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Analysis Flexibility and Arm Muscle Strength on Badminton Smash Stroke Ability Avanti Makassar Club

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Abstract

Effective badminton smash performance requires the integration of physical capacity, movement control, racket coordination, and the ability to generate a fast and accurate attacking stroke. This study examined the contribution of wrist flexibility and arm muscle strength to smash performance among players of Avanti Badminton Club Makassar. A quantitative descriptive-correlational design with a regression approach was used. The sample consisted of 40 badminton players, with complete valid data for all research variables. Wrist flexibility was measured using a flexiometer, arm muscle strength was measured using a 30-second push-up test, and smash performance was assessed using a badminton smash skill test. Data were analyzed using descriptive statistics, the Kolmogorov-Smirnov normality test, Pearson correlation, simple regression, and multiple regression. The results showed that wrist flexibility contributed significantly to smash performance, $R = 0.802$, $R^2 = 0.643$, $p < 0.001$. Arm muscle strength also showed a significant contribution, $R = 0.815$, $R^2 = 0.665$, $p < 0.001$. Simultaneously, both predictors explained 74.3% of the variance in smash performance, $R = 0.862$, $R^2 = 0.743$, $F = 53.600$, $p < 0.001$. These findings indicate that badminton smash performance is supported by the interaction between wrist mobility and upper-limb strength. Training programs should therefore combine arm-strength development, wrist-flexibility exercises, and smash-specific coordination drills.

Keywords: Arm muscle strength; badminton; smash performance; wrist flexibility; sport performance.

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INTRODUCTION

Badminton is a racket sport characterized by rapid changes in direction, short rally intervals, explosive strokes, perceptual anticipation, and precise coordination between the upper limb, trunk, and lower limb. Among its technical components, the smash is one of the most decisive attacking strokes because it enables players to accelerate the shuttlecock downward, reduce the opponent's response time, and create direct scoring opportunities. The quality of a badminton smash is therefore not merely a matter of hitting force, but a complex motor performance involving movement sequencing, racket control, visual anticipation, and the ability to coordinate joint actions under time pressure. Previous research has shown that badminton players' anticipatory responses are closely related to how they interpret opponent kinematics and visual cues, especially cues from the arm and racket during stroke preparation (Alder et al., 2014). Biomechanical evidence further indicates that the overhead forehand smash is a high-speed movement requiring the interaction of multiple muscle-tendon units and joint forces in the upper limb (Barnamehei et al., 2020). From a neuromuscular perspective, advanced players display more complex modular control patterns during smash execution than beginners, particularly through coordinated trunk and forearm muscle activation (Matsunaga & Kaneoka, 2018). These findings suggest that smash performance should be examined through physical and biomechanical indicators that are directly related to stroke execution. In this context, wrist flexibility and arm muscle strength become relevant variables because they are associated with movement range, racket acceleration, impact control, and shuttlecock direction.

Despite the recognized importance of the smash in badminton, club-level training often emphasizes repetitive technical practice without adequately identifying which physical components most strongly support the quality of the stroke. This creates a practical problem for coaches because players may repeatedly practice smash technique, but still show inconsistent accuracy, insufficient hitting power, or limited ability to direct the shuttlecock effectively. Match-structure research has shown that elite and youth international badminton players differ in match duration, game duration, shots per rally, rally duration, ball-in-play time, and rest intervals, indicating that technical performance must be supported by physical readiness that matches the demands of the game (Leong & Krasilshchikov, 2016). Notational analysis of outdoor badminton also demonstrates that technical and tactical characteristics can be systematically examined through stroke-use patterns, confirming that badminton performance requires measurable indicators rather than intuitive coaching judgment alone (Pérez-Turpin et al., 2020). More specifically, the outcome of the smash is sensitive to racket-shuttlecock impact location, which affects post-impact velocity and horizontal direction of the shuttlecock (McErlain-Naylor et al., 2020). Three-dimensional kinematic analysis has also shown that forehand and backhand smash techniques involve different movement contributions, including shoulder internal rotation, elbow extension, forearm supination, and wrist palmar flexion (Rusdiana, 2021). Therefore, the problem addressed in this study is important because wrist flexibility and arm muscle strength may help explain why some players are more capable of producing effective smash strokes than others. If these components are empirically linked to smash performance, they can be developed through targeted and measurable training.

Previous badminton studies have examined various aspects of performance, including lower-limb biomechanics, footwork, balance training, training intervention, stretching, sports technology, and injury-related factors. For example, arch support insoles have been studied in relation to lower-limb biomechanics and performance during right-forward lunging steps (Chen et al., 2022), while balance training has been found to improve dynamic balance and sport-specific footwork performance in school-level competitive badminton players (Malwanage et al., 2022). Other studies have examined training programs using speed-specific strength exercises to improve sensory-motor perception and forehand smash learning (Al-Haliq, 2020), and stretching protocols have been tested to determine their immediate effects on jump smash height and shuttlecock velocity (Jang et al., 2018). Alongside these training-based approaches, technological studies have introduced deep learning-based coaching systems for classifying badminton strokes, stances, and player performance (Ghosh et al., 2022), as well as robotic trajectory simulation for badminton movement modeling (Cui et al., 2020). However, these studies do not specifically examine the simultaneous contribution of wrist flexibility and arm muscle strength to smash performance among local club players. In addition, research on perceptual-cognitive expertise has emphasized anticipation and brain function in sport-related video tasks rather than field-based physical determinants of smash ability (Wimshurst et al., 2016), while injury-focused studies have addressed badminton safety concerns such as ocular trauma rather than physical predictors of offensive stroke performance (Yu et al., 2020). The novelty of the present study lies in its focused analysis of two accessible upper-limb physical indicators within a club-level badminton context, using a correlational-regression model to quantify their individual and combined contributions to smash performance.

Accordingly, this study aims to analyze the contribution of wrist flexibility and arm muscle strength to badminton smash performance among players of Avanti Badminton Club Makassar. Specifically, the study seeks to determine whether wrist flexibility contributes significantly to smash performance, whether arm muscle strength contributes significantly to smash performance, and whether both predictors jointly explain variation in players' smash ability. The scope of the study is limited to club players from PB Avanti Makassar, with wrist flexibility measured using a flexiometer, arm muscle strength measured through a 30-second push-up test, and smash performance assessed through a badminton smash skill test. The study uses a descriptive correlational design with regression analysis because the objective is not to test an intervention, but to examine the statistical contribution of naturally existing physical characteristics to a sport-specific skill outcome. This scope also defines the limitations of the study: demographic characteristics such as age, sex, training experience, handedness, and competition level were not reported in the source data; the study did not measure shuttlecock velocity, racket-head speed, or detailed kinematic variables; and the instruments were applied as field-based tests rather than laboratory-based biomechanical assessments. Nevertheless, the study is expected to contribute to badminton coaching practice by providing empirical evidence for integrating wrist mobility and arm-strength development into smash training. It also offers a methodological contribution by showing how accessible field measurements can be used to support evidence-based evaluation in club-level badminton training.

METHOD

Research Design

This study used a quantitative descriptive-correlational design with simple and multiple regression analyses. The design was selected because the study aimed to examine the contribution of two predictor variables, namely wrist flexibility and arm muscle strength, to one criterion variable, namely badminton smash ability. The available data were numerical test scores collected from badminton players; therefore, a quantitative approach was appropriate for summarizing central tendency, testing distributional assumptions, estimating bivariate associations, and determining the proportion of variance in smash ability explained by the predictors. Similar quantitative approaches are commonly used in badminton research when sport-specific performance, biomechanical variables, physical capacities, or movement outcomes are measured objectively and linked to player performance (Barnamehei et al., 2020; Chen et al., 2022; Jang et al., 2018; Malwanage et al., 2022).

The study was not experimental because no treatment, training program, or intervention was manipulated by the researcher. Instead, the research measured naturally existing levels of wrist flexibility, arm muscle strength, and smash ability, and then analyzed the statistical contribution among those variables. The research model consisted of two independent variables and one dependent variable: X1 = wrist flexibility, X2 = arm muscle strength, and Y = badminton smash ability. The operational structure of the design is summarized in Table 1. The source document did not report a randomized intervention procedure, control group, treatment group, or repeated measurement schedule; therefore, the design is reported as correlational-regression rather than experimental.

Table 1. Research design and operational variables

Variable Code	Variable Name	Role in the Model	Measurement Indicator
X1	Wrist flexibility	Predictor / independent variable	Flexibility score measured using a flexiometer
X2	Arm muscle strength	Predictor / independent variable	Number of push-ups completed within 30 seconds
Y	Badminton smash ability	Criterion / dependent variable	Total score obtained from the badminton smash test

B. Participants

The population in this study consisted of badminton players from PB Avanti Makassar. The source document reported 40 players as the population and 40 players as the sample. Thus, all available player data were included in the final analysis. The statistical output showed that each research variable had 40 valid observations and no missing value; therefore, the final dataset used for analysis was N = 40. The document described the sampling procedure as simple random sampling by lottery. However, because the number of participants analyzed was equal to the reported population size, the sample may also be interpreted as covering all available players in the study setting. No participant was excluded from the dataset reported in the source document.

The available source data did not report participants' age, sex, playing level, years of training experience, handedness, training frequency, or competitive category. Consequently, those demographic and athletic characteristics are not added to this Method section. The research context was limited to PB Avanti Makassar, and the measurements were conducted at the badminton facility used by the club. The inclusion criterion that can be derived from the source document was membership or participation as a PB Avanti Makassar badminton player during data collection. Formal exclusion criteria, health screening procedures, injury status, or consent documentation were not reported in the source document and should be completed in a future manuscript if required by the target journal.

Table 2. Participant information available from the source document

Component	Reported Information
Research site	PB Avanti Makassar badminton club
Population	40 badminton players
Sample analyzed	40 badminton players
Valid data	40 valid cases for wrist flexibility, arm muscle strength, and smash ability
Missing data	0 missing cases for all measured variables
Sampling technique reported in the source document	Simple random sampling by lottery
Demographic characteristics	Age, sex, and training experience were not reported in the source document

C. Instruments and Research Procedures

The study used three field-based measurement instruments corresponding to the three research variables. Wrist flexibility was measured using a flexiometer. During the test, the participant extended the arm forward with the back of the hand positioned upward and the palm facing downward. The flexiometer was placed on the back of the hand, and the participant flexed the wrist upward. The source document states that the movement was performed twice, and the score recorded was the scale value achieved during the test. Arm muscle strength was measured using a 30-second push-up test. Participants assumed a push-up position on a flat floor and performed as many correct push-ups as possible after the start command. The recorded score was the number of push-ups completed within 30 seconds.

Badminton smash ability was measured through a smash performance test. Participants stood in the designated area, and the tester fed shuttlecocks for the participants to smash. If the feed was not appropriate, the attempt was cancelled and not counted. A smash was considered valid when the shuttlecock passed over the net and below a string installed 30 cm above the net. The test provided 10 scoring opportunities, with two additional attempts used as trials. The final score was the total score obtained from the valid smash attempts. This form of sport-specific testing is consistent with the broader methodological orientation in badminton studies that assess performance through task-specific movement or stroke outcomes, such as jump smash performance, overhead forehand smash mechanics, lunging performance, and footwork tasks (Barnamehei et al., 2020; Chen et al., 2022; Jang et al., 2018; Malwanage et al., 2022).

The research procedure was conducted in several stages. First, the researcher prepared the testing site, equipment, data recording sheets, shuttlecocks, rackets, stopwatch, flexiometer, and badminton court arrangement. Second, participants were organized for field testing and completed the required measurements. Third, wrist flexibility, arm muscle strength, and smash ability were measured using the procedures described above. Fourth, all test results were tabulated into a dataset for statistical analysis using SPSS. The source document included documentation of warm-up, flexibility testing, arm muscle strength testing, and smash testing. However, instrument validity and reliability coefficients were not reported. Therefore, this Method section does not claim specific validity or reliability values for the flexiometer test, push-up test, or smash ability test beyond the procedures described in the source document.

Table 3. Instruments and measurement procedures

Variable	Instrument / Test	Indicator	Procedure Summary	Score Recorded
Wrist flexibility	Flexiometer	Range of wrist movement	Participant extended the arm forward; the flexiometer was placed on the back of the hand; the wrist was flexed upward.	Flexiometer scale value
Arm muscle strength	30-second push-up test	Upper-limb strength endurance during push-up movement	Participant performed push-ups on a flat floor for 30 seconds after the start command.	Number of push-ups completed in 30 seconds
Badminton smash ability	Badminton smash test	Accuracy and effectiveness of smash attempts	Tester fed shuttlecocks; participant performed smashes; valid attempts passed over the net and below the 30-cm string above the net.	Total score from 10 valid opportunities

D. Data Analysis

The collected data were analyzed quantitatively using SPSS. The analysis began with descriptive statistics to summarize the empirical characteristics of each variable, including valid N, missing data, mean, median, mode, standard deviation, variance, range, minimum, maximum, and sum. Frequency distribution tables were also used to describe the distribution pattern of scores for wrist flexibility, arm muscle strength, and badminton smash ability. These descriptive analyses were used to present the overall data structure before inferential testing.

Before conducting regression analysis, the normality assumption was tested using the One-Sample Kolmogorov-Smirnov test. The criterion used in the source analysis was a significance value greater than 0.05 to indicate a normal distribution. After normality was confirmed, Pearson correlation analysis was used to examine bivariate relationships between wrist flexibility, arm muscle strength, and badminton smash ability. Simple regression analysis was then conducted separately to determine the contribution of wrist flexibility to smash ability and the contribution of arm muscle strength to smash ability. Multiple regression analysis was used to determine the simultaneous contribution of both predictors to smash ability. The significance level used for hypothesis testing was 0.05. The source document did not report linearity, homoscedasticity, residual independence, or variance inflation factor diagnostics; therefore, those additional assumption tests are identified as information not available in the source document.

The regression outputs were interpreted using R, R Square, adjusted R Square, standard error of estimate, F statistic, degrees of freedom, and significance value. R Square was used as the basis for estimating the percentage of variance in badminton smash ability explained by each predictor and by the combined predictor model. In the multiple regression model, unstandardized coefficients were used to express the prediction equation, whereas standardized Beta coefficients were used to compare the relative contribution of wrist flexibility and arm muscle strength. Comparable badminton studies have used quantitative modeling, performance assessment, and sport-specific task measurement to evaluate relationships among physical, biomechanical, and skill-related variables (Alder et al., 2014; Barnamehei et al., 2020; Chen et al., 2022; Leong & Krasilshchikov, 2016; Malwanage et al., 2022).

Table 4. Data analysis plan

Analysis Stage	Statistical Technique	Purpose	Decision Criterion / Output
Descriptive analysis	Mean, median, mode, standard deviation, variance, range, minimum, maximum, sum, frequency distribution	Describe the empirical distribution of each research variable	Descriptive values and frequency patterns
Assumption test	One-Sample Kolmogorov-Smirnov test	Assess whether each variable followed a normal distribution	$p > 0.05$ indicates normal distribution
Bivariate relationship	Pearson correlation	Determine the direction and strength of relationships among variables	r value and p value
Individual contribution	Simple regression	Estimate the contribution of each predictor to	R, R Square, F, and p value

		badminton smash ability	
Simultaneous contribution	Multiple regression	Estimate the combined contribution of wrist flexibility and arm muscle strength	R, R Square, adjusted R Square, F, df, and p value
Relative predictor strength	Regression coefficient analysis	Compare predictors using unstandardized and standardized coefficients	B, standard error, Beta, t, and p value

RESULTS AND DISCUSSION
RESULT

This section presents the empirical findings on the contribution of wrist flexibility and arm muscle strength to badminton smash performance among players of PB Avanti Makassar. The dataset consisted of 40 players, and all observations were valid for the three research variables; no missing values were reported in the source data. The first predictor variable was wrist flexibility (X1), the second predictor variable was arm muscle strength (X2), and the criterion variable was badminton smash performance (Y). Demographic characteristics such as age and sex were not reported in the source document; therefore, the sample description in this Results section is limited to the number of valid cases and the measured research variables. The analysis was organized sequentially through descriptive statistics, frequency distribution, histogram-based visual evidence, normality testing, Pearson correlation, simple regression, multiple regression, regression coefficients, hypothesis decisions, and a final synthesis of the main statistical pattern.

Table 5. Descriptive statistics of research variables

Variable	N	Mean	Median	Mode	SD	Variance	Range	Min	Max	Sum
Wrist flexibility (X1)	40	86.8000	88.0000	80.00	9.44132	89.138	32.00	70.00	102.00	3472.00
Arm muscle strength (X2)	40	21.9250	22.0000	19.00a	3.37705	11.404	13.00	15.00	28.00	877.00
Smash performance (Y)	40	18.0000	18.0000	18.00	3.46410	12.000	12.00	12.00	24.00	720.00

The descriptive statistics are presented in Table 5. Wrist flexibility had the highest mean score because it was measured on a wider degree-based scale, with a mean of 86.8000, median of 88.0000, standard deviation of 9.44132, and range of 32.00. Arm muscle strength produced a mean of 21.9250, median of 22.0000, standard deviation of 3.37705, and range of 13.00. Smash performance had a mean of 18.0000, median of 18.0000, standard deviation of 3.46410, and range of 12.00. The largest dispersion appeared in wrist flexibility, as indicated by the highest standard deviation and variance. The output also indicated that arm muscle strength had multiple modes; the smallest modal value displayed in the source output was 19.00. Overall, the descriptive results show that the three variables had complete data across 40 valid cases, with different score ranges according to the measurement scale of each variable.

Table 6. Frequency distribution of each variable

Variable	Score	Frequency	Percent	Cumulative Percent
Wrist flexibility	70.00	3	7.5	7.5
Wrist flexibility	75.00	3	7.5	15.0
Wrist flexibility	76.00	1	2.5	17.5
Wrist flexibility	78.00	1	2.5	20.0
Wrist flexibility	79.00	2	5.0	25.0
Wrist flexibility	80.00	5	12.5	37.5
Wrist flexibility	85.00	2	5.0	42.5
Wrist flexibility	86.00	2	5.0	47.5
Wrist flexibility	87.00	1	2.5	50.0
Wrist flexibility	89.00	2	5.0	55.0
Wrist flexibility	90.00	4	10.0	65.0
Wrist flexibility	91.00	1	2.5	67.5
Wrist flexibility	94.00	2	5.0	72.5
Wrist flexibility	95.00	4	10.0	82.5
Wrist flexibility	97.00	1	2.5	85.0
Wrist flexibility	98.00	1	2.5	87.5
Wrist flexibility	99.00	1	2.5	90.0
Wrist flexibility	100.00	1	2.5	92.5
Wrist flexibility	101.00	1	2.5	95.0
Wrist flexibility	102.00	2	5.0	100.0
Arm muscle strength	15.00	1	2.5	2.5
Arm muscle strength	16.00	1	2.5	5.0
Arm muscle strength	17.00	2	5.0	10.0
Arm muscle strength	18.00	3	7.5	17.5
Arm muscle strength	19.00	4	10.0	27.5
Arm muscle strength	20.00	4	10.0	37.5
Arm muscle strength	21.00	4	10.0	47.5
Arm muscle strength	22.00	2	5.0	52.5
Arm muscle strength	23.00	4	10.0	62.5
Arm muscle strength	24.00	4	10.0	72.5
Arm muscle strength	25.00	4	10.0	82.5
Arm muscle strength	26.00	4	10.0	92.5
Arm muscle strength	27.00	2	5.0	97.5
Arm muscle strength	28.00	1	2.5	100.0
Smash performance	12.00	4	10.0	10.0
Smash performance	15.00	10	25.0	35.0
Smash performance	18.00	12	30.0	65.0
Smash performance	21.00	10	25.0	90.0
Smash performance	24.00	4	10.0	100.0

The frequency distribution is shown in Table 6, while the histogram is presented in Figure 1. For wrist flexibility, the most frequent score was 80.00, which appeared in 5 players or 12.5% of the sample. The next most frequent scores were 90.00 and 95.00, each appearing in 4 players or 10.0%. For arm muscle strength, the highest frequency was distributed across several scores: 19.00, 20.00, 21.00, 23.00, 24.00, 25.00, and 26.00 each appeared in 4 players or 10.0%. For smash performance, the most frequent score was 18.00, recorded by 12 players or 30.0% of the sample, followed by 15.00 and 21.00, each recorded by 10 players or 25.0%. This pattern indicates that smash performance scores were concentrated around the middle score category, whereas wrist flexibility and arm muscle strength showed broader distributions across the observed score intervals.

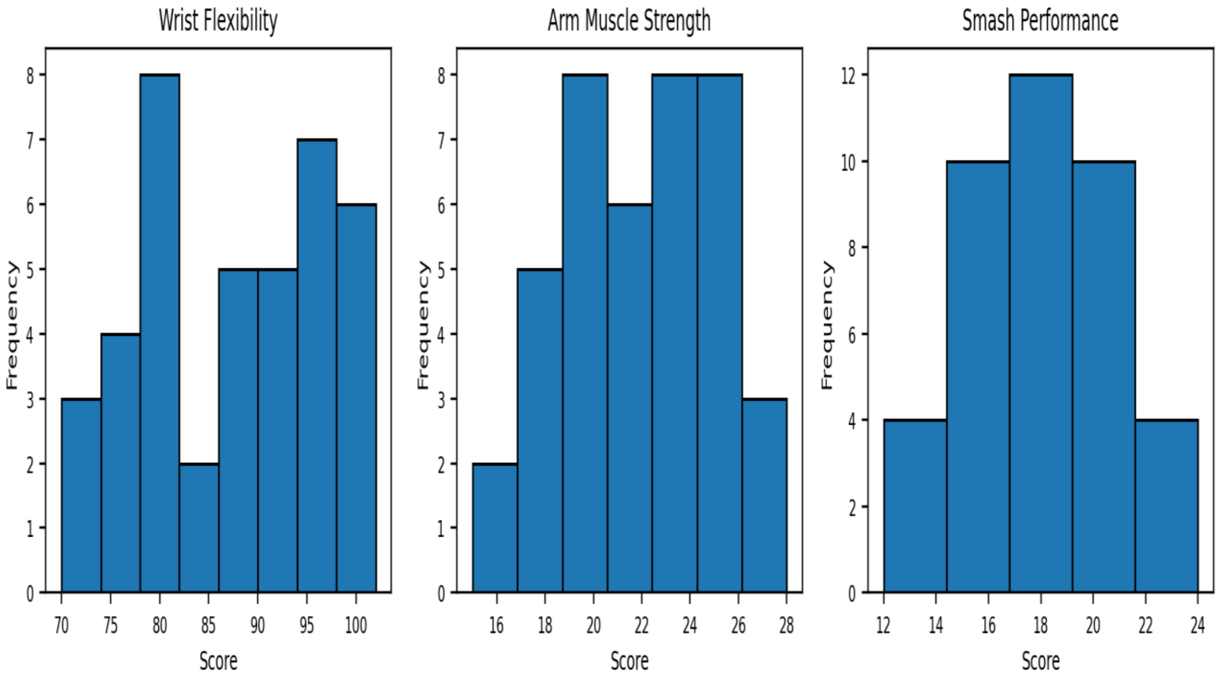

Figure 1. Histograms of wrist flexibility, arm muscle strength, and smash performance scores

Table 7. Normality test results

Variable	N	Kolmogorov-Smirnov Z	Asymp. Sig. (2-tailed)	Decision
Wrist flexibility (X1)	40	0.881	0.419	Normally distributed
Arm muscle strength (X2)	40	0.667	0.764	Normally distributed
Smash performance (Y)	40	0.991	0.279	Normally distributed

The normality test results are presented in Table 7. The one-sample Kolmogorov-Smirnov test showed that all variables had significance values greater than 0.05. Wrist flexibility obtained $Z = 0.881$ with $p = 0.419$, arm muscle strength obtained $Z = 0.667$ with $p = 0.764$, and smash performance obtained $Z = 0.991$ with $p = 0.279$. These results indicate that the distribution of the three variables met the normality assumption. Consequently, the inferential analyses were conducted using parametric procedures, namely Pearson correlation, simple regression, and multiple regression. Linearity, homogeneity, and multicollinearity tests were not reported in the source output; therefore, those assumption test results are not presented in this section.

Table 8. Pearson correlation matrix

Variable	Wrist flexibility (X1)	Arm muscle strength (X2)	Smash performance (Y)
Wrist flexibility (X1)	1	r = 0.760; p = 0.000	r = 0.802; p = 0.000
Arm muscle strength (X2)	r = 0.760; p = 0.000	1	r = 0.815; p = 0.000
Smash performance (Y)	r = 0.802; p = 0.000	r = 0.815; p = 0.000	1

The Pearson correlation matrix is presented in Table 8. Wrist flexibility was positively and significantly correlated with smash performance, r = 0.802, p = 0.000. Arm muscle strength was also positively and significantly correlated with smash performance, r = 0.815, p = 0.000. In addition, wrist flexibility and arm muscle strength were positively and significantly correlated with each other, r = 0.760, p = 0.000. The direction of all reported correlations was positive, indicating that higher predictor scores were associated with higher smash performance scores. Among the two bivariate relationships with the criterion variable, arm muscle strength showed a slightly higher correlation coefficient with smash performance than wrist flexibility.

Table 9. Simple regression results

Predictor	R	R Square	Adjusted R Square	Std. Error of Estimate	F	df1	df2	Sig.
Wrist flexibility (X1)	0.802	0.643	0.634	2.09612	68.515	1	38	0.000
Arm muscle strength (X2)	0.815	0.665	0.656	2.03177	75.370	1	38	0.000

The simple regression results are presented in Table 9. The simple regression model testing the contribution of wrist flexibility to smash performance produced R = 0.802, R Square = 0.643, Adjusted R Square = 0.634, standard error of estimate = 2.09612, F (1, 38) = 68.515, and p = 0.000. The R Square value of 0.643 indicates that wrist flexibility explained 64.3% of the variance in smash performance. The simple regression model testing the contribution of arm muscle strength to smash performance produced R = 0.815, R Square = 0.665, Adjusted R Square = 0.656, standard error of estimate = 2.03177, F(1, 38) = 75.370, and p = 0.000. The R Square value of 0.665 indicates that arm muscle strength explained 66.5% of the variance in smash performance. Both simple regression models were statistically significant because their significance values were below 0.05.

Table 10. Multiple regression model summary

Predictors	R	R Square	Adjusted R Square	Std. Error of Estimate	F	df1	df2	Sig.
Wrist flexibility (X1) and arm muscle strength (X2)	0.862	0.743	0.730	1.80153	53.600	2	37	0.000

Table 10a. ANOVA of the multiple regression model

Source	Sum of Squares	df	Mean Square	F	Sig.
Regression	347.917	2	173.958	53.600	0.000
Residual	120.083	37	3.245		
Total	468.000	39			

The multiple regression model is shown in Table 10, and the ANOVA summary is presented in Table 10a. The simultaneous regression model involving wrist flexibility and arm muscle strength produced R = 0.862, R Square = 0.743, Adjusted R Square = 0.730, standard error of estimate = 1.80153, $F(2, 37) = 53.600$, and $p = 0.000$. The R Square value of 0.743 indicates that wrist flexibility and arm muscle strength jointly explained 74.3% of the variance in smash performance. The remaining 25.7% of the variance was not explained by the two predictors included in the model. Based on the significance value below 0.05, the simultaneous contribution of both predictors to smash performance was statistically significant.

Table 11. Regression coefficients

Predictor	B	Std. Error	Beta	t	Sig.
Constant	-6.703	2.677	-	-2.504	0.017
Wrist flexibility (X1)	0.158	0.047	0.432	3.367	0.002
Arm muscle strength (X2)	0.500	0.132	0.487	3.801	0.001

The regression coefficients are presented in Table 11. The unstandardized regression equation generated by the multiple regression model was $Y = -6.703 + 0.158X1 + 0.500X2$. In this model, wrist flexibility had $B = 0.158$, $SE = 0.047$, $Beta = 0.432$, $t = 3.367$, and $p = 0.002$, indicating a significant partial contribution to smash performance. Arm muscle strength had $B = 0.500$, $SE = 0.132$, $Beta = 0.487$, $t = 3.801$, and $p = 0.001$, also indicating a significant partial contribution. Based on the standardized Beta values, arm muscle strength showed a stronger relative contribution than wrist flexibility within the simultaneous regression model.

Table 12. Hypothesis decision summary

Hypothesis	Statistical Evidence	Decision
H1: Wrist flexibility contributes significantly to smash performance.	R = 0.802; R Square = 0.643; F = 68.515; p = 0.000	Supported
H2: Arm muscle strength contributes significantly to smash performance.	R = 0.815; R Square = 0.665; F = 75.370; p = 0.000	Supported
H3: Wrist flexibility and arm muscle strength jointly contribute significantly to smash performance.	R = 0.862; R Square = 0.743; F = 53.600; p = 0.000	Supported

Based on the regression results, the first, second, and third hypotheses were supported because all significance values were below 0.05. The first hypothesis was supported by the significant simple regression result for wrist flexibility, the second hypothesis was supported by the significant simple regression result for arm muscle strength, and the third hypothesis was supported by the significant multiple regression result involving both predictors simultaneously. Overall, the data showed a consistent positive pattern: wrist flexibility and arm muscle strength were both positively associated with smash performance, both predictors had significant individual contributions, and their simultaneous contribution explained 74.3% of the variance in smash performance. Within the multiple regression model, arm muscle strength had the higher standardized Beta value, indicating the stronger relative contribution between the two predictors.

DISCUSSION

The first major finding, that wrist flexibility contributed significantly to badminton smash performance, indicates that the quality of a smash depends not only on the amount of force generated but also on the player's capacity to organize the racket face, wrist action, and follow-through within an effective range of motion.

In movement-control terms, wrist flexibility provides the mechanical freedom required to adjust impact angle, maintain racket orientation, and direct the shuttlecock toward the intended target. This interpretation is compatible with evidence that badminton smash velocity increases with skill level, suggesting that expert performance emerges from coordinated motion rather than isolated strength alone (Phomsoupha & Laffaye, 2014). It is also consistent with shoulder-profile research showing that repeated badminton match exposure can alter range of motion and strength characteristics in youth players (Fernandez-Fernandez et al., 2019). Field-based skill studies similarly emphasize that technical outcomes must be interpreted through task-specific execution quality, not merely through general fitness scores (Freeston et al., 2014; Pedersen et al., 2014). A different emphasis appears in Kimyon and Ince (2020), where dominant-hand grip strength was more directly linked with goalball shot performance. The difference is understandable because goalball throwing depends strongly on hand release and grip force, whereas badminton smashing requires racket-mediated impact, wrist mobility, and timing. The limitation is that this study measured static wrist flexibility, not dynamic wrist behavior during impact. Practically, flexibility training should therefore be integrated with racket-control drills, not treated as an isolated stretching component.

The second major finding, that arm muscle strength made a significant and slightly stronger relative contribution than wrist flexibility, confirms that upper-limb force capacity is central to smash execution. A badminton smash is a rapid overhead striking action in which force must be generated through the shoulder, upper arm, elbow, forearm, and wrist before being transferred to the racket and shuttlecock. This finding is strongly supported by badminton-specific evidence showing that triceps brachii fatigue can impair elbow movement, shuttle velocity, and overhead smash accuracy (Alkhawaldeh, 2022). Hussein et al. (2019) also reported that altered exercise techniques using heavier rackets helped improve smash skill, indicating that upper-limb loading can influence smash development. Comparable evidence from other open-skill sports supports this interpretation: strength and power components predicted tackle outcomes in rugby league (Redman et al., 2022), physical qualities were associated with key performance indicators in international rugby union (Cunningham et al., 2018), and strength-power training improved volleyball skill performance (Kitamura et al., 2020). However, Crang et al. (2022) showed that preseason training load was not uniformly associated with technical match performance, which suggests that greater physical workload does not automatically translate into better skill execution. The difference likely reflects the distinction between general training exposure and task-specific strength capacity. This study used a 30-second push-up test, which is closer to upper-limb strength endurance than maximal force or racket-head power. Future research should therefore compare push-up scores with grip strength, medicine-ball throw, racket velocity, and shuttlecock speed.

The third major finding, that wrist flexibility and arm muscle strength jointly explained a large proportion of smash performance, supports a multifactorial interpretation of badminton skill. Strength supplies the capacity to accelerate the racket, whereas flexibility supports range, sequencing, and fine control in directing the force produced. The combined model therefore suggests that smash performance is not the product of one isolated physical quality but of coordinated physical-skill interaction. This interpretation is consistent with evidence from team handball showing that technical match characteristics and body-related factors interact in shaping elite performance (Michalsik et al., 2015). It also fits findings that high-intensity running can affect lower- and upper-body explosive strength differently while not producing uniform changes in throwing velocity (Seipp et al., 2022), and that physiological adaptations to sprint interval training in soccer do not automatically explain all technical-performance changes (Thom et al., 2020). In badminton, the need for sport-specific testing has also been emphasized through the AIR-BT, which showed that badminton performance assessment benefits from tests designed around badminton movement demands rather than generic protocols (Abián-Vicén et al., 2021). The difference between these studies and the present study lies in the outcome: previous work often focused on endurance, match activity, or physiological response, whereas this study focused on smash skill. A methodological caution is that wrist flexibility and arm muscle strength were highly correlated, and the source analysis did not report tolerance or variance inflation factor values. Thus, the simultaneous model should be interpreted as combined predictive value, not proof of independent causal pathways.

The relative dominance of arm muscle strength within the multiple regression model should not be interpreted as evidence that flexibility is secondary or dispensable. Instead, it indicates that, within this specific dataset and measurement model, the push-up-based strength score had a slightly larger standardized contribution to smash performance than wrist flexibility. This is plausible because smash scoring depends on the player's ability to produce a forceful and stable impact. However, badminton-specific studies show that the mechanics of performance are not limited to strength alone. Phomsoupha and Laffaye (2014) linked shuttlecock velocity to skill level, suggesting that skilled players are more effective in converting body and racket motion into shuttle speed. Fernandez-Fernandez et al. (2019) showed that competitive match demands can change shoulder range of motion and strength profiles, indicating that the upper limb should be considered as a functional system. In contrast, lunge-oriented studies focus more on lower-limb load, stability, and injury risk (Lam et al., 2017; Valldecabres et al., 2018). Those studies differ because they analyze movement into the shuttle rather than the striking action itself. The present dependent variable was smash performance, making upper-limb strength and wrist flexibility more directly relevant. Nevertheless, the study did not include lower-limb power, trunk rotation, balance, or approach-step quality; these omitted variables may account for part of the unexplained variance. The implication is that coaches should build arm strength while also training mobility, timing, and whole-body coordination.

Methodologically, the findings demonstrate the usefulness of accessible field-based assessment for club-level badminton, but they also reveal the need for stronger measurement standardization. The use of a flexiometer, a 30-second push-up test, and a smash performance test offers a practical model for coaches who do not have motion-capture systems, inertial sensors, or radar devices. This practical orientation is supported by studies showing that sport-specific field tests can provide valid performance information when the test reflects the demands of the sport. The Badcamp agility test, for example, was shown to be more specific for badminton players than a more generic shuttle-run agility test (de França Bahia Loureiro et al., 2017), while the AIR-BT was developed as a reliable and accessible badminton-specific endurance test (Abián-Vicén et al., 2021). In other sports, simple field tasks have also been used to differentiate technical ability across competitive levels (Pedersen et al., 2014), and reliable performance testing has been emphasized for interpreting speed-accuracy outcomes (Freeston et al., 2014). The present study differs because the available source did not report local validity and reliability coefficients for the three tests, nor detailed control of feeding consistency, rest intervals, testing order, fatigue state, dominant hand, or playing experience. These limitations may influence the magnitude of the observed associations. The methodological implication is that future club-based research should retain accessible tests but improve procedural control, inter-rater reliability, and repeated-measure verification.

Overall, the findings contribute to a task-specific model of badminton smash performance in which force production, joint range, and movement control interact to support technical effectiveness. The study extends previous badminton research by showing that simple physical indicators can predict smash ability among club players, a context that differs from laboratory-based biomechanics, elite-player monitoring, and intervention studies. The findings are compatible with evidence that upper-limb function is sensitive to fatigue and training load in badminton (Alkhawaldeh, 2022; Fernandez-Fernandez et al., 2019), while also aligning with broader sport-performance literature showing that strength and power can predict selected technical outcomes when the measured physical quality is directly related to the task (Cunningham et al., 2018; Redman et al., 2022). At the same time, the results should not be overgeneralized. Studies in rugby, volleyball, handball, and soccer indicate that transfer from physical capacity to technical performance depends on sport context, task constraints, and measurement design (Berriel et al., 2021; Crang et al., 2022; Kitamura et al., 2020; Michalsik et al., 2015; Thom et al., 2020). The present study was cross-sectional, involved one club, did not report demographic details, and did not measure shuttlecock velocity, racket-head speed, trunk rotation, balance, or visual anticipation. Therefore, the practical recommendation is to integrate arm-strength development, dynamic wrist flexibility, racket-face control, and smash-specific repetition, while the research recommendation is to test this integrated model experimentally with larger samples and biomechanical measurement.

CONCLUSION

This study concludes that wrist flexibility and arm muscle strength are significant contributors to badminton smash performance among players of Avanti Badminton Club Makassar. The findings directly support the proposed hypotheses, indicating that both physical components individually and jointly play an important role in explaining players' ability to perform an effective smash. In synthesis, smash performance should not be viewed merely as a technical skill produced through repeated stroke practice, but as a movement outcome supported by the interaction between adequate joint mobility, upper-limb strength, movement control, and the capacity to transfer force efficiently through the racket.

Theoretically, this study strengthens the understanding that badminton smash performance is influenced by specific physical attributes related to the upper limb. Wrist flexibility supports the movement range and racket control required to direct the shuttlecock, while arm muscle strength contributes to the force production needed to generate a fast and sharp attacking stroke. Practically, the results suggest that coaches should integrate wrist mobility exercises, dynamic flexibility training, arm-strength development, and smash-specific coordination drills into regular training programs. Methodologically, the study also shows that simple field-based tests can be used as preliminary tools for monitoring physical determinants of smash ability at the club level.

This study is limited by the absence of detailed participant characteristics, instrument reliability data, biomechanical motion analysis, and direct measurement of shuttlecock velocity. Future research should involve larger and more diverse samples, validated sport-specific instruments, experimental training designs, and kinematic or sensor-based assessment to examine whether targeted improvements in wrist flexibility and arm muscle strength produce measurable gains in smash speed, accuracy, and competitive performance.

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