INTER-INDIVIDUAL VARIABILITY IN KNEE KINEMATICS DURING THE TENNIS SERVE

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This study aimed to (1) evaluate inter-individual variability in knee kinematics during tennis serve among professional players and (2) investigate the relationships between these knee kinematics and indicators of serve performance. Twenty-three male ATP ranked players participated in this study. Their serve motion was captured using a marker-based motion capture system. The assessment of inter-individual variability was carried out via coefficient of variation (CV). Knee joint angle at maximum flexion and knee extension ROM for both knees are significantly and strongly correlated with ball impact height. This finding highlights the role of knee motion in serve performance. During the flexion phase, players employ individual strategies of knee kinematics whereas this is much less the case during the extension phase, probably because they must primarily respond to the task constraints.

KEYWORDS: Inter-individual execution variability, range of motion, performance.

INTRODUCTION: The tennis serve is characterized by a flexion of the legs followed by their powerful extension that initiates the proximo-distal kinetic chain favouring the energy transfer from the ground to the racquet (Kovacs & Ellenbecker, 2011). The sequence of energy transfer starts with leg flexion, enabling the storage of energy, and progresses to leg extension, where the stored energy is released. In the literature, the main role of leg action in service remains debated (Colomar et al., 2022). Several experts grant the lower body a main coordinating role providing a stable proximal base for distal mobility while other studies prefer to see the rapid vertical extension of the lower limbs as a primary contributor to ball impact height. Consequently, there is a need to ascertain how knee kinematics influence ball impact height which is a performance factor (Vaverka & Cernosek, 2013), given the current lack of a comprehensive understanding on this topic. Moreover, according to Kovacs & Ellenbecker (2011), the start of the serve during which the flexion phase occurs may reflect style and individual tendency rather than substance. A closer examination of literature data reveals important individual variations (Dossena et al., 2016; Fleisig et al., 2003). For instance, significant variability was observed among professional players in the range of knee flexion angles, with a coefficient of variation (CV) approaching 60% (Fleisig et al., 2003). Furthermore, the inter-individual variability in serve jump height is twice as pronounced as that observed in countermovement jumps, with a CV of approximately 26% for serves when it is only 13% for countermovement jumps (Dossena et al., 2016). Unfortunately, the investigation of inter-individual variability in lower limb motion during the serve remains limited and coaches are not always sure whether to recommend a unique knee kinematics model to their players or allow more freedom of movement. Therefore, an investigation into the inter-individual variability in lower limb motion, with a specific focus on knee kinematics at each stage of the serve, is necessary. Consequently, the aims of this study were to describe knee kinematics among professional players, evaluate inter-individual variability in the range of the calculated values, and identify significant relationships between these parameters and ball impact height. We hypothesize a notable degree of variability during the leg flexion phase, with comparatively less variability during the leg extension phase.

METHODS: A total of 23 male professional tennis players (age: 22.9 ± 3.4 years; height: 1.89 ± 0.08 m; body mass: 80.5 ± 7.7 kg) with a mean ATP ranking of 233 (highest 17; lowest 565) voluntarily took part in the study. All players serve using a foot-up technique in which they bring the back foot up to meet the front foot during the ball toss, prior to push against the floor. Following a warm-up session and after a few trials, each player performed 5 successful flat serves in a target area (1 m x 2 m bordering the "T" zone) in deuce service box for right-handed player or in ad service box for left-handed player. Three-dimensional markers trajectories were recorded at 300 Hz using a 23-camera Qualisys motion analysis system (Oqus 7+, Qualisys AB, Gothenburg, Sweden).
A set of kinematic variables related to knee motion as well as ball impact height were selected and calculated using Matlab (Version R2018a, Mathworks, Natick, Massachusetts, USA). The internal knee angles of both front (FK) and rear knee (RK) were determined by computing the scalar (dot) product of vectors that define the thigh and shank segments in three dimensions. We sequenced the serve between the instant of the knee flexion starts and the instant of ball impact. All variables were derived from individual serves and subsequently averaged over five successful trials for each player. It is recommended to consider a minimum of three trials for obtaining accurate and representative movement kinematics (Mullineaux et al., 2001).
The Shapiro-Wilk test was used to assess the normality of the data distribution. Inter-individual variability was evaluated using CV calculated as the ratio of the standard deviation to the mean and expressed as a percentage. When data does not follow a normal distribution and follows a log-normal distribution, CV was calculated using another method described in the literature (Canchola, 2017). Based on the thresholds set by Bańkosz & Winiarski, (2020), a CV below 20% indicates low variability, a CV between 20% and 40% indicates medium variability, a CV between 40% and 60% indicates high variability and a CV higher than 60% indicates very high variability. To verify that variability is mainly attributed to inter-individual differences rather than intra-individual variability resulting from the five successful serves, we also assessed intra-individual variability.
Pearson's correlation coefficients were used to assess relationships between knee kinematics and ball impact height. If normality assumption fails, Spearman's correlation coefficients were used instead. Statistical analyses were performed using Jamovi software (The Jamovi project, version 2.3.28). The level of significance was set at $p < 0.05$.

RESULTS: Results showed that players hit the ball at 147.9 ± 2.8% of their body height (BH) along the vertical axis. Knee kinematics are presented in Table 1 with their corresponding CV. Knee joint angles showed low variability at the start of flexion, at maximum flexion, and at ball impact (CV < 10%). Table 1 demonstrates that knee ROM are more variable during flexion than during extension (RK: CV = 21.8% *vs.* CV = 9.0%; FK: CV = 22.3% *vs.* CV = 16.6%, respectively). The same result was observed for maximum RK angular velocity (CV = 22.8% *vs.* CV = 12.1%, respectively). However, there was no difference in the CV values for maximum FK angular velocity between flexion and extension (CV = 24.9% *vs.* CV = 26.9%, respectively). Moreover, the duration of knee flexion showed greater inter-individual variability than the duration of knee extension for both RK and FR (RK: CV = 38.1% *vs.* CV = 16.6%; FK: CV = 30.4% *vs.* CV = 19.2%, respectively). The inter-individual variability in knee kinematics across all variables was four to twenty times higher than the corresponding intra-individual variability.

Table 1. Descriptive data about knee kinematics.

	RK		FK	
	Mean ± SD	CV (%)	Mean ± SD	CV (%)
Internal knee joint angle at the start of the flexion (°)	155.4 ± 14.4	9.3	170.1 ± 13.3	8.4
Internal knee joint angle at maximum flexion (°)	91.8 ± 7.7	8.4	108.8 ± 8.1	7.5
Internal knee joint angle at ball impact (°)	172.6 ± 7.7	4.8	154.8 ± 8.3	5.3
Knee flexion ROM (°)	63.6 ± 13.9	21.8	61.5 ± 13.7	22.3
Knee extension ROM (°)	83.8 ± 7.6	9.0	63.3 ± 10.5	16.6
Maximum knee flexion velocity ($°\cdot s^{-1}$)	362.9 ± 82.6	22.8	202.4 ± 55.1	24.9
Maximum knee extension velocity ($°\cdot s^{-1}$)	668.4 ± 81.0	12.1	584.5 ± 157.2	26.9
Duration of knee flexion (ms)	473.1 ± 180.3	38.1	810.0 ± 245.9	30.4

Duration of knee extension until ball impact (ms)	387.5 ± 66.4	16.6	395.3 ± 76.0	19.2

Notes: SD: standard deviation, CV: coefficient of variation, RK: rear knee, FK: front knee.

Results about relationships between knee kinematics and ball impact height show that knee joint angle at maximum flexion and knee extension ROM for both knees are significantly and strongly correlated with ball impact height (RK: r = -0.72 FK: r = -0.62; RK: r = 0.74 FK: r = 0.69). Moreover, maximum FK extension velocity and the duration of RK extension are moderately and weakly correlated with ball impact height, respectively (r = 0.53 and r = 0.42, respectively). No significant correlations were found between ball impact height and other knee kinematic parameters.

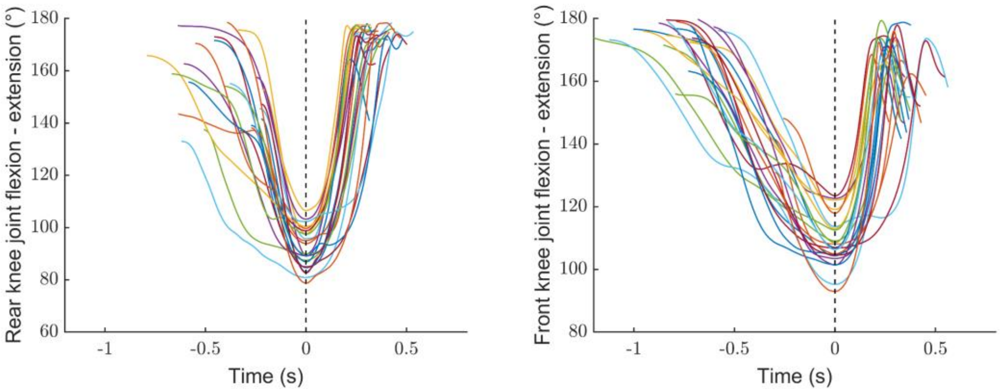

Figure 1. Mean RK joint angle (left) and mean FK joint angle (right) of each player (5 successful serves) from the start of flexion to ball impact position. To better visualize the durations of flexion and extension (until ball impact), time was represented in absolute values, starting from the point at which the knee joint angle reaches its minimum (dotted line). ***Notes*****: RK: rear knee, FK: front knee.**

DISCUSSION: Inter-individual variability in knee angles appear to be stable in players at the start of knee flexion, at maximum flexion, and at ball impact (Table 1). Our values of maximum knee flexion are close to those observed in professional female players, with the RK flexed at approximately 110 ± 8° and the FK at about 92° ± 8° (Whiteside et al., 2013). CV for RK and FK are approximately 7% and 8%, respectively.

The findings revealed that knee ROM, maximum knee velocity of the RK and durations of flexion / extension exhibit greater variability during flexion compared to extension. Figure 1 provides a visual representation of this result. In a previous study, Fleisig et al. (2003) showed a very high inter-individual variability (CV = 61%) in knee flexion ROM and a moderate variability (CV = 35%) in maximum knee extension velocity among twenty professional players. These values are greater than our findings, likely influenced by the fact that the two main leg drive techniques (foot-up and foot-back) were present in their sample which is not the case in our study. Elliott et al. (2003) showed that a minimum FK flexion ROM of 15° is recommended for an effective front leg drive. While flexion appears important, our results suggest that there are knee flexion ROM strategies that vary among players. This could suggest the existence of subtle individualities or "signature" patterns that may manifest during this phase (Kelso, 1999). Our findings also suggest that the acceleration phase (extension) seems to offer less scope for inter-individual variability. This is probably because of the need to generate a lot of maximum extension angular velocities to achieve the task's demand of hitting the ball as high as possible over the net.

Despite the low inter-individual variability found in knee joint angles at key instants, when we take a closer examination of the results, we observe that players flexing more their knees, achieving higher knee extension ROM, and producing greater maximum FK extension velocity, achieve a higher ball impact position. This aligns with the findings of Girard et al. (2007), who emphasized the important role of knee motion in serving effectiveness regardless of the players' skill levels. Our findings confirm the importance of leg flexion depth and leg extension velocity in enhancing serve impact height (Hornestam et al., 2021; Reid et al., 2008).

One limitation of our study is that we did not assess the physical capabilities of each player, which could provide more comprehensive insights into inter-individual variabilities. Quantifying these physical capacities would offer a more robust foundation in the exploration of the knee kinematics and their relationship with performance.

CONCLUSION: The inter-individual variability in knee motion was very pronounced during leg flexion. These findings emphasize the importance for coaches to provide more personalized instructions regarding knee action. While doing this, they must not overlook the importance of encouraging knee flexion in order to meet the task's demands. Further research is needed to ascertain the underlying factors contributing to this inter-individual variability, such as potential motor strategies employed during the serve, as well as the influence of physical capabilities and anthropometric parameters.

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ACKNOWLEDGEMENTS: This study was partially funded by the ANR within the framework of the PIA EUR DIGISPORT project (ANR-18-EURE-0022). The authors would like to thank the players who participated in the study.