Impact Distance Detection in Tennis Forehand by an Inertial System

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Abstract: Assessing the distance to the ball in the tennis forehand is fundamental. In this context, a non-invasive assessment system can help technicians even more in amateur tennis, where players who are still unaware of the act need continuous feedback. Three amateur tennis players with an average of 4 years of playing experience were recruited. The subjects wore a sensorized chest strap with an inertial unit and received two sets of 10 balls each. Two action cameras captured 20 forehands of each player from lateral and rear perspectives, aligned about 6m from the point of impact. Video analysis was conducted to identify the anteroposterior and lateral distance of the ball at the point of impact from the longitudinal axis coincident with the first toe of the nondominant foot. Pearson's correlation between distance and trunk inclination during the impact phase was investigated, and a strong correlation was found for all the subjects. This prompts us to consider the potential of a sensorized chest strap to assess the individual optimal distance from the ball in the forehand of tennis amateurs. Subsequent studies are needed to develop the system's full potential, expand the number of subjects, and examine all the fundamentals of the game.

1 INTRODUCTION

Tennis is a highly technical sport and requires fine motor coordination (Casale, 2003; Roetert & Kovacs, 2019). The learning process is particularly demanding, and it is common to make various mistakes in improving skills (Reid et al., 2013). The technique can be continuously refined (Castellani et al., 2007), and biomechanical analysis of the movement can effectively correct improper actions. Studies comparing high-level and amateur players have provided insights into optimal angles and body positions during various strokes (Fleisig et al., 2003; Knudson & Elliott, 2004; Landlinger et al., 2010; Nesbit et al., 2008; Reid & Elliott, 2002; Roetert & Kovacs, 2019). However, playing technique is strongly influenced by the tactical context and how the player reaches the position. That is why, in recent years, the concept of pure technique has lost its value, and coaches are increasingly talking about technique applied to the tactical context (Castellani et al., 2007). Even in simple, controlled situations in training, amateur players have difficulty always positioning themselves at an optimal distance from the ball, presenting a higher variability in stroke execution, unlike advanced athletes (Caprioli et al., 2024). This variability occurs because less experienced players are less able to read the ball's trajectory and less aware of their technical gestures.

For this reason, assessing the distance to the ball in rebound shots (forehand and backhand) is critical,

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particularly for amateur tennis players. Proper distance maximizes ball contact in the ideal area of the racquet, known as the "sweet spot" allowing more control over the direction and power of the shot. If the impact occurs too close to the body the extension of the arm is limited, and as well as in the case of excessive distance reduced power and accuracy of the shot. Keeping the right distance from the ball can also help reduce the risk of injury, as it allows you to execute the shot with proper technique and without excessive stress on joints, muscles, and ligaments (Fu et al., 2018; Reid et al., 2013).

1.1 Forehand Shot Assessment

Forehand is considered the most important technical gesture after the serve (Johnson & McHugh, 2006), and in the game, forehand shots are about 25 percent more than backhand shots. Players are constantly striving to improve their forehand from a technical standpoint. In the forehand, we can observe different personalisms among tennis players; however, some technical parameters are present in all of them, and it can be divided into six main phases: starting position, preparation (unit-turn), opening phase, stance, impact, final (Bertino et al., 2012). In the forehand, the greatest linear and internal rotation velocity expressions occurred quite late in the forward swing phase toward impact (Elliott, 2006; Elliott et al., 1997; Seeley et al., 2016).

Among the methods currently most widely used for technical assessment are 2D and 3D video motion tracking systems (Annino et al., 2023; Edriss et al., 2024; Lambrich & Muehlbauer, 2023; Martin et al., 2021). However, these systems often prove to be expensive or time-consuming. For this purpose, proposed as a valid alternative solution to optical motion tracking systems the inertial sensors (Inertial Motion Unit – IMU) (Delgado-García et al., 2021; Hernández-Belmonte & Sánchez-Pay, 2021; Zanela et al., 2024) IMUs contain MEMS-type accelerometers, gyroscopes, and magnetometers, and through a sensor fusion estimation 3D orientation is obtained. The advantages of inertial sensors include, among others, the accuracy, convenience, and quickness of measuring and analyzing data, which can potentially take place even in real-time without the need for very expensive hardware components, unlike current 3D motion capture systems (Edriss et al., 2024). Despite their small size and applicability in almost any environment, these devices face several technical challenges (Alcala et al., 2021). In some studies, inertial sensors were placed on the racket or wristband for stroke analysis and classification (Ebner & Findling, 2019; Kos & Kramberger, 2018). Although this approach allows the direct measurement of important kinematic parameters such as accelerations, angular velocities, and the exact position of joint segments using quaternions, the extensive use of these devices may prove invasive. Although very lightweight, several sensors placed on the tennis player's body could sensitively limit movement or otherwise impair the naturalness of the gesture. In the same way, even a single sensor of a few grams placed on the tennis racket can compromise the technique of the strokes.

The help a non-invasive assessment system can provide a technician is even more apparent in amateur tennis, where players still unaware of the act need continuous feedback. In this study, an inertial measurement system was applied to detect the distance from the ball at the impact in the forehand shot of 3 amateur players.

2 MATERIALS AND METHODS

The analysis was conducted on three amateur tennis players (one female and two males; 32.7 ± 6.8 years, 175.3 ± 8.2 cm) with an average of 4 years of playing experience. All recruited subjects were in good health, had not suffered recent injuries, and consented to data processing for research purposes. The subjects wore a sensorized chest strap on which a Movella DOT inertial unit was mounted (Table 1). The device was positioned as tightly as possible without allowing the sensor to move freely and as comfortably as possible for each subject, depending on the physical conformations of each male and female. The inertial sensors, previously calibrated, were set to an offline acquisition mode at 120 Hz.

Table 1: Inertial Measurement Unit details.

Dimensions:	36.3 × 30.35 × 10.8 mm
Weight:	11.2 g
Recording Mode	Offline
Sampling Rate	120Hz
Connection	Bluetooth 5.0

All measurements were conducted on a sunny day with no adverse wind conditions in an outdoor court. The subjects followed a 20-minute physical and technical warm-up and then played two sets of 10 forehand strokes in a controlled situation, with a three-minute rest between sets. A Tennis Tutor Plus ball-launching machine, positioned on the opposite baseline at 1.60m from the mid-point, was set to two settings for the two practice sets. For the first set, subjects received ten balls each, at speed 4, with no effect and easy to handle. In the second, ten balls at speed 6 with top spin instead. Two action cameras 240 Hz captured 20 forehands of each player from lateral and rear perspectives, both aligned about 6m from the point of impact and placed on a stand at 1.10m above the ground. The cameras were synchronized with each other through a luminous pulse. Video analysis was conducted using Kinovea software (version 0.9.5) (Charmant & contributors, 2021) to identify the lateral and anteroposterior distance of the ball at the point of impact concerning the longitudinal axis coincident with the first toe of the nondominant foot (Figure 1). Since the players did not have the same position on the court in each shot, in each impact frame, calibration was re-performed using the racquet of a known size equivalent to 68.50 cm as a reference placed on the measurement plane (subjects used standard-length racquet models).

Figure 1: Distance measurement by video analysis. The racket measurement was used as a reference placed on the measurement plane in the calibration process.

2.1 Data Analysis

From the data acquired by the IMU, the trunk inclination angle (Euler Y) during the impact phase, coinciding with the point of the maximum angular velocity of trunk rotation (Gyr X), was analyzed. The Shapiro-Wilk test was used to validate the assumption of normality. Since no significant deviations from normality were detected, parametric tests were used for inference. The coefficient of variation (CV) for repeated measurement, interclass correlation coefficients (ICC), standard error of measurement (SEM) and 95% confidence interval (95% CI) were calculated to determine the set-to-set reliability for lateral and anteroposterior distance, and trunk angle (Euler Y). Moreover, the ICC was used as an assessment test of consistency and the repeatability of quantitative measurements made by the same operator in two different sets. Paired t-tests and the Pearson correlation coefficient (r) were used for repeatability of test-re-test measurements. In addition, the effect sizes (ES) were also calculated using Cohen's d between the first set and the second set of means (Cohen, 2013), where the small effect was 0.1, moderate 0.3, and large was 0.5 (Cooper et al., 2019).

Pearson's correlation between ball distance and trunk inclination during the impact was investigated for each player and the group. MedCalc software (Version 23.0.2) was used for statistical analysis.

3 RESULTS

3.1 Reliability

Test-retest values of Mean, SD, SEM, ICC, Pearson correlation coefficient (r), and the CV relative to the lateral distance (LD), trunk inclination (Euler Y), and anteroposterior distance (APD) performed in the two sets are reported in Table 2.

Table 2: Set-to-set repeatability of average lateral distance LD (cm) and trunk angles Euler Y of the forehands performed by three amateur tennis players. r Pearson correlation coefficient; CV, Coefficient of Variation for repeated measurements; ICC, Interclass Correlation Coefficient; 95% Confidence Interval (CI); SEM, Standard Error of Measurement; and ES, Effect Size.

Different Set	**Set 1**	**Set 2**	**r**	**CV [a] %**	**ICC**	**95% CI**	**SEM**	**ES**
Parameters	**Mean ± SD**	**Mean ± SD**						
LD (cm)	88.43 ± 16	87.45 ± 23	0.998	4.75	0.966	-0,3021 to 0,9991	0,730	0,382
Euler Y (°)	75.50 ± 5	77.03 ± 4	0.902	2.13	0.934	-1,5807 to 0,9983	1,052	-0,049
APD (cm)	-6,77 ± 18	-12,42 ± 23	0.972	244.54	0,968	-0,2674 to 0,9992	2,881	0,272

[a] Root mean square method

ICC found no significant differences between the first and second sets of measurements, showing high reproducibility for all measurements. The CV was high or extremely high in the case of APD. The effect size is small or moderate in the case of LD. The two measurements have a strong Pearson correlation (Table 2).

3.2 Descriptive Statistics

Sixty forehand shots were analyzed. The mean lateral distance measured among all trials was 88.52cm with a standard deviation of ± 18cm, with a minimum value of 61cm and a maximum value of 120cm. The mean anteroposterior distance was -9.42cm ± 23cm with a minimum value of -53cm and a maximum value of 20cm. As for trunk inclination (Euler Y), it was an average of 76.30° with a standard deviation of 5°, minimum value of 63° and maximum value of 85°.

3.3 Inferential Statistics

A highly significant strong Pearson's correlation was found in all the subjects between trunk angle Euler Y (i.e., flexion-extension angle) and lateral distance from the ball. In particular, in Player 1 was found a medium-high correlation (r= 0.69 p<0.001) (Figure 2), strong in Player 2 (r= 0.79 p<0.001) and Player 3 (r= 0.70 p<0.001) (Figure 3). A more moderate partial correlation (r= 0.40 p<0.001) was found in the analysis of the 60 forehand shots of the whole group due to the variability of distance to the ball in players with different body stature and joint levers. However, no significant correlations were found with anteroposterior distance.

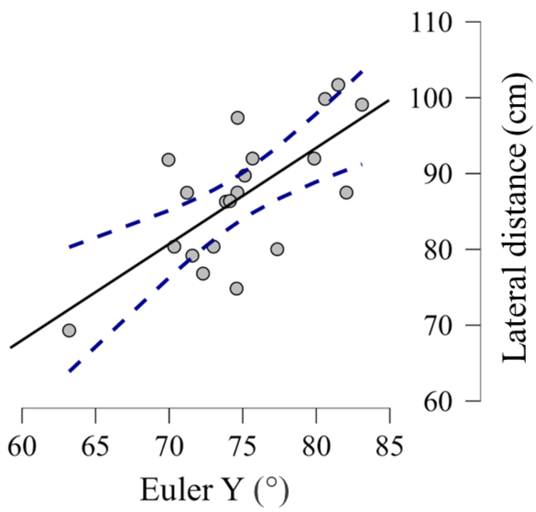

Figure 2: Pearson's correlation in Player 1.

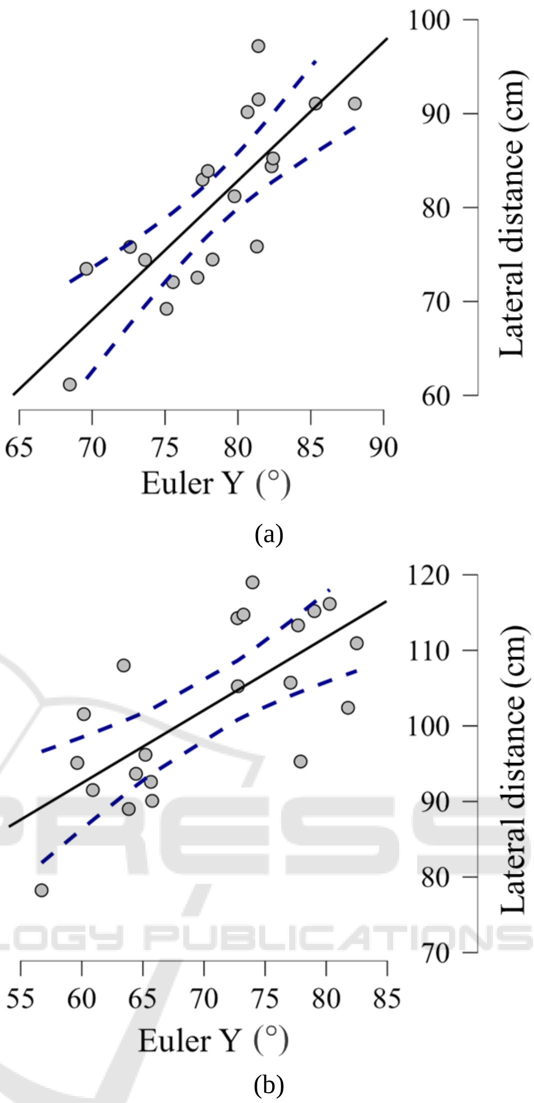

Figure 3: Pearson's correlation in Player 2 (a) and 3 (b).

4 DISCUSSION

This study allowed us to evaluate, even if in preliminary form and on a sample of only three subjects, the reliability of a system for distance assessment in the forehand based on a single inertial sensor applied on the athlete through a chest strap. The measurements were reliable, and a strong, significant correlation was found between torso tilt and lateral distance. The correlation found confirms what was logically hypothesized at the beginning of the study: a proper distance from the ball may allow for better body weight transfer through forward torso tilt, as opposed to distances that are too short. It should be considered from a simple observation that amateur players generally tend not to position themselves at a sufficient distance from the ball. In the face of these results, the study opens new on-court applications for improving amateur tennis performance through personalized feedback. Indeed, it is possible to develop, via the SDK provided by the manufacturer, simple mobile apps connected via Bluetooth to the sensor that can indicate a customized correction in real-time. The study's main limitation is the small number of subjects, which will need to be expanded. Furthermore, in this study, only the forehand technique was examined without analyzing the stroke result, and because of the need to standardize the investigation protocol, a single structured situation was assessed, and not all possible game situations that may occur during a match were examined.

5 CONCLUSIONS

This preliminary study found a strong correlation between the torso tilt detected by the IMU system and the lateral distance to the ball at the impact point. This bodes well for how a sensorized chest strap can aid the technician in assessing the individual optimal distance to the ball in the forehand of amateur tennis players. Subsequent studies are needed to develop the system's full potential, broaden the investigation's sampling, and examine all game fundamentals.

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