Title: Probabilistic Structure of Errors in Forehand and Backhand Groundstrokes of advanced Tennis Players.

Authors: Gabriel Delgado-García[1,2]*, Jos Vanrenterghem[3], Alejandro Muñoz-García[1,2], Emilio José Ruiz-Malagón[1,2], Alfonso Mañas-Bastidas[1,2], Víctor Manuel Soto-Hermoso[1,2].

[1]Department of Physical Education and Sports, Faculty of Physical Activity and Sports Sciences, University of Granada, Spain.

[2]Sport and Health Research Institute (iMUDS), University of Granada, Spain.

[3]Department of Rehabilitation Sciences, Faculty of Kinesiology and Rehabilitation Sciences, KU Leuven, University of Leuven, Belgium

"*Corresponding author:"
Gabriel Delgado Garcia
Calle Menendez Pelayo 32, (Granada, Spain), 18016.
gabrieldg@ugr.es
+34 858 98 70 12

Abstract

Accuracy and speed are two important factors related with performance in tennis and the correct design of tennis drills requires a profound knowledge off both concepts. Most research has focused on speed and little is known about the probabilistic structure of error (i.e. accuracy). In the present study thirty-one advanced tennis players performed a standardized field test. Ball speed and accuracy were measured using a sport radar gun and video analysis. Parameters describing 95% confidence ellipses (CEs) were calculated. Results showed that for both groundstrokes the long axis of the CEs was oriented almost parallel to the sideline. Despite greater ball speed (107.2 ± 10.3 $m \cdot s^{-1}$ vs. 97.3 ± 9.3 $m \cdot s^{-1}$; $p < 0.001$; $d = 1.06$), the forehand groundstroke showed in comparison to the backhand groundstroke a smaller longitudinal distance to the target (123.3 ± 65.9 cm vs. 164.0 ± 56.9 cm; $p = 0.024$; $d = 0.66$) and a smaller CE area (34.4 ± 10.7 m^2 vs. 40.3 ± 9.7 m^2; $p = 0.045$; $d = 0.58$). Overall, this means that tennis shot placements fit a bivariate normal distribution (represented by an ellipse), similar as seen in other throwing sports, and with tangible differences between the forehand and backhand groundstrokes. Further research will need to explore the underlying causes of these non-uniform error distributions, which in turn may open up opportunities for coaches to modify them in their players according to what is deemed most vital for improved performance.

Keywords: Motor control; performance; variability; hitting/batting; tennis.

1. Introduction

Success in tennis depends on numerous factors such as physical condition, technical skill and tactical strategy. One important performance indicator is being able to generate high ball speeds with high accuracy (Landlinger, Stöggl, Lindinger, Wagner, & Müller, 2012). Accuracy, in global terms, is typically defined as a distance-based error, i.e., the distance between a target location and the actual ball landing position. Most field tests used in the scientific literature of tennis include accuracy as a measure of performance by dividing the court into zones of different accuracy ratings (Davey, Thorpe, & Williams, 2002; Smekal et al., 2000; Strecker et al. 2011). Few studies have reported in more detail and with a higher resolution the spatial distribution of errors. Overall, it has been suggested that the mean of the longitudinal error is typically greater than the mean of the medio-lateral error (Vergauwen, Madou, & Behets, 2004; Vergauwen, Spaepen, Lefevre, & Hespel, 1998; Yamamoto, Shinya, & Kudo, 2018). Yamamoto reported that tennis shot placements on the court fit a bivariate normal distribution -represented by an ellipse- in the tennis forehand. This kind of distribution has also been found in a targeted movement task (Van Beers, 2012) and in baseball pitching locations (Kawamura et al., 2017; Kawamura, Shinya, Kobayashi, & Obata, 2016; Shinya et al., 2017). This concept is exemplified in Figure 1, where a fictitious tennis player hits the balls launched by a tennis coach. The probabilistic structure of the error for the forehand and backhand is represented by a bivariate normal distribution of the shot placements for each type of groundstroke, i.e. in the form of an ellipse (Figure 1). If the player has to hit balls in the down-the-line direction, the distribution of forehand shot landing may be more elongated than backhand shot landing (seen by shape and size of the ellipses). The fictitious player in the figure has more probability to commit long error than lateral error with the forehand than with the backhand and vice versa and should devote more training hours to improve control of the longitudinal accuracy with the forehand and control of the medio-lateral accuracy in the case of the backhand.

-------- Figure 1 near here --------

Reported differences in the magnitude of errors between the forehand and backhand stroke indicate that forehand strokes are generally more accurate than backhand strokes (Landlinger et al., 2012; Mavvidis, Stamboulis, Dimitriou, & Giampanidoy, 2010), but it remains unclear in which way error distributions would differ. A comprehensive description of typical error distributions in both forehand and backhand tennis groundstrokes, is still lacking. Having a better understanding of error distributions benefits learning (van Beers, 2012), allowing the design of tennis drills tailored specifically for each type of stroke.

The aim of our study was therefore to determine the probabilistic structure of errors in forehand and backhand groundstrokes. Based on previous knowledge we hypothesized that the probabilistic structure of errors will display an elongated bivariate normal distribution (represented by an ellipse) in both forehand and backhand strokes, but with notable differences in error distribution between both groundstrokes.

2. Methods

2.1. Participants

The sample consisted of 31 adult male players, aged 27.3 ± 6.7 (mean ± SD), with a minimum of 15 years of experience. All of them were taking part in regional competitions. During the month before data collection, each participant played tennis for more than 3 hours per week. They had an international tennis number (ITN) of 3 (advanced tennis players according to the classification by the ITF [2017]). Twenty-five of them performed the two-handed backhand, six of them the one-handed backhand, and three players were left-handed. Body composition was assessed through bioimpedance (Inbody 230), respecting two hours without eating or drinking and not having undertaken strenuous physical exercise 48 hours before the test. The anthropometric characteristics of the sample were: height, 178.4 ± 5.2 cm; body weight, 75.5 ± 10.2 kg; skeletal muscle mass, 36.3 ± 3.5 kg; body mass index, 23.7 ± 3.0; body fat percentage, 14.9 ± 6.4 %. Exclusion criteria were: 1) a musculoskeletal injury that would limit their stroke or shifting technique; 2) use of drugs due to serious illness. Participants were informed of the benefits and risks of the investigation prior to signing an institutionally approved informed consent according to ethical principles for medical research involving human subjects as defined by the Declaration of Helsinki.

Each participant used their own racket, each of which was in good state of use and approved by the International Tennis Federation (ITF, 2018). Given that racket string tension affects the stroke control and power

(Allen, Choppin, & Knudson, 2016) we verified at the start of the test if it was within the range recommended by the manufacturer by using a string tensiometer (Tourna Stringmeter).

2.3. Design and procedures

Measurements were performed at the University of Granada Institute for Sport and Health (IMUDS). The court was a hardcourt with an acrylic surface, which would correspond to a surface of type A (ITF, 2015). It was a half-covered court practically without wind. Tennis balls of a weight and a diameter allowed by the ITF (2015) were used (Wilson Trainer). Before beginning the test, a standardized 8-minute warm-up was performed which consisted of joint mobility exercises, running, and a 5-minute rally with a player whose level was similar to the participant's level.

The specific tennis hitting test was based on one that has been described in previous literature (Davey, Thorpe, & Williams, 2002; Delgado, Vanrenterghem, Munoz, Molina & Soto, 2018; Lyons et al., 2013) using the same number of throws per series, the same sequence (forehand-backhand) and a similar location of the center of the target. All shots were down-the-line in order to minimize the radar cosine effect error (Kelley, Choppin, Goodwill, & Haake, 2010). Players had to deliver the ball into a 2 x 2 m square floor target placed on the baseline (see Figure 1). The closer in distance to the center of the target that the ball touched the floor, the more accurate it was considered. From video images recorded from an aerial point of view (Panasonic HC-V160EC-K, 50 fps), the bounce of the court was manually digitized using Kinovea software (0.8.24 version) generating

2D coordinates (cm). The camera perspective distortion was corrected using coordinates of a known position of 100 balls placed in the court, based on linear regression equations. We evaluate the accuracy of the method placing 100 balls randomly distributed in the court and comparing the distance measured with the method with that obtained using a measuring tape. Accuracy error was of 2.61 ± 1.65 cm along the direction of the baseline (medio-lateral) and of 3.81 ± 4.28 cm along the direction perpendicular to the baseline (longitudinal). We considered this precision sufficient for the purpose of this research. With the 2D coordinates of the bounce, we computed the medio-lateral (X-axis), longitudinal (Y-axis) and Euclidean distances relatives to the center of the target.

Each participant performed four series of 20 strokes (80 strokes in total), hitting alternatively forehand and backhand and returning to the starting position at the baseline. They were asked to hit the target with the greatest possible speed with minimal loss of accuracy. Only the shots that passed over the net and came into the viewing angle of the camera were considered valid trials. A trial was not included if the ball touched the net but still passed to the other side of the court. Recovery time between sets was 4 minutes in order to minimize any effects of fatigue. The ball was stroke fed by an expert coach -with more than 20 years of teaching experience in tennis- at an approximate frequency of 20 throws/min, with flat and slow shots, where the ball should fall approximately at a line marked on the court at 3.7 m distance from the baseline. Although the throw frequency and the bounce areas of the ball may have had a greater variability than if a ball machine had been used, receiving from an expert feeder is known to allow for a more ecological stroke preparation (Shim et al., 2006; Pinder, 2009). Video analysis confirmed that throw rates remained constant throughout sets both within and between participants, ranging between 18 and 22 throws per minute.

Probabilistic structure of the errors was evaluated using bivariate normal distribution and 95% confidence ellipses (CE). Figure 1 shows the parameters of the ellipse that were calculated based on two similar previous studies (Shinya et al., 2017; Yamamoto et al., 2018): I) CE center location in the medio-lateral direction (X-axis), in the longitudinal direction (Y-axis), and the Euclidean distance of the center of the ellipse with respect to the center of the target as measures of the mean error (CE-x, CE-y, and CE-euc, respectively); II) CE area as a measure of global accuracy; III) CE eccentricity as a measure of ellipse shape; IV) CE tilt, as the angle between the long radius and the sideline (0 degrees would be parallel to the sideline). CE-euc, was not used for the principal aim of the work, it served as a simple measure of the player accuracy in the different series of the test, as we will see in the *Statistical analysis* section. As mentioned above CE-x and CE-y also measure the magnitude of the error but discriminate between the longitudinal error and the medio-lateral error. CE area gives a global idea of the magnitude of the error. CE eccentricity and CE tilt give information about how the shots are distributed in the space.

The confidence ellipse parameters were computed with Real Statistic Using Excel packages (Zaiontz, 2015). This excel add-in computes the confidence ellipse based on the eigenvectors and eigenvalues. The mathematics that underlie this computation are summarized in Figure 1 (Zaiontz, 2015, Schubert & Kirchner, 2014).

2.4. Statistical analysis

All statistical analyses were carried out using the OriginLab 9 software (OriginLab Northampton, MA) and Real Statistic Using Excel packages (Zaiontz, 2015). Shapiro Wilk test for normality was performed in all variables.

One-way ANOVA and Bonferroni post-hoc analyses were used to test for within-subjects differences between the four series of the test in terms of accuracy (based on CE-euc) and ball speed. For this analysis backhand and forehand were taken into account together. In only one player differences between sets were found on accuracy (he showed a declining trend, indicating that in this player fatigue could affect the accuracy of the last series). Eight players obtained greater ball speeds in the last sets (in most of players set 3 and/or 4 with respect to set 1). This suggests that in those players a *warming-up effect* took place. In only one player the first set showed significantly higher ball speeds than the last sets. Those result suggest that overall fatigue did not affect our test outcomes.

Two tailed paired sample *t*-tests (within-participant) were performed to compare error distribution variables between forehand and backhand strokes. Effect size (Cohen's *d*) was computed using Psychometrica freeware (Lenhard & Lenhard, 2016). Effect size was considered as follows (Cohen, 2013): I) 0-0.20, "negligible effect"; II) 0.20-0.50, "small effect"; III) 0.50-0.80, "medium effect"; IV) 0.80-1, "large effect".

To ensure that the accuracy variables used in paired *t*-tests were uncorrelated and that they provide separate information we inspected the correlation matrix between the selected variables, the variance inflation factors (VIFs) and we conducted a factor analysis (FA) involving principal component extraction and varimax rotation.

Significance level was set to an alpha of 0.05 and Holm–Bonferroni correction was applied to adjust for multiple comparisons (Gaetano, 2013; Holm, 1979).

Results

The number of valid shots (pass over the net and enter in the camera field-of-view) was of 32.9 ± 4.3 for the forehand and of 34.3 ± 4.9 for the backhand. The correlation matrix, the VIF coefficients and the factorial analysis, indicated that the accuracy variables selected were not related to each other and that multicollinearity was not a problem. Although there were some *r* values above 0.3 (specifically the correlation between the CE area and the CE-y was 0.47 and between the area and the CE eccentricity was of -0.44), VIFs were typically low (1.08, 1.26, 1.26, 1.06 and 1.12 for CE-x, CE-y, CE area, CE tilt and CE eccentricity, respectively). A factor analysis with five factors explained 100% of the total variance. Each factor was highly correlated with only one variable as shown in table 1.

-------- Table 1 near here --------

Ball speed and error distribution outcomes are summarised in Table 2. Ball speed of the forehand was significantly higher than of the backhand with large effect size. In terms of accuracy, CE-y and CE area were significantly lower in the forehand (with medium effect size in both cases). In the remaining variables there were no differences, including CE tilt, with the primary CE axis almost parallel to the sideline in both groundstrokes. CE-y was -also in both groundstrokes- away from the target (123.3 ± 65.9 cm in the forehand and 164.0 ± 56.9 cm in the backhand) in the positive direction. CE-euc was of 129.6 ± 62.8 cm for the forehand and of 169.89 + 54.9 cm for the backhand.

-------- Table 2 near here --------

Figure 2 shows the error distribution of the entire sample, whilst Figure 3 shows confidence ellipses for each participant, demonstrating that the population-based results are representative for most of the players. Eight out of the 31 players (2, 4, 12, 13, 17, 20, 27 and 29) displayed a smaller CE area with the backhand than with the forehand stroke. Eleven players had a greater CE eccentricity for the backhand than the forehand (1, 5, 12, 13, 14, 15, 18, 22, 23, 26, 27, and 29). In most of the players the ellipse was oriented almost parallel to the sideline: CE tilt was between one and fifteen degrees in all players for both groundstrokes except player 10 who showed a lateral tilt in both the forehand (40 degrees) and the backhand stroke (70 degrees) and in player 21 which backhand CE was tilted 23 degrees in the positive direction. Figure 2 and 3 also demonstrate the consistent bias of error distribution towards the positive side of the Y-axis (with only forehand of player 17 as an exception). Relative to CE area some players show values above 30 m^2 (18 in the forehand and 31 in the backhand) and only players 2, 4, 12, 13, 17, 20, 27 and 29 show a higher value in the forehand than in the backhand.

-------- Figure 2 near here --------

-------- Figure 3 near here --------

3. Discussion and implications

This study was the first to report a comprehensive error distribution analysis in forehand and backhand groundstrokes in tennis. Although the error distribution was adjusted to an ellipse (they fitted a bivariate normal distribution) in both the forehand and the backhand stroke, we found significant differences between forehand and backhand ellipses in the CE area and CE-y, indicating that the forehand was more accurate than the backhand.

Comparison with previous literature

The mean speed of the groundstrokes, both in the backhand and in the forehand stroke, was higher than what was previously reported by Rota, Morel, Saboul, Rogowski, & Hautier (2014), in young tennis players with a minimum of ten years playing, but it was lower than the values reported by

Landlinger et al. (2012) in elite and ATP players. Since our sample was of an advanced level, this suggests that our results are consistent with the literature. We also found that ball speed achieved with the forehand was higher than the speed achieved with the backhand (Table 2), which is similar to what has been reported previously in elite tennis players (Fernandez-Fernandez; Kinner, Vanessa; Ferrauti, 2010; Kraemer et al., 1995; Kraemer et al., 2003; Landlinger et al., 2012; Pluim et al., 2006), and in intermediate tennis players (Mavvidis et al., 2005, 2010).

In our study the mean CE-euc was only 1.3 ± 0.6 m for the forehand, ranging between ~0.07 m and ~3 m and of 1.7 ± 5.5 for the backhand (range between ~0.45 and ~2.8). This was lower than CE-euc for the forehand groundstroke reported in the Yamamoto study (2018), with an average of 2.00 ± 0.46 m and ranging between 1.25 m and 3.31 m. Landlinger et al. (2012) reported a mean Euclidean distance to the center of the target in elite and high-performance players of 1.48 ± 0.23 m and 1.62 ± 0.35 m, respectively, for the forehand, and of 1.46 ± 0.37 m and 1.74 ± 0.26 m, respectively, for the backhand. Vergauwen et al. (1998) reported a distance to the sideline of about 1.65 m and a distance to the baseline of about 3.40 m, major than in the present research (Table 2). The task in the study of Vergauwen et al. (1998) was more complex with players being signalled whether to deliver the ball cross-court or down-the-line through a light signal at the time of ball delivery, which may explain these poorer performances. Overall though, performance was largely as expected and in line with previous reports.

As reported in Yamamoto et al. (2018) for the tennis forehand stroke, errors could be fit through an elongated bivariate normal distribution, represented by an ellipse (Figure 2 and Figure 3). In the present study the ellipse was oriented parallel to the sideline (CE tilt was very close to zero) in all players except one, both in the forehand and in the backhand stroke, suggesting that longitudinal error (Y-axis) is more pronounced than medio-lateral error (X-axis). This error orientation had also been found in baseball (Kawamura et al., 2017; Shinya et al., 2017) or darts (Smeets, Frens, & Brenner, 2002). Based on Calvin's Launch Window Hypothesis (1983), it has been suggested that in a throwing task spatial accuracy depends heavily on the timing of release of the projectile (Freeston et al., 2015; Freeston & Rooney, 2014). We think this is especially important in tennis as the timing of the impact between two projectiles (racket and ball) needs to be optimized for longitudinal accuracy, redefining the so-called '*optimum window of release'* as the *'optimum window of impact'*. This optimum window of impact depends on the player adequately taking into account gravitational, drag and lift forces. In the lateral direction of the projectile, the thrower only has to ensure that the initial trajectory of the projectile is adequate (Smeets, Frens, & Brenner 2002). This likely explains the observed longitudinally elongated error distribution. It could also explain the considerably bigger values for the CE areas that we found relative to baseball (Kawamura et al., 2017; Shinya et al., 2017), as in some players those areas were above 30 m^2, which is consistent with the values shown by Yamamoto et al. (2008). Despite the large CE area, CE-x and CE-y were both small, which may be due to the corrections that the players made during the test trying to compensate long/lateral errors with errors in the opposite direction. Other research on stroke accuracy in tennis have proposed similar ideas of windows of initial trajectory of the racket/ball that allow for shot success, defined as the ball clearing the net and bouncing inside the limit of the baseline (Blackwell & Knudson, 2005; Brody, 1987; Knudson & Blackwell, 2005).

Whereas the longitudinally oriented bivariate error distribution was expected, a finding of the present study we had not seen in previous research was that CE-y was almost always located in the positive direction of the Y-axis, i.e., it was generally short of the target landing between the service line and the target (Figure 3), in both groundstrokes. This positive bias on the Y-axis likely comes from a conservative behaviour of the players that perform the test; they preferred to make safe short throws rather than risking to send the ball outside the limits of the court. Knowing the magnitude of this error could be important for players and coaches in the context of risk based playing strategies, i.e. seeking to play closer to the limits of the court to force the opponent into a defensive situation whilst understanding the increased risk of sending the ball outside the limits of the court.

Forehand and backhand accuracy differences

Error distributions showed a greater CE area and CE-y in the backhand than in the forehand stroke with moderate effect sizes (Table 2), which seems to indicate that the forehand is more accurate. This is in line with most previous research. Mavvidis et al. (2010) found higher accuracy with the forehand than with the backhand in young competitive tennis players and Landlinger et al. (2012) found higher accuracy with the cross-court forehand than with the cross-court backhand. Although they found accuracy differences between the cross-court forehand and the cross-court backhand they did not report any difference in the down the line shots, as we found. Some other researchers did not find significant differences between accuracy of forehand and backhand (Davey et al., 2002; Lyons et al., 2013; Mavvidis et al., 2010, Strecker et al., 2011). A viable explanation of these discrepancies may have been in the resolution of the distance to target, as they measured error as a sum of the points obtained using a target system and not as a distance measure. As the present work uses a higher resolution evaluation, we think that it is safe to conclude that - in view of our results - the forehand stroke is more accurate than the backhand stroke. A possible explanation for this is that humerus and forearm kinematics in the throwing pattern that is learned early in childhood (Stodden, Langendorfer, Fleisig, and Andrews, 2006) has greater similarity with the forehand than with the backhand stroke. Furthermore, in the particular case of junior players, fewer backhands are executed during matches, as players avoid the use of backhands using inside-out forehands (Ridhwan, Ghosh, & Keong, 2010). Future studies are needed to evaluate whether this extends to cross-court strokes, to other player levels, and to more complex tasks.

Practical implications

Several practical implications come from the results of the present study. First of all, knowing of the existence of a probabilistic structure of error can help coaches and players identify more focused strategies to improve stroke success rates and guide training plans. More specifically, the results of the present work suggest that in order to improve accuracy it is important to include drills to control the depth of the strokes, both for the forehand and backhand. Changing the locations of the target used in the drills seems more important in the longitudinal direction than in the medio-lateral direction in terms of improving overall accuracy. With previous research having demonstrated that accuracy in the longitudinal direction mainly depends on racket kinematics (Blackwell & Knudson, 2005; Brody, 1987; Knudson & Blackwell, 2005), it also seems important to include exercises that try to make players conscious of the racket head position near the time of impact. For example the use of kinaesthetic aids on the part of the trainer, or performing strokes with static balls at ultra-slow speed, may be of benefit. Other ways to improving the control of longitudinal accuracy could be including exercises where the player has to alter the speed, altitude and/or spin of the ball, as these three factors determine the trajectory of the ball in the longitudinal direction. Alterations of altitude can for example be imposed by using ropes over the net dividing zones of different altitude, or speed can be altered by marking a *power-line* behind the baseline which the ball has to cross after the first bounce (see Smekal et al., 2000). Otherwise, training plans could also address the conservative behaviour of players (in the present work the tennis players made more short throws than long throws), or the backhand stroke’s poorer error distributions. The effectiveness of such focused training strategies would of course need to be confirmed with specific stroke training intervention studies.

Limitations

The homogeneity of our sample and the controlled nature of our test strengthen but also weaken the present work, as it does not allow to directly translate our findings to other populations or to more open ended play situations. We expect that the observed error distributions will be fairly consistent between players of different levels, ages and sex, but this would need to be confirmed by further research. Studying the error distributions in a more realistic situation would also be of interest in elite players who may wish to improve success rates of specific shots under specific circumstances. Similarly, the evaluation of error distributions for different ball speeds could help reveal individual speed-accuracy trade-offs and provide further guidance in terms of training priorities.

4. Conclusions

We found that the error distribution was adjusted to an elongated bivariate normal distribution in both forehand and backhand groundstrokes, although higher speed with higher accuracy was found for the forehand. The long axis of the ellipse was oriented parallel to the sideline in both cases, and this was generally consistent across individuals. Practically our findings suggest that working on (sub-components of) groundstroke depth control, as well as speed and accuracy of the backhand stroke, has the greatest potential for improving stroke performance in advanced tennis players.

Disclosure statement

No potential conflict of interest was reported by the authors.

Acknowledgments

The authors would like to thank all those athletes who participated in this research. It was supported by the Spanish Ministry of Education (FPU15/02949).

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Table captions

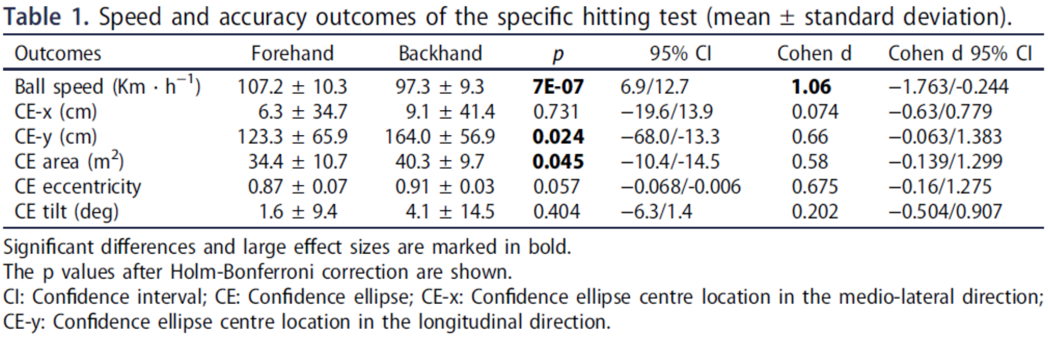


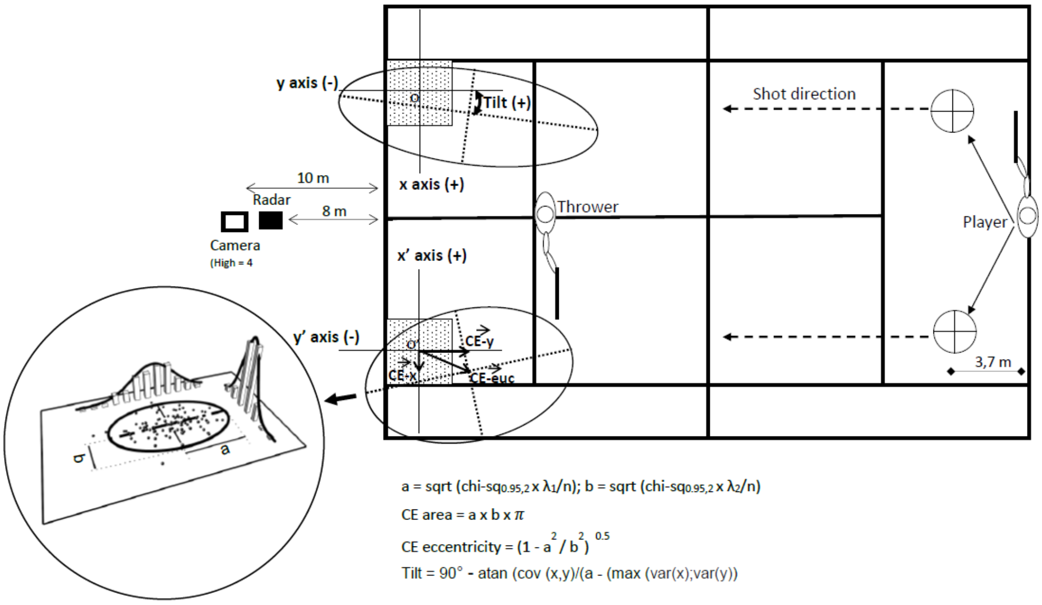
Table 1. Speed and accuracy outcomes of the specific hitting test (mean ± standard deviation).

Outcomes	Forehand	Backhand	*p*	95% CI	Cohen d	Cohen d 95% CI
Ball speed (Km · h^{-1})	107.2 ± 10.3	97.3 ± 9.3	**7E-07**	6.9/12.7	**1.06**	−1.763/-0.244
CE-x (cm)	6.3 ± 34.7	9.1 ± 41.4	0.731	−19.6/13.9	0.074	−0.63/0.779
CE-y (cm)	123.3 ± 65.9	164.0 ± 56.9	**0.024**	−68.0/-13.3	0.66	−0.063/1.383
CE area (m^2)	34.4 ± 10.7	40.3 ± 9.7	**0.045**	−10.4/-14.5	0.58	−0.139/1.299
CE eccentricity	0.87 ± 0.07	0.91 ± 0.03	0.057	−0.068/-0.006	0.675	−0.16/1.275
CE tilt (deg)	1.6 ± 9.4	4.1 ± 14.5	0.404	−6.3/1.4	0.202	−0.504/0.907

Significant differences and large effect sizes are marked in bold.
The p values after Holm-Bonferroni correction are shown.
CI: Confidence interval; CE: Confidence ellipse; CE-x: Confidence ellipse centre location in the medio-lateral direction; CE-y: Confidence ellipse centre location in the longitudinal direction.

Table 1. Speed and accuracy outcomes of the specific hitting test (mean ± standard deviation).

Figure captions



a = sqrt (chi-sq$_{0.95,2}$ x λ_1/n); b = sqrt (chi-sq$_{0.95,2}$ x λ_2/n)

CE area = a x b x π

CE eccentricity = $(1 - a^2 / b^2)^{0.5}$

Tilt = 90° - atan (cov (x,y)/(a - (max (var(x);var(y))

Figure 1. A fictitious situation where the distribution of the error of a player in the form of confidence ellipse is shown. chi-sq$_{0.95,2}$: chi-square cumulative distribution function with two degrees of freedom at a probability level of 95% (≈ 5,99146); var(x) and var(y) the variance of the x and y positions of the ball landing; cov (x,y) the covariance between x and y; λ_1 and λ_2 the maximum and minimum eigenvalue of the covariance matrix; *a*: long radius (Y-axis); *b*: short radius (X-axis); $\overrightarrow{CEx}, \overrightarrow{CEy}, \overrightarrow{CEeuc}$: Confidence ellipse center location in the medio-lateral direction and longitudinal direction and

Euclidean distance of the center of the ellipse respect to the center of the target. It also includes a graph illustration of a bivariate normal distribution.

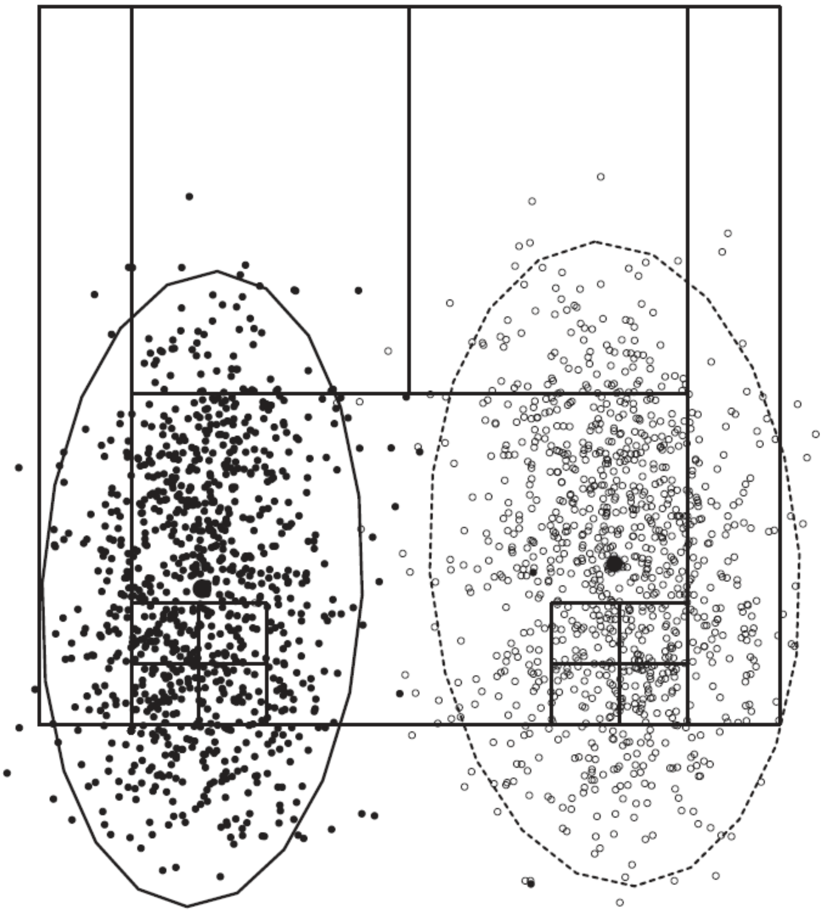


Figure 2. 95% confidence ellipses of the whole sample shot locations, including the tennis court. Forehand strokes are represented with black dots and backhands strokes with white dots. Forehand confidence ellipse is drawn with a continuous line and backhand ellipse is drawn with a discontinuous line. Big black dots are the confidence ellipse centers.

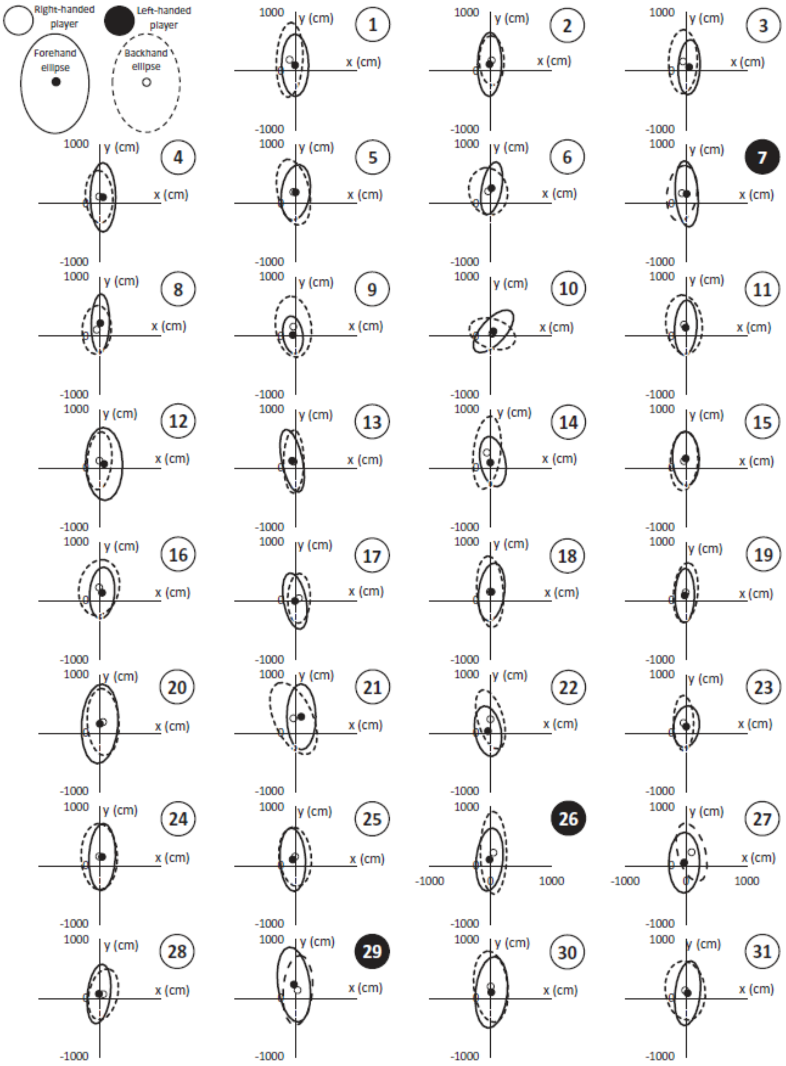


Figure 3. Confidence ellipses of each participant (numbered in the right-up corner). The superimposed ellipses of the forehand and backhand strokes are displayed in a common coordinate system. The continuous line represents the forehand ellipse and the discontinuous line the backhand ellipse (see first cell).