DOI: 10.30827/Digibug.80901 Original Investigation

Validation of wearables for technical analysis of tennis players

Validación de sensores inerciales para el análisis técnico de tenistas

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Received: 06-05-22

Accepted: 17-03-23

Abstract

The aim of the study was to analyze the validity of three well-known commercial sensors (Zepp1, Zepp2 and Qlipp) by comparing the speed data they provide with a speed radar and a 3D photogrammetric system. Thirteen tennis players of different levels were part of the present study: In the first experiment, performed in the tennis field, 4 players executed a total of 100 strokes (serves and groundstrokes), in the groundstrokes using a ball throwing machine to standardize throws at a speed of 70 km/h and with the minimum spin effect allowed by the machine. The ball speed measured with the Zepp1 sensor and with the Qlipp sensor was compared with the speed recorded by a radar (Stalker Pro II, USA) and with a photogrammetric system composed by 4 USB cameras (ELP, China) recording at 100 Hz. The ball and the end of the racket frame were digitized on the video using the freeware Kinovea and their real 3D coordinates were obtained by applying the DLT algorithm, using the Kinemat tool in the mathematical analysis software GNU Octave. The velocity was calculated by deriving the 3D coordinates using a fifth degree spline. In the second experiment, performed inside the laboratory, 9 players executed 20 forehand and backhands each one (n = 360 groundstrokes). Ball speed was computed with the Zepp2 device and with an highly accurate photogrammetric device (Qualisys), considered as the reference. The data of the present work indicate that the hitting kinematics of each player and the speed of the stroke affects the accuracy of the sensor, so we consider that further studies are required to evaluate the error in players of different levels and playing styles. The Zepp1 and Zepp2 inertial sensors evaluated in this work seem adequate to measure ball speed in intra-subject studies and the Lin CCC values in the first study and the adjusted values in the second study were almost all greater than 0.75.

Keywords: *Tennis, performance, validation, racket sports, photogrammetry, Zepp, Qlipp.*

Resumen

El objetivo del estudio fue analizar la validez de tres sensores comerciales conocidos (Zepp1, Zepp2 y Qlipp) comparando los datos de velocidad que proporcionan con los de un radar de velocidad y con los de un sistema fotogramétrico 3D. Trece tenistas de diferentes niveles formaron parte del presente estudio. En el primer experimento, realizado en una pista de tenis, 4 tenistas realizaron un total de 77 golpeos (saques y golpeos de fondo), en el caso de los golpeos de fondo se usó una máquina lanza-pelotas para estandarizar los lanzamientos a una velocidad de 70 km/h y con el mínimo efecto liftado permitido por la máquina. La velocidad de la pelota medida con el sensor Zepp1 y con el sensor Qlipp se comparó con la velocidad registrada por un radar (Stalker Pro II, USA) y con un sistema fotogramétrico compuesto por 4 cámaras USB (ELP, China) grabando a 100 Hz. La pelota y el extremo de la raqueta fueron digitalizados en el vídeo utilizando el freeware de análisis de vídeo Kinovea y se obtuvieron sus coordenadas 3D reales aplicando el algoritmo DLT, usando la herramienta Kinemat en el software de análisis matemático GNU Octave. La velocidad fue calculada derivando las coordenadas 3D mediante un spline de quinto grado. En el segundo

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Cite this article as:
Delgado García, G., Siquier Coll, J., Castro Infantes, S., Ruiz Malagón, E. J., Benito-Colio, B., & González-Fernández, F. T. (2022). Validation of wearables for technical analysis of tennis players. *International Journal of Racket Sports Science*, 4(2), 56-61.

experimento, realizado en el laboratorio, 9 jugadores de tenis ejecutaron 20 derechas y 20 reveses cada uno (n = 360 golpeos) y la velocidad de la pelota se midió con el Zepp2 y con un sistema fotogramétrrico de alta precisión (Qualisys), considerado como la referencia. Los datos del presente trabajo indican que la cinemática de golpeo y la velocidad de golpeo de cada jugador afectan la precisión del sensor, por lo que consideramos que se requieren más estudios para evaluar el error en jugadores de diferentes niveles y estilos de juego. Los sensores Zepp1 y Zepp2 evaluados en este trabajo parecen adecuados para medir la velocidad de pelota en estudios intra-sujeto y los valores Lin CCC en el primer estudio y los valores ajustados en el segundo estudio fueron casi todos mayores de 0.75.

Palabras clave: *Tenis, rendimiento, validación, deportes de raqueta, fotogrametría, Zepp, Qlipp.*

INTRODUCTION

The use of wearable technology for technical analysis of tennis players is becoming increasingly common (Shan et al., 2015; Kos et al., 2016; Delgado et al., 2021; Ruiz-Malagón et al., 2022; Ruiz-Malagón et al., 2023). These technologies in addition to performance enhancement allow the quantification of training load, thus being able to help prevent overuse injuries such as epicondylitis (Edelmann-Nusser, 2019; Keaney & Reid, 2018). Some brands that market these sensors are Babolat, Zepp, Qlipp or Sony. These devices usually provide information of the stroke speed (either they estimate the speed of the racket or the ball), the spin of the stroke, the type of stroke and the impact point of the ball on the racket. We have found only two scientific works indexed in the Journal Citation Report, concerning the validity of the Babolat sensor and the (Edelmann-Nusser, 2019; Keaney & Reid, 2018). In the research by Keaney & Reid (2018) the sample consisted of a single athlete, so more studies validating these devices with a more heterogeneous sample are required. In other racket sports there are also similar publications and for example Jaitner and Gawin (2010) found high correlations between racket speed measured with an inertial sensor and badminton shuttlecock speed.

There are other publications showing other inertial sensors for technical analysis oriented to racket sports. Yang et al. (2017) develop a sensor (TennisMaster), and evaluate its performance by collecting the acceleration and angular velocity data of 1030 serves performed by 12 subjects of different playing levels. The results showed that the TennisMaster device achieves an accuracy in serve detection of 96% and an accuracy in splitting the phases of the stroke of 95%. Kos et al. (2016) also obtained high accuracy (above 95%) using algorithms for classification of forehand, backhand and serve strokes.

Considering that the quantification of training load is fundamental for both training improvement and musculoskeletal injury prevention the aim of the study was to study the validity of three known commercial sensors (Zepp1, Zepp2 and Qlipp) by comparing the speed data they provide with those of a speed radar and with those of a 3D photogrammetric system, including tennis players of different levels of play.

METHODS

Participants

The study sample for the first experiment consisted of 4 tennis players. Who performed a total of 100 strokes. One of the subjects was of competition level and the other three were beginners (Table 1). In the second experiment 9 players were included (5 of competitive level [one included in the sample of the first experiment]) and 4 beginners and the study complied with the guidelines established in the Declaration of Helsinki for research in humans.

Procedures

Part 1: On-track evaluation

Different types of strokes were performed (services and groundstrokes). In the case of the groundstrokes the ball was launched by a ball throwing machine (Lobster GrandSlam 4, see figure 1) at a speed of 70 km/h and with the minimum spin effect allowed by the device. Table 1 shows the strokes made by each player.

Table 1. Players included in the study and strokes made by each player.

Player number	Level	Characteristics	Analyzed strokes
1	Comp.	Male, 28 y.o.	30 forehands*
2	Beg.	Male; 48 y.o.	16 forehands
3	Beg.	Male, 28 y.o.	16 serves
4	Beg.	Female, 26 y.o.	16 forehands, 12 backhand & 10 serves.

Notes: Comp.: Competition; Beg.: Beginner.
*The competition player performed forehands varying the hitting effect (flat, slice or topspin).

The ball velocity measured with the Zepp1 (classic) sensor and with the Qlipp sensor was compared with the velocity recorded by a radar (Stalker Pro II, USA, see figure 1) and with a photogrammetric system composed of 4 USB cameras (ELP, China) recording at 100 Hz. The ball and the end of the racket were digitized using the freeware Kinovea and their real 3D coordinates were obtained by applying the DLT algorithm using the Kinemat tool (Reinschmidt &

van den Bogert, 1997) in the mathematical analysis software GNU Octave. The velocity was calculated by deriving the 3D coordinates using a fifth-degree spline (and computing the average speed of five frames just after the impact of the ball).

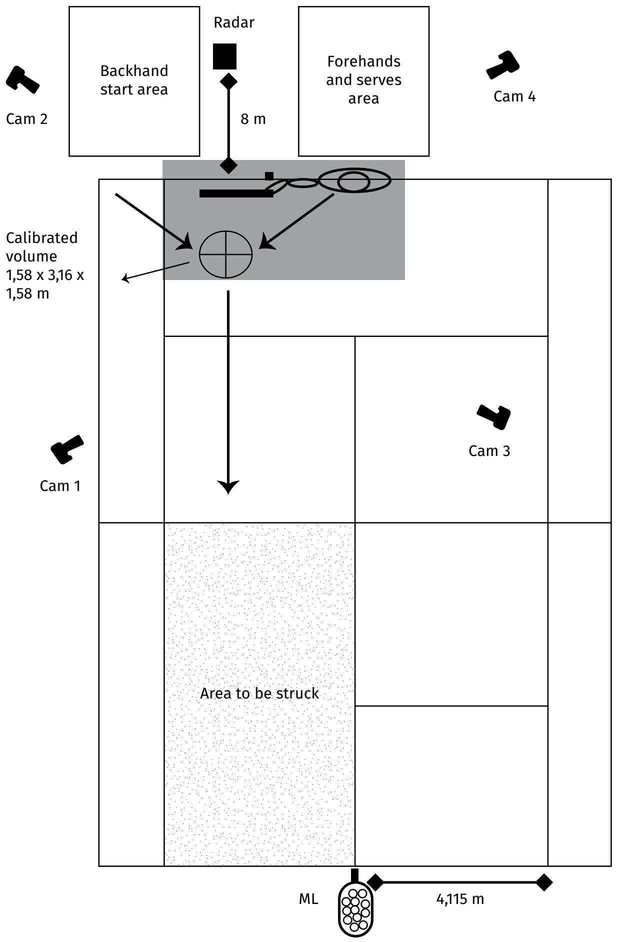

Figure 1. Scheme of the experiment carried out on track for the validation of the Zepp1 and Qlipp devices.
ML: Ball machine. Cam 1 and Cam 2 allow to analyze the serve and forehand and Cam 3 and Cam 4 the backhand.

Part 2: Laboratory evaluation

The Zepp2 (new version) device was placed on the racket grip, following manufacturer indications. The player was asked to perform 20 forehand and 20 backhand strokes against a ball attached to a flexible stick with a retroreflective marker below the ball, so a total of 360 strokes were collected (9 players x 2 types of strokes [forehand and backhands]) x 20 strokes of each type). The speed of the retroreflective marker was computed straightly after each stroke with an highly accurate photogrammetric system composed by 8 Qualisys cameras, used as the reference (Delgado-García et al., 2020).

Statistical procedures

The following statistical parameters were used to evaluate the validity of the sensor: RMSE, MAE, Pearson's r, Lin CCC and Bland-Altman (BA) plots. In order to analyze the quality of the correlations, the Evans scale (1996) was used.

In the second study the type of stroke (forehand or backhand) was considered in the statistical analysis. Both the whole sample and each groundstroke (forehand or backhand) independently were taken into account. In addition, the databases (n = 357 for the groundstrokes; n = 177 for the forehand [only three strokes were not stored] and n = 180 for the backhand) were divided in two: I) the first three databases called training databases (n = 179 for the groundstrokes; n = 89 for the forehand and n = 90 for the backhand) allowed the calculation of a ridge regression line (including the slope and the intercept at the y-axis of the line) that allowed to compute the racket speed based on the Zepp2 estimated racket speed (slope and ordinate at the origin); II) the rest of the data, called test databases were fitted based on the calculated regression equation and compared with the gold standard.

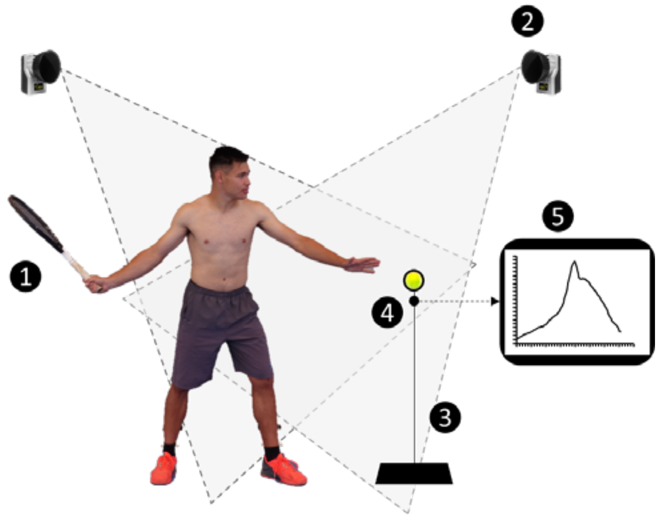

Figure 2. Set-up of the experiment number 2. The key elements are indicated with numbers: (1) tennis racket with the Zepp2 device; (2) photogrammetric system composed by 8 Qualisys cameras ; (3) Flexible stick with a tennis ball in the extreme to be hit by the player; (3) retroreflective marker for estimating ball speed with the photogrammetric system in the moment of the impact; (5) computer connected to Qualisys that allow to compute the retroreflective marker maximum speed just after the stroke.

RESULTS

Part 1: On-field evaluation

The racket velocity measured with the Zepp1 device had a high correlation score with the velocity determined with the other devices, while in the case of the Qlipp sensor the correlations were moderate (see table 2).

The values of *MAE* were (V = Velocity):

- V Radar vs. V *Zepp* = 23 km/h; V Radar vs. V *Qlipp* = 18 km/h; V Radar vs. V Ball *3D* = 5 km/h.
- V Racket *3D* vs. V *Zepp* = 7 km/h; V Racket *3D* vs. V *Qlipp* = 22 km/h.

- V Ball *3D* vs. V *Zepp* = 25 km/h; V Ball *3D* vs. V *Qlipp* = 21 km/h.

Figure 3 shows the BA plot of the racket speed measured with the Zepp1 and the racket speed measured with the 3D system. Differences in error are observed as a function of player and type of stroke (only in player 4).

Table 2. Lin CCC and Pearson's r between the speed measurements taken with different.

	VB Rad (km/h)	VR (3D) (km/h)	VB (3D) (km/h)	VR Qlipp (km/h)	VR Zepp1 (km/h)
VB Rad (km/h)	1	0.58	0.98	0.72	0.57
VR (3D) (km/h)	0.86	1	0.55	0.49	0.91
VB (3D) (km/h)	0.99	0.83	1	0.64	0.55
VR Qlipp (km/h)	0.75	0.71	0.66	1	0.57
VR Zepp1 (km/h)	0.85	0.95	0.83	0.8	1

*Above the diagonal the Lin CCC values are shown and below the diagonal the Pearson's R values are shown.
V: velocity; R: racket; B: ball.

Part 2: Laboratory evaluation

This section shows the data for the unadjusted values and the data for the adjusted values in parentheses. In the case of the groundstrokes sample (forehands and backhands) the ridge regression equation to compute the Qualisys ball speed (reference) based on the Zepp ball speed was: y = x - 6.99 (km/h) (lambda = 0.5; r = 0.76; $p < 0.001$). In the case of the forehand the ridge regression equation was y = x - 5.89 (km/h) (lambda = 10.63; r = 0.80; $p < 0.001$) and in the case of the backhand it was y = 0.859x + 5.69 (lambda = 0.89; r = 0.62; $p < 0.001$). If one doesn´t one to consider the type of stroke the adjustment proposed simply consist on substracting the value of 7 km/h to the ball speed provided by the Zepp2 device. This correction must be considered with caution as the retroreflective marker wasn´t placed exactly on the ball but a little down in the flexible stick, and considering the relation between angular and linear speed it is obvious that the speed in the extreme (ball measured with the Zepp2) will be higher, with the same angular speed. When all strokes were taken into account the Lin CCC value was 0.66 (0.75) and the MAE value was approximately 9 km/h (7 km/h). The mean error was approximately -7 km/h ± 10 km/h (0 ± 9.62 km/h), with the Zepp2 device measuring higher velocity values than Qualisys. At the intra-subject level, the highest MAE value found was 18 km/h (13 km/h) and the lowest was 4 km/h (4 km/h). When the strokes were evaluated according to the type of stroke, the following data were obtained for the forehand stroke:

- *Lin CCC* = 0.75 (0.85).
- *MAE* ~ 8 km/h (6 km/h).
- Maximum *MAE* ~ 15 km/h (10 km/h).
- Minimum *MAE* ~ 4 km/h (3 km/h).
- Mean error ~ -8 km/h ± 8 km/h (0 ± 7 km/h).

In the case of the backhand stroke the data were as follows:

- *Lin CCC* = 0.56 (0.67).
- *MAE* ~ 11 km/h (9 km/h).
- Maximum valor *MAE* ~ 20 km/h (13 km/h).
- Minimum valor *MAE* ~ 4 km/h (3 km/h).
- Mean error ~ -8 km/h ± 11 km/h (1 ± 11 km/h).

The BA plots showed heterodasticity for the groundstrokes, forehands and backhands, and the error has a positive tendency regression line while the stroke speed increases (Figures 4).

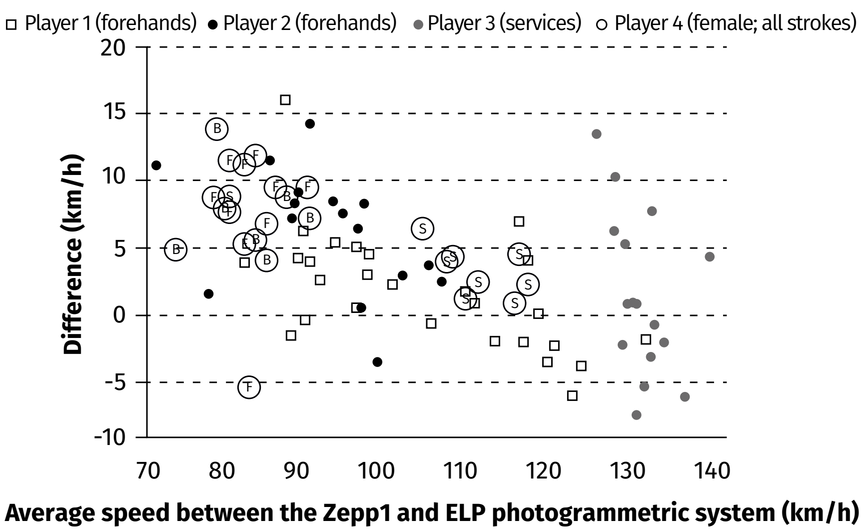

Figure 3. Bland-Altman (BA) plots of Zepp1 vs. 3D (racket) speed comparisons. * For player 4, each type of stroke is indicated by letters (F being forehand, B being backhand and S being serve).

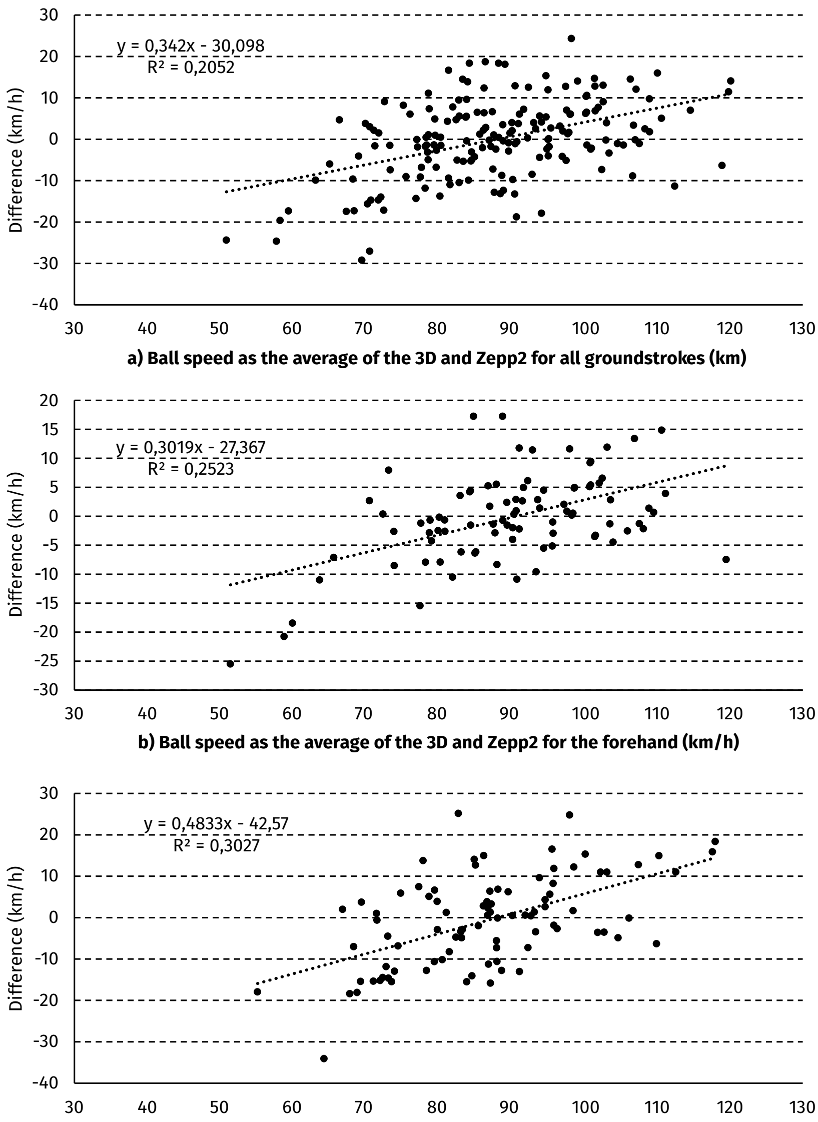

Figure 4. Bland-Altman plots that relate the average speed with the ball speed measured difference between the Zepp2 and the photogrammetric system for the total groundstrokes (a), for the forehand (b) and for the backhand (c)

DISCUSSION

The use of wearable devices for technical analysis is becoming increasingly common both in the field of training and in research. Although there are numerous companies that have developed this type of devices in tennis, the studies that analyze their validity and reliability are scarce, this experiment being one of the few in this regard. It is suggested that the error of the devices is sufficient for use in training, but not for research, where it is advised the use of photogrammetric systems.

We have only found one research paper in a journal indexed in the Journal Citation Report studying the validity of the Zepp device (Keaney & Reid, 2018). Although a high precision photogrammetric system was used as the gold standard the sample consisted of a single player and only 24 strokes were analyzed. The data of the present work indicate that the stroke kinematics of each player affects the accuracy of the sensor (for example, in Figure 3 it is observed that in the player 1 represented with white squares the magnitude of the error for the forehands is lower than that of the player 2 represented with black circles), where the error seem to be positive in almost all forehands, as well as the ball speed, as can be deduced from the Figure 4 were the speed of the strokes executed at lower speeds seem to be underestimated by the Zepp2 device while the speed of the ball of the strokes exerted at high speed seem to be overestimated (the error has a positive tendency regression line, relative to the stroke speed) so we consider that more studies are required to evaluate the error in players of different levels and styles of play. The type of stroke also seems to affect accuracy and for example in the player 4 (Figure 3) the Zepp1 overestimated the speed of the serve less than the speed of the groundstrokes. The aforementioned article indicates that the Zepp sensor and the Babolat branded smart racket, determined the volume and intensity of the strokes with good accuracy (mean error for stroke speed was 2.69 ± 5.63 km/h), but were less effective in identifying the type of stroke or the location of the impact on the racket.

Keaney & Reid (2018) point out that quantifying training using these types of sensors is critical, but that further validation studies are required. They also indicate that there is a need to improve inertial sensors for technical analysis of tennis players so that they can accurately measure impact location. This is of great interest, both for performance improvement and injury prevention, taking into account that this variable (point of impact of the ball on the racket) is related - in addition to the delivery speed of the ball after impact - with the vibrations transmitted from the racket to the arm and therefore with musculoskeletal injuries such as epicondylitis.

PRACTICAL APPLICATIONS

Despite the importance of further research, inertial sensors seem to be suitable for measuring tennis ball velocity in intrasubject studies and for trainning in the case of beginners were change in velocity after a trainning program could be sustantials.

CONCLUSIONS

The inertial sensors evaluated in this work (Zepp1, Zepp2 and Qlipp) seem adequate for measuring ball velocity in intra-subject studies (the Lin CCC values in the first study and the adjusted values in the second study were almost all greater than 0.75). Specifically, the Zepp brand sensor obtained higher values. However, the Zepp2 errors were approximately 10 km/h when evaluating the unadjusted data and approximately 7 km/h for the adjusted data (in the laboratory study). These values are quite similar to those obtained in the Keaney & Reid (2018) study. It is suggested that the measurement error of the Zepp is high in case of use with high-level players, where changes in velocity after a training program may be unnoticeable. In the case of beginner players, it could be useful since the changes after a training program will surely be more evident. It is necessary to validate the rest of the variables provided by these sensors (type of stroke, location of the impact on the racket, and stroke effect) and to include a larger number of players, taking into account that the stroke pattern could affect the sensor measurements.

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