



Associations of shoulder rotational range of motion and isokinetic peak torque with shuttlecock velocity during the forehand jump smash in trained male badminton players

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Abstract

Background: Shoulder joint mobility and rotational strength of the shoulder muscles are important factors in badminton performance. **Aims:** To determine the correlations of shoulder range of motion (ROM) and isokinetic rotational peak torque with shuttlecock velocity during the forehand jump smash in trained male badminton players.

Methods: A cross-sectional study was conducted in 30 trained male badminton players (age= 28.4 ± 3.3 years; body mass= 83.2 ± 7.8 kg; height= 192.5 ± 4.2 cm). Isokinetic dynamometry was used to assess internal-rotation (IR) and external-rotation (ER) shoulder peak torque during concentric (IRcon and ERcon) and eccentric (IREcc and EREcc) contractions. Peak shuttlecock velocity during the forehand jump smash was recorded using a radar gun.

Results: Internal and external shoulder ROM were $55.58 \pm 7.10^\circ$ and $104.00 \pm 8.11^\circ$, respectively. EREcc, ERcon, IREcc, and IRcon peak torque values were 38.43 ± 7.63 Nm, 30.91 ± 8.22 Nm, 79.61 ± 7.05 Nm, and 49.01 ± 6.10 Nm, respectively. Mean shuttlecock velocity was 273.0 ± 3.5 km/h. In the unadjusted analysis, IRcon peak torque was positively correlated with shuttlecock velocity ($r = 0.380$, 95% CI [0.023, 0.651], $p = 0.038$). However, this association did not remain significant after Bonferroni correction for eight correlation tests (adjusted $\alpha = 0.00625$; adjusted $p = 0.304$), and none of the examined correlations was significant after correction for multiple comparisons.

Conclusion: After correction for multiple comparisons, no statistically significant associations were detected between shuttlecock velocity and shoulder ROM or isokinetic rotational peak torque in the present sample. Although IRcon peak torque showed a nominal positive association with shuttlecock velocity in the unadjusted analysis, this finding did not remain significant after Bonferroni correction. Further research is needed to clarify these relationships.

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INTRODUCTION

Sports involving repetitive overhead actions, including volleyball, baseball, tennis, and badminton, place substantial mechanical demands on the shoulder complex and require coordinated muscle activation to maintain dynamic stability and transfer energy through the upper limb (Ramasamy et al., 2023; Kibler et al., 2024; Tajik et al., 2025). In many overhead actions, momentum generated by the lower limbs and torso is transferred through the upper limb, with successive distal segments typically achieving progressively greater end-point velocities (Serrien & Baeyens, 2017; Liu et al., 2025), and the shoulder joint also contributes substantially to distal racket velocity during high-speed strokes in badminton and tennis (Awatani et al., 2018; Pedro et al., 2022; Rusdiana et al., 2021). This biomechanical understanding underscores the importance of shoulder stability and coordination in executing shots such as the smash, the primary finishing shot in badminton (Ramasamy et al., 2022). Precise shoulder coordination is therefore a fundamental element of high-

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level performance in badminton, consistent with biomechanical principles observed in other overhead sports (Barnamehei et al., 2021).

Badminton, known for its fast-paced nature among racquet-based games, requires exceptional physical fitness and technical skills (Pardiwala et al., 2020). The sport involves vigorous movements, including swift accelerations, sudden decelerations, and explosive directional changes (Rusdiana et al., 2021). Proficient motor coordination and mastery of racquet techniques are crucial (Indora et al., 2022). The smash, a traditional offensive technique, is considered the primary finishing shot (Asif et al., 2018), with forehand and backhand smashes used in 39.8% of instances (Barreira et al., 2016). The forehand smash, a particularly significant offensive move, accounts for 54% of shots in international matches and often results in either an "unconditional winner" or a "forced failure" (Tong & Hong, 2000).

The effectiveness of the badminton stroke depends primarily on the ability to generate high shuttlecock velocity while maintaining sufficient accuracy. Very high initial shuttlecock velocities have been documented during smash actions performed by elite and international players (Collet, 2026), while skilled players have produced greater shuttlecock speeds than novices, with these differences linked to technical execution and whole-body coordination (Li et al., 2023). This velocity is achieved through a proximal-to-distal kinetic chain, in which body segments move in a coordinated sequence to transfer energy from the legs and trunk through the arm, forearm, and hand to the racket (Rasmussen et al., 2010). Upper-body joint moments contribute substantially to racket-head speed during rapid overhead movements; among elite Malaysian badminton players, greater shoulder internal-rotation moment was strongly associated with racket-head speed (Ramasamy et al., 2022). During the badminton jump smash, a larger shoulder internal-rotation moment has been associated with greater racket-head speed, whereas radio-ulnar pronation has been shown to contribute substantially to maximal racket velocity (Phomsoupha et al., 2020; Ramasamy et al., 2022). Similarly, Rusdiana et al. (2021) identified shoulder internal-rotation velocity, elbow extension, and wrist palmar flexion as important components of upper-limb motion during the forehand smash.

Consequently, recent studies have examined associations between shoulder strength and performance-velocity outcomes in overhead sports, including throwing velocity in handball, ball velocity in baseball, and serve velocity in tennis (Arnold et al., 2022; Baiget et al., 2016; García-Buendía et al., 2025; Kayhan et al., 2024; Ölmez et al., 2025). These relationships appear to vary according to the sport, contraction mode, testing velocity, strength-normalization method, and joint position; notably, the seated position with 90° of shoulder abduction and 90° of elbow flexion remains one of the most frequently used configurations for isokinetic shoulder-strength assessment in overhead athletes (Arnold et al., 2022; Leahy et al., 2024). It has been proposed that greater shoulder strength contributes to higher smash velocity and improved stroke trajectory (Phomsoupha & Laffaye, 2015). However, research on rotational shoulder strength in badminton remains limited (Stausholm et al., 2021), and evidence simultaneously examining passive shoulder rotational range of motion, concentric and eccentric isokinetic rotational peak torque, and directly measured shuttlecock velocity within the same sample remains limited. Establishing whether these isolated joint capacities are associated with on-court shuttlecock velocity would clarify their relevance for performance assessment, athlete monitoring, and future training research in badminton. Therefore, this study aimed to evaluate shoulder internal- and external-rotation range of motion and isokinetic rotational peak torque and to examine their associations with shuttlecock velocity during the forehand jump smash in trained male badminton players. It was hypothesized that shoulder rotational range of motion and isokinetic rotational peak torque would be significantly associated with shuttlecock velocity.

METHOD

Research Design

A cross-sectional study design was used to examine the relationships of shoulder rotational strength and shoulder ROM with shuttlecock velocity during the forehand jump smash in trained male badminton players. Participants completed two testing days separated by at least 48 hours. Shoulder ROM measurements and isokinetic shoulder-strength tests were conducted on the first testing day. This interval was incorporated into the study protocol to minimize residual fatigue and enable participants to exert maximal effort during the second testing day. Maximum shuttlecock

velocity during the forehand jump smash was assessed on the second testing day (Figure 1). Shoulder ROM and isokinetic strength testing were performed in the biomechanics and movement analysis laboratory, whereas shuttlecock velocity was measured on an official full-size badminton court. Participants were instructed to abstain from strenuous physical activity and caffeinated beverages during the 48 hours preceding each testing session and to maintain their usual daily routines. The study was conducted in accordance with the principles of the World Medical Association Declaration of Helsinki. The study protocol was reviewed and approved by the Gazi University Rectorate Ethics Commission (Research Code No. 2023-734; Meeting No. 10, 23 May 2023; official approval letter dated 6 June 2023, No. E-77082166-604.01.02-666796). Written informed consent was obtained from all participants prior to participation.

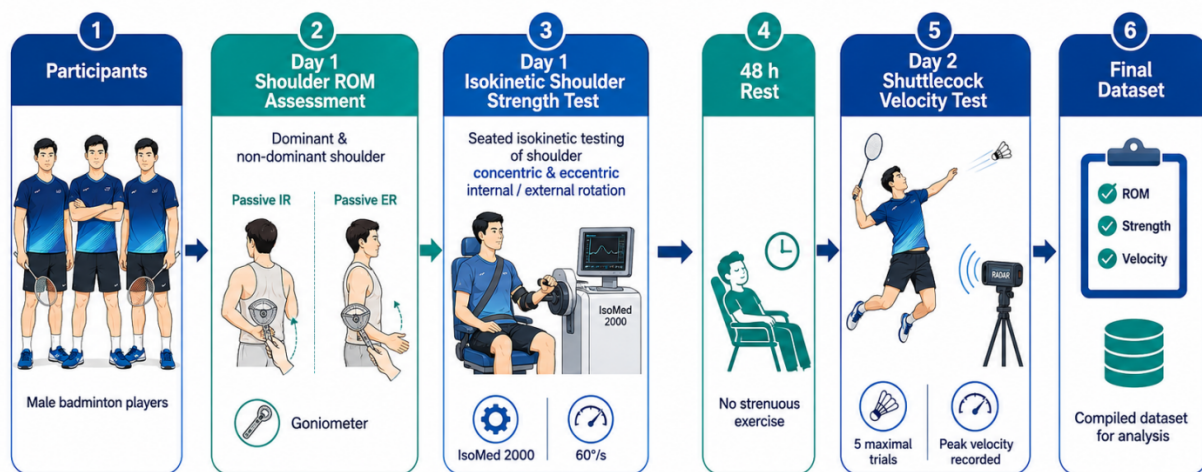


Figure 1. The Study Design for Measuring Shoulder Range of Motion (ROM), Rotational Isokinetic Strength, and Shuttlecock Velocity.

Participants

A literature-based a priori sample-size estimation was performed using G*Power software. The calculation was based on a two-tailed correlation test, with an expected correlation magnitude of $|r| = 0.484$, a significance level of $\alpha = .05$, and a statistical power of 80%. The expected effect magnitude was informed by King et al. (2020), who reported a badminton-specific association between a kinematic determinant and shuttlecock speed. The analysis indicated a target sample size of 31 participants. A total of 30 healthy, trained male badminton players (age, 28.4 ± 3.3 years; body mass, 83.2 ± 7.8 kg; and height, 192.5 ± 4.2 cm) participated voluntarily; thus, the final sample was one participant below the original target. The inclusion criteria were: (1) at least 5 years of badminton training experience and (2) a weekly badminton training volume of at least 8 hours. Participants were excluded if they had experienced a musculoskeletal injury within the previous six months, had undergone upper-limb surgery, or had current shoulder pain, soreness, or overuse-related symptoms.

Testing procedures

A standardized 10-minute warm-up protocol was conducted for both shoulder mobility and shoulder strength tests before each measurement. The warm-up consisted of static stretches for the upper body, held for 10 seconds, and dynamic movements such as jumping jacks, arm circles, flyes, and shoulder rotations and abductions (Cross et al., 2023). In addition to this warm-up, a 5-minute badminton-specific warm-up protocol was applied by the head coach for the shuttlecock velocity test. The protocol consisted of the typical activities players perform before a badminton match.

Shoulder Range of Motion (ROM)

A hand-held manual goniometer (Baseline™ Metal Goniometer, USA) was used following a previously described method (Cools et al., 2014) to assess passive glenohumeral internal-rotation (IR) and external-rotation (ER) ROM in the dominant and non-dominant shoulders. According to the

scapular stabilization method described by Wilk et al. (2015), all measurements were performed with the participant in the supine position, the shoulder abducted to 90°, and the elbow flexed to 90°. The fulcrum of the goniometer was positioned over the olecranon, while the moving arm was aligned with the forearm using the ulnar styloid process as the reference point.

Two measurements were performed for each shoulder movement on both the dominant and non-dominant sides. The highest value obtained from the two trials was retained for the primary analysis to represent the participant's maximal available ROM under standardized testing conditions. Within-session trial-to-trial reliability was excellent, with intraclass correlation coefficients ranging from 0.959 to 0.971.

Shoulder Rotational Strength

Shoulder rotational peak torque was assessed using an IsoMed 2000 isokinetic dynamometer (D&R Ferstl GmbH, Hemau, Germany), which was calibrated according to the manufacturer's instructions before testing. Participants were tested in a seated position with the shoulder abducted to 90° and the elbow flexed to 90°. The starting position of 0° shoulder rotation was defined as the forearm in a neutral position, consistent with previously described isokinetic shoulder testing procedures (Wilk et al., 1991).

Based on previous isokinetic testing protocols that used relatively slow angular velocities for shoulder rotational strength assessment in overhead athletes (Forthomme et al., 2005; Vargas et al., 2021), concentric and eccentric internal and external rotation were assessed bilaterally at an angular velocity of 60°/s. Before formal testing, participants completed familiarization trials using the non-dominant limb. Following familiarization, the order of the formal measurements was randomized. Each test consisted of five concentric contractions (IRcon and ERcon) and five eccentric contractions (IREcc and EREcc). A 2-minute rest interval was provided between testing conditions. Each condition was performed twice within the same testing session. The peak torque obtained from each trial was recorded, and the mean of the two trial-specific peak torque values was used for statistical analysis. Peak torque was expressed in absolute units (Nm) and was not normalized to body mass. Within-session trial-to-trial reliability was good to excellent, with intraclass correlation coefficients ranging from 0.83 to 0.86.

Shuttlecock Velocity

Peak shuttlecock velocity during the forehand jump smash was measured using a radar gun (Pocket Radar, Inc., Santa Rosa, CA, USA) with a manufacturer-reported accuracy of ± 2 km/h. The radar gun was positioned directly behind the net, with its measurement axis directed toward the expected shuttlecock flight path. Shuttlecocks were fed from the center of the opposite court by the same international-level badminton coach, who attempted to provide a consistent feed and hitting opportunity for every trial. Participants were instructed to perform each forehand jump smash with maximal effort. Each participant completed five maximal attempts, and the highest peak shuttlecock velocity recorded across the five trials was retained as the participant's maximal shuttlecock-velocity performance (Figure 2).

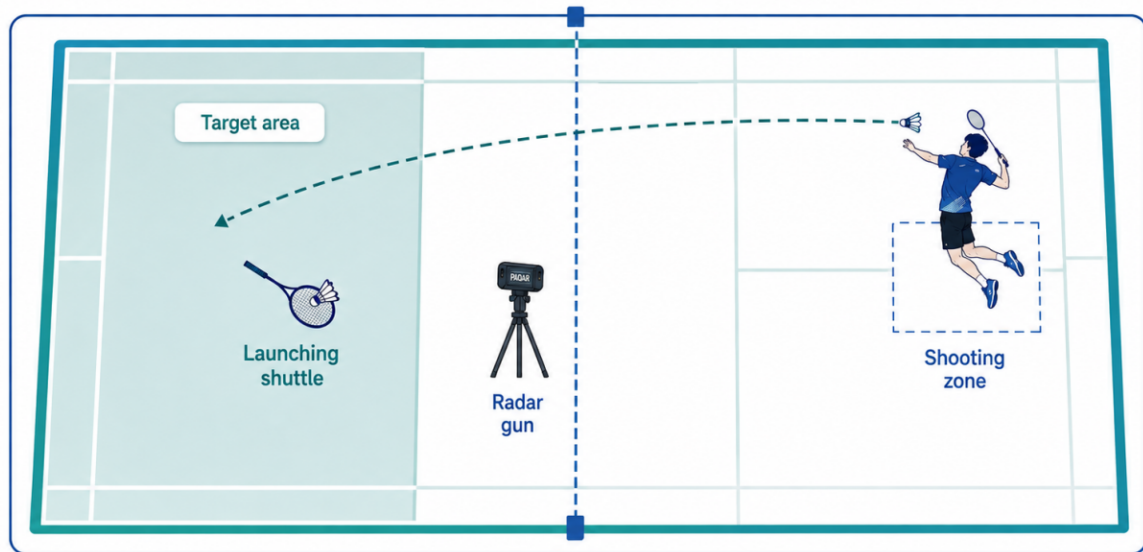


Figure 2. The Experimental Setup for the Shuttlecock Velocity Test

Statistical Analyses

Descriptive statistics are presented as mean $\pm$ standard deviation (SD). The Shapiro–Wilk test was used to assess the normality of the data, and no significant departures from normality were detected ($p > 0.05$). Eight dominant versus non-dominant inter-limb comparisons were conducted using paired-samples t-tests. These comparisons were treated as secondary exploratory analyses and were not included in the primary confirmatory family of correlation tests. Accordingly, no multiplicity adjustment was applied to the inter-limb comparisons; two-tailed unadjusted p-values are reported and should be interpreted descriptively as nominal evidence rather than confirmatory findings. Because these comparisons involved paired measurements, effect sizes were calculated as Cohen's d_z , defined as the mean of the paired differences divided by the standard deviation of the paired differences. Cohen's d_z values were interpreted according to Hopkins et al. (2009) as trivial (<0.20), small (0.20 – 0.59), moderate (0.60 – 1.19), large (1.20 – 1.99), and very large (≥ 2.00).

Pearson's correlation coefficients (r) were used to examine the relationships between shoulder ROM, isokinetic shoulder rotational peak torque, and shuttlecock velocity. Eight primary correlation tests were performed. Therefore, to control the family-wise type I error rate across these primary tests, a Bonferroni-adjusted significance threshold of $\alpha = .00625$ ($.05/8$) was applied. Unadjusted two-tailed p-values and 95% confidence intervals are reported for transparency; where an adjusted p-value is presented, it was calculated by multiplying the corresponding unadjusted p-value by eight, with a maximum possible value of 1.00. Only correlation results with $p < .00625$ were considered statistically significant in the primary analysis.

A supplementary sensitivity analysis based on the exact test for a bivariate normal correlation was conducted using the actual sample size of $N = 30$ and the Bonferroni-adjusted two-tailed $\alpha = .00625$. Under these conditions, the study had approximately 49.9% power to detect the originally anticipated correlation of $|r| = 0.484$. With $N = 30$, an absolute correlation of approximately $|r| = 0.587$ was required to achieve 80% statistical power. Detecting $|r| = 0.484$ with 80% power at the adjusted significance threshold would have required approximately 48 participants. Statistical analyses were performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

Results

Descriptive data for shoulder ROM, isokinetic rotational shoulder peak torque, and shuttlecock velocity, together with their respective inter-limb differences, are presented in Table 1.

Table 1. Mean and SD of Shoulder Mobility, Strength, Shuttlecock Velocity and Inter-Limb Difference Variables

Variable	Dominant limb (Mean ± SD)	Non-dominant limb (Mean ± SD)	Inter-limb difference	
<i>Shoulder ROM</i>			<i>Unadjusted p</i>	<i>Cohen's d_z</i>
ROMint (°)	55.6 ± 7.10	54.0 ± 3.80	<0.010	0.59
ROMext (°)	104.0 ± 8.10	97.9 ± 7.60	<0.001	2.42
<i>Shoulder Isokinetic Peak Torque</i>				
ERecc peak torque (Nm)	38.4 ± 7.63	37.3 ± 7.60	0.930	0.01
ERcon peak torque (Nm)	30.9 ± 8.22	28.9 ± 9.10	0.420	0.15
IRecc peak torque (Nm)	79.6 ± 7.05	76.3 ± 7.00	0.101	0.31
IRcon peak torque (Nm)	49.0 ± 6.10	47.3 ± 5.70	0.041	0.39
ERecc/IRecc peak-torque ratio	0.48 ± 0.17	0.48 ± 0.21	0.763	-0.05
ERcon/IRcon peak-torque ratio	0.63 ± 0.14	0.62 ± 0.19	0.562	0.10
<i>Shuttlecock velocity</i>				
Peak velocity (km/h)	273.0 ± 3.5			

Note: Dominant versus non-dominant inter-limb comparisons were treated as secondary exploratory analyses. The reported *p*-values are two-tailed and unadjusted for multiple testing; values below .05 represent nominal exploratory findings and should not be interpreted as confirmatory evidence. Cohen's *d_z* was calculated as the mean paired difference divided by the standard deviation of the paired differences. ROMint = internal rotation range of motion; ROMext = external rotation range of motion; ERecc = eccentric external-rotation peak torque; ERcon = concentric external-rotation peak torque; IRecc = eccentric internal-rotation peak torque; IRcon = concentric internal-rotation peak torque.

In the secondary exploratory inter-limb comparisons, the largest dominant–non-dominant difference was observed for external-rotation ROM (Cohen's *d_z* = 2.42). Internal-rotation ROM (*d_z* = 0.59) and IRcon peak torque (*d_z* = 0.39) showed smaller dominant-side differences. Peak shuttlecock velocity also demonstrated limited between-player variability (273.0 ± 3.5 km/h; coefficient of variation ≈ 1.3%). Because the inter-limb comparisons were exploratory and were not adjusted for multiple testing, the nominal findings, particularly the IRcon result (*p* = .041), should not be interpreted as confirmatory evidence of inter-limb differences.

Correlation results are shown in Table 2 to identify the relationships between shoulder ROM, isokinetic rotational peak torque, and shuttlecock velocity.

Table 2. Pearson Correlations between Dominant-Side Shoulder Variables and Shuttlecock Velocity (*n* = 30).

Variables	Shoulder ROM	<i>r</i>	95% CI	<i>p</i>
ROMint (degree)		0.101	−0.269 to 0.445	0.595
ROMext (degree)		−0.132	−0.470 to 0.240	0.487
Shoulder Isokinetic Peak Torque				
ERecc (Nm)		−0.042	−0.396 to 0.323	0.826
ERcon (Nm)		−0.230	−0.545 to 0.142	0.221
IRecc (Nm)		0.189	−0.184 to 0.514	0.317
IRcon (Nm)		0.380	0.023 to 0.651	0.038
ERecc/IRecc ratio		0.088	−0.281 to 0.434	0.644
ERcon/IRcon ratio		0.033	−0.331 to 0.389	0.863

Note: Eight primary correlation tests were performed. Unadjusted two-tailed *p*-values and 95% confidence intervals are presented in the table. To control the family-wise type I error rate, a Bonferroni-adjusted significance threshold of $\alpha = .00625$ (.05/8) was applied. None of the correlations met this adjusted threshold. ROMint = internal rotation range of motion; ROMext = external rotation range of motion; ERecc = eccentric external-rotation peak torque; ERcon = concentric external-rotation peak torque; IRecc = eccentric internal-rotation peak torque; IRcon = concentric internal-rotation peak torque.

In the unadjusted analysis, IRcon peak torque showed a positive correlation with shuttlecock velocity (*r* = 0.380, 95% CI [0.023, 0.651], *p* = 0.038), whereas the remaining correlations were not statistically significant. However, the IRcon association did not remain significant after Bonferroni correction for eight correlation tests (adjusted α = 0.00625; adjusted *p* = 0.304). Therefore, none of

the examined correlations remained statistically significant after correction for multiple comparisons (Table 2).

Discussion

This study examined the relationships between shoulder joint mobility, isokinetic shoulder rotational peak torque, and shuttlecock velocity in trained male badminton players. The primary findings indicate that concentric internal-rotation peak torque (IRcon) showed a positive association with shuttlecock velocity in the unadjusted analysis ($r = 0.380$, 95% CI [0.023, 0.651], $p = 0.038$); however, this association did not remain statistically significant after Bonferroni correction for eight correlation tests (adjusted $\alpha = 0.00625$; adjusted $p = 0.304$). None of the examined shoulder ROM or isokinetic rotational peak-torque variables were therefore significantly associated with shuttlecock velocity after correction for multiple comparisons. These results suggest that shuttlecock velocity cannot be explained solely by the shoulder ROM and rotational peak torque measures assessed in the present study and may reflect the contributions of multiple technical and biomechanical factors.

Several studies have reported associations between shoulder ROM, shoulder strength, and ball- or racket-related performance in different sports such as handball (Bayios et al., 2001; Zapartidis et al., 2007), volleyball (Forthomme et al., 2005; Arslan & Albay, 2019; Aka et al., 2019), baseball (Cross et al., 2023), and tennis (Baiget et al., 2016; Pugh et al., 2003). However, studies directly examining relationships between shoulder characteristics and shuttlecock or racket velocity in badminton remain limited. Awatani et al. (2018) directly examined the relationship between isometric shoulder strength and racket velocity during badminton forehand smash movements. They reported positive correlations between racket velocity and shoulder extensor strength and internal-rotator strength measured in neutral and abducted positions. In contrast, Couppé et al. (2014) profiled passive shoulder ROM and isometric internal- and external-rotation strength in adolescent national-level badminton players, whereas Stausholm et al. (2021) compared isometric shoulder rotational-strength profiles in adolescent and adult national-level badminton players; neither study assessed racket or shuttlecock velocity. Accordingly, these two studies provide badminton-specific context regarding shoulder characteristics but do not provide evidence of a direct relationship between shoulder strength and racket velocity. Overall, the available evidence suggests that relationships between shoulder capacity and racket-related performance may depend on the contraction mode, testing position, and performance outcome assessed.

In the present study, most correlations between shuttlecock velocity and shoulder ROM or isokinetic rotational peak torque were weak and non-significant. Although IRcon peak torque showed a positive association with shuttlecock velocity in the unadjusted analysis, this finding did not survive Bonferroni correction and should therefore be interpreted with caution. Interpretation of these null findings is constrained by the relatively small sample size ($N = 30$), the Bonferroni-adjusted significance threshold of $\alpha = 0.00625$, and the resulting statistical power of approximately 49.9% to detect the originally anticipated correlation of $|r| = 0.484$. In addition, shuttlecock velocity showed limited between-player variability (273.0 ± 3.5 km/h; coefficient of variation $\approx 1.3\%$), which may have restricted the magnitude of observable correlations. Therefore, the absence of statistically significant associations should not be interpreted as evidence that shoulder variables are unimportant or that small-to-moderate relationships are absent. Adequate shoulder ROM may nevertheless contribute to the execution of the overhead movement; however, the present cross-sectional data do not establish that greater ROM improves smash performance or reduces injury risk. Fleck et al. (1992) found no statistically significant relationships among isokinetic strength, shoulder rotation, and ball velocity in their study of handball players. Similarly, the present findings do not provide robust evidence that greater peak shoulder internal-rotation torque is accompanied by a proportionally greater shuttlecock velocity. This may reflect the contribution of other mechanical and technical factors involved in overhead striking actions. Previous biomechanical studies have examined whole-body kinematic determinants of badminton jump-smash racket-head speed (Miller et al., 2020), kinetic and kinematic determinants of shuttlecock speed during the forehand jump smash (Ramasamy et al., 2024), and relationships between racket-arm joint moments and racket-head speed during the badminton jump smash (Ramasamy et al., 2022).

Shuttlecock velocity during the smash is strongly influenced by racket-head velocity and the coordinated contribution of multiple body segments. The present findings indicate that greater

shoulder ROM or isolated isokinetic rotational peak torque alone was not consistently associated with greater shuttlecock velocity after correction for multiple comparisons. During the badminton forehand smash, forearm pronation contributes to distal impulse transmission, while coordinated trunk, shoulder, elbow, and wrist actions generate the whip-like acceleration associated with faster smash performance (Li et al., 2023; Tan et al., 2016; Xiao et al., 2026). In examining the smash mechanics of elite badminton players, previous research has indicated that the forearm undergoes rapid sequential motion that may contribute to a stretch-shortening cycle and efficient force generation (Kwan et al., 2011). Moreover, Phomsoupha et al. (2020) found that radio-ulnar pronation may contribute more strongly than forearm extension to maximal racket velocity.

Implications

The practical relevance of the present findings primarily concerns performance assessment rather than training prescription. Shoulder rotational ROM and isokinetic rotational peak torque may be included as components of athlete profiling. Still, they should not be interpreted in isolation as indicators of forehand jump-smash velocity. Coaches and sports scientists should interpret these measures alongside task-specific characteristics such as racket-head velocity, forearm pronation-supination, intersegmental coordination, and whole-body technique. Although IRcon peak torque showed a positive association with shuttlecock velocity in the unadjusted analysis, this finding should be considered only hypothesis-generating, as it did not remain statistically significant after correction for multiple comparisons. Consequently, the present results do not support prescribing increases in internal-rotation strength as a means of improving shuttlecock velocity. Instead, they support a multidimensional assessment of smash performance and an individualized interpretation of shoulder measurements.

Research Contribution

The main contribution of this study lies in its integrated, badminton-specific assessment of passive shoulder rotational ROM, concentric and eccentric isokinetic rotational peak torque, and directly measured shuttlecock velocity within the same group of trained male players. Bringing these measures into a common analytical framework enabled evaluation of the associations between isolated shoulder measures and shuttlecock velocity using a multiplicity-adjusted inferential strategy. Rather than identifying shoulder strength as a predictor of shuttlecock velocity, the study provides badminton-specific evidence that the ROM and rotational peak-torque measures examined have limited standalone explanatory value for between-player differences in forehand jump-smash velocity. These findings contribute to the badminton-specific evidence base by illustrating the limited standalone explanatory value of local shoulder measures under the present testing conditions.

Limitations

This study has several limitations. Its cross-sectional design and relatively small, male-only sample limit causal inference and generalizability; the final sample was 1 participant below the original a priori target. Moreover, the original sample-size calculation assumed a single correlation test at $\alpha = .05$. After Bonferroni correction for eight primary correlations (adjusted $\alpha = .00625$), the study had approximately 49.9% power to detect the originally anticipated effect of $|r| = .484$, and a correlation of approximately $|r| = .587$ was required to achieve 80% power. Accordingly, the non-significant correlations do not rule out small-to-moderate associations. The inter-limb comparisons were secondary exploratory analyses for which no multiplicity adjustment was applied; therefore, the nominal findings, particularly the inter-limb IRcon comparison (unadjusted $p = .041$), should also be interpreted cautiously. Isokinetic peak torque was assessed only at $60^\circ/\text{s}$. It was expressed in absolute rather than body-mass-normalized values, while whole-body kinematics and other technical contributors to the forehand jump smash were not measured. The archived reliability output and trial-level data were unavailable; therefore, the precise ICC models, model-specific 95% confidence intervals, and standard errors of measurement could not be reconstructed retrospectively. In addition, the archived protocol did not retain sufficient detail on the exact radar-to-impact distance, radar height, angular alignment, fixed recovery interval between attempts, or formal criteria for rejecting or repeating attempts, thereby limiting procedural reproducibility. These omissions limit the reproducibility of the shuttlecock-velocity procedure. Manual shuttlecock

feeding, use of the highest value from five attempts, absence of between-session reliability data for shuttlecock velocity, and the radar gun's manufacturer-reported accuracy of ± 2 km/h may also have introduced measurement variability.

Suggestions

Future studies should recruit larger, more diverse samples, including female badminton players and athletes at different competitive levels. Sample-size calculations should be aligned with the final inferential strategy, including the number of planned primary tests and any intended multiplicity correction. To reduce the number of hypothesis tests and avoid an excessive loss of statistical power, researchers should pre-specify a limited set of primary shoulder variables based on clearly defined biomechanical hypotheses, while classifying the remaining variables and analyses as secondary or exploratory. Future research should also assess shoulder rotational strength at multiple angular velocities and report body-mass-normalized torque values alongside absolute peak torque. Shuttlecock-velocity testing should incorporate mechanical or tightly controlled shuttlecock feeding, standardized feed trajectories, predefined radar positioning and alignment, fixed recovery intervals, and explicit criteria for accepting, rejecting, or repeating attempts. Repeated shuttlecock-velocity assessments across separate sessions should be conducted to establish between-session reliability. Finally, integrating shoulder assessments with whole-body kinematic analysis, intersegmental coordination, and racket-head velocity measurements may provide a more comprehensive understanding of the biomechanical factors contributing to forehand jump-smash performance.

CONCLUSION

In this sample of trained male badminton players, none of the examined relationships between shoulder rotational ROM or isokinetic rotational peak torque and shuttlecock velocity during the forehand jump smash met the Bonferroni-adjusted significance threshold. Although IRcon peak torque showed a positive association with shuttlecock velocity in the unadjusted analysis, this association did not remain statistically significant after correction for multiple comparisons. Given the limited statistical sensitivity at the adjusted threshold, the findings do not rule out small-to-moderate associations. Therefore, the results should be interpreted as an absence of robust evidence under the present design rather than as evidence that shoulder characteristics are irrelevant to smash performance.

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AUTHOR CONTRIBUTION STATEMENT

T.C. and Y.A. contributed to the study's conception. A.G.R. and L.C. were responsible for the performance of the work. T.C. and Y.A. contributed to the interpretation and analysis of the data. L.C. and A.G.R. prepared the manuscript. A.G.R., L.C., and Y.A. revised the manuscript for important intellectual content. T.C., A.G.R., L.C., and Y.A. supervised the study.

AI DISCLOSURE STATEMENT

Generative artificial intelligence tools were used solely to assist with language editing and presentation during manuscript revision. All scientific content, analyses, interpretations, and final decisions were reviewed and approved by the authors.

CONFLICTS OF INTEREST

The authors have no conflicts of interest to report.

ETHICAL APPROVAL

The study was conducted in accordance with the principles of the World Medical Association Declaration of Helsinki. The study protocol was reviewed and approved by the Gazi University Rectorate Ethics Commission (Research Code No. 2023-734; Meeting No. 10, 23 May 2023; official

approval letter dated 6 June 2023, No. E-77082166-604.01.02-666796). Written informed consent was obtained from all participants before participation.

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