocity) (22,25,39). For example, relative net vertical concentric impulse ($I_z^{net}|_C$), rate of vertical force development and maximal rate of vertical force development are better key performance indicators for dynamic motions (e.g., squat and countermovement jumps) than F_z^{max} (14,25,35,40). This strongly suggests that only taking F_z^{max} into account would not provide enough relevant information about the leg drive performance during the tennis serve. Instead, we expect the mechanical impulse that acts on the body to be especially relevant during the serve as players need to increase and decrease the rotations of their joints and segments very quickly to reach the highest ball speed (34).

It is highly probable that restricting the relationship between GRF and serve performance solely to F_z^{max} contributed to the lack of understanding about the primary role of the leg drive reported by scientists and practitioners (7,26). As far as scientists are concerned, on the one hand, several authors grant the lower body a main coordinating role in the service movement, providing a stable proximal base for distal mobility (7), while, on the other hand, other studies prefer to see the rapid vertical extension of the lower limbs as a primary contributor to racket speed and ball velocity (16,17). According to Elliott and Colette (1993), it is primordial to understand that power is not only developed by the trunk and the serving arm. The primary source of power is instead generated from the ground reaction forces (11). Within the kinetic chain, the legs are often considered as the start of the energy production from the lower limbs to the upper limbs (16). As far as practitioners are concerned, Lester et al. (2023) recently highlighted that tennis coaches are convinced that the contribution of the lower limbs in tennis performance can become an important framework for designing physical training programs but, at the same time, they regret that their understanding of this mechanism is still extremely limited (26). Understanding how both vertical and anteroposterior GRF components and their timing influence serve performance parameters could therefore provide important scientific and practical insight about the role of the lower limbs in achieving a powerful and accurate serve.

The purpose of this study is to determine how the force-time curve variables during the leg drive correlate to serve performance parameters in competitive tennis players. We hypothesize that the usual variables extracted from the vertical force-time curve (F_z^{max}, RFD_z, RFD_z^{max}) are not relevant to predict maximum racket speed and impact height whereas temporal ground reaction force variables and relative net vertical impulse are. The results from this study provide good insights for practitioners to design specific training programs and develop appropriate strategies to improve performance in competitive tennis players.

METHODS

Experimental approach to the problem

A cross-sectional study was performed to examine the correlations between the GRF characteristics during the leg drive and serve performance indicators (V_R^{max} and h_{impact}) for competitive tennis players.

Subjects

Thirty-six competitive tennis players (twenty-five male, age: 23.8 ± 7.5 years, range: from 15 to 42 years, height: 1.84 ± 0.07 m, mass: 78.4 ± 6.5 kg, Universal Tennis Rating: 10.9 ± 3.1, range from 5.9 to 15.5; and eleven females, age: 21.9 ± 8.6 years, range: from 15 to 44 years, height: 1.68 ± 0.06 m, mass: 65.4 ± 6.7 kg, Universal Tennis Rating: 9.5 ± 2.3, range from 6.0 to 12.6), with at least 10 years of practice, participated voluntarily in this study. Nine of them were ATP or WTA professional top players. Thirty-three were right-handed and three were left-handed. Twenty-one players served with a foot-up technique: they brought their rear foot up to the front foot before pushing against the ground. Fifteen players served with a foot-back technique meaning that they kept their feet spread apart until take-off. At the time of testing, all the players were considered healthy, with no history of surgery on the lower or upper limbs. We expect the heterogeneity of our population to unravel macroscopic tendencies between force-time curve variables and serve performance.

Procedures

Before experimentation, the players were informed of the benefits and risks of the investigation prior to signing an institutionally approved informed consent document to participate in the study. Additionally, for minor players, parental or guardian signed consent was obtained. The study was approved by an Institutional Review Board and conducted under the 1975 Declaration of Helsinki.

After the warm-up, players were equipped with 38 retro-reflective markers placed on anatomical landmarks determined in agreement with previously published data (43). Five additional landmarks were positioned on the racket as described in the literature (43). Participants used their own racket during the motion capture to ensure they felt as comfortable as possible during their serves. Prior to experiment, participants had as much time as needed to familiarize themselves with the testing environment and the landmarks set. Each player performed five flat serves with each foot on a distinct force platform to monitor the action of each leg (Figure 1). We asked players using a foot-up technique to bring their back foot close to their front foot, but without touching the front platform. Trials in which each foot did not remain completely on its respective platform until take-off were discarded from the study. It is worth mentioning that the force platforms were embedded in the ground inside the tennis court rather than behind the baseline. Thus, the serves were not performed in exact ecological conditions, but the subjects were asked to serve at their best speed as in an official tournament. A motion capture system with twenty-three cameras sampling at 300 Hz (Oqus, Qualisys AB., Göteborg, Sweden) recorded the trajectories of the 3-dimensional (3D) anatomical landmarks Players were shirtless or wore a bra and a tight short to limit movement of the markers.

****************************** Figure 1 near here ******************************

Among the validated serve trials, the performance and force-time curve variables were averaged over the 3 fastest serves for statistical analysis. 3D coordinates of the landmarks were then reconstructed with QTM software (Qualisys AB., Göteborg, Sweden) with a residual error of less than 1 mm. The 3D markers coordinates were expressed in a right-handed inertial reference frame whose origin was at the center of the baseline, X following the baseline to the right, Y pointing toward the net, and Z pointing upwards. The 3D markers coordinates were smoothed with a 2nd-order low-pass Butterworth filter with a cut-off frequency of 20 Hz, determined by residual analysis. The resultant velocity of the racket head, the trajectory and velocity of the CoM of each player were computed based on the filtered coordinates of the landmarks following previously published data (8). Ball impact height h_{impact} was measured as the height of the center of the racket head at impact and was made dimensionless using the standing body height (BH) of the player.

During each serve, the lateral, anteroposterior and vertical GRF (F_x, F_y, and F_z, respectively) were recorded at 1200 Hz with two force platforms (60 x 120 x 5.7 cm, Advanced Mechanical Technology Incorporation, Watertown, MA, USA) that were embedded into the ground (Figure 1). F_z and F_y data were smoothed with a 2nd-order low-pass Butterworth filter with a cut-off frequency of 20 Hz and were normalized to participants' BW before analysis. F_x probably plays an important role in coordination and balance maintaining but it was not analyzed in this study since it is negligible during the serve with respect to the vertical and anteroposterior forces (<0.1 N/BW) (29). F_z data from both force platform were combined to obtain the resultant vertical ground reaction force during the serve motion. The same procedure was done for F_y data. The resultant F_y and F_z were analyzed between ball release and take-ff as before ball release, the lower limb action remains limited. Take-off threshold was defined as five times the standard deviation (SD) of the residual vertical force during flight (36). For each trial analyzed, the leg motion was divided into two phases, namely eccentric and concentric, to describe the specific relationships of each force-time curve variables on serve performance parameters. These two phases were identified between critical instants of the CoM vertical velocity and the force platforms recordings. The eccentric phase starts when the vertical velocity of the CoM becomes negative and ends when the vertical velocity of the CoM becomes positive. The concentric phase initiates when the vertical velocity of the CoM becomes positive and lasts until the player takes off. The two main phases and most of the parameters are described in Figure 2, which is an example of the temporal evolution of force-time curve variables for a serve performed by one player.

****************************Figure 2 near here ****************************

Force-time variables analyzed during the serve included:

- the maximal value of F_z (F_z^{max}) and F_y (F_y^{max}) calculated between ball release and take-off (Figure 2b and 2d),
- the anteroposterior F_y value at the time of F_z^{max} ($F_y\big|_{F_z^{max}}$) since this value can differ from F_y^{max} (Figure 2d),
- the mean values of F_y and F_z during both eccentric and concentric phases (respectively named $F_y^{mean}\big|_E$, $F_z^{mean}|_E$, $F_y^{mean}\big|_C$ and $F_z^{mean}|_C$),
- the rate of vertical force development (RFD_z) from the beginning of the eccentric phase (t_E^{start}) to the instant of F_z^{max} ($t|_{F_z^{max}}$) as shown on Figure 2b and defined as:

$$RFD_z = \frac{F_z^{max} - F_z|_{t_E^{start}}}{t|_{F_z^{max}} - t_E^{start}},$$

- the maximal rates of vertical and anteroposterior force development from the beginning of the eccentric phase to the instants of F_z^{max} and F_y^{max} (Figure 2b and 2d) defined as:

$$RFD_z^{max} = \max_{t_E^{start} \leq t \leq t|_{F_z^{max}}} \left(\frac{\partial F_z}{\partial t} \right)$$

and

$$RFD_y^{max} = \max_{t_E^{start} \leq t \leq t|_{F_y^{max}}} \left(\frac{\partial F_y}{\partial t} \right)$$

$t|_{F_y^{max}}$ being the time of occurrence of F_y^{max}. They correspond to the highest increment between two consecutive vertical and anteroposterior force recordings.

- the maximal value of the vertical and anteroposterior power (P_z^{max} and P_y^{max}). Power is calculated following: $P_z = F_z V_z^{CoM}$ and $P_y = F_y V_y^{CoM}$,
- the vertical and anteroposterior velocities of the CoM at the instant of P_z^{max} ($V_z^{CoM}|_{P_z^{max}}$ and $V_y^{CoM}|_{P_z^{max}}$) (Figure 2a and 2c),
- F_z and F_y values at the instant of P_z^{max} ($F_z|_{P_z^{max}}$ and $F_y|_{P_z^{max}}$) (Figure 2b and 2d),
- the relative net vertical impulse during the concentric phase ($I_z^{net}|_C$) (see Figure 2b for a graphical representation). $I_z^{net}|_C$ was calculated by integrating F_z in the time domain during the concentric phase and by removing the vertical impulse due to bodyweight (23). Its mathematical expression is:

$$I_z^{net}|_C = \int_{t_C^{start}}^{t_{takeoff}} (F_z - mg)\, dt,$$

- the relative anteroposterior impulse during the concentric phase ($I_y|_C$) (see Figure 2d for a graphical representation) defined as:

$$I_y|_C = \int_{t_C^{start}}^{t_{takeoff}} F_y\, dt,$$

where $t_{takeoff}$ is the time of take-off.

We also measured the following temporal variables:

- the signed duration between the instants of F_z^{max} and F_y^{max} ($t|_{F_z^{max}} - t|_{F_y^{max}}$) (Figure 2d),
- the duration between the beginning of the eccentric phase and the instant of F_z^{max} ($t|_{F_z^{max}} - t_E^{start}$) (Figure 2a),
- the duration between the instant of F_z^{max} and ball impact ($t_{impact} - t|_{F_z^{max}}$) and the duration between the instant of F_y^{max} and ball impact ($t_{impact} - t|_{F_y^{max}}$) (Figure 2a and 2d).

Statistical analysis:

Mean and SD were calculated for all variables. Reliability of the variables were calculated using confidence limits (95%) and standard error of the mean (SEM). Pearson's correlation coefficients were used to assess relationships between force-time curve variables and serve performance indicators ($V_R{}^{max}$ and h_{impact}). If normality assumption failed, Spearman's correlation coefficients were used instead. The correlation was considered weak, moderate, and strong, when the coefficient was 0.25–0.5, 0.5–0.75, and above 0.75, respectively (37). The level of significance was set at $p \leq 0.05$. Power analyses indicated that the minimum sample size to yield a statistical power of at least 0.80 with an alpha of 0.05 and a correlation coefficient of r = 0.75 are 11 for a Pearson correlation and 14 in the case of a Spearman correlation. Our population sample of 36 tennis players should therefore be sufficiently large to identify correlations between GRF variables and performance. All statistical analyses were conducted using Jamovi software (The Jamovi project, version 1.6.23.0).

RESULTS

The mean, standard deviation and reliability of serve performance parameters and all force-time variables are described in Tables 1 and 2. The correlation coefficients are shown in Tables 3 and 4.

****************** Table 1 near here **

******************* Table 2 near here **

V_R^{max} was weakly and positively correlated with $F_y|_{F_z^{max}}$, $F_y^{mean}|_C$, P_z^{max}, P_y^{max}, $V_z^{CoM}|_{P_z^{max}}$, $F_y|_{P_z^{max}}$ and $I_y|_C$. V_R^{max} was weakly and negatively correlated with $F_z^{mean}|_E$. V_R^{max} was moderately and positively correlated with $V_y^{CoM}|_{P_z^{max}}$ and negatively with $\left(t|_{F_z^{max}} - t|_{F_y^{max}}\right)$ and $\left(t_{impact} - t|_{F_y^{max}}\right)$.

h_{impact} was weakly and positively correlated with F_z^{max}, RFD_z, $F_y^{mean}|_C$, $F_y|_{P_z^{max}}$ and $I_y|_C$. h_{impact} was moderately correlated with $F_z^{mean}|_C$, P_z^{max}, $V_z^{CoM}|_{P_z^{max}}$, $F_z|_{P_z^{max}}$ and strongly correlated with $I_z^{net}|_C$.

****************** Table 3 near here **

***************** Table 4 near here **

DISCUSSION

The purpose of this study was to investigate how GRF variables relate to serve performance parameters in competitive tennis players. Our results showed that the best predictors of V_R^{max} were $V_y^{CoM}|_{P_z^{max}}$ and temporal variables related to F_y^{max} occurrence ($\left(t|_{F_z^{max}} - t|_{F_y^{max}}\right)$ and $\left(t_{impact} - t|_{F_y^{max}}\right)$). $F_z^{mean}|_C$, P_z^{max}, $V_z^{CoM}|_{P_z^{max}}$

$F_z|_{P_z^{max}}$ and $I_z^{net}|_C$ were the variables best correlated with h_{impact}. The novel contribution of these results suggests that it is not relevant to focus on the variables usually extracted from the vertical force-time curve (F_z^{max}, RFD_z, RFD_z^{max}, $(t|_{F_z^{max}} - t_E^{start})$) to predict and explain serve performance parameters, and that it is essential to extend the analysis to other variables related to anteroposterior and vertical force-time curves.

The general characteristics of the GRF observed in this study were consistent with what was reported in previous work (2,16,27,32,44). Even if the values of the vertical variables extracted from the force-time curve are much greater than the anteroposterior ones during the tennis serve, our results show that V_R^{max} is not significantly correlated with F_z^{max}, nor with $F_z^{mean}|_C$, RFD_z, RFD_z^{max} or $(t|_{F_z^{max}} - t_E^{start})$. All these results confirm our first hypothesis: the common variables extracted from the vertical force-time curve are not relevant to predict V_R^{max} and consequently ball speed. These results are in agreement with previous studies that observed no relationship between F_z^{max} and ball speed in beginners, intermediate or elite tennis players (16,32). While the findings of Baiget et al. (2022) suggest that the capability to develop force (RFD_z) in short periods of time (<250 ms) in the upper limb during isometric tests of joints and movements leads to high serve speed in competition tennis players (3), the absence of significant correlation between RFD_z, RFD_z^{max} and V_R^{max} in our study shows that it is not the case for the lower limbs during the dynamic execution of the serve. Similar results have been obtained by Ramasamy et al. (2021) who reported that F_z^{max} and RFD_z were not correlated with the shuttlecock speed of a forehand jump smash in elite badminton players. In our study, $F_z^{mean}|_E$, P_z^{max} and $V_z^{CoM}|_{P_z^{max}}$ are the only vertical variables correlated with V_R^{max} (-0.444, 0.419 and 0.492 respectively). However, these correlations are weak and do not appear meaningful.

performance Our results show that V_R^{max} is significantly correlated with a greater number of anteroposterior force-time variables than vertical ones confirming our second hypothesis. This could mean that the player's forward leg drive is more important to generate high racket head speed than the vertical one. However, we need to be cautious in this interpretation because $F_y\big|_{F_Z^{max}}$, $F_y^{mean}\big|_C$, P_y^{max}, $I_y\big|_C$, $F_y\big|_{P_Z^{max}}$ and $V_y^{CoM}\big|_{P_Z^{max}}$ are only weakly correlated with V_R^{max} (Table 3). $V_y^{CoM}\big|_{P_Z^{max}}$ is the only anteroposterior variable to be moderately correlated with V_R^{max}. This suggests that a faster CoM velocity in the forward direction may increase the generation of racket head velocity. The forward CoM velocity during the concentric phase influences the production of forward body momentum and contributes to increasing the forward velocities of the dominant shoulder and racket head (10). Consequently, conditioning programs and technical instructions aiming to improve the forward CoM velocity constitute an interesting option to increase V_R^{max} and serve speed.

In the end, our findings demonstrate that among all our variables, $\left(t|_{F_Z^{max}} - t|_{F_y^{max}}\right)$ and $\left(t_{impact} - t|_{F_y^{max}}\right)$ are the best predictors of V_R^{max}. These results demonstrate the importance of the coordination between the vertical and the forward leg drive within the serve motion. The players with the highest V_R^{max} have the shortest duration between F_y^{max} and F_z^{max} occurrences: In other words, the most performant players are able to synchronize their forward and vertical push. Additionally, the shorter the delay between F_y^{max} and impact, the greater the magnitude of V_R^{max}. This last result is in agreement with a previous study in baseball which found that pitchers with slower ball velocities had maximal ground reaction forces occur earlier in the pitch cycle than pitchers with faster velocities (12). Similarly, MacWilliams et al. (1983) showed that pitchers with slower wrist velocities had earlier F_y^{max} (30).

Our results also show that h_{impact} is weakly correlated with F_z^{max} (r =0.39, p<0.05) and RFD_z (r =0.37, p<0.05). As a consequence, the ability to develop vertical force rapidly (RFD_z) and to some extent maximal vertical force (F_z^{max}) does not appear to strongly influence h_{impact}. Once again, this finding underlines the fact that F_z^{max} and RFD_z are not the best variables to describe tennis serve performance. In the literature, the relationship between F_z^{max} and h_{impact} is unclear. On the one hand, Martin et al. (2016) observed a reduced serve h_{impact} at the end of a prolonged tennis match between competitive players while no significant difference was observed for F_z^{max} in the same period of time (32). On the other hand, Girard et al. (2005) reported that h_{impact} was correlated with F_z^{max} in elite tennis players but not in intermediate and beginner players (16). Even if tennis players aim is not to jump as high as possible but rather to hit the ball as high as possible while being able to be efficient in terms of precision and speed, our results can still be discussed within the framework of vertical jumping literature. The influence of F_z^{max} on vertical jump height remains inconsistent (35). While Dowling and Vamos (1993) found that F_z^{max} was significantly correlated with vertical jump height (r = 0.519) (9), Kirby et al. (2011) obtained negative but significant correlations between F_z^{max} and jump height (23) in countermovement and static jumps performed to varying squat depths. In a volleyball spike task performed by 15 elite female players, F_z^{max} was not correlated with jump height (15). Concerning RFD_z, our results are in agreement with McLellan et al. (2011) who showed that this variable was weakly correlated (r=0.49, p<0.05) with vertical jump displacement during countermovement jump but they diverge from other studies that found no correlations between RFD_z and countermovement jump performance factors (19).

If we focus on the vertical force-time curve variables, our results reveal that it is more relevant to measure $F_z|_{P_z^{max}}$, $F_z^{mean}|_C$, P_z^{max} and $V_z^{CoM}|_{P_z^{max}}$ which are moderately correlated with h_{impact}. Once again, our results can be discussed in the light of the jumping tasks literature. They are consistent with Laffaye and Wagner (2013) who showed that maximal vertical performance during countermovement jumps in skilled male athletes (football, basketball and baseball) is primarily determined by $F_z^{mean}|_C$ (r =0.54, p <0.001) (24). It is worth noticing that several studies showed strong correlation between jump height and P_z^{max} (4,9,18). However, it is well known that the correlation between jump height and mechanical power is artificially inflated by the near-perfect correlation between jump height and the CoM velocity at maximal vertical power (28). Indeed, the way mechanical power is calculated from force and velocity induces an artefact. This artefact is present in our results since the correlation between h_{impact} and P_z^{max} (r = 0.685, p<0.001) appears largely determined by the correlation between h_{impact} and $V_z^{CoM}|_{P_z^{max}}$ (r = 0.702, p<0.001) and less related to the correlation between h_{impact} and $F_z|_{P_z^{max}}$ (r = 0.523, p<0.001).

In fact, jump height depends on impulse and not power (40). We found that the best predictor of h_{impact} is the relative net vertical impulse during the concentric phase ($I_z^{net}|_C$) (r = 0.772; p<0.001). This significant relationship means that the players who reach higher h_{impact} are those who generated the higher net vertical impulse during the concentric phase. This result is consistent with previous investigations demonstrating that relative net vertical impulse is correlated with jump height in squat and countermovement jumps (35) and that the positive impulse explains 77% of the countermovement jump height (14). Positive impulse during the concentric phase of a jump (static or countermovement) is also a strong predictor of jump height (r=0.93 and r=0.92) for competitive basketball and volleyball players (23).

This strong relationship between jump height and vertical impulse is explained by the fact that the ability to jump vertically is mainly dependent on the vertical velocity at take-off. From Newton's second law of motion, this velocity is attributable to the preceding vertical impulse and is enshrined in the impulse–momentum relationship (40). In our study, the correlation coefficient between $I_z^{net}|_C$ and h_{impact} for the tennis serve is weaker than those obtained between the jump height and relative net vertical impulse in jumping tasks. Indeed, tennis players ability to hit the ball as high as possible on serve depends not only on their take-off height, but also on the segmental organization of their upper body, which is mostly determined by the angles of trunk lateral flexion, shoulder abduction and elbow extension.

Impulse is an indicator of the accumulation of force during a given period (1). Since $I_z^{net}|_C$ is the product of amount of force generated during the concentric phase by its duration of application, tennis players have logically three ways to increase $I_z^{net}|_C$ and consequently h_{impact}: they can increase the amount of force applied, the duration of force application, or both. From a physical conditioning point of view, impulse is known to improve with resistance training as it leads to increase the amount of force generated (1). Based on our results, we recommend basic strength training methods and stretch-shortening cycle enhanced exercises such as plyometrics as they increase the specific strength and power characteristics required for a better impulse during the tennis serve (6). Colomar et al. (2023) advised to target plyometrics exercises that mimic the serve technical execution (6). From a technical point of view, the duration of force application during the serve can be longer by increasing the leg flexion depth and consequently, the vertical CoM displacement during leg flexion and extension. Indeed, for squat and countermovement jumps, previous studies showed that decreasing squat or knee flexion depth led to a decrease in relative net vertical impulse, maximal CoM vertical velocity and jump height (35,41). However, it is important to note that the reduction in jump height was only observed when the leg flexion depth was drastically reduced (41). For example, Hornestam et al. (2021) showed that a mean difference of 19° in maximal knee flexion between two groups of junior tennis players (55.6 ± 9° vs. 74.7 ± 6°) was not enough to see an influence on serve

h_{impact} (20). Liang et al. (2023) reported that larger range of hip, knee and ankle motions, and consequently higher leg flexion depth, were associated with an increased jump height during the serve in female college players (27). Girard et al. (2007) also showed that a very strong restriction of knee flexion depth (only 10° of leg flexion) significantly reduced h_{impact} (17). When comparing the leg flexion between a tennis serve and a countermovement jump, it is worth keeping in mind that the height of impact not only depends on the lower limbs action but also on the upper limbs' organization.

Another fundamental difference between a countermovement jump and a tennis serve is the time constraint that players have to face due to the height of the ball toss. Regarding countermovement jumps, correlations between squat flexion depth and relative net vertical impulse were obtained in the context of unlimited time to produce the highest vertical velocity peak. Participants were not subjected to any time restriction to reach their maximum jump height. Elite tennis players instead regulate the duration of their serve motion by taking into account the ball toss (48). In other words, elite tennis players seemingly use information from the ball toss to determine the appropriate times to initiate appropriate body movements (leg flexion and extension). As a result, if the ball toss is low, the server may be forced to choose a shallower flexion depth than if there was no time constraint to obtain the best possible impact height. Future work is needed to investigate the influence of leg flexion depth and ball toss height on $I_z^{net}|_C$ and h_{impact} in tennis. In any case, players and coaches should note the theoretically important contribution of leg flexion depth to vertical jump and h_{impact}. The same force impulse can be generated through a lower force applied over a longer time, or higher force applied over a shorter time. Future studies based on the shape of the force-time curve could perhaps reveal different strategies and cluster player profiles in terms of how impulse is developed and efficiently used during the serve.

In our study, we analyzed the relationships between GRF-time curve variables and serve performance indicators for a mixed-sex population. The heterogeneity of our population unraveled macroscopic tendencies between force-time curve variables and serve performance. The gender influence on GRF-time curve variables during the tennis serve is unknown because no study has examined this issue. Liang et al. (2023) obtained a mean F_z^{max} value of 2.02 ± 0.32 N/BW for a group of national female college tennis players during the tennis serve (27). This value appears close to the one measured by Girard et al. (2005) for national male tennis players (2.11 ± 0.41 N/BW) (16). Concerning sex differences in GRF-time curve variables during the CMJ, contradictory results have been obtained (25,38). Consequently, future research should focus on comparing tennis serve GRF-time curve variables between male and female players and separately assessing their impact on tennis serve performance. Later investigation will also focus on the specific differences due to age and level of expertise but is beyond the scope of this study.

A possible limitation of the current work is that the different serve stance techniques (the foot-up and the foot-back techniques) were not distinguished. Future studies should compare force-time curve variables between these two stance techniques and analyze their relationships with tennis serve performance within each stance technique group. We recall that our experiment was conducted inside a research laboratory facility where force plates were built into the ground and located not behind the baseline but inside the tennis court of the laboratory. We also asked players using a foot-up technique to bring their back foot close to their front foot, but without crossing the limit between the two platforms. Both the force plates location and the given instructions may have affected the way players hit their serves and limited the ecological validity of our study.

Finally, it is worth acknowledging that this study did not directly quantify the lower limbs physical capacities that may differentiate the players and their performance. In tennis, leg drive is not a maximal effort skill but rather an optimal one in order to meet the ball at a height both defined by ball toss and the will to transfer as much kinetic energy as possible to the ball (47). Further work could also evaluate the relationships between lower limbs physical capacities and force-time curve variables during the serve to provide an even finer understanding of serve performance.

PRACTICAL APPLICATIONS

The results presented here contribute to a better understanding of the mechanical demands of tennis serve motion and can be used by coaches to improve player preparation and performance. Our results do not support the value of strength training to improve RFD_z, RFD_z^{max} or F_z^{max} in expert tennis players to increase serve performance parameters. On the contrary, it is important for players to develop high vertical and forward CoM velocities near take-off to improve h_{impact} and V_R^{max}, respectively. Coaches should also encourage their players to synchronize their upward and forward pushing action during the serve to increase V_R^{max} (*i.e.* reducing the elapsed time between the maximal value of F_z and the maximal value of F_y). Moreover, it seems interesting to improve the players' relative net vertical impulse during the concentric phase ($I_z^{net}|_C$) to improve h_{impact}. From a physical conditioning point of view, basic resistance strength training methods and stretch-shortening cycle enhanced exercises such as plyometrics can be planned to increase the amount of force generated and consequently $I_z^{net}|_C$. From a biomechanical point of view, players and coaches need to be aware of the theoretically important contribution of leg flexion depth to vertical jump and h_{impact} and re-examine their self-selected depth, especially if it is quite shallow, as it may not be the best approach for improving maximum vertical CoM displacement, $I_z^{net}|_C$ and therefore h_{impact}. Because correlations do not necessarily prove causation, future experimentations should use a longitudinal (pretest-posttest) protocol design to determine if the abilities 1) to develop high vertical and forward CoM velocities near take-off, 2) to improve relative net vertical impulse during the concentric phase and 3) to synchronize the upward and forward pushing action during the serve could be trained or improved, and whether these improved abilities could actually enhance tennis serve performance indicators.

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Figure legends

Figure 1. Example of a subject performing a tennis flat serve on the two force platforms

Figure 2: Description of the main phases and variables defined in the text. a) Vertical velocity of the CoM in time. b) Dimensionless vertical GRF in time. The vertical dashed lines delimit the different phases. The grey and green dashdotted lines show the times of occurrence of F_z^{max} and P_z^{max} respectively. Dashed and dashdotted lines are the same as in a). The grey shaded area is $I_z^{net}|_C$. c) Forward velocity of the CoM in time. d) Dimensionless forward GRF in time. The vertical dashed lines delimit the different phases. The grey, green and blue dashdotted lines are the times of occurrence of F_z^{max}, P_z^{max} and F_y^{max} respectively. Dashed and dashdotted lines are the same as in c) except for the blue one only shown here for clarity. The grey shaded area is $I_y\big|_C$. Mean values of F_y and F_z are averaged over the time domain of each phase shown at the top of a) and c).

Table 1. Reliability of the performance and force-time curve variables analyzed

					95 % Confidence limits	
	Units	Mean ± SD	SEM	Range	Lower	Upper
V_R^{max}	m.s^{-1}	42.2 ± 3.6	0.61	32.1 – 46.8	40.9	43.4
h_{impact}	m/BH	1.47 ± 0.04	0.01	1.35 – 1.54	1.46	1.49
F_z^{max}	N/BW	2.04 ± 0.29	0.05	1.43 – 2.56	1.95	2.14
$F_y\|_{F_z^{max}}$	N/BW	0.13 ± 0.13	0.02	-0.14 – 0.34	0.08	0.17
F_y^{max}	N/BW	0.18 ± 0.10	0.02	0.03 – 0.35	0.15	0.22
$F_z^{mean}\|_E$	N/BW	0.99 ± 0.08	0.01	0.69 – 1.08	0.97	1.02
$F_z^{mean}\|_C$	N/BW	1.39 ± 0.18	0.03	0.92 – 1.75	1.32	1.45
$F_y^{mean}\|_E$	N/BW	0.01 ± 0.05	0.01	-0.17 – 0.10	0.00	0.03
$F_y^{mean}\|_C$	N/BW	0.04 ± 0.13	0.01	-0.15 – 0.15	0.01	0.07
RFD_z	N/BW. s^{-1}	2.05 ± 0.89	0.15	0.87 – 4.45	1.75	2.35
RFD_z^{max}	N/BW. s^{-1}	10.30 ± 4.45	0.74	3.36 – 26.40	8.77	11.80
RFD_y^{max}	N/BW. s^{-1}	8.13 ± 3.62	0.60	3.76 – 17.6	6.90	9.35
P_z^{max}	W/BW	2.25 ± 0.67	0.11	0.63 – 3.84	2.02	2.48
P_y^{max}	W/BW	0.12 ± 0.09	0.02	0.01 – 0.30	0.09	0.16
$V_z^{CoM}\|_{P_z^{max}}$	m.s^{-1}	1.23 ± 0.27	0.04	0.44 – 1.76	1.14	1.33
$V_y^{CoM}\|_{P_z^{max}}$	m.s^{-1}	0.73 ± 0.22	0.04	0.25 – 1.17	0.65	0.80
$F_z\|_{P_z^{max}}$	N/BW	1.80 ± 0.22	0.04	1.30 – 2.19	1.72	1.87
$F_y\|_{P_z^{max}}$	N/BW	-0.00 ± 0.13	0.02	-0.25 – 0.24	-0.05	0.04
$I_z^{net}\|_C$	m.s^{-1}	1.02 ± 0.41	0.07	-0.20 – 1.80	0.88	1.16
$I_y\|_C$	m.s^{-1}	0.12 ± 0.20	0.03	-0.35 – 0.53	0.05	0.18

h_{impact} = impact height; V_R^{max} = maximal racket head velocity; F_z = vertical force; F_y = anteroposterior force; RFD = rate of force development; P_z = vertical power; P_y = anteroposterior power; V_z = vertical velocity; V_y = anteroposterior velocity; CoM = center of mass; C = concentric; $I_z^{net}|_C$: relative net vertical impulse; $I_y|_C$: relative anteroposterior impulse; E = eccentric; BW = body weight; BH = body height; N = Newton; SD: standard deviation; SEM: standard error of the mean.

Table 2. Reliability of the temporal force-time curve variables analyzed

					95 % Confidence limits	
	Units	Mean ± SD	SEM	Range	Lower	Upper
$t\|_{F_z^{max}} - t\|_{F_y^{max}}$	ms	56 ± 73	12.20	-19 – 305	31	81
$t\|_{F_z^{max}} - t_E^{start}$	ms	676 ± 129	21.60	365 – 949	632	720
$t_{impact} - t\|_{F_z^{max}}$	ms	258 ± 33	5.51	203 – 339	247	269
$t_{impact} - t\|_{F_y^{max}}$	ms	315 ± 11	67.80	218 – 522	292	338

F_z^{max} = maximal vertical force; F_y^{max} = maximal anteroposterior force, t_E^{start}= starting time of the eccentric phase and t_{impact}= the time of impact.

Table 3. Correlation coefficients between serve performance parameters and force-time curve variables during serve

	V_R^{max}	h_{impact}
F_z^{max}	0.153	0.394*
$F_y\|_{F_z^{max}}$	0.425*	0.301
F_y^{max}	0.247	0.202
$F_z^{mean}\|_E$	-0.444**	0.023
$F_z^{mean}\|_C$	0.204	0.693***
$F_y^{mean}\|_E$	-0.064	-0.237
$F_y^{mean}\|_C$	0.396*	0.461**
RFD_z	0.212	0.368*
RFD_z^{max}	0.102	0.201
RFD_y^{max}	0.215	0.002
P_z^{max}	0.419*	0.685***
P_y^{max}	0.351*	0.144
$V_z^{CoM}\|_{P_z^{max}}$	0.492**	0.702***
$V_y^{CoM}\|_{P_z^{max}}$	0.513***	0.134
$F_z\|_{P_z^{max}}$	0.224	0.523***
$F_y\|_{P_z^{max}}$	0.399*	0.404*
$I_z^{net}\|_C$	0.321	0.772***
$I_y\|_C$	0.413*	0.418*

h_{impact} = impact height; V_R^{max} = maximal racket head velocity; F_z = vertical force; F_y = anteroposterior force; RFD = rate of force development; P_z = vertical power; V_z = vertical velocity; C = concentric; $I_z^{net}|_C$: vertical net impulse; E = eccentric; BW = body weight; N = Newton. *Statistically significant at $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 4. Correlation coefficients between serve performance parameters and temporal ground reaction force variables during serve

	V_R^{max}	h_{impact}
$t\|_{F_z^{max}} - t\|_{F_y^{max}}$	-0.519***	-0.101
$t\|_{F_z^{max}} - t_E^{start}$	0.058	0.059
$t_{impact} - t\|_{F_z^{max}}$	0.081	0.216
$t_{impact} - t\|_{F_y^{max}}$	-0.522***	-0.045

h_{impact} = impact height; V_R^{max} = maximal racket head velocity; F_z^{max} = maximal vertical force; F_y^{max} = maximal anteroposterior force, t_E^{start}= starting time of the eccentric phase and t_{impact}= the time of impact.

Figure

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Figure

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