# Effects of an Extrinsic Constraint on the Tennis Serve

**Pedro C. Mendes[1,2], Micael Santos Couceiro[2], Rúben Rocha[2,4], Filipe Manuel Clemente[3,4], Fernando Manuel Lourenço Martins[2,3,5], Rui Manuel Mendes[2,5] and Juan Pedro Fuentes García[6]**

[1]Research Centre for Sport and Physical Activity, University of Coimbra, Portugal
E-mail: mendespc@hotmail.com
[2]RoboCorp, Polytechnic Institute of Coimbra, ISEC, Portugal
[3]Polytechnic Institute of Coimbra, ESEC, Portugal
[4]Faculty of Sport Sciences and Physical Education, University of Coimbra, Portugal
[5]Instituto de Telecomunicações, Delegação da Covilhã, Portugal
[6]Sport Science Faculty. University of Extremadura, Caceres, Spain

**ABSTRACT**

This study analysed the extrinsic constraint of induced aerodynamic flow (IAF) on the first serve by expert tennis players with temporal organization of the movement, as well as the velocity and amplitude of the racket motion analyzed. Twelve expert right-handed tennis players voluntarily participated in this study. Each player performed 20 trials without IAF and another 20 trials for each different speed configuration of induced cross-wind: 2.4 m/s; 4.3 m/s; 5.8 m/s; and random speed. The coefficient of variation, r-pearson test and the inferential test one-way ANOVA were used to compare movement data. The results suggest spatio-temporal adjustments depending on the wind speed. Moreover, statistical differences were identified on both the temporal organization of the serve and on the racket's motion amplitude and velocity. The intra- and inter-individual variability of the motor behavior shows the uniqueness of the serve movement of each player.

**Key words:** Induced Aerodynamic Flow, Tennis Racket Motion, Variability, Wind Speed

## INTRODUCTION

Variability is an intrinsic characteristic of human movement systems and may be observed as the inability to accurately replicate two movements. Therefore, the repetition of a specific motor task is a unique and unrepeatable movement that emerges from given ecological

Reviewer: Bruce Elliott (University of Western Australia, Australia)

constraints [1, 2]. This perspective is not a limitation, but a great opportunity for new researches, to better understand dynamic motor behavior [3]. Moreover, the variability of the motor system constrains the self-organization of players, in order to adjust to a different kind of constraints (*e.g.*, organic, task and environment) [4]. These constraints are always existent in the human movement and, as such, self-organization is inevitable [5].

This theoretical approach has been accepted by many researchers that have studied tennis movements, to bridge the gap between theoretical knowledge and the practice involved in training and during a match [6, 7]. Girard et al. [8] analyzed the kinematic of first tennis serve, while constraining the knee flexion angle, while Menayo et al. [9] changed the type and size of the tennis racket and ball to assess the same movement. Nevertheless, although task constraints are usually easy to manipulate by coaches and researchers, the manipulation of environmental constraints is still a challenge [4]. Despite this experimental limitation, it is also important to understand how extrinsic constraints interact with the performance of tennis players [10, 6].

Among the many environmental constraints, the relevance of the wind in the tennis game is highlighted by several authors [11, 6, 12]. However, little or no scientifically based knowledge has been made so far. In our previous study [13] with experienced tennis coaches, we concluded that the wind is the most important environmental constraint in performance of the tennis serve. In this context, Brody et al. [14, 15] and the *American Sport Education Program* [16] analyzed, with some degree of importance, the three wind directions in the tennis serve: behind, against and cross wind to the player. The choice on studying the cross wind is justified by the physical limitations of the herein proposed experimental setup. On the other hand, there is only a small number of publications that have analyzed the variability of the racket motion in the tennis serve [17, 18]. For that reason, we considered it relevant to conduct this type of analysis with experienced tennis players, under the effect of crosswind.

The aim of this study is to analyze the intra- and inter-individual first serve performance variability of expert tennis players, while constrained by different crosswind speeds. Three process variables will be analyzed: *i*) temporal organization of the movement; *ii*) velocity of the racket motion; and *iii*) amplitude of racket motion. The concern about the intra- and inter-variability under these constrained conditions is in line with the recommendations of Davids et al. [5] regarding the study of motor behavior variability.

## METHOD

### SAMPLE

Twelve male, right-handed players of mean age 25.17 ±3.93 years participated in this study. The anthropometric characteristics of this group of players were as follows: height of 177±6 cm, wingspan of 181±5 cm and body mass of 72.29±4.17 kg. All players had participated in tennis for 16.25±5.56 years, of which 13.67 ± 4.29 years were competitive at the national level. The study was conducted according to the Ethics code of the University of Coimbra and the recommendations of the Helsinki Declaration on Research with Human Beings.

### TASK

The movement under study was the flat serve from behind the base line of the tennis court, on the right-hand side and 80 cm away from the central mark. The indoor tennis court had the standard dimensions for a singles game (2377 cm long and 823 cm wide). All the participants were asked to serve at maximum speed and accuracy, targeting the intersection point between the center line and the service line (also known as "*T*-point").

In order to prepare the participants for the task, each had a five minute warm-up followed by a period of five minutes to perform eight serves at increasing intensity: the first four serves were with low intensity, the following two serves with medium intensity and the last two serves with full intensity. During all the procedures, including data collection, players did not receive any verbal information on the quality of the movement or the outcome of the test, although they could see where the ball landed.

## EXPERIMENTAL SETUP

Following the warm up, players executed 20 free serves as a control condition (i.e., without instructional or wind constraints – IAF0). Afterwards, they performed four sets of 20 serves under different practice conditions: 1) minimum induced aerodynamic flow from left to right and parallel to the baseline (IAF) speed of 2.4 $ms^{-1}$ (called IAF1); 2) medium IAF speed of 4.3 $ms^{-1}$ (called IAF2), 3) maximum IAF speed of 5.8 $ms^{-1}$ (called IAF3) and; 4) random IAF speed with random sequences of all three IAF speeds (called IAFr). Therefore, each player executed a total of 100 serves. We previously conducted a pilot study with three competitive players and there were no decrease in performance (speed and serve accuracy) between the control condition and the last set of trials [19].

In the first series of 20 serves the players served without IAF and then, they served 20 times in each condition in a counterbalance of the four following conditions: minimum, medium, maximum and random cross-winds (i.e., variation of the three speeds of IAF). They had a recovery time of 20 seconds between the serves or trials and 180 seconds between the 5 different conditions (following the rules of change between court sides).

In this study, we analyzed the racket motion based on a single head medium point in the three axes (cf., red point in Figure 1).

## INDUCED AERODYNAMIC FLOW DEVICE

The development of the IAF device was adapted from an industrial helical ventilator *METEC - HCT - 45 - 4T*[1]. The speed of the engine was set up using an electronic speed variator (*SEW Eurodrive*[2]) installed on the ventilator with an 11-positions potentiometer. In order to regulate the air flow, a steel mesh of 0.045 m was adapted to an air duct of 1.20 m length and 0.45 *m* diameter [7] which was connected to the ventilator's output.

Our setup also considered the differences between players' heights and, as a consequence, the variations in the ball toss. As the ventilator was limited to a diameter of 0.45 m, a telescopic lift *GUILE ELC – 506*[3] was used to adjust the height of the ventilator up to a maximum of 5.20 m. The calibration of the ventilator for each tennis player was made based on a preliminary study, which consisted on analyzing the average of the highest point of the ball in 20 serves and determining the average impact point [7].

The ventilator had a stable air flow rate of 0.60 m diameter, independently of the position of the potentiometer. It was stipulated that the upper edge of the conduct would be positioned at the average level of the highest point reached by the ball during the toss.

## ANALYSIS DEVICE

The recording of the racket motion was obtained from two cameras: 1) a camera in the sagittal plane of the tennis player: *Casio Exilim Pro EX-F1*[4], operating at 210 Hz, positioned 7.005 m away from the service mark and fixed on a tripod 2.065 m high (viewpoint from

[1] http://www.metec.pt/pdf_metec_semi/axiais/hct_hch_pt.pdf
[2] http://www.seweurodrive.com/
[3] http://www.guil.es/img/ELC-506.pdf
[4] http://www.fastplus.sk/sites/default/files/casio_ex_f1.pdf

Figure 1); and (2) a camera in the frontal plane, positioned behind the player: *Casio EX-FH25*[5], also operating at 210 Hz, positioned 3.63 m away from the tennis player and fixed on a tripod 2.63 m high. The cameras were synchronized using a common light-emitting diode (LED) as a visual [20, 21] trigger.

A 3D analysis of the collected images was carried out, with a maximum error of 0.01 m, i.e., the furthest plane from the camera presented a resolution of 1 cm$^2$ per pixel (Figure 1). The space was calibrated using Matlab (version *2009R*), in which a physical structure (parallelepiped) with a 2.50 × 2.50 m base and 3.20 m height was used as the reference system. In other words, the workspace was calibrated considering the eight vertices of the structure with a predefined relation between metric and virtual dimensions [7, 20]. A script, which included the automatic loading of the captured images, was developed to calculate the position and real-world coordinates on each axis by manually clicking on the desired points. According to the studies of Reid et al. [18], we chose the position of the left foot at the beginning of the serve, as the origin of the reference system; i.e., 0.80 m away from the central mark of the court. After capturing the serve, the physical space was calibrated using direct linear transformation (*DLT*), which transforms the position of the tennis racket in pixels into the metric space, thus obtaining the Cartesian positioning over time. For a more detailed description of the 3D analysis, please refer to Mendes et al [20].

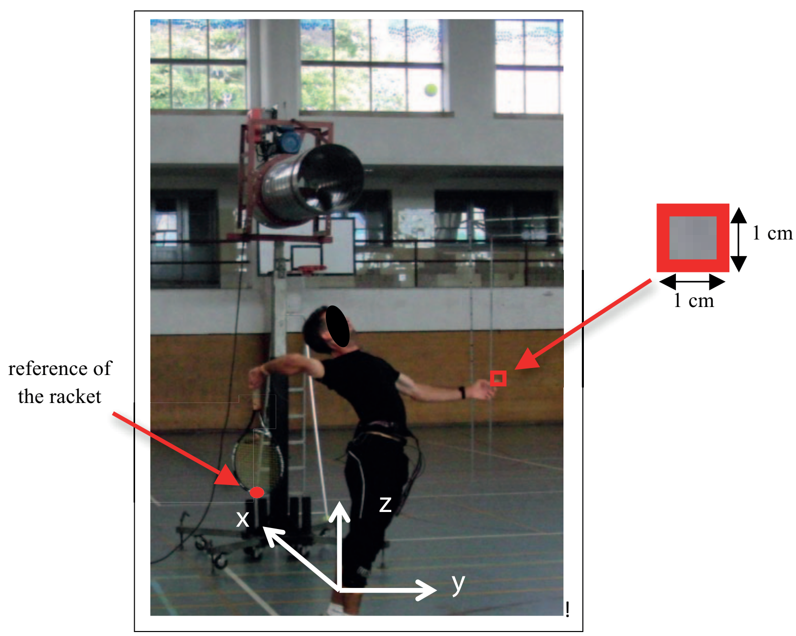


Figure 1. Three-dimensional reference system for the analysis of the racket motion of the players

By using a fitting function for the *z*-axis (vertical dimension of the racket motion), it was possible to determine each phase of the serve: preparation, backswing, forward swing (acceleration), time of impact on the ball and follow through. Those serve phases are in line

[5] http://support.casio.com/en/manual/001/EXFH25_M10_FB_EN.pdf

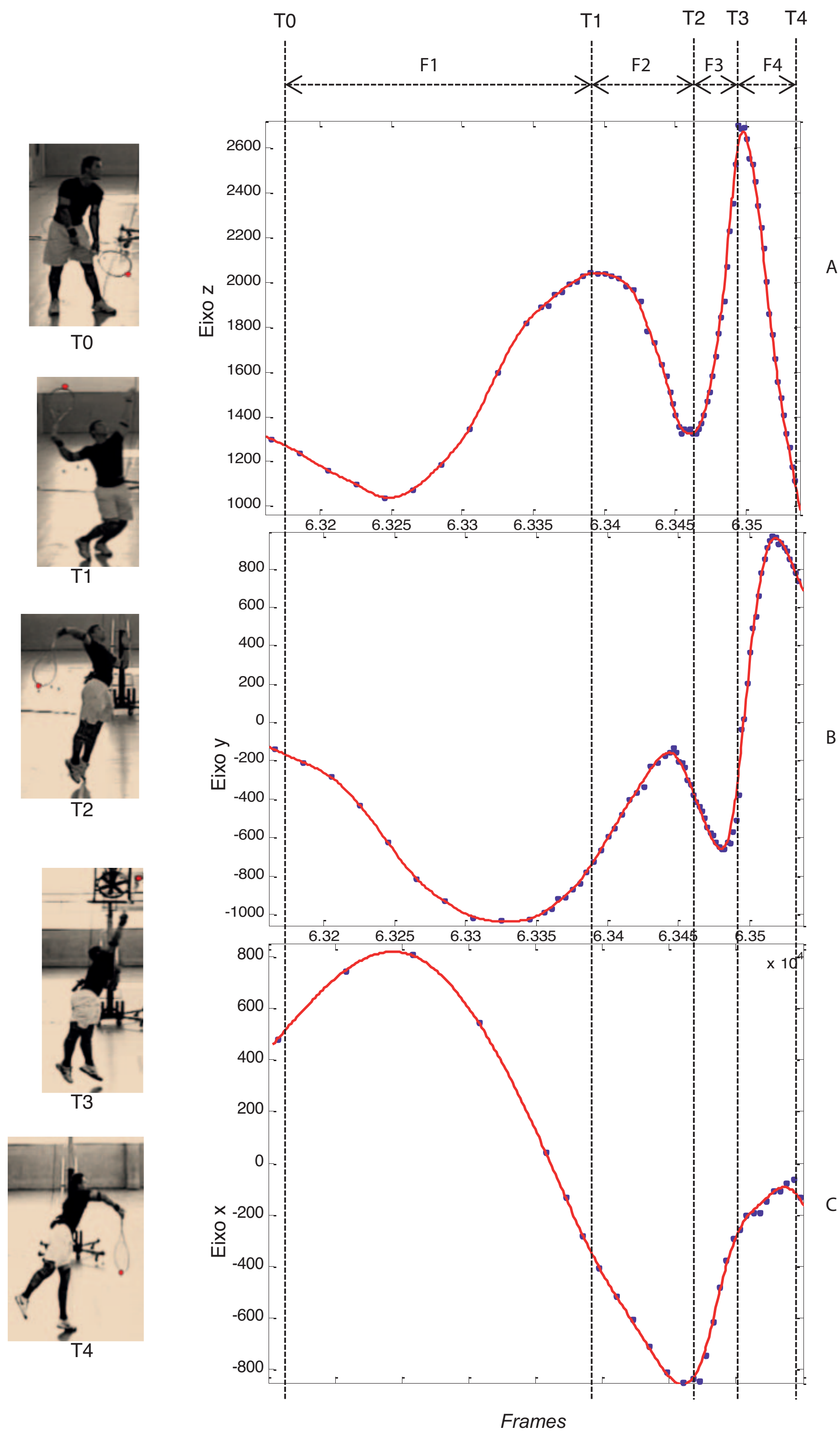


Figure 2. A – Curve of racket trajectory on y-axis; B – Curve of racket trajectory on z-axis; C – Curve of racket trajectory on x-axis

with the work of Chow et al. [22] and Bonnefoy et al. [23].

The backswing phase was identified between the beginning of movement (T0) and the higher racket position before the impact on the ball (T1) (see Figure 2). The downswing phase was measured between the higher racket position before the impact on the ball (T1) and the lower racket position (T2). The acceleration phase was measured between the lower racket position (T2) and the impact on the ball (T3). The follow through was measured between the impact on the ball (T3) and the moment of foot reception on the court (T4) (see Figure 2).

### STATISTICAL ANALYSIS

The variability analysis of the racket motion was completed for each axis, that is, in a one-dimensional way. The variability was measured using the standard deviation (SD) and the coefficient of variation (CV).

Also, following the conjecture of a one-dimensional analysis (axis-by-axis), the statistically significant differences between the 5 conditions of practice for each player (intra-individual analysis), in the temporal organization of movement and in the parameters of speed and amplitude of racket motion, were assessed using a one-way analysis of variance (ANOVA). The Scheffé post-hoc test was used whenever the assumptions of normality and homogeneity were verified, whereas when the assumption of homogeneity was not observed, the Games-Howell post-hoc test was used. As the samples were below 30, the assumption of normality was verified using the Shapiro-Wilk test [24]. In situations where the normality was not verified, we analyzed the symmetry under the following assumption:

$$|\text{skewness/std errorskewness}| \leq 1.96 \quad [24]$$

Levene's test was used to verify the assumption of homogeneity of the one-way ANOVA. This analysis was performed using the IBM program *SPSS* (version 19) for a significance level of 5%. The effect size, $\eta^2$, was also estimated; i.e., the proportion of variation of the independent variable which is explained by the dependent variable [24].

In order to analyze the correlation between quantitative variables, a statistical *r*-pearson test was carried out, thus checking and verifying the assumptions of normality and homogeneity (as previously described for the analysis of variance).

## RESULTS

From the 3D racket motion, it was possible to analyze the temporal tennis serve organization, as well as the linear speed and the amplitude of the racket's motion on each axis (see Figure 2).

### TEMPORAL SERVE ORGANIZATION

On the inter-individual analysis, we did not observe any statistical differences between the control condition (IAF0) and the other IAF task conditions on the ascending windup duration phase and descending windup duration phase. It was also possible to observe that there were no statistical differences on the inter-individual analysis of the swing and movement durations (Table 1). On the acceleration phase, it was possible to observe statistical differences on the inter-individual analysis between IAF0 condition and IAF1 (*p*-value = 0.001) and IFA2 (p-value = 0.001). In both cases, the acceleration phase was performed faster than in the IAF0 condition (see Table 1). It was also possible to observe statistical differences between the five task conditions in the early follow through phase (landing duration), being smaller for the IAF1 condition (p-value = 0.02).

Table 1. Descriptive statistics of process variables from 12 players on 5 task conditions

| (n = 240) | IAF0 | | | IAF1 | | | IAF2 | | | IAF3 | | | IAFr | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variable** | $\bar{X}$ | **SD** | **CV** | $\bar{X}$ | **SD** | **CV** | $\bar{X}$ | **SD** | **CV** | $\bar{X}$ | **SD** | **CV** | $\bar{X}$ | **SD** | **CV** | $F_{(4,1195)}$ | $p$ | $\eta^2$ |
| Aw_P1 (s) | 0.871 | 0.158 | 18.14 | 0.861 | 0.166 | 19.28 | 0.863 | 0.168 | 19.47 | 0.853 | 0.169 | 19.81 | 0.853 | 0.163 | 19.11 | 0.672 | 0.612 | 0.02 |
| Dw_P2 (s) | 0.230 | 0.125 | 54.34 | 0.239 | 0.122 | 51.04 | 0.244 | 0.129 | 52.87 | 0.232 | 0.127 | 54.74 | 0.244 | 0.126 | 51.64 | 0.672 | 0.611 | 0.02 |
| Acc_P3 (s) | 0.131 | 0.012 | 9.16 | 0.129 | 0.012 | 9.30 | 0.129 | 0.013 | 10.07 | 0.129 | 0.011 | 8.52 | 0.129 | 0.016 | 12.40 | 5.544 | 0.001** | 0.02 |
| Lan_P4 (s) | 0.110 | 0.031 | 28.18 | 0.101 | 0.031 | 30.69 | 0.107 | 0.027 | 25.23 | 0.103 | 0.033 | 32.04 | 0.110 | 0.031 | 28.18 | 4.330 | 0.002** | 0.014 |
| SD (s) | 1.23 | 0.15 | 11.79 | 1.23 | 0.15 | 12.52 | 1.22 | 0.16 | 12.75 | 1.22 | 0.15 | 12.55 | 1.23 | 0.15 | 12.31 | 0.281 | 0.890 | 0.001 |
| MD (s) | 1.34 | 0.15 | 10.88 | 1.33 | 0.16 | 11.86 | 1.33 | 0.16 | 11.82 | 1.33 | 0.16 | 11.92 | 1.34 | 0.16 | 11.87 | 0.517 | 0.723 | 0.002 |

Note. Aw_P1 = Ascending windup duration. Dw_P2 = Descending windup duration. Acc_P3 = Acceleration duration. Lan_P4 = early follow-through/ landing duration. SD = Sing Duration. MD = Movement duration. $\bar{X}$ = average (cm); SD = Standard deviation (cm). CV = coefficient of variation (%). IAF0 = "without wind". IAF1 = 2.4m/s. IAF2 = 4.3 m/s. IAF3 = 5.8 m/s. IAFr = random wind velocity
*$p < 0.05$ **$p < 0.01$

An intra-individual analysis was also carried out with one-way ANOVA. Under such analysis it was possible to find statistical differences between the IAF0 and the other four IAF conditions in 10 tennis players. A decrease of the duration of the ascending windup phase in conditions IAF2 and IAF3 was observed in five of those players and in conditions IAFr and IAF1 in four of them. The results also show a time decrease of ascending windup phase in five players on conditions IAF2 and IAF3, and in four players on conditions IAFr (random wind) and IAF1. Such a decrease in the duration of the acceleration phase showed statistical differences in four players between the conditions IAF0 and IAF3, and in three players on the remaining conditions. In the descendent and early follow-through phases, it was not possible to find a clear intra-individual decreasing or increasing tendency on the IAF constraints.

On the correlation analysis regarding the duration of each serve phase, the relations between the swing duration (SD) and acceleration (Acc_P3), ascending windup (Aw_P1) and the movement duration (MD) were characterized by the moderate, large and nearly perfect intensities, being always linear and positives on the five task conditions. Regarding the SD and the descending windup (Dw_P2), the intensities were low but still linear and positive in all task conditions (see Table 2).

Table 2. Relations between SD and variables of time serve on 5 task conditions

| **IAF (n=240)** | **SD IAF 0** | **SD IAF 1** | **SD IAF 2** | **SD IAF3** | **SD IAFr** |
|---|---|---|---|---|---|
| Aw_P1 (s) | 0.617** | 0.673* | 0.634** | 0.654** | 0.624** |
| Dw_P2 (s) | 0.323** | 0.291** | 0.329** | 0.274** | 0.349** |
| Acc_P3 (s) | 0.524* | 0.472** | 0.446** | 0.598** | 0.353** |
| Lan_P4 (s) | — | — | — | — | — |
| Movement duration (s) | 0.977** | 0.981** | 0.985** | 0.978** | 0.976** |

Note. See Table 1 for other abbreviations
$*p < 0.05$ $**p < 0.01$

The relation between the swing duration (SD) and the early follow through phase (Lan_P4) is very small and nonlinear (p-value> 0.05).

## RACKET'S AMPLITUDE AND MAXIMAL VELOCITY

No statistical differences were found in the racket's amplitude of movement on both vertical and horizontal axes (Amp_z e Amp_y) between the control condition (IAF0) and the other IAF conditions. However, the racket's amplitude on the lateral axis (Amp_x) depicted statistical differences between conditions IAF and IAF1, wherein the players performed the serve with a smaller amplitude in this axis for a small increase of the cross wind speed (see Table 3).

On the intra-individual analysis, it was possible to observe a statistical tendency to decrease the horizontal racket's amplitude on four players, mainly on IAF2 and IAF3 conditions. About the lateral dimension, it was possible to observe a uniform player behavior for three participants. Nevertheless, despite the observed statistical differences in some of the players under the IAF0 and the other four IAF conditions, it was not possible to observe an intra-individual tendency on the Amp_z variable.

Table 3. Descriptive statistics of kinematic variables of 12 tennis players in 5 task conditions

| (n = 240) | IAF0 | | | IAF1 | | | IAF2 | | | IAF3 | | | IAFr | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variable** | $\bar{X}$ | **SD** | **CV** | $\bar{X}$ | **SD** | **CV** | $\bar{X}$ | **SD** | **CV** | $\bar{X}$ | **SD** | **CV** | $\bar{X}$ | **SD** | **CV** | $F_{(4,1195)}$ | $p$ | $\eta^2$ |
| Amp_z (cm) | 228.77 | 14.39 | 6.29 | 227.06 | 12.94 | 5.70 | 228.49 | 15.19 | 6.65 | 230.40 | 14.42 | 6.26 | 228.94 | 12.74 | 5.56 | 1.746 | 0.138 | 0.006 |
| Amp_y (cm) | 297.80 | 45.73 | 15.36 | 293.08 | 48.35 | 16.50 | 293.03 | 45.06 | 15.45 | 291.74 | 47.53 | 16.29 | 291.68 | 46.01 | 15.77 | 0.700 | 0.592 | 0.002 |
| Amp_x (cm) | 152.56 | 53.69 | 35.19 | 140.00 | 43.31 | 30.94 | 142.05 | 42.79 | 30.12 | 144.38 | 49.93 | 34.58 | 141.52 | 47.25 | 33.39 | 2.634 | 0.033* | 0.002 |
| Vel_z (m/s) | 28.99 | 4.66 | 16.07 | 29.15 | 4.25 | 14.58 | 28.68 | 4.53 | 15.79 | 29.55 | 4.23 | 14.31 | 27.90 | 3.68 | 13.19 | 4.953 | 0.001** | 0.016 |
| Vel_y (m/s) | 26.92 | 2.51 | 9.32 | 28.53 | 3.82 | 13.39 | 28.01 | 2.96 | 10.57 | 28.73 | 3.17 | 11.03 | 27.93 | 3.63 | 13.00 | 11.211 | 0.001** | 0.036 |
| Vel_x (m/s)) | 19.52 | 12.26 | 62.81 | 15.47 | 7.46 | 48.22 | 16.39 | 8.84 | 53.94 | 17.22 | 7.33 | 42.57 | 15.39 | 9.42 | 61.21 | 7.781 | 0.001** | 0.025 |

Note. Amp_z – Racket amplitude in the vertical (z) axis; Amp_y – Racket amplitude in the horizontal (y) axis; Amp_x – Racket amplitude in the lateral (x) axis; Vel_z – Maximal racket velocity in the vertical (z) axis; Vel_y – Maximal racket velocity in the vertical (z) axis; Vel_x – Maximal racket velocity in the vertical (z) axis. See Table 1 for other abbreviations

*$p < 0.05$ **$p < 0.01$

Statistical differences were recorded for the maximal vertical racket's velocity (Vel_z), between the control condition (IAF0) and the IAFr condition (p-value=0.006). The "random crosswind" (IAFr) resulted in lower values of Vel_z. Despite most players presenting statistically significant differences under the five practice conditions, it was not possible to observe an intra-individual tendency on this variable.

The Vel_y variable showed statistical differences on the five task conditions, namely between the condition IAF0 and IAF1 (p-value=0.001), IAF2 (p-value=0.001), IAF3 (p-value=0.001) and IAFr (p-value=0.004). Players constrained by cross wind generally executed the serve at higher speed on the *y*-axis, Vel_y.

On the *x*-axis, more specifically regarding the Vel_x variable, it was once again possible to observe statistical differences between IAF0 and conditions IAF1 (p-value=0.001), IAF2 (p-value=0.012) and IAFr (p-value=0.001). Players reacted to the cross wind by reducing the speed on the lateral axis, Vel_x.

A correlation analysis was then performed between different variables. The correlation analysis between Vel_y and Acc_P3 returned linear and negative relations under all practice conditions. Nevertheless, the correlation levels were larger on both IAF2 and IAF3 conditions. The relations between Vel_y and SD were linear, negative and moderate (see Table 4).

Table 4. Relation between $Vel_{\_y}$ and the time variables of acceleration phase (Acc_F3) and swing duration (SD) on five practice conditions

| EAI (n=240) | $Vel_{\_y}$ | $Vel_{\_y}$ | $Vel_{\_y}$ | $Vel_{\_y}$ | $Vel_{\_y}$ |
|---|---|---|---|---|---|
| | IAF 0 | IAF 1 | IAF 2 | IAF3 | IAFr |
| Acc_P3 | -0.290** | -0.306** | -0.577* | -0.508** | -0.324** |
| SD | -0.512** | -0.510** | -0.405** | -0.455** | -0.372** |

Note. See Table 1 for other abbreviations
*$p < 0.05$ **$p < 0.01$

## DISCUSSION

The temporal movement structure analysis of the tennis serve has been studied by many researchers [23, 18, 26]. As previously observed, the racket's position during the tennis serve was the criterion used to define each movement phase: i) ascending windup; ii) descending windup; iii) acceleration; and iv) early follow through or landing [23, 22, 18]. The ascending windup showed a higher time duration when compared with the remaining phases. This result is in line with studies by Chow et al. [22], Girard et al. [26] and Reid et al. [18] on elite tennis players.

The inter-individual analysis did not showed any statistical differences on the duration of the preparation phase between the IAF0 and the remaining IAF conditions. Nevertheless, there is a decreasing tendency on the duration of the movement. It was also possible to observe a strong, linear and positive correlation between ascending windup (Aw_P1) and swing duration standard deviation (SD) in all task conditions. Therefore, these players performed shorter preparations, thus carrying out the impact on the ball sooner than in the no wind condition.

In comparison with the other serve phases, the ascending windup phase was the one depicting the highest intra-individual variability on any condition constrained by IAF. This higher variability at the beginning of the movement is in accordance to other tasks, such as table tennis [27] and cricket bowling [28].

On the acceleration phase (Acc_P3), players tend to reduce the movement time, showing inter-individual statistical differences on conditions IAF1 and IAF3. In line with the previous analysis carried out for the ascending windup phase, the swing duration (SD) and the acceleration duration (Acc_P3) phases have positive and linear correlation, wherein the higher value are observed in the higher wind task condition (moderate correlation). These variations on the acceleration phase (concentric phase) were also reported by Girard et al. [26] between novices and elite players. The expert players depicted shorter concentric phases [26].

This significant reduction of the Acc_P3 observed in some players on conditions with IAF (intra-individual analysis), as well as the smaller duration of the swing, may suggest an adaptation of players to anticipate the ball impact local in situations of stronger wind and random situations. On the other hand, these results are not in line with Bootsma and Van Wieringen [27], Davids et al. [28] and Laurent et al. [30], in which the authors observed small variability levels on the ball impact moment. Expert players that participated in these studies showed a convergent control (funnel-like type of control) [18], in order to adjust the impact in interceptive skills (e.g., forehand in table tennis). Nevertheless, as the constraints considered on such researches do not affect the ball's trajectory, they maintain the temporal movement structure.

On the descending windup and early follow through phases, it was not possible to observe a clear intra-individual tendency induced by the IAF constraints. Nevertheless, these phases showed a higher intra-trial (trial-to-trial) variability with higher coefficient of variation in some players. On a study performed by Koenig et al. [29] on the golf swing, it was also possible to observe an increasing variability on the medial downswing point and on the early follow through phase, thus supporting the insights presented in this tennis study.

The intra-individual analysis of the racket's motion amplitude on the vertical component (Amp_z) showed its stability on the five practice conditions. Nevertheless, despite the statistical differences observed in some players when constrained by the wind (IAF), any intra-individual tendency in the adjustment process was verified. These results are in line with the positional stability of the ball impact point on the vertical dimension observed by Reid et al. [18] and Mendes et al. [21]

Four players reduced the racket's amplitude on the horizontal and lateral components when facing cross wind constraints. These players reduced the amplitude of the serve in order to achieve a satisfactory synchronization level, simplifying the action rhythm (adjusting the body segments coordination). Considering the results obtained, it is possible to conclude that some players follow the redundancy of the degrees-of-freedom described by Bernstein [1], seeking an optimized control of shoulder and elbow joints, thus simplifying the kinetic chain coordination [31]. As such, the spatio-temporal motor redundancy have been observed on reception tasks for different ball's speeds [32, 33] and even in timing perceptive tasks, such as hitting a target in movement [34, 35].

Finally, the intra-trial analysis depicted a lower stability of Vel_x, thus suggesting a higher number of spatial adjustments in the presence of the experimental device. On the other hand, Girard et al. [17] observed a great stability on the racket's amplitude on the tennis serve (right and left) and on player's centre-of-gravity. Nevertheless, as those movements are open-tasks, they present a large range of adjustments based on the trajectory to the ball. On the tennis serve, as this range of trajectories is not allowed, the adjustment to possible perturbations is performed in line with the kinetic chain and with the racket's motion.

The players constrained by IAF showed a decreasing tendency of on the maximal velocity peak within the lateral and vertical (only in the random condition) dimensions and an increasing on the depth dimension. On the other hand, the intra-individual analysis suggests a polarization of motor solutions; i.e., players that serve with higher values of maximal velocity on the vertical (Vel_z) and the lateral (Vel_x) dimensions differ from other players depicting lower values. Regarding the environment, players are able to perceive that the ball's trajectory perturbations resulted from the IAF are from the left to right and, as such, players performed a faster movement in depth (*y*-axis) to anticipate the impact on the ball.

It was observed a relationship between Vel_y and the acceleration duration phase and swing duration (SD). This is an expected outcome since the Vel_y occurs immediately before the impact on ball (0.005s according to Elliott et al. [36]). These relations were linear, negative and statistical significant. Therefore, the increase in Vel_y is related with the decreasing tendencies observed in both SD and acceleration phase. On the other hand, the players constrained by an extrinsic perturbation (IAF) self-organize their motor system in order to emerge a compensatory behavior increasing the Vel_y. This behavior aims to improve the spatio-temporal racket's adjustment in the moment of impact on ball. These factors are important because the environmental changes may influence the movement patterns. In the present study, the experimental lateral wind conditions (left to right in right-handed tennis players) influenced the action parameters of service patterns on expert tennis players.

The IAF is a useful constraint to avoid the plateau effect on expert tennis players' serve [10]. Thus, coaches can use some strategies to improve the serve maximal velocity in conditions of crosswind in order to reduce the effects of this constraint, increasing the racket's Vel_y. As a determinant to the post-impact serve velocity [38], the horizontal dimension (y-axis) may be used to constraint tennis players on training using non-linear pedagogies that increase the adjustment to the environmental and task constraints [39].

In a previous study we also analyzed the impact of the crosswind constraint (IAF) on the tennis serve performance of these players [20]. In this work, no differences were observed on the accuracy and precision with constant (IAF1, IAF2, IAF3) and random crosswind (IAFr). Therefore, it seems that the variation noted in the x and y axes "was not enough" to produce statistical differences in the serve's accuracy and precision.

## CONCLUSION

This study has been able to illustrate that extrinsic IAF constraint (artificial cross wind) modifies the temporal organization of the tennis serve. Considering this perturbation, it was possible to observe a shorter racket's preparations, as well as faster acceleration phase. Moreover, it was possible to observe a decreasing swing time to impact. It was also possible to observe that some players reduced the racket's amplitude on lateral (*x*-axis) and depth (*y*-axis) dimensions on services influenced by the IAF effect. The IAF constrained compensatory movements in the tennis serve. This was observed on spatio-temporal trajectory adjustments on racket's trajectories and resulted from Vel_*y* increasing.

The results obtained from this study allowed identification of the importance of this constraint for tennis training and competition. The crosswind used in this study allowed a functional variability for players and not an extreme variability, thus being an interesting constraint to be used by coaches on tennis training for expert players.

## ACKNOWLEDGEMENTS

We would like to thank Cátia Costa, Jonathan Gonçalves, Anabela Santos, Francisco Corbi, Vicente Baltrán, Ruperto Menayo, Carlos Figueiredo and Miguel Luz for their valuable assistance in data collection.

## REFERENCES


1. Bernstein, N., *The Coordination and Regulation of Movement*, Pergamon Press, New York, 1967.
2. Latash, M., Scholz, J. and Schöner, G., Motor Control Strategies Revealed in the Structure of Motor Variability, *Exercise and Sport Sciences Reviews*, 2002, 30(1), 26-31.
3. Riley, M.A. and Turvey, M.T., Variability and Determinism in Motor Behaviour, *Journal of Motor Behaviour*, 2002, 34(2), 99-125.
4. Newell, K.M., Constraints on the Development of Coordination, in: *Motor Development in Children: Aspects of Coordination and Control*, Martinus Nijhoff, Boston, 1986, 341-360.
5. Davids, K., Glazier., P., Araújo, D. and Bartlett, R., Movement Systems as Dynamical Systems: The Functional Role of Variability and its Implications for Sports Medicine, *Sports Medicine: Reviews of Applied Medicine and Science in Sport and Exercise*, 2003, 33(4), 245-260.
6. Elliott, B., Reid, M. and Crespo, M., *Technique Development in Tennis Stroke Production*, International Tennis Federation, London, 2009.
7. Mendes, P., Mendes, R., Coelho e Silva, M.J., Luz, M., Dias, G. and Couceiro, M., Dispositivo de Escoamento Aerodinâmico Induzido para Análise do Desempenho do Serviço de Ténis, *Revista da Educação Física*, 2013, 24(1), 193-208.
8. Girard, O., Micallef, J. and Millet, G., Influence of Restricted Knee Motion During the Flat First Serve in Tennis, *The Journal of Strength and Conditioning Research*, 2007, 21(3), 950-957.
9. Antúnez, R., Hernández, F., García, J., Vaíllo, R. and Arroyo, J., Relationship Between Motor Variability, Accuracy, and Ball Speed in the Tennis Serve, *Journal of Human Kinetics*, 2012, 33, 45-53, 2012.
10. Davids, K., Button, C. and Bennett, S. J., *Dynamics of Skill Acquisition: A Constraints-Led Approach*, Human Kinetics Publishers, Champaign, Illinois, 2008.
11. Hoskins, T., The Tennis Drill Book, *Human Kinetics*, Champaign, Illinois, 2003.
12. Loehr, J., How to Battle the Elements, *Tennis*, 1996, 32(7), 40.
13. Mendes, P., Mendes, R., Fuentes, J., Campos, F., Menayo, R. and Araújo, D., Fatores de Rendimento no Primeiro Serviço em Tenistas de Competição, *Revista da Educação Física*, 2011, 22(3), 315-326.
14. Brody, H., *Tennis Science for Tennis Players*, University of Pennsylvania Press, Philadelphia, 1987.
15. Scott, W. and Randy, P., Serious Tennis, *Human Kinetics*, Champaign, 2000.
16. Program, A.S.E., Coaching Tennis Technical and Tactical Skills, *Human Kinetics*, Champaign, 2009.
17. Girard, O., Leroy, D., Thouvarecq, R., Mégrot, F. and Stein, J.F., Movement-Production Strategy in Tennis: A Case Study, *The Journal of Strength and Conditioning Research*, 2010, 24(7), 1942-1947.
18. Reid, M., Whiteside, D. and Elliott, B., Effect of Skill Decomposition on Racket and Ball Kinematics of the Elite Junior Tennis Serve, *Sports Biomechanics*, 2010, 9(4), 296-303.
19. Mendes, P.C., O Efeito do Constrangimento Escoamento Aerodinâmico Induzido na Variabilidade do Primeiro Serviço Plano em Tenistas Experientes, Unpublished PhD Thesis, Faculty of Sport Sciences and physical Education - University of Coimbra, Coimbra, Portugal, 2012.
20. Mendes, P.C., Dias, G., Mendes, R., Mendes, F.M.L., Couceiro, M.S. and Araújo, D., The Effect of Artificial Side Wind on the Serve of Competitive Tennis Players, *International Journal of Performance Analysis in Sport*, 2012, 12(3), 546-562.
21. Mendes, P.C., Fuentes, J.P., Mendes, R., Martins, F.M., Clemente, F.M. and Couceiro, M.S., The Variability of The Serve Toss in Tennis Under the Influence of Artificial Crosswind, *Journal of Sports Science and Medicine*, 2013, 12, 309-315.
22. Chow, J.W., Shim, J.H. and Lim, Y.T., Lower Trunk Muscle Activity During the Tennis Serve, *Journal of Science and Medicine in Sport*, 2003, 6(4), 512-516.
23. Bonnefoy, A., Slawinski, J., Leveque, J.M., Riquet, A. and Miller, C., Relationship Between the Vertical Racquet Head Height and the Lower Limb Motions of Elite Players' Flat Serve, *Computer Methods in Biomechanics and Biomedical Engineering*, 2009, 12(1), 55-57.

24. Pallant, J., *SPSS Survival Manual: A Step by Step Guide to Data Analysis Using the SPSS Program*, Allen & Unwin, Australia, 2011.

25. Hopkins, K.D., Hopkins, B.R. and Glass, G.V., *Basic Statistics for the Behavioral Sciences*, Allyn and Bacon, Boston, 1996.

26. Girard, O., Micallef, J. and Millet, G., Lower-Limb Activity During the Power Serve in Tennis: Effects of Performance Level, *Medicine and Science in Sports and Exercise*, 2005, 37, 1021-1029.

27. Bootsma, R.J. and Van Wieringen, P.W.C., Timing an Attacking Forehand Drive in Table Tennis, *Journal of Experimental Psychology: Human Perception and Performance*, 1990, 16, 21-29.

28. Davids, K., Renshaw, I. and Glazier, P., Movement Models from Sports Reveal Fundamental Insights into Coordination Processes, *Exercise and Sport Sciences Reviews*, 2005, 33(1), 36-42.

29. Koenig, G., Tamres, M. and Mann, R.W., The Biomechanics of the Shoe-Ground Interaction in Golf, in: Cochran, A.J. and Farrally, M.R., eds., *Science and Golf II - Proceedings of the World Scientific Congress of Golf*, E & FN Spon, London, 1994, 40-45.

30. Laurent, M., Montagne, G. and Savelsbergh, G.J.P., The Control and Co-ordination of One-Hand Catching: The Effect of Temporal Constraints, *Experimental Brain Research*, 1994, 101, 314-322.

31. Reid, M., Whiteside, D. and Elliott, B., Hitting to Different Spots on the Court: The Ball Kinematics of Professional Tennis Service, *Portuguese Journal of Sport Sciences*, 2011, 11(2), 373-376.

32. Mazyn, L.I.N., Montagne, G., Savelsbergh, G.J.P. and Lenoir, M., Reorganization of Catching Coordination Under Varying Temporal Constraints, *Motor Control*, 2006, 10, 143–159.

33. Tijtgat, P., Bennett S.J., Savelsbergh, G.J., De Clercq, D. and Lenoir, M., Advance Knowledge Effects on Kinematics of One-handed Catching, *Experimental Brain Research*, 2009, 201, 875–884.

34. Tresilian, J.R. and Lonergan, A., Intercepting a Moving Target: Effects of Temporal Precision Constraints and Movement Amplitude, *Experimental Brain Research*, 2002, 142, 193-207.

35. Tresilian, J.R., Plooy, A.M. and Marinovic, W., Manual Interception of Moving Targets in Two Dimensions: Performance and Space-time Accuracy, *Brain Research*, 2009, 1250, 202-217.

36. Elliot, B., Marshal, R. and Noffal, G., Contribution of Upper Limb Segment Rotations During the Power Serve in Tennis, *Journal of Applied Biomechanics*, 1995, 11, 433-442.

37. Warren, W.H., The Perception-Action Coupling, in: Bloch, H. and Bertenthal, B.I., eds., *Sensory-Motor Organizations and Development in Infancy and Early Childhood*, Kluwer Academic Publishers, Dordecht, 1990, 23-37.

38. Tanabe, S. and Ito, A., A Three-Dimensional Analysis of the Contributions of Upper Limb Joint Movements to Horizontal Racket Head Velocity at Ball Impact During Tennis Serving, *Sports Biomechanics*, 2007, 6(3), 418-433.

39. Farrow, D. and Reid, M., Skill Acquisition in Tennis. Equipping Learners for Success, in: Renshaw, I., Davids, K. and Savelsbergh, G.J.P., eds., *Motor Learning in Practice: A Constraints-Led Approach*, Routledge, London, 2010, 231-240.