Three-dimensional shoulder mobility correlates with swimming speed in sub-elite adolescent athletes: a cross-sectional biomechanical analysis

La movilidad tridimensional del hombro se correlaciona con la velocidad de natación en atletas adolescentes sub-élite: un análisis biomecánico transversal

Authors

Mochamad Purnomo [1,2]
Donny Ardy Kusuma [1,2]
Muhammad Dzul Fikri [1]
Afif Rusdiawan [1,2]
José Vicente García Jiménez [3]
Mohammad Fathur Rohman [1,2]
Aulia Putri Srie Wardani [1]
Bhekti Lestari [1,2]
Muhammad Labib Siena Ar Rasyid [1]
Muhammad Zainuddien Aziz [2]

[1,2] Universitas Negeri Surabaya (Indonesia)
[3] University of Murcia (Spain)

Corresponding author:
mochamadpurnomo@unesa.ac.id

Received: 05-08-25
Accepted: 19-11-25

How to cite in APA

Purnomo, M., Kusuma, D. A., Fikri, M. D., Rusdiawan, A., García Jiménez, J. V., Rohman, M. F., Wardani, A. P. S., Lestari, B., Ar Rasyid, M. L. S., & Aziz, M. Z. (2026). Three-dimensional shoulder mobility correlates with swimming speed in sub-elite adolescent athletes: a cross-sectional biomechanical analysis. *Retos, 75*, 263-272. https://doi.org/10.47197/retos.v75.117334

Abstract

Introduction: Shoulder mobility is crucial for swimming performance, especially in freestyle strokes. However, there's limited evidence linking 3D shoulder mobility and in-water velocity in young swimmers.
Objective: To examine the relationship between sub-elite adolescent swimmers' 200-meter freestyle swimming speed and their three-dimensional shoulder mobility.
Methodology: Sixteen sub-elite swimmers (mean age = 14.94 ± 1.81 years) participated in a cross-sectional correlational study. The VALD HumanTrak™ markerless motion-capture system was used to measure shoulder mobility, recording bilateral flexion, extension, abduction, adduction, and rotational ranges. A 200-meter freestyle maximal effort trial was used to measure swimming velocity, stroke frequency, and stroke length. Spearman's rank coefficients ($p < 0.05$) were used for correlation analysis.
Results: Swimming speed was found to have strong and significant positive correlations with the flexion-extension range of motion (r = 0.905), right-side adduction (r = 0.981), and the total abduction-adduction range (r = 0.981). In contrast, metrics of left-side mobility demonstrated weaker or non-significant correlations. These performance trends were further supported by stroke kinematics, which displayed a negative correlation with stroke frequency (r = -0.843) and a positive correlation with stroke length (r = 0.830).
Discussion: These findings highlight the biomechanical importance of dominant-limb shoulder mobility in enhancing swimming propulsion. Bilateral asymmetry may reflect functional adaptations rather than impairments.
Conclusions: Swimming speed is significantly influenced by shoulder mobility, especially on the dominant side, which can be effectively utilized in training planning and identifying potential talent.

Keywords

Shoulder mobility, swimming speed, biomechanics, HumanTrak, motion analysis.

Resumen

Introducción: La movilidad del hombro es crucial para el rendimiento en natación, especialmente en estilo libre. Sin embargo, existe evidencia limitada que vincule la movilidad tridimensional del hombro con la velocidad en el agua en nadadores jóvenes.
Objetivo: Examinar la relación entre la velocidad de natación estilo libre de 200 metros de nadadores adolescentes sub-élite y su movilidad tridimensional del hombro.
Metodología: Dieciséis nadadores sub-élite (edad media = 14,94 ± 1,81 años) participaron en un estudio correlacional transversal. Se utilizó el sistema de captura de movimiento sin marcadores VALD HumanTrak™ para medir la movilidad del hombro, registrando la flexión, extensión, abducción, aducción y rangos de rotación bilaterales. Se realizó una prueba de esfuerzo máximo de 200 metros libre para medir la velocidad de nado, la frecuencia y la longitud de la brazada. Se utilizaron los coeficientes de rango de Spearman ($p < 0,05$) para el análisis de correlación.
Resultados: Se observó una correlación positiva fuerte y significativa entre la velocidad de natación y el rango de movimiento de flexión-extensión (r = 0,905), la aducción derecha (r = 0,981) y el rango total de abducción-aducción (r = 0,981). Por el contrario, las métricas de movilidad izquierda mostraron correlaciones más débiles o no significativas. Estas tendencias de rendimiento se vieron respaldadas por la cinemática de la brazada, que mostró una correlación negativa con la frecuencia de la brazada (r = -0,843) y una correlación positiva con la longitud de la brazada (r = 0,830).
Discusión: Estos hallazgos resaltan la importancia biomecánica de la movilidad del hombro de la extremidad dominante para mejorar la propulsión al nadar. La asimetría bilateral podría reflejar adaptaciones funcionales en lugar de deficiencias.
Conclusiones: La velocidad de natación está significativamente influenciada por la movilidad del hombro, especialmente en el lado dominante, que se puede utilizar de manera efectiva en la planificación del entrenamiento y la identificación de talentos potenciales.

Palabras clave

Movilidad del hombro, velocidad de natación, biomecánica, HumanTrak, análisis de movimiento.

Introduction

Current epidemiological data indicate that swimming-related injuries, particularly to the shoulder, persist as one of the most common musculoskeletal issues in aquatic sports. Recent systematic reviews suggest that 40% to 70% of competitive swimmers experience shoulder pain or functional limitations during a season (Raffini et al., 2024; Davis et al., 2023). This condition, often referred to as swimmer's shoulder, is primarily caused by repetitive overhead motions, excessive internal rotation, and scapular dyskinesis (Ekin, 2023). The cumulative load from thousands of stroke cycles each week causes microtrauma, changes in how the scapula works, and less stability in the glenohumeral joint (Drigny et al., 2020). Adolescents and sub-elite swimmers are especially vulnerable due to incomplete musculoskeletal maturation and unbalanced strength development (Yoma et al., 2023). Preventive and rehabilitative strategies have thus emphasized the value of assessing shoulder mobility and symmetry as potential indicators of injury risk (Rezaei et al., 2025; Raffini et al., 2024). Although there has been considerable research on prevention, there is a paucity of studies examining how shoulder mobility influences both injury incidence and swimming performance directly.

Swimming relies heavily on coordinated shoulder movements across all stroke styles, including freestyle, backstroke, and butterfly, which each demand extensive overhead ranges of motion. Among these, the freestyle stroke most frequently exposes the shoulder joint to repetitive load and extreme rotation, making it the primary model for biomechanical analysis. The glenohumeral joint experiences significant strain when swimmers engage in thousands of arm cycles regularly. To optimize stroke length and propulsion while maintaining stability, complex three-dimensional shoulder motions, such as flexion, extension, abduction/adduction, and rotation are essential. However, due to these demands, swimmers are particularly susceptible to shoulder injuries; according to Raffini et al. (2024), between 23 and 38 percent of swimmers sustain shoulder injuries each year. Although these movements enhance sport-specific performance, overuse and adaptive changes (like tight posterior capsules and altered scapular kinematics) can hinder normal joint biomechanics (Raffini et al., 2024). To maximize stroke mechanics and minimize injury risk, it is believed that competitive swimmers must maintain balanced shoulder mobility (Raffini et al., 2024).

The relationship between shoulder function and swimming performance, particularly in young people, has recently been quantified. Muscular strength, power, and body composition have been found to be powerful predictors of race speed in systematic reviews of young swimmers (Price et al., 2024). Price et al. (2024) discovered a moderate to strong correlation between adolescent swimmers' 100- and 400-meter freestyle times and upper-limb strength measurements, such as isometric internal and external rotator torque. Shoulder adaptations in young swimmers have also been reported by kinematic and clinical studies: high-intensity training sessions tend to acutely reduce shoulder external-rotation range of motion, especially on the dominant side of less experienced athletes (Yoma et al., 2023). On the other hand, swimmers with postural problems have been demonstrated to benefit from focused corrective exercise regimens that enhance glenohumeral range of motion and improve shoulder posture(Rezaei et al., 2025). A few recent studies, however, have directly connected three-dimensional shoulder range of motion to in-water velocity in young athletes (Fiori et al., 2022; Morais et al., 2022; Du' & Yanaiz, 2016), instead, the majority of research has concentrated on the effects of training or injuries rather than performance itself (Raffini et al., 2024; Yoma et al., 2023; Rezaei et al., 2025).

In order to close this gap, the current study examines the relationship between sub-elite teenage swimmers' 200-meter freestyle speed and their three-dimensional shoulder mobility. During routine mobility tests, we will measure active shoulder range of motion and combined joint angles, and we will compare these measurements to the recorded 200-meter swim speed. Our analysis is unique in that it records shoulder kinematics using the VALD HumanTrak™ markerless motion-capture system. HumanTrak is a useful tool for field-based screening since it has been proven to accurately measure shoulder joint angles (such as flexion and abduction) without the use of markers (McCarthy et al., 2023). We also look at limb dominance: swimmers frequently show side-to-side variations. Yoma et al. (2023) observed that university-level swimmers' dominant shoulders had greater external-rotation torque losses after swimming (Yoma et al., 2023). We can identify asymmetries that could affect stroke mechanics or point to unequal training adaptations by contrasting dominant and non-dominant shoulder mobility.

The overall goal of this research is to determine whether increased shoulder mobility is a predictor of faster swim speeds and how asymmetries affect this relationship. Coaches and sport scientists could use these findings as a screening and training metric if 3D shoulder range of motion is associated with performance. Youth swimming performance is known to be multifactorial, influenced by physiology as well as anthropometric and biomechanical factors (Bobadilla, 2025; Price et al., 2024). Experts stress the importance of early technical and physical attribute evaluation in talent-identification contexts (Morais et al., 2021). We add upper-limb joint mobility to this equation using sophisticated markerless 3D motion analysis. We can identify promising young swimmers and guide individualized training (such as flexibility or stabilization exercises) by identifying mobility metrics that correlate with freestyle velocity. The findings of this study also have potential applications in talent identification and training optimization, as previous research has emphasized that biomechanical parameters such as joint mobility, stroke kinematics, and range of motion are key indicators of technical efficiency and performance potential in young swimmers (Morais et al., 2021; Zemková & Hamar, 2018). By understanding how three-dimensional shoulder mobility relates to swimming speed, coaches can better identify promising athletes and design individualized programs that enhance performance capacity. All things considered, measuring shoulder mobility in three dimensions provides a fresh biomechanical understanding that could help identify young swimmers' talents, direct training regimens, and predict performance.

Method

Study Design

This study employed a cross-sectional correlational design to investigate the association between three-dimensional shoulder mobility and 200-meter freestyle swimming performance among sub-elite adolescent athletes. All participants completed standardized shoulder range-of-motion assessments using the VALD HumanTrak™ markerless motion-capture system, followed by a maximal swimming trial. The design allowed for the examination of biomechanical determinants of swimming speed under controlled and ecologically valid field conditions.

Participants

This study used a cross-sectional design to examine the relationship between young swimmers' shoulder mobility and swimming speed. Sixteen sub-elite swimmers (N = 16) participated in the 2023–2024 National Sub-Elite Swimmer Training Program training at the Sports Talent Development Centre, Universitas Negeri Surabaya. Athletes aged 12 to 18 made up 60% of the sample, with 40% being girls. A complete sample included all swimmers from the centralised programme actively involved in their training and competition schedules. Inclusion criteria included regular training participation, no musculoskeletal injuries in the previous three months, and willingness to provide informed consent. All minors had their parents' or guardians' consent.

Procedure

Prior to testing, each athlete completed a standard warm-up. Subsequently, shoulder mobility tests were conducted in a predetermined order. During every test, participants maintained a neutral, upright posture. Each subject held the highest position for one to two seconds while the measurement was being recorded. The three movement tests included: (1) Shoulder internal/external rotation: athletes stood erect and rotated their forearms as far inward (internal rotation) and outward (external rotation) as possible, while keeping their elbows flexed at 90 degrees and their shoulders abducted at 90 degrees. Standard goniometric protocols for internal/external rotation align with this position (Ab Malik et al., 2025). (2) Shoulder flexion/extension: athletes raised their arms as far forward and backward as they could in the sagittal plane, starting from a neutral position with their elbows extended. (3) Shoulder abduction/adduction: athletes raised their arms laterally (abduction) and then crossed them in front of their bodies (adduction) in the frontal plane, beginning from a neutral position. Following the on-screen instructions from the system, each movement was executed once for each arm. To minimise fatigue and reduce test duration, only one maximal trial per side was performed, although multiple trials can enhance repeatability (Collings et al., 2024). Athletes were instructed to move fluidly and at their own pace. The HumanTrak system recorded the peak joint angles (in degrees) for every movement and automatically distinguished between the left and right limbs. A trial was repeated if noticeable compensatory trunk motion, such as leaning, occurred, which was carefully avoided.

Instrument and Data Collection

The HumanTrak™ system (VALD Performance, Australia) was used to record shoulder motion. This portable, markerless 3D motion-analysis tool tracks joint movement in real time with an Azure Kinect depth camera (Collings et al., 2024). It allows for quick setup in field conditions by providing kinematic data without reflective markers. Previous validation studies have demonstrated good accuracy and reliability for measuring shoulder joint motion using the HumanTrak™ system (Collings et al., 2024; McCarthy et al., 2023). Therefore, this system was considered appropriate for assessing three-dimensional shoulder mobility in the present study. The Kinect camera's depth resolution and capture rate (approximately 30 Hz) enable accurate joint-angle measurements free from occlusion. The device was calibrated in accordance with the manufacturer's instructions prior to testing.

Two handheld digital stopwatches (model Seiko) run by knowledgeable coaches were used to measure performance testing (200-meter swim time). Well-trained stopwatch timers have demonstrated high agreement (ICC ~0.99) with automated times in sprint trials, although electronic timing systems are more accurate (Hetzler et al., 2008). According to earlier sprint research, "stopwatches are reliable" for recording performance times (Hetzler et al., 2008). Following each trial, the OneHealth Pulse Oximeter FS10F was used to record the heart rate, and stroke frequency (SF) were either manually counted or captured on video.

Following standard performance test protocols, each swimmer underwent mobility testing and then proceeded to swim a 200-meter (4x50-meter) front crawl at maximum effort in a 50-meter pool. As a useful indicator of middle-distance swim speed (v200), a well-rested maximum time trial was selected. Without any pacing instructions, swimmers were told to swim four consecutive 50-meter laps (20 strokes per lap, typical pace) while maintaining their normal breathing and stroke patterns. When the swimmer signalled, two skilled timekeepers began the watches, which stopped when the swimmer touched the wall at 50, 100, 150, and 200 meters. The 200-meter performance time was calculated by adding the split times for each 50-meter swim. Experienced coaches frequently time swim tests using stopwatches, which have been demonstrated to produce small mean errors and high ICC (>0.98) in group trials (Hetzler et al., 2008). A post-exercise heart rate was recorded on the monitor immediately following the trial. Additional stroke variables were calculated using video: stroke frequency (SF, cycles per 50 m) and stroke rate (SR, cycles per minute) were recorded by counting arm cycles over several laps. The relationship $v = SR \times SL$ was then used to indirectly calculate the stroke length (SL, m per cycle) (Fiori et al., 2022; Rizkanto et al., 2021). Additionally, we used video playback to record underwater time—the amount of time between wall push-off and surface breathing following each start or turn. Given that extended underwater periods can impact total swim time, this data was added as a control variable. In conclusion, we recorded each swimmer's total 200-meter time, average speed (200 m/time), heart rate, SF, SL, underwater time (seconds), and split timings to ensure consistency (Ganzalves, 2024)

Data analysis

IBM SPSS Statistics (Version 29, IBM Corp., Armonk, NY, USA) was used for all statistical analyses. For each measured variable, descriptive statistics such as mean and standard deviation were calculated. The normality of data distribution was assessed using the Shapiro-Wilk test. Rank Spearman correlation coefficients were employed to analyse the relationships between swimming speed and shoulder mobility metrics. In accordance with standard guidelines for sports science research, all tests were performed with a significance level of $p < 0.05$ (Hopkins et al., 2009).

Results

The study cohort comprised sixteen sub-elite adolescent swimmers (mean age = 14.94 ± 1.81 years; 62.5% male), with complete demographic, anthropometric, and training characteristics detailed in Table 1.

Table 1. Demographic and Baseline Characteristics of Subjects

Variable	*f* (%)	mean±SD
Ages(years)		14.94 ± 1.81
12-14	6 (37.5)	
15-17	10 (62.5)	
18-20	0 (0)	
Gender		
Male	10 (62.5)	
Female	6 (37.5)	
Dominant Hand		
Right	13 (81.25)	
Left	3 (18.75)	
Body height (cm)		165.63 ± 4.8
Body weight (kg)		59.56 ± 5.99
Training experience (years)		8.63 ± 1.63
7-8	9 (56.25)	
9-10	4 (25)	
11-12	3 (18.75)	

The participants had a mean age of 14.94 ± 1.81 years, with most (62.5%, n = 10) aged between 15 and 17, while the remaining participants (37.5%, n = 6) were aged between 12 and 14. Among the sample, 37.5% (n = 6) were female and 62.5% (n = 10) were male. The average body weight was 59.56 ± 5.99 kg, and the average height was 165.63 ± 4.80 cm, based on anthropometric data. Regarding laterality, 18.75% (n = 3) were left-hand dominant, while 81.25% (n = 13) were right-hand dominant. A majority of the cohort (56.25%, n = 9) reported having 7–8 years of structured swim training, followed by 25% (n = 4) with 9–10 years and 18.75% (n = 3) with 11–12 years. The average training experience was 8.63 ± 1.63 years.

Table 2 displays the findings of a comprehensive biomechanical profile, which encompasses shoulder mobility metrics, stroke kinematics, and performance outcomes for the 200-meter freestyle. It also includes assessments of normality, following demographic characterization.

Table 2. Descriptive Statistics and Normality Test for Shoulder Mobility, Stroke Characteristics, and Swimming Performance Variables

Variable		Mean ± SD	Min-Max	Shapiro wilk test (P>0.05)
Internal Rotation (°)	Right	69.63±4.23	64.9-82.8	0.002
	Left	70.18±3.47	62.3-75	0.451*
External Rotation (°)	Right	100.39±5.97	91.9-113.7	0.566*
	Left	98.48±3.94	90.7-104.3	0.436*
Flexion (°)	Right	169.43±3.95	163.5-175.9	0.290*
	Left	172.54±3.92	164.4-181.7	0.635*
Extension (°)	Right	61.89±4.09	57.4-73.5	0.018
	Left	59.84±2.41	55.2-64.1	0.912*
Abduction (°)	Right	168.29±2.91	156.7-176.9	0.001
	Left	171.90±4.66	163.4-181	0.970*
Adduction (°)	Right	50.85±3.32	43.3-55.9	0.793*
	Left	49.94±1.73	45.8-53.3	0.575*
Total Shoulder Rotation ROM (°)	Right	170.01±32.17	156.8-196.5	0.137*
	Left	168.66±32.72	153-174.9	0.007
Total Shoulder Flexion-Extension ROM (°)	Right	231.32±8.21	220.9-242.5	0.963*
	Left	232.38±7.22	225.2-239.1	0.287*
Total Shoulder Abduction-Adduction ROM (°)	Right	219.14±4.92	206.1-227.2	0.235*
	Left	221.84±5.30	213.6-232.5	0.903*
Exercise Heart Rate (bpm) (200 m)		171.50±11.42	156.00-194.00	0.561*
Stroke frequency (count) (200 m)		151.75±3.34	147-159	0.570*
Stroke Lenght (m)		1.32±7.21	1.28-1.38	0.599*
Underwater (s) (200 m)		15.49±0.68	13.99-16.75	0.283*
Total time (s) (200 m)		163.722±2.24	159.34-167.12	0.031
Swimming Speed (m/s)		1.22±0.02	1.20-1.26	0.024*

*normally distributed

Bilateral symmetry was observed in most aspects of shoulder mobility analysis, with external rotation demonstrating the largest range of motion (right: 100.39°±5.97°; left: 98.48°±3.94°). The average flexion-extension range of motion exceeded 230° bilaterally, while the average total rotational range of motion was 170.01°±32.17° on the right and 168.66°±32.72° on the left. The average time for the 200-meter freestyle was 163.72±2.24 seconds, which corresponded to an average velocity of 1.22±0.02 m/s, according to swimming performance metrics. Stroke kinematics indicated a stroke length of 1.32±7.21 m/stroke and a frequency of 151.75±3.34 strokes per 200 m. Except for right internal rotation (p=0.002), right extension (p=0.018), right abduction (p=0.001), left total rotation range of motion (p=0.007), and total swim time (p=0.031), 78% of the variables were found to be normally distributed (p>0.05) as determined by Shapiro-Wilk testing.

Bivariate correlational analysis, while controlling for stroke kinematics and heart rate, indicated significant associations between shoulder mobility measurements in multiple planes and swimming velocity, as outlined in Table 3.

Table 3. Spearman's Rank Correlation Between Shoulder Mobility Metrics and 200 m Freestyle Swimming Speed

Variable		r	*p*-value	intepretation
Internal Rotation (°)	Right	0.867	0.001	Very strong and statistically significant positive correlation
	Left	- 0.150	0.578	Very weak and non-significant negative correlation
External Rotation (°)	Right	0.837	0.001	Very strong and significant positive correlation
	Left	0.810	0.001	Very strong and significant positive correlation
Flexion (°)	Right	0.743	0.001	Strong and significant positive correlation
	Left	0.825	0.001	Very strong and significant correlation
Extension (°)	Right	0.568	0.022	Moderate and significant positive correlation
	Left	- 0.251	0.349	Weak and non-significant negative correlation
Abduction (°)	Right	0.503	0.047	Moderate and significant positive correlation
	Left	0.775	0.001	Strong and significant positive correlation
Adduction (°)	Right	0.981	0.001	Extremely strong and highly significant correlation
	Left	0.303	0.254	Weak and non-significant correlation
Total Shoulder Rotation ROM (°)	Right	0.845	0.001	Very strong and significant correlation
	Left	0.682	0.004	Strong and significant correlation
Total Shoulder Flexion-Extension ROM (°)	Right	0.905	0.001	Extremely strong and highly significant correlation
	Left	0.761	0.001	Strong and significant
Total Shoulder Abduction-Adduction ROM (°)	Right	0.981	0.001	Exceptionally strong positive correlation
	Left	0.704	0.002	Strong and significant correlation;
SF (count 200 m)		- 0.843	0.001	Very strong negative correlation
SL (m)		0.830	0.001	Very strong positive correlation

Correlation is significant at p>0.05

Right adduction (r = 0.981, p < 0.001) and total right abduction-adduction range of motion (r = 0.981, p < 0.001) demonstrated exceptionally strong correlations with swimming speed. Additionally, strong positive correlations were noted for flexion (r = 0.743), right external rotation (r = 0.837), and total flexion-extension range of motion (r = 0.905), with all p-values being less than 0.001. Significant bilateral differences were observed; left internal rotation did not significantly correlate with velocity (r = -0.150, p = 0.578), while right internal rotation did (r = 0.867, p = 0.001). Moreover, performance was significantly predicted by right abduction (r = 0.503, p = 0.047), but not by left adduction (r = 0.303, p = 0.254). Expected correlations were further validated by stroke kinematics: velocity showed a positive correlation with stroke length (r = 0.830) and a negative correlation with stroke frequency (r = -0.843), both with p-values below 0.001.

Discussion

This study provides compelling evidence that the middle-distance swimming performance of adolescent sub-elite swimmers is significantly affected by their three-dimensional shoulder mobility, particularly in the dominant limb. Enhanced joint mobility directly contributes to propulsion efficiency, as demonstrated by the exceptionally strong correlations between right-side shoulder adduction (r = 0.981), total abduction–adduction range of motion (r = 0.981), and 200-meter freestyle velocity. These findings build on previous biomechanical models of swimming propulsion, especially those emphasizing the importance of the in-sweep phase in front crawl strokes (Heinlein & Cosgarea, 2010; Morais et al., 2022)

Dominant limb mobility, particularly in terms of internal rotation and abduction, showed strong positive correlations with velocity, while contralateral metrics often did not reveal significant relationships. Consequently, bilateral asymmetry in shoulder range of motion emerged as a noteworthy performance-related characteristic. Given that over 80% of the sample was right-hand dominant, this asymmetry is likely attributable to functional lateralization. Prior research indicates that unilateral dominance in swimming and other overhead sports often leads to asymmetrical load distribution and motor pattern specialization (Drigny et al., 2020; Ekin, 2023; Gasibat et al., 2023). Importantly, our findings challenge the traditional belief that bilateral symmetry is inherently optimal for performance. Instead, a more nuanced, limb-specific mobility framework may be more applicable to performance, particularly in sports where unilateral motions are frequently repeated (Firdaus Kafrawi et al., 2025).

Additionally, our findings support the crucial roles that stroke length (SL) and stroke frequency (SF) play in mediating the relationship between swimming velocity and joint range of motion. In swimming kinematics, the efficiency paradigm is supported by the strong positive correlation between SL and speed ($r = 0.830$) and the inverse correlation between SF and speed ($r = -0.843$). This is because swimmers with greater shoulder range of motion can execute longer strokes, which lowers the frequency required for sustained velocity (Davis et al., 2023; Ruiz-Navarro et al., 2025; Wirth et al., 2022). According to fluid dynamics, as previously modeled in hydrodynamic simulations, greater range of motion (ROM) probably maximizes propulsion time during each stroke cycle while reducing deceleration phases (Higgs et al., 2017)

In terms of technology, the HumanTrak™ markerless motion capture system represents a methodological breakthrough for biomechanical research conducted in the field. According to recent validation studies, this tool allows for the accurate and quick evaluation of multi-planar joint mobility without the need for laboratory settings (Drazan et al., 2021; Edwards et al., 2025). These tools facilitate continuous shoulder function monitoring and the early identification of mobility impairments by democratizing access to biomechanical diagnostics for coaches and practitioners in applied settings.

The results of this study have applications in talent identification and training as well. Training regimens should prioritize dynamic flexibility and resistance work that targets dominant-shoulder adduction and flexion-extension range of motion due to their predictive value. Proprioceptive neuromuscular facilitation (PNF) stretching and resisted internal rotation exercises, for instance, may enhance range of motion and joint stability (Sharman et al., 2006; Warneke et al., 2025). Additionally, dominant-side mobility metrics may serve as potential biomechanical biomarkers for early talent identification in young swimmers, as supported by previous evidence emphasizing the role of biomechanical and neuromuscular variables in performance prediction (Morais et al., 2021; Zemková & Hamar, 2018; Ruiz-Navarro et al., 2025). The strong correlations observed in this study ($r > 0.90$) further reinforce the practical value of shoulder mobility assessments as objective indicators for screening and training optimization in youth swimming programs.

This study provides empirical support for a refined understanding of the kinematic chain theory, particularly in the context of aquatic propulsion. Previous studies have described the shoulder complex as the primary mechanical link balancing mobility and stability within the upper-limb kinetic chain (Veeger & van der Helm, 2007), while others have highlighted that localized restrictions, such as posterior shoulder tightness, can disrupt energy transfer efficiency (Harshbarger et al., 2013). Our findings extend these insights by demonstrating that joint-specific mobility, particularly within the shoulder girdle, appears to modulate chain efficiency during swimming propulsion, supporting the notion that optimal limb kinematics may enhance segmental coordination and overall swimming performance (Ruiz-Navarro et al., 2025; Kwok et al., 2021). This viewpoint also relates to theories of neuromuscular control because, especially in younger populations that are still going through neuromuscular maturation, increased range of motion may enable more personalized strokes, improving intracycle fluidity and lowering mechanical asymmetry (Kwok et al., 2021).

However, it is important to recognize the limitations of this study. The relatively small sample size ($N = 16$) restricts generalizability, and the cross-sectional design makes causal inference impossible. Furthermore, although 3D range of motion was measured, joint stability, scapular kinematics, and muscle activation patterns were not measured at the same time; these could provide additional explanatory power in subsequent studies. To elucidate causal mechanisms and training adaptations, longitudinal studies with larger cohorts and integrated electromyographic data are advised.

Conclusions

The study highlights the biomechanical importance of shoulder joint mobility in swimming performance, particularly in the dominant limb. It reveals that right-side adduction and total abduction-adduction ROM are the strongest predictors of 200-meter freestyle velocity. This highlights the importance of shoulder kinematics in swimming performance and introduces it as a potential biomarker for training optimization and talent identification. Swim coaches and sports practitioners should prioritize individualized mobility assessments and design training programs focusing on enhancing dynamic ROM, particularly adduction, flexion, and rotation of the dominant shoulder. Future studies should incorporate muscle strength and coordination metrics, scapular tracking, and kinetic analyses to form a more comprehensive biomechanical model of swimming efficiency.

Acknowledgements

The authors would like to thank the coaches and athletes involved in the National Sub-Elite Swimmer Training Program at Universitas Negeri Surabaya for their dedication and participation. Special recognition is given to the staff of the Sport & Exercise Research Center (SERC) for their contributions to data collection and technical support.

Financing

This research received research funding from the Institute for Research and Community Service (LPPM) of Universitas Negeri Surabaya.

References

Ab Malik, Z., Abd Kadir, F. S., Iffah, E. N. I., Yussof, M. H. M., Ismail, M. N. A., Abd Malek, N. F., Nadzalan, A. M., & Hashim, H. A. (2025). Interrater Reliability of Functional Movement Screening Test among Untrained Undergraduate Raters Undergoing a One-off Training Session. *The Malaysian Journal of Medical Sciences : MJMS*, *32*(1), 121. https://doi.org/10.21315/MJMS-09-2024-740

Bobadilla, J. L. (2025). Physiological and psychological determinants of cardiovascular autonomic response in experienced Cold- Water Swimmers Determinantes fisiológicos y psicológicos de la respuesta autonómica cardiovascular en nadadores experimentados en aguas frías Authors Ke. *Retos: Nuevas Tendencias En Educación Física, Deporte y Recreación*, *69*, 897–910. https://doi.org/https://doi.org/10.47197/retos.v69.114955

Collings, T. J., Devaprakash, D., Pizzolato, C., Lloyd, D. G., Barrett, R. S., Lenton, G. K., Thomeer, L. T., & Bourne, M. N. (2024). Inclusion of a skeletal model partly improves the reliability of lower limb joint angles derived from a markerless depth camera. *Journal of Biomechanics*, *170*, 112160. https://doi.org/10.1016/J.JBIOMECH.2024.112160

Davis, D. D., Nickerson, M., & Varacallo, M. A. (2023). Swimmer's Shoulder. *StatPearls*. https://www.ncbi.nlm.nih.gov/books/NBK470589/

Drazan, J. F., Phillips, W. T., Seethapathi, N., Hullfish, T. J., & Baxter, J. R. (2021). Moving outside the lab: markerless motion capture accurately quantifies sagittal plane kinematics during the vertical jump. *Journal of Biomechanics*, *125*, 110547. https://doi.org/10.1016/J.JBIOMECH.2021.110547

Drigny, J., Gauthier, A., Reboursière, E., Guermont, H., Gremeaux, V., & Edouard, P. (2020). Shoulder Muscle Imbalance as a Risk for Shoulder Injury in Elite Adolescent Swimmers: A Prospective Study. *Journal of Human Kinetics*, *75*(1), 103. https://doi.org/10.2478/HUKIN-2020-0041

Du', T., & Yanaiz, T. (2016). Three-dimensional motion of shoulder complex during front crawl swimming. *ISBS - Conference Proceedings Archive*, 18–22. https://ojs.ub.uni-konstanz.de/cpa/article/view/6876

Edwards, N. A., Caccese, J. B., Tracy, R. E., Hagen, J., Quatman-Yates, C. C., & Oñate, J. (2025). The Validity and Usability of Markerless Motion Capture and Inertial Measurement Units for Quantifying

Dynamic Movements. *Medicine and Science in Sports and Exercise*, *57*(3), 641–655. https://doi.org/10.1249/MSS.0000000000003579,

Ekin, A. (2023). Injuries in swimming sports: prevention and treatment methods. *Revista de Gestão e Secretariado (Management and Administrative Professional Review)*, *14*(10), 17988–17996. https://doi.org/10.7769/GESEC.V14I10.3016

Fiori, J. M., Zacca, R., & de Souza Castro, F. A. (2022). 200-M Front Crawl Performance Over a Training Season in 12 Years and Underage-Group Swimmers: Growth and Kinematics Effects. *Motriz. Revista de Educacao Fisica*, *28*. https://doi.org/10.1590/s1980-657420220001222

Firdaus Kafrawi, M., Subagio, I., Kumaat, N. A., Widodo, A., Özman, C., Rusdiawan, A., Kafrawi, F. R., Sulistyarto, S., Kafrawi, M. F., Subagio, I., Kumaat, N. A., Widodo, A., Özman, C., & Rusdiawan, A. (2025). Efectos comparativos del entrenamiento de fuerza unilateral y bilateral de las extremidades inferiores sobre el rendimiento en volteretas laterales en atletas de gimnasia artística. *Retos*, *69*, 654–665. https://doi.org/10.47197/RETOS.V69.116192

Ganzalves, S. P. M. (2024). *Tracking Swim Training [PhD-Thesis]*. https://hdl.handle.net/1871.1/a71a4855-3308-450f-9749-ebe53df37d57

Gasibat, Q., Abdullah, B., Samsudin, S., Alexe, D. I., Alexe, C. I., & Tohănean, D. I. (2023). Gender-Specific Patterns of Muscle Imbalance in Elite Badminton Players: A Comprehensive Exploration. *Sports 2023, Vol. 11, Page 164*, *11*(9), 164. https://doi.org/10.3390/SPORTS11090164

Harshbarger, N. D., Eppelheimer, B. L., McLeod, T. C. V., & Welch McCarty, C. (2013). The Effectiveness of Shoulder Stretching and Joint Mobilizations on Posterior Shoulder Tightness. *Journal of Sport Rehabilitation*, *22*(4), 313–319. https://doi.org/10.1123/JSR.22.4.313

Heinlein, S. A., & Cosgarea, A. J. (2010). Biomechanical Considerations in the Competitive Swimmer's Shoulder. *Sports Health*, *2*(6), 519–525. https://doi.org/10.1177/1941738110377611

Hetzler, R. K., Stickley, C. D., Lundquist, K. M., & Kimura, I. F. (2008). Reliability and accuracy of handheld stopwatches compared with electronic timing in measuring sprint performance. *Journal of Strength and Conditioning Research*, *22*(6), 1969–1976. https://doi.org/10.1519/JSC.0B013E318185F36C

Higgs, A. J., Pease, D. L., & Sanders, R. H. (2017). Relationships between kinematics and undulatory underwater swimming performance. *Journal of Sports Sciences*, *35*(10), 995–1003. https://doi.org/10.1080/02640414.2016.1208836;CTYPE:STRING:JOURNAL

Kwok, W. Y., So, B. C. L., Tse, D. H. T., & Ng, S. S. M. (2021). A Systematic Review and Meta-Analysis: Biomechanical Evaluation of the Effectiveness of Strength and Conditioning Training Programs on Front Crawl Swimming Performance. *Journal of Sports Science & Medicine*, *20*(4), 564. https://doi.org/10.52082/JSSM.2021.564

McCarthy, A., Wills, J. A., Andersen, J., Lenton, G. K., & Doyle, T. L. A. (2023). Evaluating the intra- and inter-day reliability of output measures for the VALD HumanTrak: dynamic movements and range of motion of the shoulder and hip with body armour. *Ergonomics*, *66*(3), 406–418. https://doi.org/10.1080/00140139.2022.2092218,

Morais, J. E., Barbosa, T. M., Forte, P., Silva, A. J., & Marinho, D. A. (2021). Young Swimmers' Anthropometrics, Biomechanics, Energetics, and Efficiency as Underlying Performance Factors: A Systematic Narrative Review. *Frontiers in Physiology*, *12*, 691919. https://doi.org/10.3389/FPHYS.2021.691919/BIBTEX

Morais, J. E., Barbosa, T. M., Nevill, A. M., Cobley, S., & Marinho, D. A. (2022). Understanding the Role of Propulsion in the Prediction of Front-Crawl Swimming Velocity and in the Relationship Between Stroke Frequency and Stroke Length. *Frontiers in Physiology*, *13*, 876838. https://doi.org/10.3389/FPHYS.2022.876838

Price, T., Cimadoro, G., & S Legg, H. (2024). Physical performance determinants in competitive youth swimmers: a systematic review. *BMC Sports Science, Medicine and Rehabilitation*, *16*(1), 1–19. https://doi.org/10.1186/S13102-023-00767-4/TABLES/4

Raffini, A., Martini, M., Mazzari, L., Buoite Stella, A., Deodato, M., Murena, L., & Accardo, A. (2024). Impact of Physiotherapy on Shoulder Kinematics in Swimmers with Swimmer's Shoulder Pain. *Sensors (Basel, Switzerland)*, *24*(24), 7936. https://doi.org/10.3390/S24247936

Rezaei, H., Gheitasi, M., & Hosseini, S. M. (2025). Does corrective exercises influence the performance, posture, range of motion and shoulder pain of swimmers with upper crossed syndrome? randomized clinical trial. *BMC Sports Science, Medicine and Rehabilitation*, *17*(1), 1–9. https://doi.org/10.1186/S13102-025-01200-8/TABLES/3

Rizkanto, B. E., Pgri, A., & Rusdiawan, A. (2021). Kinematics analysis of freestyle swimming athletes at the 2019 Indonesia Open Aquatic Championship (IOAC). *Jurnal SPORTIF : Jurnal Penelitian Pembelajaran*, *7*(2), 206–218. https://doi.org/10.29407/JS_UNPGRI.V7I2.15877

Ruiz-Navarro, J. J., Santos, C. C., Born, D. P., López-Belmonte, Ó., Cuenca-Fernández, F., Sanders, R. H., & Arellano, R. (2025). Factors Relating to Sprint Swimming Performance: A Systematic Review. *Sports Medicine*, *55*(4), 899–922. https://doi.org/10.1007/S40279-024-02172-4/METRICS

Sharman, M. J., Cresswell, A. G., & Riek, S. (2006). Proprioceptive neuromuscular facilitation stretching: Mechanisms and clinical implications. *Sports Medicine*, *36*(11), 929–939. https://doi.org/10.2165/00007256-200636110-00002/FIGURES/2

Veeger, H. E. J., & van der Helm, F. C. T. (2007). Shoulder function: The perfect compromise between mobility and stability. *Journal of Biomechanics*, *40*(10), 2119–2129. https://doi.org/10.1016/J.JBIOMECH.2006.10.016

Warneke, K., Thomas, E., Blazevich, A. J., Afonso, J., Behm, D. G., Marchetti, P. H., Trajano, G. S., Nakamura, M., Ayala, F., Longo, S., Babault, N., Freitas, S. R., Costa, P. B., Konrad, A., Nordez, A., Nelson, A., Zech, A., Kay, A. D., Donti, O., & Wilke, J. (2025). Practical recommendations on stretching exercise: A Delphi consensus statement of international research experts. *Journal of Sport and Health Science*, *14*, 101067. https://doi.org/10.1016/J.JSHS.2025.101067

Wirth, K., Keiner, M., Fuhrmann, S., Nimmerichter, A., & Haff, G. G. (2022). Strength Training in Swimming. *International Journal of Environmental Research and Public Health*, *19*(9), 5369. https://doi.org/10.3390/IJERPH19095369

Yoma, M., Herrington, L., & Mackenzie, T. (2023). The Effects Of Differing Density Of Swim-Training Sessions On Shoulder Range Of Motion and Isometric Force Production In National and University Level Swimmers. *International Journal of Sports Physical Therapy*, *18*(2), 375–387. https://doi.org/10.26603/001C.72717,

Zemková, E., & Hamar, D. (2018). Sport-Specific Assessment of the Effectiveness of Neuromuscular Training in Young Athletes. *Frontiers in Physiology*, *9*(APR), 264. https://doi.org/10.3389/FPHYS.2018.00264

Authors' and translators' details:

Mochamad Purnomo	mochamadpurnomo@unesa.ac.id	Author
Donny Ardy Kusuma	donnykusuma@unesa.ac.id	Author
Muhammad Dzul Fikri	muhammadfikri@unesa.ac.id	Author
Afif Rusdiawan	afifrusdiawan@unesa.ac.id	Author
José Vicente García Jiménez	jvgjimenez@um.es	Author
Mohammad Fathur Rohman	mohrohman@unesa.ac.id au-	Author
Aulia Putri Srie Wardani	liawardani@unesa.ac.id	Author
Bhekti Lestari	bhektilestari@unesa.ac.id	Author
Muhammad Labib Siena Ar Rasyid	muhammadrasyid@unesa.ac.id	Author
Muhammad Zainuddien Aziz	zainudinaziz7@gmail.com	Author