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Original Article

Vertical and shear impulses affecting racket speed in tennis serve

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Abstract:
A high-speed tennis serve offers a competitive advantage, with racket speed commonly serving as an indicator of serve performance and showing a correlation with ground reaction force (GRF). The maximum vertical GRF has been associated with serve performance; however, this measure reflects only a single value and does not capture the temporal dynamics of GRF generation by leg power. Impulse is a more appropriate variable for correlating with serve performance because it accounts for the duration of force application. Studies have shown that vertical impulse exhibits a weaker relationship with racket speed compared to anterior–posterior impulse. However, the medial–lateral direction may also correlate with racket speed because it contributes to trunk rotation and facilitates the transfer of kinetic energy through the upper limb to the racket. Therefore, this study investigated the relationship between racket speed, GRF in the vertical and shear directions, and trunk kinematics to better understand the kinetic chain during tennis serves. Ten experienced Thai tennis players were recruited to perform serves. Racket speed and force–time data were collected using motion capture cameras and two force plates, respectively. The results indicated that racket speed was more strongly correlated with shear impulse ($r = 0.5021$) than with vertical impulse ($r = 0.1322$). Linear regression analysis revealed that shear impulse was highly correlated with trunk kinematics, confirming the presence of a kinetic chain during the tennis serve. This finding can be applied in training sessions to improve serve performance. Tennis coaches and players can use this parameter as a target for optimizing training programs and improving overall serve effectiveness.
Keywords: ground reaction force, impulse, tennis serve, kinetic chain

Introduction

Tennis players can gain a competitive advantage over their opponents by delivering a high-speed serve (Reid et al., 2013). Statistics from the US Open indicate that players who achieve higher serve speeds tend to have a greater likelihood of winning matches. This advantage can place considerable pressure on opponents, making it more difficult for them to return the ball and sustain play (Martin, 2018). Previous biomechanical studies have mainly focused on upper limb and racket kinematics (Reid et al., 2013; Whiteside et al., 2013, 2014; Colomar et al., 2022; Bilić et al., 2025) in an effort to identify key performance indicators such as the angular velocities of the shoulder, elbow, and hand, as well as peak racket speed. Although ball speed has commonly been used as an indicator of serve performance (Fett et al., 2021; Ölmez et al., 2025), maximum racket speed has also been investigated in several studies (Fourel et al., 2024; Jamkrajang et al., 2025). Therefore, identifying the correlation between racket speed and body kinematics may provide valuable insights for developing more effective training programs.

Many studies reported a positive relationship between the GRF and the racket speed (Bahamonde & Knudson, 2001; Elliott & Wood, 1983; Fourel et al., 2024; Girard et al., 2005, 2007; Knudson & Bahamonde, 2001). Girard et al. (2005) compared tennis serve performance across three groups of different expertise levels. Although they reported a positive correlation between vertical ground reaction force (GRF) and maximum ball speed, differences in vertical GRF were observed only between the expert and beginner groups. Additionally, the maximum ball speed of the expert group was significantly higher than that of both the intermediate and beginner groups. The authors also noted that there were no significant differences in leg performance, as indicated by hopping tests, among the three expertise levels. Even though racket or ball speed showed a positive correlation with maximum vertical GRF, this measure represents only a single value and may not adequately capture the overall dynamics of the serve motion. In addition, Girard et al. (2007) reported that vertical GRF did not show a significant correlation with ball speed across the three expertise levels, but it did correlate with ball impact height. The vertical component of GRF alone may not provide sufficient insight into force production because the shear components measured on a force plate are often overlooked in the literature. In studies of overhead sport movements, such as handball, it has been shown that maximum vertical GRF can be influenced by ground contact time (Rousanoglou et al., 2014). Rousanoglou et al. (2014) also reported correlations between ball speed and GRF components, finding that ball speed was more strongly associated with impulse than with maximum

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force in both the vertical and anterior–posterior directions. Results from Fourel et al. (2024) also agreed with those of Rousanoglou et al. (2014), demonstrating that impulse showed a stronger correlation than maximum GRF in both directions. They also noted that the vertical components of the GRF were not correlated with racket speed in tennis but rather with ball impact height (Fourel et al., 2024). However, the medial–lateral direction of GRF was not considered in their analysis. The shear component of GRF consists of both the anterior–posterior and medial–lateral directions; therefore, combining these two components of ground reaction impulse may reveal a stronger relationship with racket speed than considering only the anterior–posterior direction.

From the literature, it is evident that maximum GRF alone is insufficient to explain its relationship with racket speed because the duration of GRF production during leg drive influences the impact of maximum vertical GRF. Moreover, previous research has primarily considered only the anterior–posterior component of shear GRF, potentially overlooking the contribution of the overall shear force to trunk rotation. To address this limitation, this study aims to improve the understanding of the kinetic chain by explicitly examining the predictive value of shear impulse and its correlation with trunk kinematics, thereby bridging the gap between instantaneous force and rotational momentum transfer. Confirming this kinetic relationship will provide tennis coaches and sports scientists with practical, evidence-based insights to guide the development of more effective training strategies focused on optimizing power generation and serve performance.

Our hypothesis is that (1) the racket speed would have a greater correlation with shear than vertical impulse (Fourel et al., 2024; Rousanoglou et al., 2014) and (2) shear impulse would exhibit a high correlation with trunk kinematics, confirming the role of the kinetic chain in transferring power from the GRF to the racket through the trunk. The findings of this study are expected to provide valuable insights for coaches in designing training programs aimed at improving serve performance.

Materials and methods

Participants

The dataset was obtained from Jamkrajang et al. (2025), which included ten right-handed, experienced Thai tennis players (5 males and 5 females; age, 22.3 ± 4.2 years; height, 1.70 ± 0.06 m; body mass, 63.1 ± 5.6 kg). Inclusion criteria required that participants had competed in national and/or international competitions for at least five years and were members of the Thai national tennis team. All participants confirmed that they had no history of injury in the six months preceding data collection. The study protocol was reviewed and approved by the Mahidol University Ethics Committee (MU-CIRB 2021/439.1510).

Protocol

All participants completed a 10-min warm-up consisting of light jogging and practice tennis serves. Each participant used their own racket to follow the testing protocol. Participants were instructed to perform a minimum of 10 successful first serves aimed at a 1 × 1 m target within each designated court zone (Figure 1), with the goal of delivering their fastest possible first serve for each attempt. For analysis purposes, the tennis court was divided into two main zones (Figure 1): the deuce court (A) on the right side and the advantage court (B) on the left side, as viewed from the server's perspective facing the net. In these zones, four specific serving locations were defined. Condition 1 (C1) represented the wide serve position in the deuce court, located at the junction of the service line. Condition 2 (C2) corresponded to the broader T-line area of the deuce court. Condition 3 (C3) corresponded to the broader T-line area of the advantage court, while Condition 4 (C4) represented the wide serve location in the advantage court. Participants were allowed to rest as needed between individual serves, with a standardized 2-min rest period between serving conditions. For each participant, a total of 40 successful serves—10 per condition—were analyzed. Players were allowed to use either the "foot-up" or "foot-back" serve technique according to their personal preference, with five participants using the foot-up technique and the remaining five using the foot-back approach.

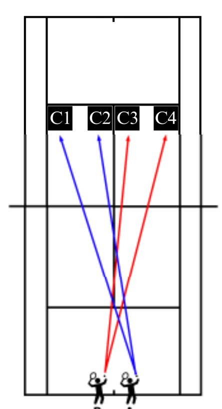

Figure 1: Illustration of the tennis court, showing the deuce court (A) and the advantage court (B). The four serving locations are designated as Condition 1 (C1), Condition 2 (C2), Condition 3 (C3), and Condition 4 (C4).

Apparatus

Twelve infrared cameras (sampling rate: 200 Hz; BTS Bioengineering, Milan, Italy) were used to capture the trajectories of 68 reflective markers placed on participants' bodies. In accordance with the two serving locations described in Jamkrajang et al. (2025), each location was equipped with two force plates (sampling rate: 2000 Hz; Kistler Instrument AG, Switzerland) to record GRF, with each plate assigned to one lower limb. Kinetic and kinematic data were collected simultaneously from the cameras and force plates. To minimize potential timing biases, both systems were synchronized using BTS capture software (BTS Bioengineering, Milan, Italy) so that recordings started at the same time (t = 0 s).

Data analysis

The laboratory coordinate system was aligned with the baseline of the tennis court, with the X-axis perpendicular to and pointing toward the net, the Y-axis perpendicular to the ground, and the Z-axis parallel to the net orientation (Jamkrajang et al., 2025). This coordinate system was applied to analyze GRFs and all trajectories of the reflective markers.

All calculations were performed using Visual3D software (V6; HAS-Motion, Ontario, Canada). The start of each trial was defined as the moment when the non-racket upper arm was parallel to the ground, while the end of the trial was defined as the first frame in which participants jumped or both feet left the ground.

This endpoint was manually identified in the software as the frame where the magnitude of the GRF reached zero. Data were filtered using a fourth-order Butterworth filter with a cutoff frequency of 16 Hz, except for the trajectory of the reflective marker on the tennis racket, which was filtered at 36 Hz to minimize temporal and magnitude distortions caused by the impact of the tennis stroke (Knudson & Bahamonde, 2001).

Statistical analysis

Processed data from Visual3D were exported for statistical analysis, which was performed using MATLAB R2024b (MathWorks Inc., Natick, Massachusetts, USA). The maximum racket speed was compared with two parameters derived from GRFs: shear impulse and vertical impulse. Both impulses were calculated using the following equations:

$$shear\ impluse = \left|\int_{T_{s1}}^{T_{joff}} (GRF_x + GRF_z)\, dt\right|,\ vertical\ impluse = \left|\int_{T_{s1}}^{T_{joff}} GRF_y\, dt\right|$$

where GRF_x and GRF_z represent the X- and Z-directions of the GRF, parallel to the court floor, while GRF_y represents the GRF normal to the court floor. T_{s1} denotes the time at which the non-racket upper arm was parallel to the court floor (Jamkrajang et al., 2024), and T_{joff} represents the first time frame when both feet left the force plate.

The Kolmogorov–Smirnov test was used to determine whether each dataset was normally distributed at a 5% significance level before performing further statistical analyses. Because all datasets were found to be normally distributed, the strength and direction of relationships were assessed using the Pearson correlation. Levels of relationship strength were classified according to Chan (2003) and applied in this study.

According to the serving location indicated by Jamkrajang et al. (2024), both shear and vertical impulses were divided into four groups. A one-way analysis of variance (ANOVA) was then performed to identify any significant differences in the impulses across these groups.

Post hoc comparisons using Tukey's honestly significant difference test were performed when a significant main effect was observed, to identify differences between serving locations. The significance level for both main effects and post hoc tests was set at 0.05.

In addition, linear regressions were performed to examine the relationships between independent and dependent variables. Each dependent variable was analyzed using three regression models: two simple regressions using either shear or vertical impulse, and one multiple regression using both impulses. In total, 15 regression equations were evaluated. Outliers were accounted for by applying the bi-square robust method in the regression analyses.

Results

The results of the Kolmogorov–Smirnov test indicated that all variables in this study were normally distributed, allowing for the use of parametric analyses ($p < 0.001$). Figure 2 shows the shear (overall mean = 0.0623 ± 0.0437 BW) and vertical impulses (overall mean = 0.9092 ± 0.0996 BW) across different serving positions. A significant main effect was observed only for shear impulse ($p = 0.0067$), whereas vertical impulse did not show a significant difference ($p = 0.0620$).

Post hoc pairwise comparisons of shear impulse across serving locations revealed that racket velocity was significantly greater at C4 than at C1 and C2 ($p = 0.0259$ and 0.0450, respectively).

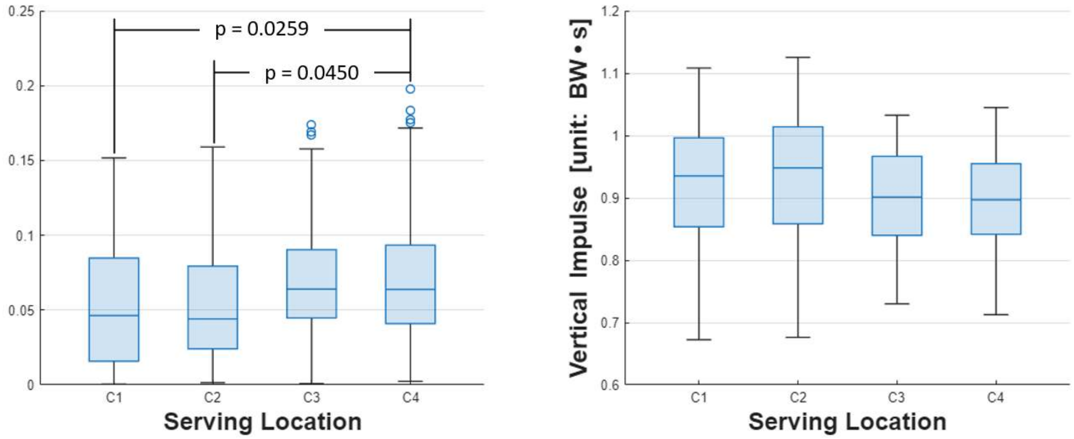

Figure 2: (Left) Shear and (Right) vertical impulses calculated from ten participants performing an overhead tennis serve

Table 1 presents the Pearson correlation coefficients to indicate the strength of the relationship between the independent and dependent variables. Shear and vertical impulses were considered as the independent variables, while the dependent variables included maximum racket speed, maximum trunk angular velocities about the X-, Y-, and Z-axes, and the resultant maximum trunk angular velocity. Maximum racket speed showed a stronger relationship with shear impulse than with vertical impulse. Additionally, shear impulse exhibited a stronger association with trunk rotation compared to vertical impulse, which was near zero.

Table 1: Pearson correlations between two independent variables (shear and vertical impulses) and five dependent variables

Impulse	Trunk angular motion				Maximum Racket Speed
	Flexion/Extension	Rotation	Lateral Flexion	3D Resultant	
Shear	0.1433	0.1657	−0.0229	0.0600	0.5012
Vertical	0.1587	$-0.0001 < r < 0$	0.0609	0.0073	0.1322

The constant values of the 15 regression equations are presented in Table 2. Ten simple linear regressions were performed using either shear or vertical impulse as the independent variable, while five multiple regressions included both impulses. The single regressions based on shear impulse demonstrated stronger relationships with all dependent variables compared to those using vertical impulse or both impulses, except for trunk flexion/extension, where vertical impulse yielded a higher R^2. Additionally, multiple regressions using both impulses generally produced lower R^2 values than the single regressions, with the exception of maximum racket speed. Only one negative R^2 was observed, occurring in the relationship between maximum racket speed and vertical impulse.

Table 2: Linear regression results based on three sets of independent variables: shear, vertical, and both impulses. Constant values are presented as mean ± standard deviation

Regression Equation	*a*	*b*	*c*	R^2
Maximum Racket Speed				
Shear Impulse $(a \cdot s + c)$	45.67 ± 8.22		39.47 ± 0.62	0.2688
Vertical Impulse $(b \cdot v + c)$		9.584 ± 4.218		−0.0025
Both Impulses $(a \cdot s + b \cdot v + c)$	45.10 ± 8.36	0.993 ± 3.664	38.59 ± 3.31	0.2643
Trunk Flexion/Extension				
Shear Impulse $(a \cdot s + c)$	22.87 ± 266.73		470.9 ± 20.2	0.9141
Vertical Impulse $(b \cdot v + c)$		−178.5 ± 115.15	634.0 ± 105.4	0.9165
Both Impulses $(a \cdot s + b \cdot v + c)$	103.4 ± 285.3	−186.7 ± 125.1	634.7 ± 112.9	0.9043
Trunk Rotation				
Shear Impulse $(a \cdot s + c)$	664.5 ± 199.8		256.2 ± 15.1	0.9133
Vertical Impulse $(b \cdot v \mid c)$		64.3 ± 93.8	237.4 ± 85.8	0.9005
Both Impulses $(a \cdot s + b \cdot v + c)$	657.5 ± 216.6	17.44 ± 94.96	240.8 ± 85.8	0.9009
Trunk Lateral				

Flexion/Extension				
Shear Impulse ($a \cdot s + c$)	466.4 ± 180.5		126.6 ± 13.7	0.9625
Vertical Impulse ($b \cdot v + c$)		−146.9 ± 83.6	293.0 ± 76.5	0.9581
Both Impulses ($a \cdot s + b \cdot v + c$)	533.4 ± 209.5	−182.0 ± 91.8	289.1 ± 82.9	0.9509
Trunk 3D Resultant				
Shear Impulse ($a \cdot s + c$)	278.1 ± 369.3		575.9 ± 28.1	0.9779
Vertical Impulse ($b \cdot v + c$)		−106.6 ± 161.9	690.3 ± 148.0	0.9780
Both Impulses ($a \cdot s + b \cdot v + c$)	343.4 ± 474.9	−135.1 ± 208.1	693.5 ± 188.0	0.9646

Discussion

This study emphasized the role of ground reaction impulses in influencing maximum racket speed during tennis serves. All statistical analyses indicated that the shear impulse of the GRF was more strongly associated with racket speed than vertical impulse, highlighting the importance of horizontal force generation in powerful tennis serves and confirming our hypotheses. Furthermore, trunk kinematics in all three directions showed stronger relationships with shear impulse than with vertical impulse.

Linear regression confirmed a strong relationship between shear impulse and trunk kinematics, reinforcing the concept of the kinetic chain in tennis serve motion (Colomar et al., 2022; Bilić et al., 2025). Our findings indicate that efficient trunk rotation and angular velocity are key mediators in transmitting GRF upward, consistent with previous studies highlighting trunk and pelvis rotation as major contributors to upper limb velocity in overhead sports (Orishimo et al., 2023). Previous literature has reported that vertical GRFs during the tennis serve vary by serve stance, while differences in horizontal forces were less evident (Bahamonde & Knudson, 2001; Elliott & Wood, 1983). In contrast, this study demonstrated that vertical impulses of the GRF exhibited weaker relationships with racket speed than shear impulses. This may be explained by the role of vertical impulse primarily contributing to upward lift of the body, with a limited effect on forward acceleration of the racket. Additionally, a key difference exists between the parameters used in this study—impulses—and those commonly reported in the literature, which often focus on the magnitude of force at a specific timestamp. The main difference is that impulses are averaged over a period of time, whereas single force magnitudes represent only a single value at a designated moment. Fourel et al. (2024) reported that racket speed was not significantly correlated with any parameters of vertical GRFs, whereas frontal impulse showed a significant correlation with racket speed. Our results are consistent with those findings. The primary difference between the shear impulses in this study and those reported by Fourel et al. (2024) lies in the time range analyzed. Despite this difference, both studies demonstrate that racket speed is more strongly associated with shear impulse than with vertical impulse, suggesting that shear impulse is one of several contributors to racket speed. Therefore, shear impulse plays a critical role in transferring energy through the kinetic chain, particularly from the ground through the trunk to the upper limbs and racket. Moderate correlations may reflect substantial inter-individual differences in technique and force generation strategies. Efficient tennis serving relies not only on the magnitude of force but also on the timing, direction, coordination, and sequencing of movements. Furthermore, the tennis serve is not only a vertical jump but a complex rotational and translational task with a pronounced forward (horizontal) component.

Racket speed is closely related to GRF. The findings of this study indicate that racket speed is more strongly associated with shear impulse than with vertical impulse. This aligns with the conclusions of Fourel et al. (2024), who reported that temporal parameters of the maximum frontal GRF served as better predictors of racket speed than maximum vertical force. Our results further demonstrate that shear impulse is strongly correlated with trunk rotation, confirming the presence of a kinetic chain during the tennis serve, in which energy from the shear impulse is transferred through the trunk and upper limbs to the racket. In contrast, vertical impulse mainly contributes to ball impact height (Fourel et al., 2024), which may explain why racket speed is more closely related to shear than vertical impulse. Overall, these findings support the existence of a coordinated kinetic chain during the tennis serve, particularly linking lower-body force generation to trunk motion (Sweeney et al, 2012).

However, individual lower- and upper-limb performance was not considered in this study, which may involve different levels of muscle activation in the lower (Hansen et al., 2023, 2024; Zhang et al., 2025) and upper limbs during the tennis serve (Wang et al., 2019; Myers et al., 2024; Zhang et al., 2025). Different players may achieve similar racket speeds using different movement strategies such as increased hip drive. In this study, GRFs were normalized only to individual body weight before analysis. Future research should consider including lower-limb performance during GRF production, which may improve the observed correlations between GRF and racket speed. Furthermore, it is important to examine how athletes balance vertical and horizontal force demands across different serve types (flat, kick, and slice), as well as the coordination and timing of distal segments, such as shoulder external/internal rotation and wrist flexion. Muscle activation also changes owing to the accumulation of fatigue during a match or practice, which should be considered when data collection spans a long period (Wang et al., 2019). Additionally, incorporating time-series or phase-specific data (e.g., force onset relative to trunk rotation) can provide a better understanding of coordination. Furthermore, combining GRF with inverse dynamics allows computation of joint torques and segmental power flows.

For practical performance applications, training should emphasize horizontal force production, such as lateral bounds and rotational medicine ball throws, which may be more effective than vertical jump training alone for enhancing serve velocity. Coaches should prioritize trunk strength and rotational control in training to enhance kinetic chain efficiency. Furthermore, emphasizing technical drills that coordinate foot drive, trunk rotation, and arm acceleration may be beneficial for players.

Conclusions

This study highlighted the relationship between racket speed and ground reaction impulses during the tennis serve. The findings demonstrate that the shear impulse of the GRF is a significantly stronger and more relevant predictor of maximum racket speed than vertical impulse, which primarily influences jump height. These results confirm our hypothesis that the superior correlation with racket speed is driven by the direct and intrinsic role of shear impulse in enhancing trunk rotational kinematics. In particular, angular velocity and trunk rotation provide robust evidence that efficient trunk rotation acts as a key mediator in the kinetic chain, transferring accumulated GRF upward through the body and into the racket head. These findings have practical applications for training because they offer coaches and players a clear parameter to guide program design and enhance serve performance. Emphasizing exercises that maximize horizontal force production, along with developing trunk strength and rotational control, can contribute to a more efficient and higher-velocity serving technique.

Conflicts of interest The authors declare no conflicts of interest.

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