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Physical and coordinative predictors of 50-m freestyle swimming performance among male students

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ABSTRACT

This study aimed to examine the direct and indirect effects of arm muscle strength, leg muscle explosive power, and hand–eye coordination on 50-m freestyle swimming speed among students of the Pandu Mahawira Swimming Guidance Program, Padang. This quantitative study employed a path analysis design involving 30 male students selected through purposive sampling. Data were collected using a hand grip dynamometer, Vertical Jump Test, Hand Wall Toss Test, and a 50-m freestyle swimming test. The data were analyzed using descriptive statistics and path analysis. Arm muscle strength contributed 24.20%, leg muscle explosive power 7.30%, and hand–eye coordination 6.40% to swimming speed. Through mediation by hand–eye coordination, the total contributions of arm muscle strength and leg muscle explosive power increased to 26.03% and 17.28%, respectively. Collectively, the predictors explained 77.8% of the variance in swimming performance. Arm muscle strength, leg muscle explosive power, and hand–eye coordination are significant determinants of 50-m freestyle swimming speed and should be developed simultaneously to optimize sprint swimming performance.

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Introduction

Swimming is one of the most popular competitive and recreational sports worldwide and has long been recognized as an effective activity for improving physical fitness, motor development, and athletic performance (Chen et al., 2025; Hartoto et al., 2025). Among competitive events, the 50-m freestyle is the shortest sprint race, requiring swimmers to generate maximal velocity within a very limited duration while minimizing hydrodynamic resistance. Success in this event is determined not only by technical proficiency but also by the interaction of biomechanical, physiological, and coordinative capacities that enable efficient force production throughout the race. Previous biomechanical investigations have demonstrated that stroke efficiency, propulsion, start performance, and body alignment collectively determine sprint swimming outcomes (Hartono et al., 2024; Kauki et al., 2024). Despite these advances, evidence explaining how physical and coordinative factors interact to influence sprint swimming performance, particularly among developing adolescent swimmers, remains limited.

Upper-body muscular strength has consistently been identified as one of the principal determinants of freestyle swimming performance because the arms generate most of the propulsive force during the pull and push phases of the stroke cycle. Greater arm strength enables swimmers to produce higher propulsive impulses, maintain longer stroke length, and reduce stroke time, thereby improving swimming velocity over short distances. Resistance-based dry-land and aquatic training programs have also been shown to enhance upper-body force production and sprint swimming performance (Gözel & Aka, 2023; Kurniawan et al., 2025). Nevertheless, previous studies have primarily examined the independent contribution of arm strength using correlational or intervention-based approaches, with limited attention to how muscular strength interacts with coordinative abilities to optimize performance (Đurović et al., 2025; Kuberski, Musial, Krużołek, et al., 2026). Consequently, the mechanism through which muscular strength is translated into effective swimming performance has not been comprehensively explained.

Lower-limb explosive power also plays a decisive role in 50-m freestyle performance, particularly during the start, underwater glide, and kicking phases, where swimmers must rapidly convert muscular force into forward propulsion. Athletes with superior explosive power generally produce greater take-off forces, achieve higher underwater velocities, and maintain more effective body positioning throughout the sprint race (AlFadly & Mohsen, 2023; Kuberski, Musial, Choroszucho, et al., 2026). However, explosive force alone does not guarantee superior performance because efficient propulsion depends on accurate movement timing, neuromuscular control, and effective coordination between the upper and lower extremities. Although previous studies have confirmed the importance of lower-limb power, most have evaluated this variable independently without considering its interaction with coordinative functions within a comprehensive causal framework. This limitation indicates that the biomechanical pathways linking physical capacity to sprint swimming performance remain insufficiently understood, particularly among student swimmers participating in community-based training programs.

Besides physical capacities, coordinative ability represents another essential determinant of sprint swimming performance because effective propulsion depends on precise synchronization between sensory input and motor execution. Hand–eye coordination enables swimmers to integrate visual information with neuromuscular responses, facilitating accurate stroke timing, rhythmic breathing, body alignment, and efficient movement transitions throughout the swimming cycle. From the perspective of motor control theory, coordinated movement improves the efficiency with which muscular force is translated into propulsion, thereby reducing unnecessary energy expenditure and enhancing swimming economy. Although previous studies have demonstrated that coordinative ability contributes to motor control and technical execution in aquatic sports, empirical evidence explaining its role as a mechanism linking physical capacity to swimming performance remains scarce (Kamal et al., 2026; Zaitsev, 2025). Therefore, the potential mediating function of hand–eye coordination warrants further investigation.

Existing studies have provided valuable evidence regarding the influence of muscular strength, explosive power, and coordinative ability on swimming performance; however, several important limitations remain. Most previous investigations have examined these variables independently using correlational or experimental approaches, with relatively little attention given to their simultaneous interactions within a structural causal model (Gorgees, 2022; Kadhim, 2025). Moreover, the majority of published studies have focused on elite or highly trained swimmers, whereas evidence involving adolescent students participating in community-based swimming programs is still limited. Consequently, it remains unclear whether hand–eye coordination functions as an intermediary mechanism through which arm muscle strength and leg muscle explosive power contribute to sprint swimming performance in developing swimmers.

Therefore, this study aimed to examine the direct and indirect effects of arm muscle strength, leg muscle explosive power, and hand–eye coordination on 50-m freestyle swimming performance among male students enrolled in the Pandu Mahawira Swimming Guidance Program, Padang. The novelty of this study lies in the development of an integrated path analysis model that simultaneously evaluates the relationships among physical and coordinative variables while positioning hand–eye coordination as an intervening variable linking muscular strength and explosive power to swimming performance (Pluto-Prądzyńska & Wąsik, 2026; Sriundy Mahardika, 2023). By extending previous studies that largely examined these determinants separately, this research provides a more comprehensive explanation of the mechanisms underlying sprint swimming performance. The findings are expected to enrich the theoretical understanding of swimming biomechanics and motor performance while providing evidence-based guidance for coaches in designing integrated training programs to improve sprint swimming achievement among adolescent swimmers.

Method

This study employed a quantitative explanatory design using path analysis to examine the direct and indirect effects of arm muscle strength, leg muscle explosive power, and hand–eye coordination on 50-m freestyle swimming performance. The study was conducted from April to May 2026 at the Pandu Mahawira Swimming

Guidance Program, Padang. The population comprised 40 student swimmers, and 30 male students were selected through purposive sampling based on their active participation in training and relatively low freestyle performance. Arm muscle strength (X_1) and leg muscle explosive power (X_2) were specified as exogenous variables, hand–eye coordination (X_3) as the intervening variable, and swimming performance (Y) as the endogenous variable.

Data were collected using standardized and validated instruments. Arm muscle strength was measured with a hand grip dynamometer (validity = 0.880; reliability = 0.938), leg muscle explosive power using the Vertical Jump Test (validity = 0.860; reliability = 0.920), and hand–eye coordination using the Hand Wall Toss Test (validity = 0.922; reliability = 0.835). Swimming performance was assessed through a standardized 50-m freestyle swimming test, with the best performance recorded for analysis. All measurements were conducted by experienced swimming coaches following standardized testing procedures.

Data were analyzed using IBM SPSS Statistics. Descriptive statistics were calculated to summarize participant characteristics and study variables. Before hypothesis testing, the assumptions of normality, homogeneity, linearity, and multicollinearity were examined to ensure the suitability of the data for path analysis. Path analysis was then performed to estimate the direct, indirect, and total effects among variables, with statistical significance established at $p < 0.05$.

Results and Discussions

Descriptive Statistics

The descriptive statistics of the study variables are presented in Table 1. The participants demonstrated an average arm muscle strength of 47.80 ± 8.10 kg, leg muscle explosive power of 90.80 ± 12.50 kg·m/s, and hand–eye coordination score of 16.00 ± 3.90 points. The mean time for completing the 50-m freestyle swimming test was 42.83 ± 7.89 s. These findings indicate moderate physical performance among the participants, with considerable variability observed across all variables.

Table 1. Descriptive Statistics of the Study Variables (n = 30)

Variable	Unit	Mean	SD	Minimum	Maximum
Arm muscle strength (X_1)	kg	47.80	8.10	29.80	61.40
Leg muscle explosive power (X_2)	kg·m/s	90.80	12.50	73.40	117.00
Hand–eye coordination (X_3)	score	16.00	3.90	9.00	23.00
50-m freestyle swimming speed (Y)	s	42.83	7.89	31.07	58.95

Distribution of Study Variables

Table 2 summarizes the distribution of participants according to the dominant performance category of each variable. Most participants demonstrated moderate arm muscle strength (43.3%), low leg muscle explosive power (66.7%), and moderate-to-good hand–eye coordination (43.3%). Furthermore, swimming performance was predominantly classified as good and moderate (36.7% each), indicating heterogeneous swimming abilities among participants.

Table 2. Distribution of Study Variables

Variable	Dominant Category	Frequency	Percentage (%)
Arm muscle strength (X_1)	Moderate	13	43.3
Leg muscle explosive power (X_2)	Low	20	66.7
Hand–eye coordination (X_3)	Good	13	43.3
Hand–eye coordination (X_3)	Moderate	13	43.3
50-m freestyle swimming speed (Y)	Good	11	36.7
50-m freestyle swimming speed (Y)	Moderate	11	36.7

Assumption Testing

Prior to hypothesis testing, normality, homogeneity, and linearity assumptions were examined. The Kolmogorov–Smirnov test revealed that all variables were normally distributed ($p > 0.05$). Levene's test showed homogeneous variances across all relationships ($p > 0.05$). Moreover, all variable relationships satisfied the linearity assumption because the significance values exceeded 0.05. These findings indicate that the dataset fulfilled the assumptions required for path analysis.

Table 3. Assumption Testing

Test	Variable/Relationship	Statistic	p-value	Decision
Normality	Arm muscle strength	KS	0.200	Normal
Normality	Leg muscle explosive power	KS	0.108	Normal
Normality	Hand–eye coordination	KS	0.200	Normal
Normality	Swimming speed	KS	0.200	Normal
Homogeneity	Y and X_1	F = 2.429	0.088	Homogeneous
Homogeneity	Y and X_2	F = 2.850	0.096	Homogeneous
Homogeneity	Y and X_3	F = 1.001	0.460	Homogeneous
Linearity	Y and X_1		0.748	Linear
Linearity	Y and X_2		0.978	Linear
Linearity	Y and X_3		0.436	Linear
Linearity	X_3 and X_1		0.386	Linear
Linearity	X_3 and X_2		0.578	Linear
Linearity	X_2 and X_1		0.690	Linear

Structural Model and Path Coefficients

The path analysis consisted of three structural models. Arm muscle strength significantly predicted leg muscle explosive power ($\beta = 0.722$, $p < 0.001$). Both arm muscle strength and leg muscle explosive power significantly contributed to hand–eye coordination. Furthermore, arm muscle strength, leg muscle explosive power, and hand–eye coordination exerted significant direct effects on 50-m freestyle swimming speed. The final model explained 77.8% of the variance in swimming performance, indicating substantial explanatory power.

Table 4. Structural Model and Path Coefficients

Path	β	R^2	p-value	Decision
X_1 to X_2	0.722	0.521	<0.001	Significant
X_1 to X_3	0.072	0.005	0.040	Significant
X_2 to X_3	0.576	0.332	0.010	Significant
X_1 to Y	0.492	0.242	0.010	Significant
X_2 to Y	0.270	0.073	0.040	Significant
X_3 to Y	0.253	0.064	0.040	Significant
Final Model (X_1, X_2, X_3 to Y)		0.778	<0.001	Significant

The decomposition of effects demonstrated that arm muscle strength exerted the strongest total influence on swimming speed. Although leg muscle explosive power showed a relatively modest direct effect, its contribution substantially increased through mediation by hand–eye coordination. These findings suggest that coordinative abilities partially mediate the relationship between physical capacities and sprint swimming performance.

Table 5. Direct, Indirect, and Total Effects

Pathway	Direct Effect	Indirect Effect	Total Effect	Contribution (%)
X_1 to Y	0.492	0.018	0.510	26.03
X_2 to Y	0.270	0.146	0.416	17.28
X_3 to Y	0.253		0.253	6.40

All proposed hypotheses were supported. Arm muscle strength, leg muscle explosive power, and hand–eye coordination each significantly affected 50-m freestyle swimming speed. Moreover, hand–eye coordination significantly mediated the effects of arm muscle strength and leg muscle explosive power on swimming performance. Collectively, the predictors explained approximately 78% of the variability in 50-m freestyle swimming speed among male students participating in the Pandu Mahawira Padang Swimming Guidance Program.

Table 6 summarizes the results of hypothesis testing in the proposed path model. All six hypotheses were supported at the 5% significance level. Arm muscle strength exhibited a significant direct effect on 50-m freestyle swimming speed ($\beta = 0.492$, $p = 0.010$), contributing 24.20% of the explained variance. Leg muscle explosive power also demonstrated a significant direct effect on swimming performance ($\beta = 0.270$, $p = 0.040$), accounting for 7.30% of the variance. Likewise, hand–eye coordination significantly influenced freestyle swimming speed ($\beta = 0.253$, $p = 0.040$), contributing 6.40% of the variance. Furthermore, hand–eye coordination significantly mediated the effects of arm muscle strength and leg muscle explosive power on swimming performance, increasing their total contributions to 26.03% and 17.28%, respectively. Collectively, arm muscle strength, leg muscle explosive power, and hand–eye coordination explained 77.8% of the variance in 50-m freestyle swimming speed ($R^2 = 0.778$, $p < 0.001$), indicating a substantial explanatory capacity of the proposed model.

Table 6. Hypothesis Testing

Hypothesis	Relationship	Coefficient	p-value	Result
H1	Arm muscle strength to Swimming speed	0.492	0.010	Supported
H2	Leg muscle explosive power to Swimming speed	0.270	0.040	Supported
H3	Hand–eye coordination to Swimming speed	0.253	0.040	Supported
H4	Arm muscle strength to Hand–eye coordination to Swimming speed	0.018	<0.05	Supported
H5	Leg muscle explosive power to Hand–eye coordination to Swimming speed	0.146	<0.05	Supported
H6	X_1, X_2, and X_3 to Swimming speed	$R^2 = 0.778$	<0.001	Supported

To provide a comprehensive representation of the relationships among the study variables, the significant direct and indirect effects identified through path analysis are illustrated in Figure 1. The final path model depicts the standardized path coefficients among arm muscle strength, leg muscle explosive power, hand–eye coordination, and 50-m freestyle swimming speed. The model highlights arm muscle strength as the strongest direct predictor of swimming performance, while hand–eye coordination functions as an important mediating variable that strengthens the effects of physical capacities on freestyle swimming speed. Overall, the final model demonstrates strong explanatory power, accounting for 77.8% of the variance in 50-m freestyle swimming performance among male students participating in the Pandu Mahawira Padang Swimming Guidance Program.

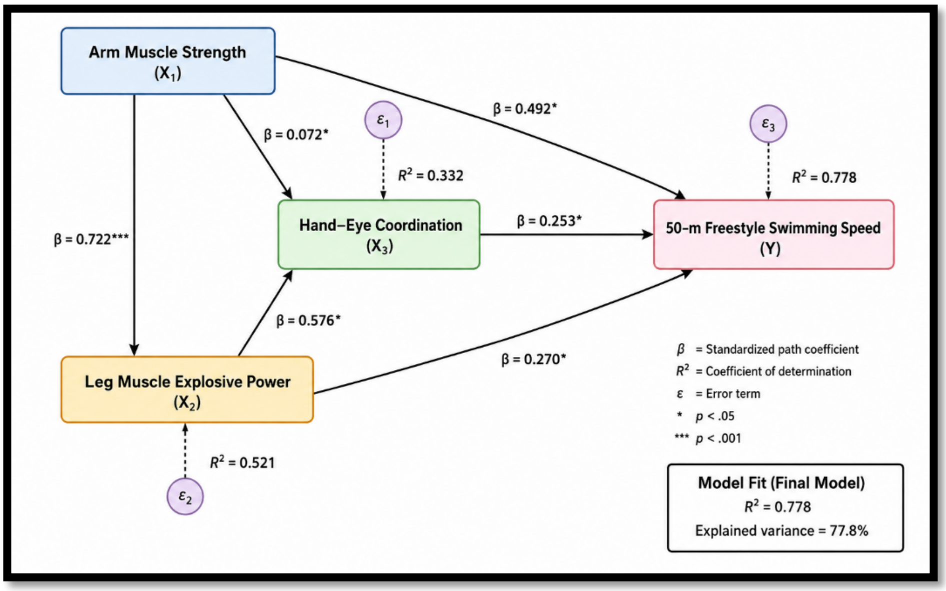

Figure 1. Final Path Model of the Effects of Arm Muscle Strength, Leg Muscle Explosive Power, and Hand–Eye Coordination on 50-m Freestyle Swimming Speed.

Arm muscle strength was the strongest predictor of 50-m freestyle swimming performance, contributing 24.20% of the explained variance ($\beta = 0.492$, $p = 0.010$). This finding confirms that upper-body strength is the primary source of propulsion during the pull and push phases, enabling swimmers to generate greater force, maintain stroke length, and increase swimming velocity. The relatively large contribution may also reflect the characteristics of the participants, who were developing swimmers with relatively low performance levels, making strength improvements more influential than in elite athletes. These findings are consistent with previous studies highlighting the importance of upper-body strength for stroke power and sprint swimming performance (Đurović et al., 2025; Kuberski, Musial, Krużołek, et al., 2026).

Leg muscle explosive power also had a significant direct effect on swimming performance (β = 0.270, p = 0.040), although its contribution (7.30%) was smaller than that of arm muscle strength. This is expected because explosive power mainly affects the start and underwater phases, whereas propulsion during most of the race relies on upper-body movements. The relatively low explosive power observed in 66.7% of participants may explain this modest contribution. These findings agree with previous studies showing that lower-limb explosive power improves start performance and underwater velocity but is strongly influenced by technical execution and training level (Mahmood & Ibrahim, 2026; Matitaputty, 2023, 2024; Salman, 2024). Likewise, hand–eye coordination significantly contributed to swimming performance (β = 0.253, p = 0.040; 6.40%) by improving stroke timing, breathing rhythm, body alignment, and movement efficiency. Although its direct contribution was relatively small, coordination plays an essential role in converting muscular capacity into effective propulsion, supporting previous findings on the importance of neuromuscular control in sprint swimming (Dalamitros et al., 2018; Fattah & Tarawneh, 2020; Powell et al., 2026; Valentino Latuheru et al., 2026).

An important finding of this study is that hand–eye coordination partially mediated the effects of arm muscle strength and leg muscle explosive power on swimming performance. Through coordination, the total contribution of arm muscle strength increased from 24.20% to 26.03%, while the contribution of leg muscle explosive power increased from 7.30% to 17.28%. These results indicate that physical capacity can only be translated into optimal swimming performance when supported by effective neuromuscular coordination, particularly during the start, kicking, and stroke phases. This finding extends previous studies by demonstrating the interconnected roles of physical and coordinative capacities within a single structural model rather than examining them independently (Amara et al., 2026; Garcia-Hermoso et al., 2013; Gonjo et al., 2025; Mazzilli, 2019; Nasirzade et al., 2014; Santos-García et al., 2021; Soares et al., 2014; Toussaint & Truijens, 2006).

Collectively, arm muscle strength, leg muscle explosive power, and hand–eye coordination explained 77.8% of the variance in 50-m freestyle swimming performance, indicating that these variables are major determinants of sprint swimming ability. The remaining 22.2% may be explained by factors such as stroke technique, anthropometry, flexibility, physiological capacity, psychological readiness, and training experience (Arellano et al., 2022; Gonjo et al., 2021; Zaras et al., 2022). These findings should be interpreted cautiously because the study involved a relatively small sample from a single swimming program. Nevertheless, this study contributes by proposing an integrated path model that explains how physical and coordinative factors interact to influence sprint swimming performance.

From a practical perspective, coaches should implement integrated training programs that simultaneously develop upper-body strength, lower-limb explosive power, and coordinative ability rather than focusing on a single physical component. Such an approach is expected to improve force production, movement efficiency, and sprint swimming performance more effectively. Future studies should validate this model using larger and more diverse samples while incorporating additional biomechanical, physiological, and psychological variables to improve the model's generalizability and predictive accuracy.

Conclusions

This study concludes that arm muscle strength, leg muscle explosive power, and hand–eye coordination significantly influence 50-m freestyle swimming speed among male students of the Pandu Mahawira Swimming Guidance Program, Padang. Arm muscle strength exhibited the greatest contribution to swimming performance, followed by leg muscle explosive power and hand–eye coordination. Furthermore, hand–eye coordination partially mediated the effects of arm muscle strength and leg muscle explosive power on swimming speed. Collectively, these variables explained 77.8% of the variance in 50-m freestyle swimming performance. Therefore, improving sprint swimming performance requires an integrated training approach that simultaneously develops upper-body strength, lower-limb explosive power, and coordinative abilities.

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