International Journal of Performance Analysis in Sport

ISSN: 2474-8668 (Print) 1474-8185 (Online) Journal homepage: https://www.tandfonline.com/loi/rpan20

The effect of artificial side wind on the serve of competitive tennis players

C. Pedro Mendes, Gonçalo Dias, Rui Mendes, Fernando M. L. Martins, S. Micael Couceiro & Duarte Araújo

To cite this article: C. Pedro Mendes, Gonçalo Dias, Rui Mendes, Fernando M. L. Martins, S. Micael Couceiro & Duarte Araújo (2012) The effect of artificial side wind on the serve of competitive tennis players, International Journal of Performance Analysis in Sport, 12:3, 546-562, DOI: 10.1080/24748668.2012.11868618

To link to this article: https://doi.org/10.1080/24748668.2012.11868618

International Journal of Performance Analysis in Sport
2012, 12, 546-562.

The effect of artificial side wind on the serve of competitive tennis players

Pedro C. Mendes[1,2], Gonçalo Dias[1], Rui Mendes[2,3], Fernando M. L. Martins[5], Micael S. Couceiro[2] e Duarte Araújo [3,6]

[1] Research Centre for Sport and Physical Activity of FCDEF, University of Coimbra, Coimbra, Portugal.

[2] Robocorp, Engineering Institute of Coimbra, Polytechnic Institute of Coimbra, Portugal.

[3] CIPER - Interdisciplinary Center for Study of Human Performance, Technical University of Lisbon, Portugal.

[4] College of Education, Polytechnic Institute of Coimbra, Portugal.

[5] Instituto de Telecomunicações, Pólo de Coimbra, Delegação da Covilhã, Portugal.

[6] Faculty of Human Kinetics, Technical University of Lisbon, Portugal.

Abstract

In tennis, the serve is the shot of greatest importance. The serve depends mainly on the player's technique, however, environmental factors can influence the accuracy of the serve. This study highlights the effect of side wind on the serve of 12 experienced tennis players. The players were asked to hit the intersection point between the central and the service line at maximum speed while a wind effect was artificially generated by a ventilator setup with various speed of Induced Aerodynamic Flow (IAF). Each player's serve was then analyzed using error ellipses as a statistical measure. This method allowed us to evaluate the effect of "random wind" in comparison to "constant wind" on the accuracy of the serves. The truncated Fourier series analysis showed that there was an adaptive pattern in the accuracy of the serve depending on the random wind. However in four players, the more unpredictable the impact of the wind the more accurate they became with the serve. The fact that there was not a linear trend in the accuracy of serves when IAF increased shows that each player adapts differently to the wind influence.

Keywords: Variability, Wind, Performance, Error Ellipses, Tennis.

1. Introduction

The efficiency of the tennis serve influences the success of a player's game (Bahamonde, 2000; Haake et al., 2000; Tanabe and Ito, 2007). In fact, the serve is the most important shot in the game (Bonnefoy et al., 2009; Jones, 1986; Reid et al., 2010).

Although the serve is the part of the game that is more self-controlled, it is subject to several types of constraints, including environmental factors (e.g., wind). The environmental constraints in conjunction with the characteristics of the player are key factors in the performance of the serve (Newell, 1986). Moreover, constraints such as the wind are difficult to manipulate in the context of the training sessions (Elliott et al., 2009). Importantly, Mendes et al. (2011a) found that tennis coaches consider the wind as the environmental factor that most affect the quality of the first serve. This has been researched to some extent, but controlled conditions of testing are needed to fully understand what influence the wind can have on the serve task (e.g., Loehr, 1996; Hoskins, 2003; Elliott et al., 2009).

The process of evaluation of performance in the tennis serve has focused mainly on analysis of the maximum ball velocity and accuracy (e.g., radial error) of the location of the first bounce on the court (e.g., Knudson et al., 2004, Carlton et al., 2006; Mendes et al., 2011b). Another important aspect of the performance of the serve, precision (e.g., error ellipses), has hardly been studied (for exceptions see Menayo, 2010; Mendes et al., 2012). For clarification, accuracy is the amplitude error obtained by the players, or measurement of location, while precision refers to the proximity of several measurements, representing a measure of dispersion (see International Organization for Standardization, 2007). Concerning the accuracy of the serve, the use of a temporal analysis using truncated Fourier series of degree n allows for the identification of behavioral trends of each player when performing a test sequence. This type of analysis was already performed for the putting in golf (see Vicente et al., 2010).

In sports science, the variability of actions related to the tennis serve has already been addressed. In particular, the compensatory variability of the impact point in the x- (side-to-side) and y - axis (back-to-front) of the overhead service in volleyball allows for the stabilization of the z-axis (vertical) (Davids et al., 1999; Handford, 2006). Variation in the serve has been studied by using variables such as speed and linear acceleration (e.g., Humpert, 2004; Humpert and Schöllhorn, 2006; Menayo, 2010). To our knowledge, there has been no research into the variability of the impact point (IP) and ball toss in the serve despite its influence on the level of performance of this movement (see also Elliott et al., 2009).

The objective of this work was to study how Induced Aerodynamic Flow (IAF), or artificial wind influence the flat first serve of experienced tennis players. More precisely, we aimed to study the effect of wind (four conditions manipulated by IAF, and a control condition) on the tennis serve output variables, i.e., speed, accuracy and precision, and the process variable impact point

2. Methods

2.1. Sample

Twelve participants voluntarily participated in this study, they were all right handed males, 25.17±3.93 years old. The anthropometric characteristics of this group of players were as follows; height 177±6.00 cm, upper limb span (dactylion-dactylion) of 181±5.00 cm and body mass of 72.29±4.17 kg.

They had been playing tennis for a mean of 16.25±5.56 years, and the mean years of competitive tennis at a national level was 13.67 ± 4.29 years. The study was conducted according to the code of ethics of the University of Coimbra and the recommendations of the Helsinki Declaration on Research with Human Beings.

2.2. Task

The movement required was the flat first serve from behind the base line of the tennis court, on the right-hand side and 80 cm away from the centre mark. The indoor tennis court had the regulation dimensions for the singles game, 2377 cm long and 823 cm wide. All the participants were asked to serve at maximum speed and accuracy targeting the point of intersection of the centre line and service line ("T" point).

2.3. Experimental Set up

All the tennis players performed 20 free serves (without instructional or wind constraints), called IAF0 (a control condition), and then performed four sets of 20 serves under different practice conditions: (1) minimum IAF speed of 2.4 ms^{-1} (called IAF1); (2) medium IAF speed of 4.3 ms^{-1} (called IAF2), 3); (3) maximum IAF speed of 5.8 ms^{-1} (called IAF3) and; (4) random IAF speed with random sequences at the three IAF speeds (called IAFr). Therefore, there was a total of 100 serves.

The independent variable corresponded to the experimental conditions under the influence of IAF mentioned above. The dependent variable accuracy was measured from the radial error (RE) and the variable precision from the areas ellipses of error (Darling and Cooke, 1987). For the dependent variable serve velocity, the values of the post-impact speed of the ball were considered. For the process variable impact point it was measured the position of the ball in the 3 axes (3D analysis).

2.4. Induced Aerodynamic Flow device

The production of the IAF device was adapted from an industrial helical fan METEC - HCT - 45 - 4T. The speed of the engine was set up using an electronic device (SEW Eurodrive) installed in the fan coupled with an 11 positions potentiometer. In order to homogenize the air flow, a steel mesh of 0.45 cm and a conduct of 120 cm length and 45 cm in diameter (see also Mendes et al., 2010a) were placed at the fan output.

The players varied in height and therefore threw up the ball at different heights. The fan had a diameter of 45cm so a telescopic lift GUILE ELC – 506 was used to adjust the height of the ventilator up to a maximum of 520 cm. The calibration of the ventilator for each tennis player was made based on a preliminary study which consisted of analyzing the mean of the highest point of the ball in 20 serves and determining the impact point (see details on “Device for analysis of the impact point” described below).

The ventilator had a homogeneous flow rate of air flow in a diameter of 60 cm, irrespectively of the position of the potentiometer. It was stipulated that the upper edge of the vent would be positioned at the mean level of the highest point reached by the ball during the toss.

2.5. Serve accuracy measurement device

The measurement of accuracy was performed by calculating the depth of serve, i.e., vertical location (y axis) and lateral location (x axis), of the point corresponding to the first bounce of the ball. Two digital cameras Casio Exilim Pro Ex-F1 (Figure 1) were used, which shot at 300 Hz. Camera 3 was attached to a tripod (5.04 m high) and directed towards the player at the opposite end of the court, and camera 2 was on a tripod 112 cm in height in line with the tennis net. To calibrate the space four points were used, with the point (0.0) of the reference system coinciding with the intersection point of the centre line with the service line, i.e., the target (cf. Figure 1). For each serve, we proceeded to the image analysis corresponding to the ball landing location on the court using Kwon® 3.16 (2D tracking software) and respective transformation into real coordinates, the serve direction (lateral location) and the depth of the serve (anterior-posterior location), with an measure error of the 0.000032 cm. Camera 2 was used to analyse the ball trajectory when it intersects the net. For the synchronization of the two cameras two synchronizers with a trigger and two light-emitting diodes (LEDs) were used (Figure 1).

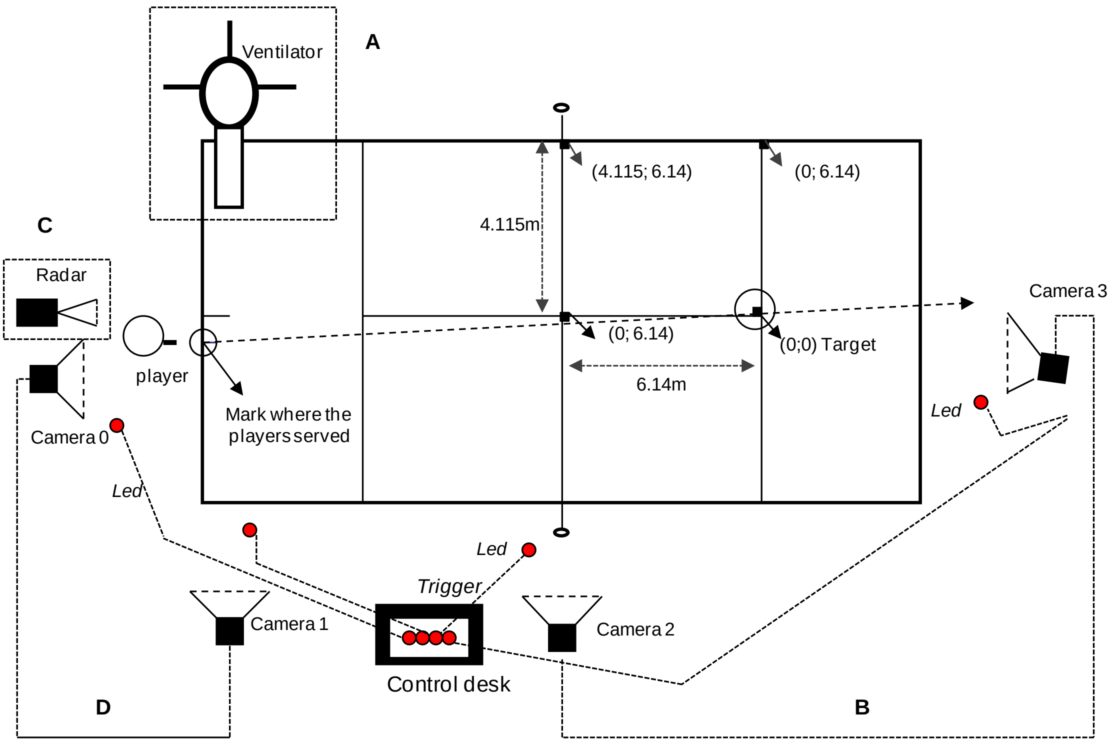

Figure 1. Experimental set up. A - Device IAF. B - Accuracy registration device. C - Device for recording the velocity of the serve. D - Device for analyzing the impact point in the serve. Dashed arrow indicates a possible direction of tennis serve.

2.6. Device for measuring the output speed of the ball

The output speed of the ball, after impact, was recorded by a radar Stalker ® Sport model, capable of recording the speed of a moving object with an accuracy of ±1.61 kmh^{-1} in a range of 8.05 to 400 kmh^{-1}. The radar was positioned 200 cm behind the player at variable heights according to players' height, and respective impact points.

2.7. Device for analysis of the impact point

The recording of the impact point (IP) was obtained from the two cameras: (1) camera in the sagittal plane of the tennis player: Casio Exilim Pro EX-F1, shooting at 210 Hz, positioned at 700.5 cm away from the service mark and fixed on a tripod at 206.5 cm in height and (2) camera in the frontal plane, positioned behind the player: Casio EX-FH25, shooting at 210 Hz, positioned at 363 cm away from the tennis player and fixed on a tripod at 263cm in height (Figure 1). The timing of the beginning of the footage for each of the two cameras was synchronized by the connection and visualization of a LED per camera.

A 3D analysis of the collected images was carried out. It started when the racket hit the ball during the serve (*i.e.*, impact point), with a maximum error of 1cm, *i.e.*, the farthest plane from the camera presents a resolution of $1cm^2$ per pixel (Figure 2). The space was calibrated with a square base parallelepiped with 250 cm of edge and 320 cm in height, giving a reference system in eight points in the space (Mendes, et al., 2011b) using Matlab2009R. A script, which included the capture of images related to the IP, was developed for the calculation of the positions and their coordinates (*x*, *y*, *z*).

Figure 2. Three-dimensional reference system for the analysis of the impact point (*x*, *y*, *z*) of the players.

2.8. Procedures

The purpose of the task was explained to the players: to serve at maximum speed and accuracy targeting the intersection point between the centre line and the service line ("T" point). Players were assessed individually. In order to prepare the participants for the task, they 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 at low intensity, the following two serves at medium intensity and the last two serves at full intensity. During all the procedures, including data collection, the players did not receive any verbal information on the quality of the movement or the outcome of the test.

The players served 100 times in five different conditions. In the first series of 20 serves the players served without IAF and then, they serve 20 times in each condition in a counterbalance of the four following conditions: minimum, medium, maximum and random speeds (i.e., variation of the three speeds of IAF). They had a recovery time of 20 s between the serves or trials and 180 s between the 5 different conditions (following the rules for changing between court sides). .

2.8.1. Statistical Analysis

ANOVA one way test was used for statistically significant differences between the five practice conditions for each player (intra-individual analysis) on the dependent variables, accuracy and serve velocity. The Scheffé post hoc test was used if the assumption of normality and homogeneity were verified. When the assumption of homogeneity was not observed, we used the Games-Howell post hoc test (Martinez and Ferreira, 2007; Laureano, 2011). As the samples were below 30 the assumption of normality was verified using the Shapiro-Wilk test (Gageiro and Pestana, 2005; Marôco, 2010; Pallant, 2011). In cases of non-verification of normality, the following equation was used for the analysis of the symmetry (Gageiro and Pestana, 2005, p.288):

$$\left|\frac{\text{Skewness}}{\text{Std errorSkewness}}\right| \leq 1.96 \qquad (1)$$

The Levene's test was used to verify the assumption of homogeneity of One-way ANOVA. This analysis was performed using the IBM program SPSS (version 19) for a significance level of 5%. Estimates of the effect sizes, partial η^2 (η_p^2), i.e., the proportion of variation of the independent variable which is explained by the dependent variable (Maroco, 2010; Pallant, 2011) and the power of the test was determined.

2.8.2. Performance Analysis

To analyze the performance of the players, we used the metrics related to a scale of 0 to 1 for both the product variables (accuracy and precision), and process variable, (precision in the point of impact), in the transverse plane *xOy* (ellipses of error).

2.8.2.1. Accuracy.

To analyze the accuracy of the serve, a formula was used to calculate the radial error. This formula allows us to determine product measure resulting from the performance of the players (e.g., Van Den Tillar and Ettema, 2003, Carlton et al., 2006; Mendes, et al., 2012). Through analysis of the error in length, width and radial, it is possible to obtain quantitative data resulting from the position of the first bounce of the ball, measuring the distances of the error in length and lateral error against the target, thereby determining the radial error. The radial error obtained in each test is calculated as follows (Couceiro et al., 2011):

$$\mu_R = \frac{1}{N}\sum_{i=1}^{N} \varepsilon_i \qquad (2)$$

ε_i being the radial error of the trial *i*.

The arithmetic mean μ_R however is represented by an absolute value which makes the comparison between multiple participants complex. This limitation can be overcome by applying a ratio measure based on a maximum value of radial error ε_{max} that will depend on the assessment criteria (e.g., athlete level, boundaries of the court, higher radial error recorded, etc.). This ratio is always higher or equal to the radial error ε_i for any trial *i* of any player, i.e., $\varepsilon_i \leq \varepsilon_{max}\ \forall$ i.. Therefore, starting from the equation (2) the following formula is obtained (Couceiro et al., 2011):

$$\eta_R = \frac{1}{N}\sum_{i=1}^{N}\left(1 - \frac{\varepsilon_i}{\varepsilon_{max}}\right) \qquad (3)$$

2.8.2.2. Precision

Analysis of the position of the first bounce of the ball on the court was carried out using the error ellipses representation. The error ellipses allow a two-dimensional graphical analysis of the precision in all directions of a plane (Vincente et al., 2010; Mendes et al., 2011b). These represent equally the maximum direction and minimum direction of errors, the standard deviation in the axes that form the plane and the distribution (i.e., variability) through the area of the ellipse. By observing the shape, area and orientation of the ellipse, it is possible to make quick and significant comparisons between different players and practice conditions (Messier and Kalaska, 1997). The precision of the tennis players in the different practice conditions was obtained by using the following formula:

$$\eta_A = \frac{1}{N}\sum_{i=1}^{N}\left(1 - \frac{A_i}{A_{max}}\right) \qquad (4)$$

A_i being the area of error ellipse obtained from a data set (i.e., Cartesian position of the ball on first bounce on the court) in a practice condition and A_{max} corresponding to the major area of ellipse error obtained by the different players under several practice conditions.

2.8.2.3. Precision of impact point

The analysis of the precision at the point of impact on the *xOy* plane (transverse plane) is carried out using a similar method to the one described in the previous section for the accuracy of the serve. This method allows us to evaluate the performance of a player in a certain experimental condition by comparing the precision at the point of impact (process variable), with the precision of the serve (product variable).

Moreover, to evaluate the influence of constraint on the accuracy on the point of the impact of the ball in the *x*O*y* we used the centre of the error ellipses. This point was used to observe the displacement of the "cloud" of the IP from left to right (direction of the IAF).

3. Results

In this chapter, we present the results for the product and process variables (accuracy, precision of serve, impact point accuracy and serve velocity), and the effect of wind (IAF) in the performance of players.

3.1. Accuracy

The one-way ANOVA test was used to verify the existence of significant differences in accuracy between the different practice conditions. We also analyzed the accuracy based on a metric from 0 to 1, allowing the comparison of the performance of 12 participants. From the truncated Fourier series the temporal accuracy performance of the players under each practice condition was analysed.

In the intra-individual analysis relative to the accuracy variable (i.e., radial error), the test one-way ANOVA was used and no differences were observed between the five conditions of practice ($p>0.05$). Accuracy measured by radial error showed a decrease in four players (1, 2, 3 and 11), between the condition without IAF and the remaining practice conditions with IAF. The increased intensity of IAF did not lead to a gradual decrease in accuracy (Table 1).

Table 1. Evaluation metrics η_R of the accuracy on the 12 players per condition of practice.

Variable		Players											
		1	2	3	4	5	6	7	8	9	10	11	12
		Number of serves per practice condition (n=20)											
Accuracy	IAF0	.63	.81	.80	.69	.78	.77	.72	.69	.76	.72	.71	.78
	IAF1	.56	.76	.74	.66	.78	.72	.81	.74	.76	.69	.64	.66
	IAF2	.60	.76	.76	.73	.82	.82	.80	.63	.63	.67	.64	.68
	IAF3	.61	.78	.76	.67	.79	.73	.81	.78	.75	.66	.66	.78
	IAFr	.61	.79	.74	.77	.78	.70	.80	.74	.81	.75	.59	.80

It was observed that the condition IAF3 caused a decrease in accuracy in 8 players (1, 2, 3, 4, 6, 9, 10 and 11), the IAF1 in 8 players (1, 2, 3, 4, 6, 10, 11 and 12), the IAF2 in 8 players (1, 2, 3, 8, 9, 10, 11 and 12) and the IAFr in 5 players (1, 2, 3, 6 and 11). Given the above, the condition IAFr was the one that least influenced accuracy.

3.2. Precision

The ellipse area related to the first bounce of the ball, allows the evaluation of the precision of the players. A decrease in the performance in all four practice conditions under artificial wind (IAF) was only observed in 3 players.

Precision followed a non-linear trend, i.e., the increase of IAF did not lead to a progressive deterioration of performance. In fact, players 5 and 7 improved their performance in the presence of IAF1, IAF2 and IAF3 (Table 2).

Table 2. Evaluation metrics η_A of precision in the 12 players and per practice condition.

Variable		Players											
		1	2	3	4	5	6	7	8	9	10	11	12
		Number of serves per practice condition (n=20)											
Precision	IAF0	.24	.79	.69	.43	.61	.60	.25	.58	.73	.52	.74	.61
	IAF1	.00	.81	.53	.17	.63	.50	.71	.60	.61	.38	.38	.59
	IAF2	.33	.54	.62	.41	.76	.70	.67	.66	.63	.35	.53	.72
	IAF3	.57	.69	.62	.23	.67	.50	.64	.58	.74	.62	.66	.75
	IAFr	.14	.80	.56	.41	.58	.41	.59	.58	.71	.54	.63	.71

Comparing the condition without IAF with the other practice conditions, there was a decrease in the precision of 8 players (1, 3, 4, 6, 9, 10, 11 and 12) under IAF1, of six players (2, 3, 4, 9, 10 and 11) under IAF2, five players (2, 3, 4, 6 and 11) under IAF3 and seven players (1, 3, 4, 5, 6, 9 and 11) under IAFr. The condition which least influenced the performance of the precision was the IAF3.

3.3. Effect of artificial wind on players' performance

The effect of artificial wind on players' behaviour was analyzed based on the displacement of the points cloud caused by the IAF. To this end, the area and centre of the ellipses of the impact point (IP) in the plane *xOy* were used. In the analysis of the variability of the vertical dimension (coordinate z of the IP) all players under the five practice conditions showed small variations with a coefficient of variation below 3%. Additionally, the variability observed in the coordinate *x* of the IP, was higher for all participants (when compared to the variability of the coordinate *y*), except for player 11 in the practice conditions IAF1 and IAF2. The condition EAl3 was the one that most constrained the sample in the coordinate *x* of the IP.

To determine the area of the ellipse centre we only considered the *xOy* plane (Table 3). For 8 players (1, 2, 3, 5, 8, 9, 10, 11) the ellipse centre (relative to the coordinate *x)* shifted to the right (moving away from the ventilator), as the intensity of the artificial wind (IAF) increased (Figures 5 and 6). For players 7 and 12 although there was no linear displacement of the ellipse centre to the right (with an increase in the intensity of IAFr), the condition IAF3 was the one that most constrained the movement of the serve. Players 4 and 6 did not follow this trend of displacement of the ellipse centre while increasing the intensity of the IAF, and the condition EAl2 as the one that moves furthest away (ellipse centre) from the ventilator.

Table 3. Ellipses center of the impact point (IP) per player and per practice condition (cm).

Variable		Players											
IP		1	2	3	4	5	6	7	8	9	10	11	12
		Number of serves per practice condition (n=20)											
Abcissa of ellipse (x)	IAF0	-6.6	-1.8	-27.5	-0.6	-38.8	-8.0	-28.2	-30.1	-37.1	-9.4	-6.0	-9.3
	IAF1	2.8	-1.3	-22.2	4.1	-31.6	-3.8	-40.5	-26.1	-30.6	-5.1	-5.1	-27.6
	IAF2	0.8	1.0	-14.2	19.1	-24.8	-2.3	-36.9	-28.0	-26.8	-0.6	-4.3	-21.6
	IAF3	7.3	4.9	-12.1	1.8	-20.3	-4.5	-22.2	-16.1	-17.2	5.1	-1.3	-5.0
	IAFr	2.7	0.9	-22.0	12.1	-30.2	-4.1	-30.0	-24.0	-22.3	-2.9	0.6	-12.0
Ordinate of ellipse (y)	IAF0	78.6	45.5	57.0	47.4	40.5	71.7	39.0	41.4	63.6	52.1	19.4	47.3
	IAF1	78.2	44.2	64.4	40.3	44.9	77.8	48.0	48.4	58.4	41.7	16.8	39.1
	IAF2	70.5	40.7	62.7	49.9	49.7	76.9	51.0	47.9	57.6	51.6	8.9	42.0
	IAF3	69.8	38.4	57.5	36.5	43.8	73.6	46.6	38.7	60.1	39.3	11.7	36.4
	IAFr	62.4	40.9	68.2	56.1	35.3	77.2	49.3	37.8	57.2	37.7	11.7	39.1

The displacement of the ellipse centre relative to the coordinate *y* (back-to-front) with the constraint of IAF was observed in five players (1, 2, 9, 10 and 12), a decrease in depth with the increase of the intensity of the artificial wind (Figure 3). For players 3, 6, 8, there was a decrease in depth under the IAF3 conditions and for player 11 the decrease occurred under the condition EAl2. An increase in depth in the presence of IAF was only observed for player 7.

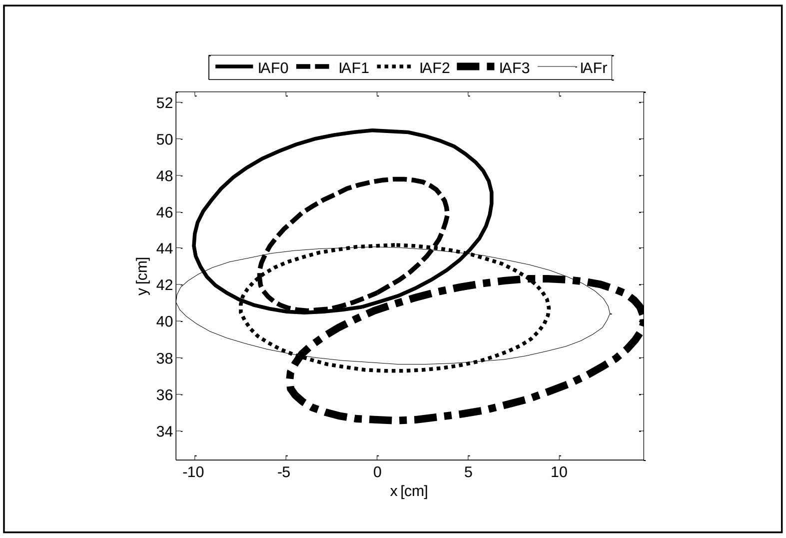

Figure 3. Ellipses Error of the impact point in the plane *xOy* of the Player 2.

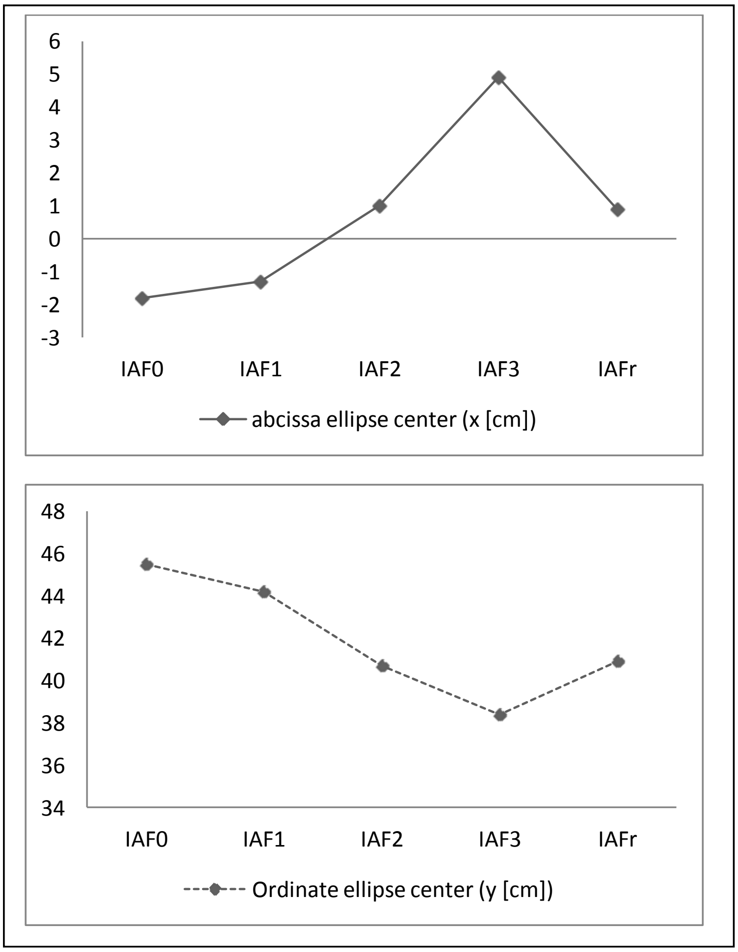

Figure 4. The coordinates of the ellipses centers (cm), relatively to the impact point, in the plane *xOy* of the player 2.

3.4. Precision of the impact point

The precision related to the impact point (ellipse area) allows for analysis of the variability for each player, values closer to 1 indicate a decrease in variability and values closer to zero mean the opposite. For players 1, 5, 6 and 9 there was a tendency to increase variability in the point of impact with the increase of the intensity of IAF.

When we compared the condition without IAF with the other conditions with IAF, we observed an increase in the variability of the IP under the IAFr conditions for seven players (1, 5, 6, 7, 9, 1. 12), for five players under IAF2 (1, 5, 6, 9, 10) and for 4 players under IAF1 and IAF3 (1, 5, 6 and 9).

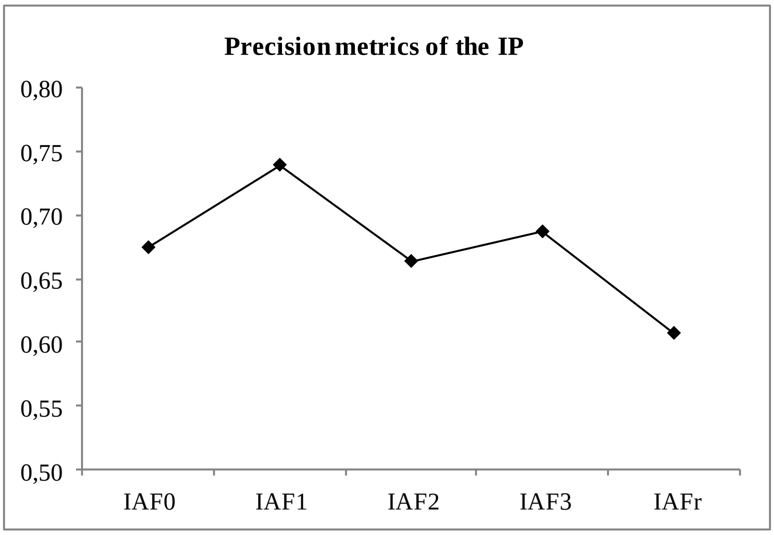

Figure 5. Precision metrics average η_A of the impact points per practice condition.

The inter-individual analysis of the impact point precision also showed an increase in the variability when players served with random wind (IAFr).

3.5. Serve velocity

With regard to the maximum speed of the ball output, the players were stable, presenting variation coefficients below 10% in all practice conditions, which confirms task completion by the players. The results also suggest that the mean is a good measure of the players' performance.

Five players however showed significant statistical differences between the condition without IAF and the conditions with IAF. IAF had a high level statistically significant effect on the speed of the serve, in player 2 ($F_{4,\,95}$ = 11.838, $P < 0.05$, $\eta_p^2 = 0.333$, *Power* = 1.0) and player 9 ($F_{4,95}$ =8.5, P =0.001, η_p^2 =0.264, *Power* =0.998]. In player 5 ($F_{4,\,95}$ = 5.035, $P < 0.05$, η_p^2= 0.175, *Power* = 0.956), player 7 ($F_{4,\,95}$ = 6.947, $P < 0.05$, η_p^2 = 0.226, *Power* = 0.993) and player 12 ($F_{4,\,95}$ = 4.155, $P < 0.05$, η_p^2 = 0.149, *Power* = 0.908) IAF had a medium level statistically significant effect. According to Scheffé post hoc test there were statistically significant differences for player 2 between IAF0 e IAFr, i.e., this player served more slowly under the IAFr. For player 7, there were differences noted between IAF0 and conditions IAF1, IAF2 e IAFr, this player reduced the serve speed under the conditions with IAF. There were differences between IAF0 e IAF3 for player 5, and for player 9 between IAF0 and conditions IAF1 e IAF3 and for player 12, between IAF0 and IAF2. These three players (5, 9 e 12) increased the velocity of the serve within the presence of IAF. In the inter-individual analysis, there were statistically significant differences between the five conditions of practice ($F_{4,1195}$=3.239, p< 0.05, η_p^2=0.011, *Power* =0.834).

The LSD post hoc test also presented statistically significant differences between the condition IAF0 and the condition IAFr (p=0.01), i.e., the players served more slowly when constrained by a "random wind."

3. Discussion

The main objective of this work was to study the influence of the IAF (artificial wind) on the performance of the flat first serve by experienced tennis players.

Data showed that the general trend demonstrated by all players at the impact point is the stabilization of the z-axis (vertical axis), which confirms the vertical dimension of the ball toss as an invariant feature of this movement (Davids et al., 1999; Handford, 2006). In addition, artificial lateral wind seems to influence the execution of the serve for the majority of the players. That is, the "impact point cloud" (i.e., ellipse centre in the plane *xOy*) tends to move from left to right, moving away from the range of action of the ventilator. Additionally, it is clear that the impact point (PI) had less depth in the presence of wind, which suggests that an adaptive process occurred (Tani, 2005). In other words, the majority of the players in the presence of an air flow, served closer to the base line of the tennis court in an attempt to minimize the effect of the wind constraint.

The intra-individual analysis related to the performance of accuracy of the players through the evaluation metric, indicates that the practice conditions IAF1, IAF2 IAF3 (constant wind) compared to the condition IAFr (i.e., random wind), had more effect on the performance of the players, in relation to their serve accuracy. For precision this trend was reversed (the practical condition IAFr inhibited most of the players). This highlights the need for the measurements of accuracy and precision of performance be made clear on experiments. In relation to accuracy, the intra and inter-individual analysis (through the truncated Fourier series) shows that there is a tendency for players to adapt gradually to the IAFr with a smaller radial error over the 20 trials. Whereas the "constant artificial wind" (IAF1, and IAF2 IAF3) causes more variability in the accuracy of the 12 players.

Regarding to the ball maximum speed, the data shows that players served with less power when constrained by the “random wind” (IAFr). However, in the intra-individual analysis, it is possible to observe a significant increase in the tennis serve under the effect of “constant wind” (IAF1, IAF2 and IAF3) in three participants. Given the data, the players under a random variation of the wind speed presented a slower tennis serve in order to stabilize, or at least not compromise, the accuracy of the service. This can be explained in the competitive context, wherein the accuracy and precision of the service are crucial for athletic performance (Bollettieri, 2001; Menayo and Fuentes, 2009; United States Tennis Association, 2004).

Data also suggested that the increased variability of the PI for four players (5, 9, 10 and 12) caused by the wind, led to an increase in their accuracy. Additionally, two players (1 and 5) improved precision with the increase of the PI variability, due to the constant wind. A greater variability corresponds to a better performance, which was also observed in Slifkin and Newell (1999) among participants producing an isometric force, Balasubramaniam et al. (2000) in a postural task, and in and Dingwell and Cusumano (2000) in patients with peripheral neuropathy.

Finally, the absence of a linear trend in the performance of players when subjected to increased intensity of IAF, reflects the "signature" of each player, regarding the constraint studied, i.e., the wind. In other words, it appears that the variability that results from the execution of the tennis serve functions as an adaptive mechanism, which emerges from the characteristics of the server, the task and importantly from the environment where it is performed (Newell, 1986; Riley and Turvey, 2002; Hamil et al., 2006).

In terms of applications, the IAF equipment recreates different practice conditions of wind, being useful for training the tennis serve. Extending this study to other wind directions within future research would be useful for a further understanding of the motor variability associated with this environmental constraint. The study herein reported analysed the lateral direction of the EAI from left to right, in righties expert players. The study of the lateral EAI in the opposite direction, *i.e.*, from right to left, would allow to understand how players adapt to this new constraint.In conclusion, results confirmed the influence of the IAF effect on the first serve in tennis on experienced tennis players, demonstrating that there is an interaction between player performance, task and environment. Given the variability that resulted from the execution of the tennis serve under the influence of different induced wind conditions, an adaptive and self-organized mechanism of the players emerged.

5. References

Ardito, R., Maier G.and Massalongo, G. (2008), Diagnostic analysis of concrete dams based on seasonal hydrostatic loading, **Journal Engineering Structure**, 30, 3176-3185.

Bahamonde, R.E. (2000), Changes in angular momentum during the tennis serve, **Journal of Sports Sciences**, 18, 579-592.

Balasubramaniam, R., Riley, M., and Turvey, M. T. (2000), Specificity of postural sway to the demands of a precision task, **Gait & Posture**, 11, 12-24.

Bollettieri, N. (2001), **Bollettieri's Tennis Handbook.** Champaign: Human Kinetics.

Bonnefoy, A., Slawinski, J., Leveque, J.M., Riquet, A., and Miller, C. (2009). Relationship between the vertical racquet head height and the lower limb motions of elite players' flat serve. **Computer Methods in Biomechanics and Biomedical Engineering**, 12(1), 55-57.

Carlton L.G., Chow, J.W., and Shim J. (2006). Variability in motor output and Olympic performancers. In Davids K., Bennett S., and Newell, K. (Eds) **Movement system variability** (pp. 85-108). Champaign: Human Kinetics.

Couceiro, M.S., Dias, G., Martins, F.M.L., and Luz, J.M.A (2011). Towards a Correction Metric to the Putting Lip-out". In **Proceedings of the 3th Symposium on FSS'2011** (pp 137-145). Coimbra: ISEC.IPC.

Darling, W.G. and Cooke, J.D. (1987), Changes in the variability of movement trajectories with practice, **Journal of Motor Behaviour**, 19(3), 291-309.

Davids, K., Bennett, S.J., Handford, C., and Jones, B. (1999), Acquiring coordination in self-paced extrinsic timing tasks: A constraints led perspective, **International journal of Sport Psychology**, 3, 437-61.

Dingwell, J. B., and Cusumano, J. P. (2000), Nonlinear time series analysis of normal and pathological human walking, **Chaos**, 1, 848-863.
Elliott, B., Reid, M., and Crespo, M. (2009), **Technique development in tennis stroke production**. London: International Tennis Federation.
Fuentes, J.P., Menayo, R. (2009), **Los golpes del tenis. De la iniciación al alto rendimento**. Sevilha: Wanceulen Editorial Deportiva.
Haake, S.J., Chadwick S.G., Dignall, R.J., Goodwill S. and Rose, P. (2000), Engineering tennis - slowing the game down, **Sports Engineering**, 3(2),131-143.
Hamill, J., Haddad, J.M., Heiderscheit, B.C., Van Emmerik, R.E.A., and Li Li (2006), Clinical relevance of variability in coordination. In Davids, K., Bennett, S. and Newell K. (Eds) **Movement system variability** (pp. 153-165). Champaign: Human Kinetics.
Handford, C. (2006). Serving up variability and stability. In Davids, K., Bennett, S. and Newell K. (Eds) **Movement system variability** (pp. 73-83). Champaign: Human Kinetics.
Hoskins, T. (2003), **The tennis drill book**. Champaign: Human Kinetics.
Humpert, V. (2004). MA thesis: Vergleichende Analyse von Techniktrainingansätzen zum Tennisaufschlag. University of Münster, Germany.
Humpert, V., and Schöllhorn W.I. (2006). Vergleich von Techniktrainingansätzen zum Tennisaufschlag. In Trainingswissenschaften im Freizeitsport-Symposium der dvs-Sektion (edited by A. Ferrouti, and H. Remmert), pp 121-124. Trainningswissenschaften vom 7 - 9 April 2005 in Bochum. Czwalina, Hamburg.
International Organization for Standardization (2007), **ISO/ IEC Guide 99-12:2007. International Vocabulary of Metrology — Basic and General Concepts and Associated Terms**. VIM, BIPM e ISO, Switzerland.
Knudson, D., Noffal, G., Bahamonde, R., Bauer, J., and Blackwell, J. (2004), Stretching has no effect on tennis serve performance, **Journal of Strength & Conditioning Research**, 3(18), 654-656.
Jones, C.M. (1986). **Match winning tennis**. London: Faber & Faber.
Laureano, R.M.S. (2011), **Testes de hipóteses com o SPSS – O meu manual de consulta rápida**. Lisboa: Edições Sílabo, Lda.
Loehr, J. (1996), How to battle the elements, **Tennis**, 32(7), 40.
Maor, E. (2002), **Trigonometric Delights**. Princeton, USA: Princeton University Press.
Maroco, J. (2010), **Análise Estatística com ultização do SPSS**. Lisboa: Edições Silabo.
Martinez, L., and Ferreira, A. (2007), **Análise de dados com o SPSS - Primeiros passos**. Lisboa: Escolar Editora.
Menayo, R. (2010), **Análisis de la relación entre la consistencia en la ejecución del patrón motor del servicio en tenis, la precisión y su aprendizage en condiciones de variabilidad**. 2010. 313f. Thesis (Phd in Sports Science) – Extremadura University - Faculty of Sport Sciences , Cáceres.
Mendes, P. C, Mendes, R., Fuentes J.P., Campos F., and Araújo D. (2011a), Fatores de rendimento no primeiro serviço em tenistas de competição, **Revista da Educação Física/ Universidade Estadual de Maringá**, 22(3), 315-326.
Mendes, P.C., Mendes, R., Martins, F., Facas Vicente, A.M., Fuentes, J.P., Menayo, R. and Dias, G. (2012), Análise do rendimento no primeiro serviço em tenistas de competição sob o efeito de um escoamento aerodinâmico induzido, **Revista Brasileira de Educação Física e Esporte**, 22(3), 193-208.

Mendes, P.C, Martins, F., Facas Vicente, A.M., Corbi, F., Couceiro, M. S., Mendes, R., and Trovão, J. (2011b), Análise às variáveis de produto na execução do serviço de ténis sob o efeito de um escoamento aerodinâmico induzido (vento artificial). In L. Roseiro, M. Augusta (Eds) **4.º Congresso Nacional de Biomecânica** (pp. 37-41). Coimbra: ISEC.

Mendes, P.C., Luz, M., Couceiro, M., Iglésias, P., Ferreira, A., Sismeiro, J., Mendes, R., and Fuentes, J.P, (2010c), Analysis of the Wind Influence in Tennis Serve. In Machado, T. (Ed) **Mathematical Methods in Engineering International Symposium 2010** (pp. 260-269). Coimbra:ISEC.

Mendes, P.C., Mendes R., Martins, F., Facas Vicente, A., and Fuentes, J.P. (2010b), Aprendizagem motora e Ténis: medida de precisão no serviço de ténis. In Barela, J. A., Ugrinowitsch, H., and Oliveira, M. A. (Eds) **Brazilian Journal of Motor Behaviour** (pp.17). Londrina. Brasil

Mendes, P.C., Simões, H., Mendes, R., Trovão, J., Luz, M., Couceiro, M.S., Ferreira, N., Dias, G., and Fuentes, J.P. (2010a), Influência do ambiente acústico no desempenho do tenista sob o efeito de um escoamento aerodinâmico induzido. In Almeida, J., Ferreira, A., Paixão, S., Pinto, M.V., Sá, N.L., Santos, C., and Simões, H. (Eds) **Congresso Internacional de Saúde Ambiental** (pp.90-95). Coimbra.

Messier, J. and Kalaska, J.F. (1997), Differential effect of task conditions on errors of direction and extent of reaching movements, **Experimental Brain Research**, 115, 469-478.

Newell, K. M. (1986). Constraints on the development of coordination. In Wade, M.G and Whiting, H.T.A. (Eds) **Motor Development in children: Aspects of coordination and control** (pp. 341-360). Boston: Martinus Nijhoff.

Pallant, J. (2011), **Spss survival manual. A step by step guide to data analysis using SPSS**. 4th edition. Australia: Allen&Unwin.

Pestana, M. H. and Gageiro, J. N. (2005), **Análise de dados para ciências sociais – A complementaridade do SPSS**. 5.ª Ed. Lisboa: Edições Sílabo, Lda.

Reid, M., Whiteside, D., and Elliott, B. (2010). Effect of skill decomposition on racket and ball kinematics of the elite junior tennis serve. **Sports Biomechanics**, 9(4), 296-303.

Riley, M. A., and Turvey, M. T. (2002), Variability and determinism in motor behaviour, **Journal of Motor Behaviour**, 34(2), 99-125.

Scott, W., and Randy, P. (2000), **Serious tennis**. Champaign: Human Kinetics.

Slifkin, A. B., and Newell, K. M. (1999), Is variability in human performance a reflection of system noise?, **Current Directions in Psychological Science**, 7, 170-176.

Tanabe, S. and Ito, A. (2007), 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**, 6(3), 418-433.

Tani, G. (2005), **Comportamento motor – Aprendizagem e Desenvolvimento**. Rio de Janeiro: Editora Guanabara Koogan S.A.

United States Tennis Association (2004), **Coaching Tennis successfully**. 2a ed. Champaign: Human Kinetics.

Van Den Tillar, R. and Ettema, G. (2003), Instructions emphasizing, velocity, accuracy, or both in performance and kinematics of overarm throwing by experienced team handball players**, Perceptual and Motor Skills**, 97, 731-742.

Vicente, M.A.F., Martins, F., Mendes, R., Dias, G., and Fonseca, J. (2010), A method for segmented-trend estimate and geometric error analysis in motor learning. In Machado, T. (Ed) **Proceedings of the First International Conference on Mathematical Methods (MME10)** (pp. 433-442). Coimbra: ISEC.IPC.