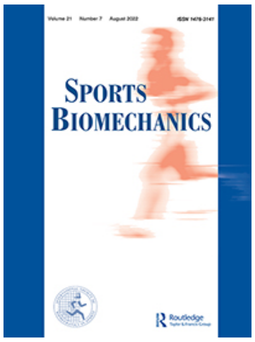

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Racket orientation angle differences between accurate and inaccurate squash shots, as determined by a racket embedded magnetic-inertial measurement unit

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ABSTRACT
Ascertaining how racket orientation angle differences at ball-impact influence the accuracy of different squash strokes could assist player skill development and possibly reduce the number of unforced errors hit within a match. The purpose of this study was to identify differences in racket orientation angles of accurate and inaccurate forehand and backhand drive, volley and drop shots. A magnetic-inertial measurement unit embedded in a racket output orientation angles of twelve male junior players, with five accurate and five inaccurate shots per player per stroke analysed. Paired samples t-tests revealed that inaccurate backhand drop shots exhibited significantly ($p < 0.05$) less racket roll angle (racket face less open) at impact than accurate shots, indicating this parameter was a determining factor in the accuracy of this stroke. Racket orientation angle differences between accurate and inaccurate shots of the remaining strokes were too small to be used to distinguish shot accuracy. There was significantly greater variability in racket orientation angles during inaccurate forehand drop and backhand drive shots compared to accurate shots. These findings demonstrate how racket orientation angle differences at ball-impact can influence the accuracy of shots and highlights the need for consistent racket orientations to allow for an accurate shot.

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Kinematics; accuracy; coaching; racquet; MIMU

Introduction

Shot accuracy is an important fundamental skill in racket sports, where the aim is to hit a projectile within an area of play. Generally, points can be won by hitting an accurate shot to an advantageous part of the area of play such that an opponent is unable to successfully return the projectile (a ‘winner’). Similarly, points can be awarded to an opponent when an inaccurate shot is hit and the projectile lands outside the area of play (an ‘unforced error’), or lands to the advantage of an opponent who’s returning shot is a winner. Shot success within a squash match has been shown to be strongly related to a player’s final tournament ranking (Williams et al., 2018). Further, it has been proposed

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that the number of points lost due to unforced errors (inaccurate shots) within both a squash and tennis match could be dependent on skill level (Brody, 2006; Williams et al., 2018). Therefore, improving shot accuracy could result in fewer unforced errors and provide a player with a greater opportunity to win more points within games.

The orientation and velocity of a racket at ball impact are two of the critical parameters that determine the direction and speed of a hit ball, and therefore shot outcome (Elliott et al., 1997). Within the racket sport literature a number of studies have used high-speed optical systems to investigate these parameters and the kinematics that influence them (Knudson & Blackwell, 2005; Kwon et al., 2017; Sheppard & Li, 2007; Whiteside et al., 2013; Williams et al., 2020a). As a consequence of these and other investigations, the orientation of the racket at ball impact has been recognised as being a key determinant of accuracy in racket sports (Davey et al., 2002; Elliott et al., 1989; Sheppard & Li, 2007; Williams et al., 2020b). Tennis racket orientation at impact has been shown to be more influential in determining the subsequent direction of a drive shot than the technique used during the swing preceding impact (Elliott et al., 1989). Racket face projection angle at impact during squash forehand drives was found to be the only parameter (rather than racket impact velocity or upper-body joint kinematics) that successfully distinguished shot accuracy within less-skilled players (Williams et al., 2020b). Furthermore, greater variability in racket impact angles has been linked to inaccurate tennis shots (Knudson & Blackwell, 2005), while less-skilled squash players have been shown to have more variable racket parameters at ball impact during a forehand drive shot and consequently a lower accuracy score than highly-skilled players (Williams et al., 2020b). Given the importance of racket orientation at ball impact to the success of a shot, further investigation into how this parameter affects the accuracy of different squash strokes is warranted.

Recently, magnetic-inertial measurement units (MIMUs) have been used to overcome some of the restrictions inherent to high-speed optical motion capture systems by providing greater portability and reduced capture volume limitations (Chambers et al., 2015). MIMUs consist of accelerometers, gyroscopes and magnetometers to enable biomechanical analysis within ecologically valid and 'real world' sporting environments (Brodie et al., 2008; Van Der Slikke et al., 2015; Walker et al., 2017). The ability of MIMUs to provide accurate and reliable data has been investigated within various sporting contexts including skiing (Brodie et al., 2008), track sprint starts (Bergamini et al., 2013), diving (Walker et al., 2017) and resistance training (Picerno, 2017). Initially there was some contrasting evidence in several aspects of MIMU applications, particularly where substantial acceleration was present (Chambers et al., 2015), however some more recent studies have found favourable results, with MIMUs able to produce accurate biomechanical data under different sporting conditions such as ball kicking (Blair et al., 2018), baseball hitting (Punchihewa et al., 2019) and squash hitting (Williams et al., 2019).

A systematic review of the use of inertial sensors for in-field sport performance evaluation found a number of publications that had used a form of inertial sensor to evaluate the movement of a sports object, such as a golf club or baseball bat (Camomilla et al., 2018). However, research to evaluate the application of MIMUs to racket sports have thus far been limited, with studies designed to classify different strokes (Connaghan et al., 2011), monitor hitting loads (Whiteside et al., 2017), evaluate temporal swing parameters (Buthe et al., 2016) and analyse tennis serves (Ahmadi et al., 2009, 2010).

However, a recent investigation found very small differences in squash racket orientation angles at impact between a MIMU system and a high-speed optical capture system (Williams et al., 2019). Further, the measurements from the MIMU system had very high correlations with those from the high-speed optical capture system (Williams et al., 2019). Given the positive results of Williams et al. (2019), it is possible that a racket mounted MIMU could be used to determine differences in the racket orientation at ball impact of accurate and inaccurate squash strokes played on a squash court.

In squash, the most prevalent match-play strokes are drives, volleys and drop shots (Vučković et al., 2013). However, as outlined above, there have been very few investigations into the racket parameters that constitute an accurate shot within these strokes. Therefore, the purpose of this study was to identify differences in racket orientation angles of accurate and inaccurate forehand and backhand drive, volley and drop shots. It is hypothesised that one of the orientation angles of the racket (pitch, yaw, or roll) at ball impact during the inaccurate shots of each stroke will significantly differ ($p < 0.05$) from those of the accurate shots.

Methods

Participants

Twelve male junior squash players (age 15.4 ± 1.8 years, height 1.69 ± 0.08 m, mass 60.8 ± 11.3 kg) from a national sports academy volunteered to participate in the study. All participants held a top 5 national ranking for their respective age groups and were free from injury at the time of testing. One participant was left-handed, with the remaining eleven being right-handed. All participants gave written informed consent before participating in the study, which was approved by the ADLQ Institutional Review Board (No. E2017000216).

Equipment setup

A MIMU ('3-Space Wireless 2.4 GHz DSSS' unit, YOST Labs, USA) comprising a triaxial accelerometer (± 235 ms^{-2}), triaxial gyroscope (± 2000°s^{-1}) and triaxial magnetometer (± 1.3 Gauss) was used for data collection. It had a filter update rate of up to 250 Hz (using the default integrated Kalman AHRS mode) and a manufacturer specified dynamic orientation accuracy of ± 1°, orientation resolution of < 0.08° and repeatability of 0.085° for all axes of orientation. During the data collection, the mean MIMU sampling frequency was 125.47 ± 4.25 Hz, a rate which was determined by the onboard 3-Space Sensor and is similar to that of a previous investigation of squash impact kinematics (Williams et al., 2019). The same MIMU had been validated previously for accuracy in measuring racket swing kinematics against a motion capture system, showing very high intraclass correlation coefficients ($r \geq 0.988$) for all orientations at ball impact and a mean orientation angle difference at ball impact of ≤ 0.47° (Williams et al., 2019).

The MIMU was removed from its original casing and inserted into a hollowed out handle of a squash racket ('Carboflex 125 S', Tecnifibre, France). The MIMU was glued inside the centre of the racket handle such that the MIMUs orientation axes were aligned with the racket handles axes. The local reference frame of the racket/MIMU is shown in

Figure 1 and was defined such that the: y-axis (yaw) was normal to the racket face; x-axis (pitch) was perpendicular to the racket's longitudinal axis and parallel to the racket face; z-axis (roll) was aligned to the racket's longitudinal axis (with 0° indicating a fully 'closed' racket face (striking surface face down) and > 90° indicating an 'open' racket face (Kwon et al., 2017). The MIMU's power switch and USB charging port were fitted into the cap at the bottom of the racket handle so the MIMU could be powered on/off and charged when required. The MIMU added 0.020 kg to the original mass of the strung racket. However, it was anticipated that any change to the properties of the racket would be minimised due to the added mass being in the handle where players hold the racket. Similarly, with the MIMU located very close to the centre of the axis of rotation of the racket (middle of the racket handle), it was further expected that the effect of the MIMU on the racket's rotational inertia, from a player's perspective, would be minimal.

Prior to data collection the racket was attached to a custom-built plastic calibration housing (Figure 1) such that the MIMU could be calibrated using the '3-Space Sensor' software (YOST Labs, USA) according to the manufacturer's instructions. The calibration housing was used to move the racket embedded MIMU through a range of orientations, as well as a reset procedure that set the zero orientation of the MIMU. This 'gradient descent calibration procedure' was required to align the axes of the sensor chip embedded reference system to those of the racket and reduces the chance of sensor errors by calibrating the compass and accelerometer. During testing, the MIMU data were transmitted in real-time and recorded via a USB '3-Space Wireless Dongle' connected to a computer running the 3-Space Sensor software.

Testing protocol

The testing protocol was based on the 'Hunt Squash Accuracy Test' (HSAT), which requires players to hit to defined target areas on a squash court and has been shown to have strong correlations to tournament shot success and the percentage of winning shots during match play (Williams et al., 2018). Target areas were marked on the court with masking tape, as described below (Figure 2). Participants performed a self-selected warm-up that allowed them to become familiar with the racket and warm the ball up

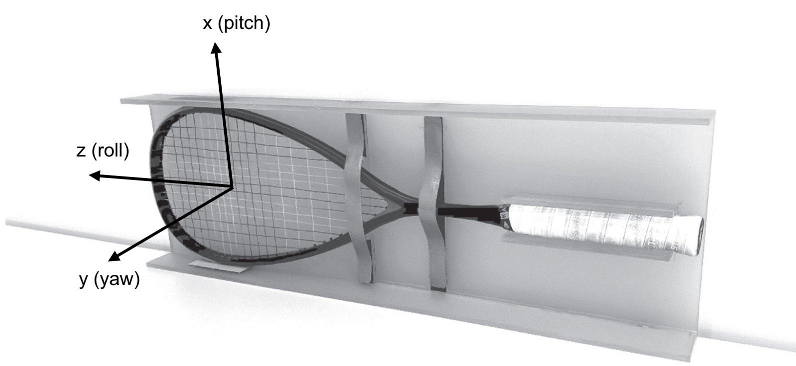

Figure 1. The instrumented racket, with MIMU coordinate system, shown mounted in the custom-built non-metallic calibration housing.

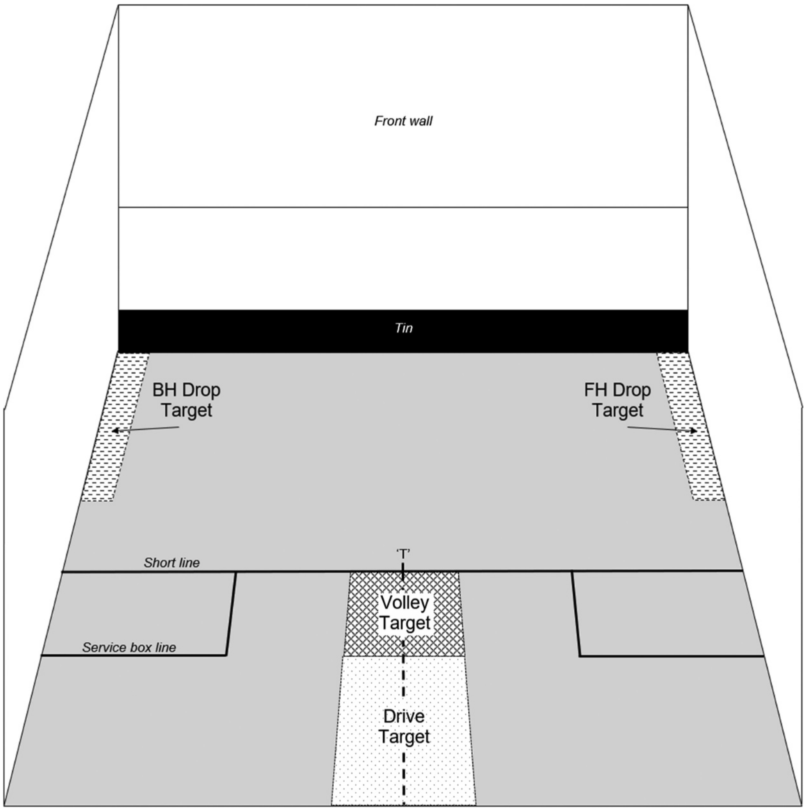

Figure 2. Target areas for the different strokes (drop shot target areas are shown for the right-handed players).

appropriately. It should be noted that participants were all part of the same training squad and were currently training and playing with the same racket model as the one embedded with the MIMU used for testing. Following the warm-up, the racket MIMU was turned on and the racket zeroed while lying flat on the centre 'T' area of the floor of the court, with the longitudinal axis of the racket aligned with the 'short line' (midline) of the court. Participants were then required to hit approximately 25 forehand (FH) and backhand (BH) drive, volley and drop shots according to the following protocol:

- Drive: standing behind the service box line, the ball is hit continuously to self, the ball must land after a line joining the back of the service boxes, within 0.5 m either side of the half court line and not touch the back wall;
- Volley: standing between the short line and service box lines, the ball must be hit continuously to self from within 0.5 m either side of the half court line;
- Drop: standing at the 'T', a fed oncoming ball must be played as a drop, the ball's 2nd bounce must land within 0.35 m of the side wall and 1 m before the short line.

All participants were familiar with the protocol having performed the HSAT previously (average 7.3 ± 3.8 times; current group mean score: 55% ± 8%). The drop shots were hit to the participants by a coach with over five years of experience running the HSAT. Participants were requested to perform each shot similar to that within a match situation and used their preferred grip and swing technique. None of the participants reported any limitations or changes to their swing mechanics as a result of the racket used for testing. Any shot that was hit and landed within the designated target area was analysed as an accurate shot, whilst all other shots were analysed as inaccurate shots (Landlinger et al., 2012).

Data analysis

In order to calculate orientation angles, fusion of data from the MIMUs various sensors (accelerometer, gyroscope and magnetometer) were done onboard using the manufacturer's algorithms. To compensate for potential magnetic field distortion within the MIMU data, the onboard 3-Space Sensor processed the data using a default integrated Kalman-based approach for attitude heading reference systems, which aims to increase measurement accuracy and decrease measurement noise. No additional filtering was applied to the time-series data generated by the MIMU. The MIMU sensor calculated orientation angles in a pitch-yaw-roll sequence and were relative to the initial orientation of the racket, which was set on the floor parallel to the 'short line' (see Figure 2) of the court (perpendicular to the side wall). Orientation angle data were then exported into MATLAB (version 9.6, The MathWorks, USA). Ball impact was determined via a spike in the acceleration trace, which has been previously shown to accurately align with a motion capture system (Williams et al., 2019). Five accurate and five inaccurate shots for each participant were selected for analysis. In order to ensure a certain level of consistency in the approaching ball direction and speed, all shots that were selected for analysis were required to be preceded by an accurate shot (Knudson & Blackwell, 2005). The following variables were then determined for each of the participants' accurate and inaccurate shots across all strokes: yaw, pitch, and roll racket orientation angles at ball impact. Further, the variability of the racket orientation angles at impact were calculated as the standard deviation of each angle for each participant's accurate and inaccurate shots for each stroke.

Statistical analysis

Means and standard deviations (SD) were calculated for all variables. Data were analysed using SPSS Statistics software (IBM, version 22). Normality of distribution for each variable was checked using a Shapiro-Wilk test. Paired samples t-tests were used to assess differences between the orientation angles for accurate and inaccurate shots and also between the variability of the orientation angles between accurate and inaccurate shots for each stroke. An alpha level of $p < 0.05$ was considered statistically significant. Means (± SD), 95% confidence intervals of the difference in means between accurate and inaccurate shots, p values and effect sizes (Cohen's d) were reported for each orientation of each stroke.

Results

The mean (± SD) orientation angles of the accurate (total of 60 shots per angle, per stroke) and inaccurate shots (total of 60 shots per angle, per stroke) for each of the different strokes are displayed in Table 1. During the BH drop, the roll orientation angle during inaccurate shots was found to be significantly smaller ($p < 0.02$, 95% CI = 0.05–5.47) by 3° (racket less open) than during accurate shots. The differences in orientation angles between accurate and inaccurate shots for the remaining strokes did not reach statistical significance ($p > 0.05$). The mean variability (± SD) of the participants trials for each racket orientation for all strokes are shown in Table 2. There was significantly more variability during the inaccurate shots for: FH drop roll angle, 2.3° greater variability than accurate shots ($p = 0.04$, 95% CI = −4.65—−0.10); BH drive yaw angle, 5.3° greater variability than accurate shots ($p < 0.00$, 95% CI = −7.99—−2.53); and BH drive roll angle, 4.4° greater variability than accurate shots ($p = 0.03$, 95% CI = −8.24—−0.58).

Discussion and implications

Shot accuracy is an important fundamental skill in squash, where an inaccurate shot could relinquish the ascendency of a rally, or even cost a player a point directly. Ascertaining how racket orientation angle at ball impact influences the accuracy of different squash strokes could assist player skill development and possibly reduce the number of unforced errors, and therefore potential points lost, within a match. As such, the purpose of this study was to identify differences in racket orientation angles of accurate and inaccurate forehand and backhand drive, volley and drop shots.

The accuracy of BH drop shots appear to be distinguishable via differences in the racket's roll orientation angle at ball impact, as indicated by the significantly less open racket face (3° less racket roll angle) found during the inaccurate shots compared to the accurate shots of this study. It is possible that during the BH drop shots, the players were trying to impart some backspin on the ball via a 'slice' action of the racket, by combining an appropriate racket face angle with a downward racket trajectory, similar to that

Table 1. Mean (± SD) pitch, yaw and roll orientation angles of the accurate and inaccurate shots for the different strokes.

			Orientation angle (°) (±SD)						95% Confidence Interval		Effect	
			Accurate			Inaccurate			Lower	Upper	size	*p* value
Forehand	Drive	Pitch	−9.5	±	9.8	−12.0	±	9.2	−1.43	6.45	0.26	0.19
		Yaw	−29.1	±	22.5	−30.7	±	21.6	−1.42	4.74	0.08	0.26
		Roll	132.1	±	15.1	130.7	±	13.9	−2.53	5.42	0.10	0.44
	Volley	Pitch	0.0	±	18.8	−2.9	±	16.0	−4.64	10.41	0.17	0.42
		Yaw	−20.2	±	21.3	−20.1	±	22.3	−5.32	5.01	−0.01	0.95
		Roll	133.6	±	10.6	134.0	±	16.1	−5.98	5.22	−0.03	0.88
	Drop	Pitch	−4.4	±	9.7	−3.0	±	8.8	−3.80	1.05	−0.15	0.24
		Yaw	−21.5	±	11.1	−21.9	±	10.3	−1.21	2.05	0.04	0.58
		Roll	117.8	±	9.2	116.9	±	7.6	−0.91	2.81	0.11	0.29
Backhand	Drive	Pitch	−22.4	±	10.2	−25.1	±	8.1	−0.71	6.09	0.29	0.11
		Yaw	−24.9	±	7.7	−20.4	±	13.4	−13.81	4.67	−0.42	0.30
		Roll	134.7	±	11.9	136.4	±	16.6	−8.34	4.94	−0.12	0.58
	Volley	Pitch	−16.8	±	15.9	−18.5	±	13.1	−5.30	8.63	0.11	0.61
		Yaw	−15.7	±	14.5	−11.7	±	18.6	−11.07	3.09	−0.24	0.24
		Roll	133.1	±	11.8	136.3	±	13.0	−8.80	2.30	−0.26	0.22
	Drop	Pitch	−9.0	±	7.9	−8.2	±	8.2	−2.89	1.24	−0.10	0.40
		Yaw	−16.8	±	12.0	−17.6	±	11.5	−1.29	2.85	0.07	0.43
		Roll	118.5*	±	7.4	115.5*	±	7.1	0.50	5.47	0.41	0.02*

*=significant difference ($p < 0.05$)

Table 2. Mean (±SD) values for the variability measures of racket orientation angles for accurate and inaccurate shots for the different strokes.

			Variability (°) (±SD)						95% Confidence Interval		Effect size	*p* value
			Accurate			Inaccurate			Lower	Upper		
Forehand	Drive	Pitch	9.9	±	4.6	9.7	±	4.0	−4.17	4.59	0.05	0.92
		Yaw	7.9	±	3.4	6.8	±	4.1	−2.10	4.32	0.30	0.46
		Roll	7.9	±	3.8	9.2	±	4.6	−3.39	0.76	−0.31	0.19
	Volley	Pitch	16.4	±	6.6	18.2	±	6.9	−6.89	3.37	−0.26	0.47
		Yaw	11.0	±	4.4	12.2	±	6.7	−3.89	1.34	−0.22	0.31
		Roll	11.9	±	5.0	12.9	±	5.0	−5.85	4.00	−0.18	0.69
	Drop	Pitch	5.3	±	2.2	6.7	±	2.0	−3.67	0.81	−0.69	0.19
		Yaw	3.6	±	1.4	3.1	±	1.7	−0.44	1.34	0.28	0.29
		Roll	5.1*	±	1.9	7.4*	±	5.0	−4.65	−0.10	−0.63	0.04*
Backhand	Drive	Pitch	7.0	±	4.9	8.5	±	5.8	−3.61	0.57	−0.28	0.14
		Yaw	8.8*	±	5.9	14.1*	±	9.1	−7.99	−2.53	−0.69	0.00*
		Roll	8.9*	±	3.3	13.3*	±	5.9	−8.24	−0.58	−0.92	0.03*
	Volley	Pitch	13.3	±	7.7	12.4	±	4.7	−5.27	6.99	0.13	0.76
		Yaw	7.1	±	2.7	10.4	±	6.6	−8.26	1.54	−0.67	0.16
		Roll	8.9	±	4.8	10.2	±	3.6	−5.08	2.56	−0.29	0.48
	Drop	Pitch	4.1	±	2.2	4.9	±	1.6	−2.34	0.90	−0.38	0.35
		Yaw	4.3	±	2.0	5.0	±	1.4	−1.80	0.50	−0.37	0.24
		Roll	4.4	±	2.2	3.9	±	1.0	−0.60	1.58	0.29	0.34

*=significant difference ($p < 0.05$)

described in coaching texts (Brunette & Durbach, 2011) and used during accurate FH drop strokes (Williams et al., 2020a). However, although ball flight path and racket trajectory were not measured in this study, the reduction in racket roll angle during the inaccurate BH drop shots, although seemingly small, may have been large enough to change the desired ball flight path and/or ball spin that contributed to the inaccuracy of the shots (Brody, 2006; Whiteside et al., 2013), although further research would be required to confirm this notion. Nevertheless, it appears there was a limit to the degree to which the racket face could deviate from a favourable roll angle at impact, that in turn allowed for an accurate BH drop shot within the constraints of the protocol used in this study. The drop shot is considered a 'difficult' shot to play relative to other shots (Brunette & Durbach, 2011). Furthermore, the skill of effectively hitting backhand squash shots could be harder to develop than that for hitting forehand shots (Mavvidis et al., 2005). It is therefore possible that during the inaccurate FH drop shots, the players were able to maintain a more appropriate orientation of their racket at impact, such that it was not a discrete limiting factor in the outcome of the shot, unlike that of the BH drop shots. As such, it could be advisable for coaches to teach players of this skill level to try to maintain a more open racket face when impacting the ball during a BH drop shot and be mindful that a deviation that 'closes' the racket face too much may adversely affect the resulting accuracy of the shot.

Racket orientation angles at ball impact during the FH drive, FH volley, FH drop, BH drive and BH volley shots were not able to be used to distinguish shot accuracy, as the differences between accurate and inaccurate shots did not reach statistical significance. These findings appear to be in disaccord with recent observations, where a difference in racket face projection angle between accurate and inaccurate FH drive shots was found (Williams et al., 2020b). However, while the testing protocol for these studies was similar, the methods of describing racket angles at ball impact differed. Racket face projection angles were reported by Williams et al. (2020b), while in the current study, racket orientation angles calculated in a pitch-yaw-roll sequence are presented and consequently, the resulting angles cannot be directly compared. It is possible that due to the relatively large size of the target areas used in the protocol of the present study, and the unavoidable variable spatial ball impact location on the court, the resulting variability in the orientation angles for both the accurate and inaccurate shots (Table 1) was too high to allow a statistical difference in the mean values. As such, it appears that the differences between racket orientation angles of accurate and inaccurate FH drive, FH volley, FH drop, BH drive and BH volley shots of the junior players in this study were too small to be able to be used to distinguish shot accuracy.

It has been proposed that there may be various combinations of racket impact parameters that allow for an accurate shot in tennis (Knudson & Blackwell, 2005). This postulation is somewhat supported by the present findings, within squash strokes, given the high variability values found in the different orientation angles at impact during the accurate shots in this study (Table 2). It is possible that this variability was a result of the necessary 'functional' adaptations to the initial task conditions; the oncoming ball's varying velocity and trajectory, as well as the unavoidable variable spatial locations of the ball at impact, that facilitated a successful outcome (Bartlett et al., 2007; Whiteside et al., 2015; Williams et al., 2020b). Furthermore, it is also conceivable that the variability values may have been influenced by the moderate skill level of the junior players (mean HSAT score of 55%) that participated in this study (compared to potentially highly-skilled 'elite' players), as the variability of task-relevant parameters has been shown to be higher in less-skilled athletes than highly-skilled athletes (Button et al., 2003; Scott et al., 1997; Williams et al., 2020b). Ultimately, the results of this study imply that each accurate shot required a unique combination of racket orientation angles to successfully hit the ball into the desired target area.

It would appear that a certain degree of consistency in racket orientation at ball impact is required for a successful outcome in FH drop and BH drive shots, as highlighted by the significant increase in variability of the orientation angles (FH drop roll, BH drive yaw and roll) during the inaccurate shots of those strokes compared to the accurate shots (Table 2). The increased variability of those orientation angles during inaccurate shots may have been the result of an unstable movement pattern indicative to the moderate skill level of the junior players participating in this study (Cortis et al., 2009). Furthermore, it is also possible that due to their moderate skill level, the players were not able to adjust their swing mechanics in a functional manner to ensure an appropriate racket orientation for the varying initial task conditions. The importance of the accuracy of the FH drop and BH drive strokes to performance in competition is indicated by a positive correlation between within-game shot success of those strokes to final tournament rank (Williams et al., 2018). Furthermore, the BH drive is one of the most prevalent strokes played during a match (Vučković et al., 2013; Williams et al., 2018). It therefore appears imperative that junior and less-skilled players develop appropriate swing mechanics that allow for a level of consistency in racket orientation at ball impact that maximises the potential success of the proceeding shot. The variability of orientation angles between accurate and inaccurate shots of the FH drive, FH volley, BH volley and BH drop strokes were found to not significantly differ, supporting recent findings showing a lack of significant differences in the variability of racket projection angles at impact between accurate and inaccurate FH drive shots (Williams et al., 2020b).

To the authors' knowledge, this study is the first attempt to estimate squash racket kinematics using a racket embedded MIMU sensor during performance on a squash court. Studies utilising racket mounted MIMUs to assess swing kinematics are very sparse within the literature, with only a limited number of conference abstracts published within the sports of: tennis (Buthe et al., 2016; Pei et al., 2017); table tennis (Boyer et al., 2013); and badminton (Jaitner & Gawin, 2010). A possible explanation for the limited number of investigations utilising MIMUs has been the potential for errors associated with the data. The accuracy of MIMU orientation estimation has been shown to be affected by parameters including the linear and angular velocity of the MIMU during data acquisition (Lebel et al., 2013; Pasciuto et al., 2015). However, due to advances in sensor technology and fusion algorithms (Robert-Lachaine et al., 2017; Santoso et al., 2017), some more recent MIMU validation studies have yielded positive results in baseball hitting (Punchihewa et al., 2019), football kicking (Blair et al., 2018) as well as in squash hitting (Williams et al., 2019). Furthermore, as mentioned earlier, the MIMU used for data collection in this study has been shown previously to be very reliable and accurate in estimating orientation angles at impact during a FH drive stroke when compared to a motion capture system (Williams et al., 2019). Additionally, in order to minimise the chance of errors, this study used the mean orientation angles at impact from five trials for each participant, which will have substantially reduced the chance of large absolute errors (Williams et al., 2019). The present study did not, however, include an evaluation of all task-relevant racket parameters that may contribute to the success of a shot, such as racket velocity or trajectory, nor did it consider any ball mechanics, limitations that should be considered when interpreting the results. Future work may therefore be advisable in investigating the use of a racket embedded MIMU, with appropriate sensor fusion algorithms, to accurately estimate other task-relevant racket parameters. Furthermore, it is recommended that this investigation be extended to other populations, such as elite adult players, to investigate whether racket orientation at ball impact can be used to distinguish their shot accuracy.

Conclusion

The accuracy of BH drop shots were distinguishable via differences in the racket's roll orientation angle at ball impact, with inaccurate shots having a significantly less-open racket face at impact than the accurate shots, thereby confirming our hypothesis for this stroke. This could be partly attributed to the inability of the junior players participating in this study to maintain an appropriate racket face angle at impact to ensure the subsequent desired ball flight path. It is therefore suggested that players of this skill level develop swing mechanics that maintain a more open racket face at ball impact for this stroke and be aware that the accuracy of the corresponding shot may be adversely affected by closing the racket face at ball impact. In the other strokes, no single angle orientation parameter at impact determined whether shots were accurate or inaccurate, thereby disproving our hypothesis for those strokes. This highlighted the complex interactions of all the task-relevant parameters to the outcome of a shot in those strokes.

Successful performance during the FH drop and BH drive shots required a level of consistency in racket orientation angles at ball impact, as indicated by the increased variability of racket angles during the inaccurate shots of those strokes. Given the apparent importance of the success of these two strokes to performance within tournament match-play (Williams et al., 2018), it is recommended that junior players develop suitable swing mechanics, that allow for adjustments due to the unavoidable varying initial conditions, such that appropriate racket orientations are consistently achieved at ball impact that in-turn allow for an accurate shot.

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