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ACCURACY OF THE BABOLAT POP SENSOR FOR ASSESSMENT OF TENNIS STROKES IN STRUCTURED AND MATCH PLAY SETTINGS

Catherine J. Raymond, Tyler J. Madar, Alexander H.K. Montoye

Alma College, Alma, MI, USA

ABSTRACT

Introduction: The Babolat Pop sensor (POP) detects tennis stroke types (forehand, backhand, overhead, serve, volley) and spins (topspin, flat, slice), but it has not yet been validated for use. Therefore, this study's purpose was to validate the POP in structured and match play settings. **Methods**: Seventeen collegiate tennis players (9 women, 8 men) wore the POP on their dominant wrist while participating in 2 sessions. Session 1 (structured) consisted of 10 drills of 5-10 shots each, each focusing on a specific shot type (forehands, backhands, serves, overheads, volleys) and spin (topspin, flat, slice). In session 2 (match play), participants played 6 games against an opponent. For both sessions, researchers observed and recorded the number and type of shot and spin hit for comparison to those recorded by the POP. Mean absolute percent error (MAPE) and bias were calculated to assess accuracy, with sub-analyes by sex and player ranking. **Results**: The POP underestimated most shots and spins during the structured session, with MAPE averaging 32.0% and ranging 5.3-93.5%. MAPE was 9.4% overall but ranged 11.3-223.9% in the match play setting. MAPE and bias were significantly lower for males than females for most shots in the structured setting but only 2 shot/spin types in the match play setting. Player ranking did not affect sensor accuracy. **Conclusion**: The POP had lowest error for detecting major stroke types, with similar or better accuracy during match play than in structured drills.

Keywords: activity tracker, wearable, sport tracker, tennis shot

INTRODUCTION

In recent years, there has been dramatically increased interest in personal physical activity tracking and, concurrently, of wearable activity trackers available for purchase by consumers. According to the American College of Sports Medicine, wearable technology has been among the top three fitness trends yearly from 2016-2018 (22-24). Most such devices have been developed to detect metrics related to health, including steps, Calories, and distance traveled. However, recently activity monitoring devices have been used for assessment of other health- and sport-specific movements and data, with devices sometimes worn on the body and sometimes embedded into equipment. For example, companies such as

Zepp (Zepp, San Jose, CA), Blast (Blast Motion, Carlsbad, CA), and Babolat (Babolat, Lyon, France) have developed monitors that attach to a baseball bat, golf glove, or tennis racket to track swing speed, quality, and type. The ability to track and give players and coaches real-time feedback on quality of play has the potential to improve individual and team performance both in practice but also during competition.

Our study focuses on the sport of tennis, a sport which is played at a professional level but is also accessible and played frequently at a recreational level. Given adults' poor adherence to national physical activity guidelines (25), some researchers and clinicians have turned to promoting physical activity through sports participation. Tennis is relatively inexpensive to play, requiring only a racket, ball, court, and opponent, and it is among the most popular sports played by adults (29). Another appeal of tennis is that it can be played at a range of intensities depending on skill level and whether it is singles or doubles (1), making it an attractive way to accrue MVPA and make progress toward meeting health-focused physical activity guidelines. For recreational and competitive players, tracking statistics playing (e.g., number of shots hit, number of serves taken, number of forehands hit) can allow for assessment of training load, skill in sport, and change in such sport skills over time. While elite players can hire coaches and/or use sophisticated tracking cameras (e.g., Hawk-Eye; Hawk-Eye Innovations Ltd., Romsey, England) to monitor tennis-specific metrics, these options are not affordable or available to non-elite players. Conversely, activity monitors are well suited for non-elite players as they are relatively inexpensive, can be used with little instruction or background knowledge, can be synchronized with smartphones to provide real time data, and are portable. Thus, the potential for activity monitors to be used for assessing tennis-specific metrics is appealing.

Mechanics of tennis strokes demonstrate consistent and predictable movement patterns of the wrist and arm needed to properly execute different strokes (18, 20, 21); therefore, there is biomechanical rationale that these different movement patterns should be detectable with an arm- or wrist-worn, accelerometer-based activity monitor. Additionally, empirical evidence from several previous studies provides strong support that tennis strokes can be assessed using a wrist-worn accelerometer. In one study, Kos et al. demonstrated that it was possible to distinguish between serves, forehand strokes, and backhand strokes with >96% accuracy in a structured drill protocol in a small sample of three participants (12). A similar study by Whiteside et al. (27) showed 93.1-97.4% accuracy for recognizing four tennis strokes (overhead, forehand, backhand, false shot) and 84.3-93.2% accuracy for detecting nine strokes (forehand rally, forehand slice, forehand volley, backhand rally, backhand slice, backhand volley, serve, overhead smash, false shot) during structured training settings in young, elite-level tennis players. These studies provide support that accelerometer technology can be used to assess sport-specific factors. However, these devices and their associated analytic methods are not readily available to the general public.

Babolat, a tennis company, produces two products capable of detecting tennis strokes. The first is a racket embedded with sensors

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(Babolat Play) to detect shot types, speeds, and spins. While appealing in that a player would not need to wear anything on their hitting wrist, a racket-embedded sensor is more expensive than a wrist-worn activity monitor and cannot be transferred to other rackets, for example if a string breaks or if players want to determine which brand and type of racket is best suited to their game. The second product Babolat produces is the Pop Sensor (hereafter referred to as POP), an accelerometer-based activity monitor which assesses many of the same metrics as the Play but in a wrist-worn device. To our knowledge, accuracy of the POP has not yet been evaluated. Without insight into the accuracy of the POP, its potential use for tracking and improving player's performance is currently unknown. Therefore, the purpose of this study was to determine the accuracy of the POP for assessment of tennis strokes in structured and match play settings.

METHODS

Participants and equipment

Participants were 17 current competitive tennis players, all of whom were currently on the roster of a Midwestern Division III collegiate tennis team; the team was not nationally ranked in the season in which the study took place. Participant ages ranged from 18-22 years and had competitive playing histories ranging from 1-15 years. All players used their own racket and other equipment (e.g., shoes, clothes) for the study. This study was approved by the Alma College Institutional Review Board, and all participants gave written informed consent prior to taking part in the study. Demographics of participants are displayed in Table 1.

TABLE 1 HERE

This study took place at an indoor facility with rubberized, multi-purpose courts used for winter tennis training and match play. Upon arrival to the facility, participants were allowed to complete their normal tennis warm-up routine before starting the research settings. Following warm-up, participants were fitted with the POP, a light-weight (18 g) activity monitor which was placed in a manufacturer-supplied pouch and secured to the dorsal side of the wrist of their dominant hand (defined as the hand in which they hold the racket for forehands and serves). All participants in this study were right-hand dominant, so the POP was placed on the right wrist for each participant.

The POP automatically tracks and stores data regarding the number and type of shots taken during tennis play. More specifically, the POP records nine types of shots: forehand (slice, flat, or topspin), backhand (slice, flat, or topspin), serve, smash/overhead, and volley. These data are then manually synchronized to a Bluetooth-enabled device through the Babolat Pop mobile application.

Procedure

Participants completed 2 tennis settings while wearing the POP. The first was a structured setting, and the second was a match play setting. Each setting took ~30 minutes to complete, and specifics of each setting follow.

A former collegiate tennis player with roughly 8 years of competitive playing experience served as the sole research assistant for this study. This individual ensured that participants completed the required number and type of shot in each drill and recorded the number and types of each shot hit.

For this study, topspin shots were operationally defined as strokes where the racket was moving in an upward path when making contact with the ball (start low, follow-through high), flat shots were defined as moving the racket in a roughly horizontal motion when contacting the ball, and slice shots were defined as moving the racket in a downward path when making contact with the ball (start high, follow-through low). Volleys were defined as shots with either no backswing or a backswing small enough to where the racket always stayed in front of the player. Finally, overheads were defined as shots hit from the forehand side in which the ball was hit while at a level above the participants' head.

Structured setting

The structured setting was developed in order to have a high degree of control over the types and number of each shot hit by participants. Participants completed 10 drills in the following order: 10 forehands with topspin, 10 backhands with topspin, 10 forehand volleys, 10 backhand volleys, 5 overheads, 10 forehands with slice, 10 backhands with slice, 5 overheads, 10 first serves, and 10 second serves. For the forehands, backhands, volleys, and overheads, balls were fed/hit to the participants from the research assistant, who was standing at the opposite baseline. For first serves, participants took two serves from the right side of the court (deuce side), then two serves from the left side of the court (ad side), and continued this pattern until 10 serves were completed. For the second serves, participants started with two serves from the ad side, then two serves from the deuce side, and continued this pattern for the 10 serves. In each of these drills, participants were told not to take practice swings that may be detected by the POP, and they were instructed not to swing at feeds deemed unhittable (e.g., fed to wrong side, double-bounced, or out of reach). After each drill, participants rested for 1-2 minutes while research staff synchronized the POP to the mobile application. This was done so that accuracy of the POP could be determined separately for each stroke type.

Match play setting

The match play setting happened either later on the same day or on a separate day from the structured setting. For this setting, two participants were scheduled for the same time so that each would have an opponent. Both participants wore the POP for the entire match play setting, but only one participant's data were recorded at a time (due to limited research staff to record criterion data). Following a warm-up, one participant was chosen at random to have their strokes recorded. Participants then played 6 games in a match play scenario with standard scoring (love, 15, 30, 40, and game; ad scoring) and participants alternated who served each game.

During the games, the research assistant observed and recorded the number and type of each shot hit during the games by the participant. After the 6 games were completed, the POP was synchronized to the mobile application for both participants and then reset to 0. For the next 6 games, the

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research staff counted stroke numbers and types for the second participant.

For the match play setting, participants were given little instruction, thus better simulating a tennis match. They could take practice swings, talk, dribble the ball, pace, take breaks, etc. The only instruction was to play out 12 games with the service switching every game. In addition to recording all actual strokes during the games, the research assistant also recorded any “shadow strokes”, which were instances in which the participant was practicing strokes (e.g., swinging between points), swung at a ball and missed, and passing strokes (e.g., when a participant hit the ball to the other side of the court between points, effectively passing it to the other participant). These shadow strokes, which were mainly flat or topspin forehands, were added to the total according to stroke and spin type.

Statistical analysis

For each setting, mean absolute percent error (MAPE) and bias were determined for POP-measured strokes compared to researcher-counted strokes for the total number of shots and for each spin type. For each stroke, paired-samples t-tests were conducted to determine if the predicted number of strokes from the POP were significantly different from shots counted by the researcher (criterion).

In the match play setting, some participants did not hit a certain shot type (i.e., criterion was 0 shots), making MAPE not possible to calculate (since calculation divides by criterion); in such cases, MAPE was set at 0% if the number of POP-measured shots was 0 (i.e., matched criterion) and 100% otherwise. Additionally, for a secondary analysis, the topspin and flat strokes were combined into a “rally shot” category for consistency with previous research (27), and the same statistical tests were conducted. As has been used in previous activity monitor validations (14), a threshold of $\leq$10% for MAPE was arbitrarily considered “low” error, and MAPE >10% was considered “high” error.

Sub-analyses were conducted by sex and by current position on tennis team (top 4 seeds for each sex vs. below top 4 seed). Independent-samples t-tests were run to determine if there were significant differences of the POP’s accuracy between 1) females and males and 2) by the top four seeds and the lower ranking seeds. Microsoft Excel 2013 (Microsoft Corp., Redmond, WA) was used for all data analyses.

RESULTS

Structured setting

Table 2 shows shots measured by the POP, along with MAPE and bias, for each shot type. All shots were either significantly underestimated by the POP or trended ($0.05 \leq p < 0.10$; forehand total for topspin drill, backhand total for topspin drill, and backhand rally) toward underestimation of shots taken during the structured drills. Additionally, MAPE indicated high error (>10%) for all but the total backhand shots during the topspin drill, backhand rally shots, and total backhand shots during slice drill. In general, slice shots were recognized with higher accuracy than topspin shots, which were frequently misclassified as flat shots. When combining topspin and flat shots into a single category

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(rally), accuracy was substantially improved for both forehands and backhands.

Volleys and overheads were detected poorly by the POP. Over 60% of volleys (both forehand and backhand) were either not detected or were misclassified as a groundstroke. Additionally, overheads were not detected in >90% of instances, and in the majority of these instances no shot was detected (remainder of time overhead was misclassified as a serve).

TABLE 2 HERE

Table 3 presents a subanalysis comparing males and females for POP accuracy. In both sexes, the POP significantly underestimated the number of shots taken in most drills. However, in all but four instances (total backhand shots during topspin drill, total backhand shots during slice drill, second serves, and overheads) MAPE and bias were either significantly lower or trended toward being lower in males than females. Additionally, MAPE was low (≤10%) for 10 of the 15 shot categories assessed for males but only 2 of the 15 shot types for females. The sub-analysis comparing the top players (top 4 seeds for males and females) compared to those in the bottom group revealed no significant differences in accuracy for any shot types (data not shown).

TABLE 3 HERE

Match play setting

Table 4 presents totals for each shot type in the match play setting. The POP significantly underestimated the total number of shots in the match play setting (4.8 shots underestimation) while also significantly underestimating the number of forehand (1.3 shots) and backhand (1.8 shots) slices taken. For topspin shots, both forehands (6.9 shots) and backhands (7.1 shots) were significantly underestimated by the POP; there was corresponding overestimation of flat shots (forehand: 8.1 shots; backhand: 8.0 shots). When combined into a single rally category, measurements from the POP were no longer significantly different from the criterion for forehands or backhands. Unlike in the structured setting, volleys were significantly overestimated (1.2 shots) by the POP, while serves and overheads were not different from the criterion. MAPE was low (≤10%) for the total number of shots taken. The activities with the highest MAPE (forehand flat shots, backhand flat shots, volleys) had a low total number of shots taken during the match play (<10 of a given shot type).

TABLE 4 HERE

Table 5 displays a sub- analysis by sex for the match play setting. Males took more total shots during the match play than females but a similar number of serves, likely signifying more shots per point (i.e., longer rallies) than females. The total number of shots recorded by the POP was not different from the criterion for either males or females, nor were the total number of forehand or backhand shots, serves, or volleys. However, there was significant underestimation of topspin forehands for both sexes as well as significant overestimation of flat forehands for females. Similarly, topspin backhands were significantly underestimated, and flat backhands significantly overestimated, by the POP for both sexes. Both forehand and backhand slices were significantly

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underestimated for males but not for females, whereas volleys were significantly overestimated for females but not for males. MAPE was significantly lower in males than females for only 3 of the 14 shot categories (total number of forehands, flat forehands, and rally forehands) and MAPE was low (≤10%) in 4 shot categories for males but 0 for females. As was the case for the structured setting, the sub-analysis comparing the top 4 males and top 4 females to those not in the top 4 for their sex revealed no significant differences for any shot types (data not shown).

TABLE 5 HERE

DISCUSSION

This study's primary purpose was determine accuracy of the Babolat POP for recognition of tennis strokes in structured and match play settings. In both settings, error varied considerably by shot type and sex, while seeding (top 4 for sex vs. not) did not affect accuracy. In both the structured and match play settings, certain shot types such as forehands and backhands (as general categories) as well as serves were more easily detectable while the POP had difficulties with volleys, overheads, and differentiating between flat and topspin shots on both the forehand and backhand side, often misclassifying topspin as flat and vice versa. This finding is in agreement with previous work by Whiteside et al. (27), who found the highest accuracy for detecting serves, forehand rally shots, and backhand rally shots and lowest accuracy for forehand slice and forehand and backhand volleys using a wrist-worn accelerometer and machine learning algorithm to identify shot types. Notably the study by Whiteside et al. (27) and other past studies (12, 15) did not attempt to differentiate between topspin, flat, and slices strokes, instead only distinguishing between slice and non-slice (e.g., "rally" or "spin") shots. While more categories of stroke recognition would allow better insight into the types of strokes used in a practice or match, our results indicate that the POP cannot accurately differentiate between topspin and flat strokes but can better distinguish between rally and slice shots. Reasons for this may include a more similar swing pattern or body position between flat and topspin shots than flat and slice shots (3). Another possibility relevant to backhand shots was that all of the current study's participants used a 2-handed backhand during flat and topspin backhand shots, but most used a 1-handed backhand for slices. This stroke pattern is common as strength required and injury risk are lower with 2-handed backhand shots (9). Past work demonstrates large biomechanical differences in 1- vs. 2-handed backhands (16), which would make a 1-handed slice easy to differentiate from 2-handed flat or topspin strokes.

Surprisingly, the POP rarely recorded any shot being taken during the overhead drill in the structured setting, most often recording 0 strokes taken. Given similar movements between serving and overheads, we expected overheads and serves to be misclassified as the other stroke, which was observed in the study by Whiteside et al. (27). However, this rarely (<10% of the time) occurred in our study. It is unknown why this occurred as it was consistent across participants and testing days. A potential reason could be that in a true match play, it would be rare to hit more than 1-2 overheads in succession, so the POP

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recognition algorithm may not be developed to classify so many overheads during the structured hitting setting; however, in practice, such repetition is common. Encouragingly, error was considerably lower during the match play setting when fewer overheads were taken than in the structured setting, which gives some indication that the POP is better suited for tracking overheads during match play.

Volleys were also poorly detected in the structured and match play setting, often being mistaken for a groundstroke (topspin, flat, slice) corresponding to the side of the volley (forehand/backhand). Our findings are in accordance with Whiteside et al. (27), who found lower accuracy for forehand and backhand volleys than any other shot type except forehand slices and who found frequent misclassification of forehand volleys as forehand slices and misclassification of backhand volleys as backhand slices. Given that volleys and groundstrokes (e.g., forehands, backhands) lie on a continuum with volleys having the least swing and groundstrokes the most, it is not surprising that these shot categories are often confused. Petkovic et al. (15) attempted to address this issue by creating a "half-volley" category, which is defined as an intermediate shot usually hit when a player is approaching the net from the baseline and which has more swing than a volley but less than a groundstroke (5). However, Petkovic et al. (15) found lower overall accuracy when adding this category. Given the difficulty in differentiating volleys and groundstrokes, additional data such as body or foot position may be necessary to assist in such shot recognition. These data would not be available from a single wrist-worn device but theoretically could be detected using a multi-monitor system, which has been done successfully in other contexts for physical activity recognition (6-8).

Sub-analyses revealed that the POP had lower error in recognizing shot types and spins for males than for females but that error was not different between players of high vs. low seeding on the teams. The males in this study were considerable taller than the females (20 cm on average) and likely longer limbs, and it may be that females had a more compact swing (due to shorter limbs) that was more difficult to recognize with a wrist-worn device. Past research does indicate differences in spin and stroke frequency between elite males and female tennis players (17), but further research into sex-specific biomechanical differences in tennis strokes may yield additional insights into the observed sex differences in accuracy found in our study.

Finally, it should be noted that the POP performed as well, if not better, during match play than during the structured setting. This is in contrast to studies of physical activity monitoring devices (e.g., Fitbit), which typically show that accuracy is higher during highly controlled, structured activities than in an unstructured, 'real-world' setting (4, 10, 11). Given that match analytics may be important in informing future training, the superior performance of the POP in match play provides some indication that it is suitable for use in match play settings, at least for detection of major stroke types (i.e., forehands, backhands, serves).

Study strengths and limitations

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One major study strength is the use of a collegiate athlete population of tennis players incorporating both females and males. This allowed for sex comparisons in accuracy of the POP as well as comparison by player skill. Another study strength is the testing during both structured and match play settings. The use of both settings allowed for determination of which types of strokes were best detected (structured setting) as well as the expected accuracy of the device when used during less structured practice and match settings.

Several limitations must also be acknowledged. Our sample was small and relatively homogenous in skill level, and device accuracy should be confirmed in follow-up testing of individuals of lesser and greater skill than the population tested. Additionally, no left-hand dominant players were tested, so we cannot comment on device accuracy in left-handed tennis players. Third, video data of the sessions were not recorded, so it was not possible to have multiple raters score the criterion data to ensure the proper shots were being recorded.

Conclusions

The Babolat POP was able to track major stroke types (forehands, backhands, serves) with low error during structured and match play, especially for the male tennis players tested in this study. Accuracy of the POP was at least as good during match play as in structured drills, providing indication that it can be used to track major shot types during practices and matches.

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