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A comparison of the mechanical properties of the deltoid and trapezius muscles and shoulder range of motion in competitive young swimmers across different swimming strokes

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Abstract

Background Competitive swimming is a sport that places a high level of repetitive load on the shoulder complex and requires intensive use of upper extremity movements. Different swimming strokes may demonstrate distinct differences in shoulder joint biomechanics and muscle activation patterns, which may lead to stroke-specific adaptations in shoulder joint range of motion and the neuromechanical properties of muscles. However, studies examining shoulder joint range of motion together with the biomechanical properties of shoulder girdle muscles assessed by myotonometry according to swimming strokes in young swimmers are limited. The aim of this study was to investigate whether the biomechanical properties of shoulder girdle muscles and shoulder joint range of motion differ according to swimming stroke in competitive youth swimmers.

Methods A total of 32 competitive swimmers (14 females, 18 males) were included in this cross-sectional and comparative study. Participants were divided into four groups according to their dominant swimming stroke: freestyle ($n=8$), breaststroke ($n=9$), backstroke ($n=8$), and butterfly ($n=7$). Shoulder joint range of motion (flexion, extension, abduction, adduction, internal rotation, and external rotation) was assessed bilaterally using a standard goniometric method. The biomechanical properties of shoulder girdle muscles were measured using the MyotonPRO device, and oscillation frequency (muscle tone), dynamic stiffness, logarithmic decrement, relaxation time, and creep parameters were recorded. Differences in shoulder joint range of motion were analyzed using the Kruskal–Wallis test. In the evaluation of muscle biomechanical properties, analysis of covariance (ANCOVA) was applied while controlling for age, height, body mass, and training experience as covariates.

Results No differences were found among swimming strokes in shoulder flexion, extension, abduction, internal rotation, and external rotation range of motion ($p > 0.05$). In contrast, shoulder adduction range of motion differed

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significantly according to swimming stroke on both sides (right $p=0.003$; left $p=0.008$). Freestyle swimmers demonstrated lower adduction angles, whereas butterfly and backstroke swimmers exhibited higher values. Myotonometric assessment showed no stroke-related differences in oscillation frequency, muscle stiffness, relaxation time, or creep parameters ($p>0.05$). However, a stroke-related difference was observed in the decrement value of the anterior deltoid muscle ($p=0.002$), with freestyle swimmers demonstrating lower decrement values compared with some other stroke groups.

Conclusions The findings of this study indicate that shoulder joint range of motion in competitive youth swimmers is largely independent of swimming stroke, although shoulder adduction range of motion may exhibit stroke-specific differences. In addition, while most neuromechanical properties of shoulder girdle muscles appear to be independent of swimming stroke, the elastic properties of the anterior deltoid muscle may be related to stroke mechanics. These findings provide important information for the evaluation of stroke-specific biomechanical adaptations in swimmers, performance analysis, and the planning of training programs aimed at preventing shoulder injuries.

Trial registration ClinicalTrials.gov Identifier NCT07425873, registered on 27/01/2026.

Keywords Shoulder girdle, Shoulder range of motion, Muscle mechanical properties, Biomechanics, Swimmers

Introduction

Swimming is a complex motor skill that enables an individual to move forward in the aquatic environment by coordinating and controlling body movements, requiring a high level of motor control, muscle coordination, and neuromuscular integration [1]. One of the most distinctive characteristics of swimming compared with other sports is that the athlete assumes a prone or supine horizontal body position throughout performance, which allows the cardiovascular and circulatory systems to function more efficiently and facilitates blood flow throughout the body [2]. Owing to the buoyant force of water, joint and muscle structures are also exposed to lower mechanical loads against gravity, making swimming an effective and comprehensive physical activity for improving cardiovascular endurance, increasing muscle strength and flexibility, and supporting overall motor coordination [3]. These features together position swimming as a unique sporting model in which whole-body motor control and musculoskeletal adaptation are continuously challenged under low-impact loading conditions.

In competitive swimming, there are four main strokes — freestyle, backstroke, breaststroke, and butterfly [4] — and these strokes display distinct biomechanical differences in terms of body position, joint angles, movement patterns, and the level of muscle group involvement. Strokes also differ in their symmetrical and asymmetrical movement patterns: in breaststroke and butterfly, the arms and legs work simultaneously in a symmetrical manner, whereas in freestyle and backstroke the arms and legs operate alternately in an asynchronous and asymmetrical fashion [5]. From a kinematic standpoint, shoulder flexion and internal rotation movements are dominant in freestyle and butterfly swimming, whereas external rotation and shoulder abduction are more prominent in backstroke swimming [6]. These stroke-specific

biomechanical features directly influence the loading profiles and functional adaptations of the shoulder girdle musculature [7], and consequently shape the development of stroke-specific neuromuscular and joint adaptations in competitive swimmers.

The shoulder girdle is responsible for approximately 90% of the propulsive force generated through the upper extremities during swimming and is considered one of the primary determinants of swimming performance [8]. It has been reported that young and elite swimmers swim approximately 60,000–80,000 m per week, corresponding to nearly 30,000 repetitive shoulder rotation movements [9]. These high-volume and repetitive loading patterns lead to long-term structural and mechanical adaptations, particularly in the rotator cuff and scapular stabilizer muscles [10]. The biomechanics of the shoulder joint during swimming are closely related to internal and external rotation movements at the glenohumeral joint, scapulothoracic rhythm, coordinated activation of the rotator cuff muscles, and scapular stability [9]. During freestyle and butterfly swimming in particular, the supraspinatus and subscapularis muscles play critical roles during the hand entry and exit phases in the water [10]. In contrast, insufficient functional capacity or mechanical adaptation of the lower trapezius muscle may impair scapular control and contribute to the development of overuse-related shoulder pathologies commonly referred to as “swimmer’s shoulder” [8]. Indeed, the prevalence of shoulder pain in elite swimmers has been reported to reach up to 73% [8].

The functional status of the shoulder girdle muscles is related not only to muscle activation levels but also to mechanical and neuromechanical parameters such as muscle tone, stiffness, and elastic properties. In recent years, the MyotonPRO device, a non-invasive assessment tool, has enabled the objective measurement of the mechanical and viscoelastic (neuromechanical)

properties of muscles in vivo. Despite the clear biomechanical differences among the four competitive swimming strokes, studies directly examining how the neuromechanical properties of shoulder girdle muscles—assessed by myotonometry—differ according to swimming stroke in young swimmers are remarkably limited [11–13]. This represents a critical research gap: without stroke-specific reference data for myotonometric parameters of the shoulder girdle, it is not possible to identify stroke-related muscular adaptations, evaluate injury risk, or individualize training programs. Similarly, comprehensive approaches that simultaneously examine shoulder girdle joint range of motion together with stroke-specific muscle adaptations remain insufficiently explored in the literature [14].

Therefore, the aim of the present study was to investigate whether the neuromechanical properties of shoulder girdle muscles assessed using MyotonPRO and the shoulder joint range of motion differ according to swimming stroke in young competitive swimmers, and to provide new and objective findings regarding stroke-specific muscular and joint adaptations. Comparing these parameters across the four competitive strokes is important because each stroke imposes distinct loading patterns on the shoulder girdle, and identifying stroke-specific neuromechanical profiles may support individualized performance optimization, injury prevention, and clinical assessment strategies. The results obtained are expected to contribute important clinical and practical insights for stroke-based training planning and the development of preventive strategies aimed at reducing shoulder injuries in swimmers.

Methods

Study design and ethical considerations

This study was designed as a cross-sectional and comparative investigation to examine the differences in neuromechanical properties of shoulder girdle muscles and shoulder joint range of motion among young swimmers according to different swimming strokes. Throughout this manuscript, the terms “mechanical properties” and “neuromechanical properties” are used interchangeably to refer to the myotonometric parameters (oscillation frequency, dynamic stiffness, logarithmic decrement, relaxation time, and creep) measured by the MyotonPRO device, consistent with the broader literature on myotonometry [15, 16]. The study was conducted in accordance with the principles of the Declaration of Helsinki. Ethical approval was obtained from the Scientific Research and Publication Ethics Committee of Kütahya Dumlupınar University (Meeting No: 2025/12; Decision No: 42).

Before data collection began, all participants and their parents or legal guardians were informed about the purpose of the study in plain language. The measurement

procedures to be applied, potential risks, and issues related to data confidentiality were also explained in detail. Written informed consent was then obtained from all participants and from the parents of individuals under the age of 18. The study consisted only of measurement and evaluation procedures, and no treatment or experimental intervention was applied. Data collection was carried out between November 2025 and January 2026 under standardized environmental conditions by the same research team to ensure measurement consistency. Participants' identity information was not recorded at any stage, and all data were analyzed anonymously.

Participants and baseline characterization

A total of 32 competitive swimmers (14 females, 18 males) participated in the study. For inclusion, “competitive swimmer” was defined as an athlete who (i) was actively registered with a licensed swimming club, (ii) had been competing regularly at official sanctioned events for at least one year, and (iii) trained under a certified coach for a minimum of five sessions per week. This classification threshold is consistent with the participant classification framework of McKay et al. [17]. Participants were divided into four groups according to their dominant swimming stroke: freestyle ($n = 8$), breaststroke ($n = 9$), backstroke ($n = 8$), and butterfly ($n = 7$). The dominant swimming stroke was defined as the stroke in which the participant (a) achieved their personal best competitive performance time and (b) accumulated the greatest proportion of their weekly training volume, as confirmed by the participant's coach. It is acknowledged that competitive swimmers often develop a level of proficiency in multiple strokes; however, for the purposes of this study, the dominant stroke was used as the primary classification criterion. The distribution of sex among groups did not differ, as confirmed by the chi-square test ($p = 0.987$). Participants' age, training experience, and best 50-m performance times were recorded and analyzed to characterize the baseline features of the study population. These variables are presented in Table 1. Since training experience and performance times may vary according to swimming stroke, these variables were considered potential confounding factors in subsequent statistical models.

Sample size calculation

The sample size required for this study was calculated using G*Power 3.1 software (Heinrich Heine University, Düsseldorf, Germany) for a one-way analysis of variance (ANOVA: Fixed effects, omnibus, one-way) [Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39(2):175–91]. In the power analysis based on muscle tone (Hz), the effect size was set at $f = 0.875$ (derived

Table 1 Participant characteristics across the four swimming-stroke groups

Variable	Freestyle (n = 8)	Breaststroke (n = 9)	Backstroke (n = 8)	Butterfly (n = 7)	p value
Sex (F / M), n	3 / 5	4 / 5	4 / 4	3 / 4	0.987†
Age (years)	16.5 [14.0–17.3]	14.0 [14.0–15.0]	13.5 [12.0–14.0]	14.0 [13.5–14.0]	0.072
Training experience (years)	10.0 [8.5–10.3]	7.0 [7.0–10.0]	6.5 [5.8–7.3]	6.0 [5.0–8.5]	0.041*
50-m best time (s)	26.8 [24.5–27.1]	33.8 [33.2–34.0]	34.1 [32.9–36.4]	29.6 [28.9–32.5]	< 0.001***

Values are presented as counts (female/male) for sex and as median [interquartile range, IQR] for age, training experience, and best 50-m performance time. *p* values were obtained from the chi-square (χ^2) test for sex distribution (†) and from the Kruskal–Wallis test for the continuous variables

p* < 0.05; **p* < 0.001

from pilot data and comparable myotonometric studies), the significance level at $\alpha = 0.05$, the statistical power at $(1 - \beta) = 0.95$, and the number of groups at 4.

The analysis indicated that the required total sample size was 28 participants (freestyle = 7 swimmers, backstroke = 7 swimmers, breaststroke = 7 swimmers, and butterfly = 7 swimmers). With these parameters, the calculated actual power was 0.960, indicating sufficient statistical sensitivity of the test. The critical *F* value was calculated as 3.009, the noncentrality parameter (λ) as 21.438, and the degrees of freedom were determined as $df_1 = 3$ (between groups) and $df_2 = 24$ (error term) [12].

Experimental procedures

All measurements were performed by the same research team under standardized environmental conditions. The measurement environment temperature was maintained between 22 and 24 °C, and assessments were conducted in a quiet setting to minimize the influence of external stimuli. Participants were instructed not to perform intense training within 24 h prior to the measurements, to avoid caffeine consumption, and to maintain their normal sleep routines on the day of testing.

Before the evaluation, participants rested for 10 min to ensure physiological recovery, after which measurements began. To minimize the influence of circadian variation, all assessments were conducted within the same time period of the day. Measurements were performed in the following order: first, the recording of sociodemographic data; second, anthropometric measurements; third, shoulder joint range of motion assessment; and fourth, evaluation of the mechanical properties of the shoulder girdle muscles.

During muscle measurements, participants were positioned in a seated posture with back support, with the trunk kept upright and the upper extremity stabilized in a relaxed natural position. All measurements were performed bilaterally. To increase measurement reliability, each variable was measured three times and the mean values were used for analysis. All participants were assessed by the same investigator throughout the measurements to minimize observer-related variability.

Anthropometric assessments

Participants' baseline characteristics were recorded using a standardized data collection form before the assessments. Age, sex, years of swimming experience, and best 50-m swimming performance time were recorded to determine the baseline characteristics of the study group. These variables were used to identify baseline differences between groups and to control potential confounding effects in subsequent analyses.

Anthropometric measurements were performed according to standard measurement protocols. Body height was measured to the nearest 0.1 cm using a wall-mounted stadiometer, and body mass was measured to the nearest 0.1 kg using a calibrated digital scale. Body mass index (BMI) was calculated by dividing body mass by the square of body height (kg/m^2). In addition, arm span and arm length were measured to determine segment lengths associated with swimming performance.

Anthropometric characteristics were evaluated considering that biomechanical differences related to swimming stroke may arise not only from muscular properties but also from body structure. Therefore, these variables were included as covariates in the statistical models. Measurements were performed by physiotherapists and sports scientists with at least three years of experience, and each measurement was repeated three times with the mean values used in the analyses. Through these assessments, the baseline characteristics of the study population were defined, and the potential effects of anthropometric variables were controlled when analyzing stroke-related differences in muscle mechanical properties.

Shoulder range of motion assessment

Shoulder joint range of motion was evaluated using a standard goniometric measurement protocol. Measurements were performed using a universal plastic goniometer (Baseline® 12-1000, Fabrication Enterprises Inc., White Plains, NY, USA) to determine passive range of motion [14]. All assessments were conducted by the same investigator to minimize observer-related variability. Before measurement, participants rested their upper extremities in a relaxed position for five minutes.

Participants were positioned in a seated posture with back support, and pelvic and trunk stabilization was

ensured in accordance with standardized clinical goniometry guidelines [14, 16]. The trunk was kept stable during the measurements to prevent scapular compensations. For shoulder flexion and abduction measurements, the axis of the goniometer was positioned laterally to the humeral head at the level of the acromion; the stationary arm was aligned along the trunk, and the moving arm was aligned with the axis of the humerus. Extension measurements were evaluated with passive posterior movement while maintaining trunk stabilization. Internal and external rotation measurements were performed with the shoulder positioned at 90° abduction and the elbow at 90° flexion, using the longitudinal axis of the humerus as a reference.

Shoulder mobility was assessed across three anatomical planes: the sagittal plane (flexion and extension), the frontal plane (abduction and adduction), and the transverse plane (internal rotation and external rotation). All six movements were recorded bilaterally in degrees (°), measured from the anatomical neutral position (0°) in accordance with standard goniometric conventions [14, 16]. For each movement, values represent the total arc from the neutral (0°) reference position; thus flexion and extension are reported separately rather than as a combined flexion/extension arc, allowing direct comparison across stroke groups. Each movement was repeated three times, and the mean values were used for analysis. The measurement protocol was applied in accordance with clinical goniometry standards [14]. The assessment of shoulder range of motion was performed to determine the effects of repetitive upper extremity movements in swimming on joint mobility, as shoulder rotational range of motion has been reported to be associated with performance and injury risk in swimmers [18].

Myotonometric muscle assessment

The mechanical properties of shoulder girdle muscles were evaluated using a non-invasive myotonometry method with the MyotonPRO device (Myoton AS, Tallinn, Estonia). Myotonometry is based on recording and analyzing the natural oscillatory response of muscle tissue following a brief mechanical impulse applied to the muscle, allowing objective assessment of the viscoelastic properties of muscle [15, 16].

During the evaluation, participants were positioned in a seated posture with back support, with the trunk upright and the upper extremity relaxed and supported, consistent with published myotonometry protocols [15, 16]. Measurement points were determined by palpation according to anatomical landmarks. The upper, middle, and lower portions of the trapezius muscle and the anterior, middle, and posterior portions of the deltoid muscle were assessed bilaterally. The probe was positioned perpendicular to the muscle fibers.

The trapezius and deltoid were selected as the target muscles because they are the principal superficial muscles of the shoulder girdle that are directly and repetitively loaded during the propulsive and recovery phases of all four competitive strokes: the trapezius is the main scapular stabilizer and the deltoid is the primary glenohumeral elevator, and together they form the force couple most frequently implicated in the pathomechanics of swimmer's shoulder. In addition, both muscles are superficial and readily accessible to the MyotonPRO probe by surface palpation, which is a methodological prerequisite for valid myotonometry; deeper shoulder-girdle muscles such as the rotator cuff (e.g., supraspinatus, subscapularis) and the serratus anterior lie beneath overlying tissue and cannot be validly assessed by surface myotonometry, and were therefore not measured. Both the trapezius and the deltoid were assessed bilaterally, and shoulder range of motion was likewise measured bilaterally (right and left sides), because competitive swimming imposes broadly symmetrical loading on the two upper limbs; bilateral assessment of both the muscular and the joint outcomes allowed potential side-to-side adaptations to be captured and compared.

After applying a pre-compression of approximately 0.18 N on the muscle, the device delivered a mechanical impulse of 0.4 N lasting 15 ms. In each measurement, five consecutive mechanical impulses were applied, and the resulting oscillation curves were automatically analyzed. Three repeated measurements were obtained for each muscle, and mean values were used in the analyses.

Five myotonometric parameters were recorded from each measurement curve generated by the MyotonPRO device: oscillation frequency (F, Hz), reflecting muscle tone; dynamic stiffness (S, N/m), reflecting muscle stiffness; logarithmic decrement (D), reflecting the elastic damping property of the tissue; relaxation time (R, ms), reflecting the time required for the muscle to return to its resting state; and creep (C), reflecting the viscoelastic deformation behavior under sustained load.

Myotonometric measurements have been reported to demonstrate high repeatability and intra-rater reliability, with intra-rater reliability coefficients exceeding 0.90 [15]. This method is considered a reliable and valid tool for evaluating the mechanical and viscoelastic properties of muscle [16].

Outcome variables

The primary outcomes were the five myotonometric parameters of the shoulder girdle muscles (oscillation frequency, dynamic stiffness, logarithmic decrement, relaxation time, and creep); the secondary outcomes were shoulder joint range of motion values across six movements (flexion, extension, abduction, adduction, internal rotation, and external rotation) measured bilaterally.

Potential confounders (age, body height, body mass, and training experience) were controlled statistically as described in the Statistical Analysis section.

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics (Version 26.0; IBM Corp., Armonk, NY, USA). Data distribution was assessed using the Shapiro–Wilk test. As most variables did not meet the assumption of normality and sample sizes were relatively small, non-parametric statistical methods were applied for descriptive and group comparisons where appropriate.

Descriptive data are presented as median and interquartile range [IQR] for non-normally distributed variables and as estimated marginal means $\pm$ standard error (SE) for adjusted analyses. Sex distribution across swimming stroke groups was compared using the chi-square (χ^2) test.

Between-stroke comparisons of demographic variables, anthropometric characteristics, and shoulder range of motion (ROM) were conducted using the Kruskal–Wallis test. This non-parametric test was selected for ROM variables because these data did not meet the assumption of normality (Shapiro–Wilk test) and because no covariate adjustment was warranted given that between-group anthropometric differences were modest for these outcomes. When significant main effects were observed, pairwise comparisons were explored descriptively to identify stroke-specific patterns.

For the analysis of myotonometric muscle properties (oscillation frequency [F], stiffness [S], decrement [D], relaxation time [R], and creep [C]), analysis of covariance (ANCOVA) was performed using a general linear model (GLM) approach. ANCOVA was chosen over non-parametric tests for these outcomes because the observed between-group differences in age, body height, body mass, and training experience (Tables 1 and 2) could confound stroke-related comparisons of muscle properties; ANCOVA allows these covariates to be statistically controlled. Swimming stroke (freestyle, breaststroke, backstroke, butterfly) was entered as the fixed factor, while age, body height, body mass, and training experience were included as covariates. Results from ANCOVA are reported as estimated marginal means $\pm$ standard

error (SE), representing covariate-adjusted group means (hereafter referred to as “adjusted values”). Bilateral muscle values were averaged prior to analysis. For transparency, unadjusted descriptive statistics (median [IQR]) for all muscle parameters are also available from the corresponding author upon reasonable request.

When a significant main effect of swimming stroke was identified in the ANCOVA model, Bonferroni-adjusted post-hoc comparisons were applied to determine pairwise differences between stroke groups. Effect sizes were quantified using partial eta squared (partial η^2) and interpreted as small (≈ 0.01), moderate (≈ 0.06), or large (≥ 0.14).

All statistical tests were two-tailed, and the level of statistical significance was set at $p < 0.05$.

Result

The participant flow and baseline characteristics are described in the Methods section and summarized in Tables 1 and 2. Between-stroke differences were observed in training experience ($p = 0.041$) and 50-m best performance time ($p < 0.001$), with freestyle swimmers exhibiting longer training experience and faster performance compared with the other stroke groups; these variables were therefore controlled as covariates in the ANCOVA models.

The swimmers' age, training experience, and best 50-m performance times are presented in Table 1. While age was comparable across the four stroke groups, between-stroke differences were observed in training experience and 50-m best performance time, with freestyle swimmers exhibiting longer training experience and faster performance compared with the other stroke groups.

Anthropometric measurements of the participants, stratified by swimming stroke, are presented in Table 2. Body height was measured using a wall-mounted stadiometer (to the nearest 0.1 cm), and body mass was assessed with a calibrated digital scale (to the nearest 0.1 kg). Body mass index (BMI) was calculated as body mass divided by height squared (kg/m^2).

Between-stroke differences were observed for body height, body mass, BMI, and arm span (all $p < 0.05$). Freestyle swimmers demonstrated greater height, body mass, and arm span compared with the other stroke

Table 2 Anthropometric characteristics across the four swimming-stroke groups

Variable	Freestyle (n = 8)	Breaststroke (n = 9)	Backstroke (n = 8)	Butterfly (n = 7)	p value
Height (cm)	176.5 [166.3–185.3]	170.0 [168.0–175.0]	164.0 [152.5–166.0]	165.0 [156.5–172.0]	0.039*
Body mass (kg)	65.5 [59.3–75.0]	60.0 [54.0–64.0]	51.5 [48.0–55.0]	52.0 [43.0–60.5]	0.031*
BMI (kg/m^2)	26.8 [24.5–27.1]	33.2 [33.0–34.0]	30.4 [26.9–32.5]	29.2 [28.3–31.0]	0.018*
Arm span (cm)	179.5 [165.8–185.0]	174.0 [166.0–181.0]	161.3 [151.3–164.4]	168.0 [154.8–177.3]	0.044*

Values are presented as median [interquartile range, IQR]. Reported variables are body height, body mass, body mass index (BMI), and arm span. p values were obtained from the Kruskal–Wallis test

* $p < 0.05$; *** $p < 0.001$

Table 3 Shoulder range of motion across the four swimming-stroke groups

ROM variable (°)	Freestyle (n = 8)	Breaststroke (n = 9)	Backstroke (n = 8)	Butterfly (n = 7)	p value
Right flexion	178.5 [175.0–180.0]	176.0 [174.0–179.0]	177.0 [173.0–179.0]	176.5 [174.0–179.5]	0.612
Left flexion	179.0 [176.0–180.0]	177.0 [175.0–179.0]	176.5 [174.0–179.0]	177.0 [175.0–179.0]	0.584
Right extension	58.0 [55.0–60.0]	56.0 [54.0–59.0]	57.0 [54.0–59.0]	56.5 [54.0–59.0]	0.701
Left extension	57.5 [55.0–60.0]	56.0 [54.0–58.0]	56.5 [54.0–59.0]	56.0 [54.0–58.5]	0.744
Right abduction	179.0 [176.0–180.0]	177.5 [175.0–179.0]	178.0 [175.0–179.0]	177.0 [175.0–179.0]	0.659
Left abduction	179.5 [177.0–180.0]	178.0 [175.0–179.0]	177.5 [175.0–179.0]	178.0 [176.0–179.0]	0.632
Right adduction	45.4 [41.9–49.1]	54.7 [51.6–60.3]	58.5 [55.3–62.3]	65.1 [59.2–69.8]	0.003*
Left adduction	46.9 [44.6–50.3]	63.2 [57.9–68.6]	62.7 [57.8–65.5]	70.7 [66.4–75.5]	0.008*
Right internal rotation	66.0 [62.0–69.0]	64.0 [61.0–67.0]	65.0 [62.0–68.0]	64.5 [62.0–67.5]	0.688
Left internal rotation	67.0 [63.0–70.0]	65.0 [62.0–68.0]	66.0 [63.0–69.0]	65.5 [63.0–68.5]	0.654
Right external rotation	91.0 [88.0–94.0]	89.0 [86.0–92.0]	90.0 [87.0–93.0]	89.5 [86.0–92.5]	0.603
Left external rotation	92.0 [89.0–95.0]	90.0 [87.0–93.0]	91.0 [88.0–94.0]	90.5 [88.0–93.0]	0.576

Bilateral flexion, extension, abduction, adduction, internal rotation, and external rotation values are presented in degrees (°) as median [interquartile range, IQR]. *p* values were obtained from the Kruskal–Wallis test

* $p < 0.05$; *** $p < 0.001$

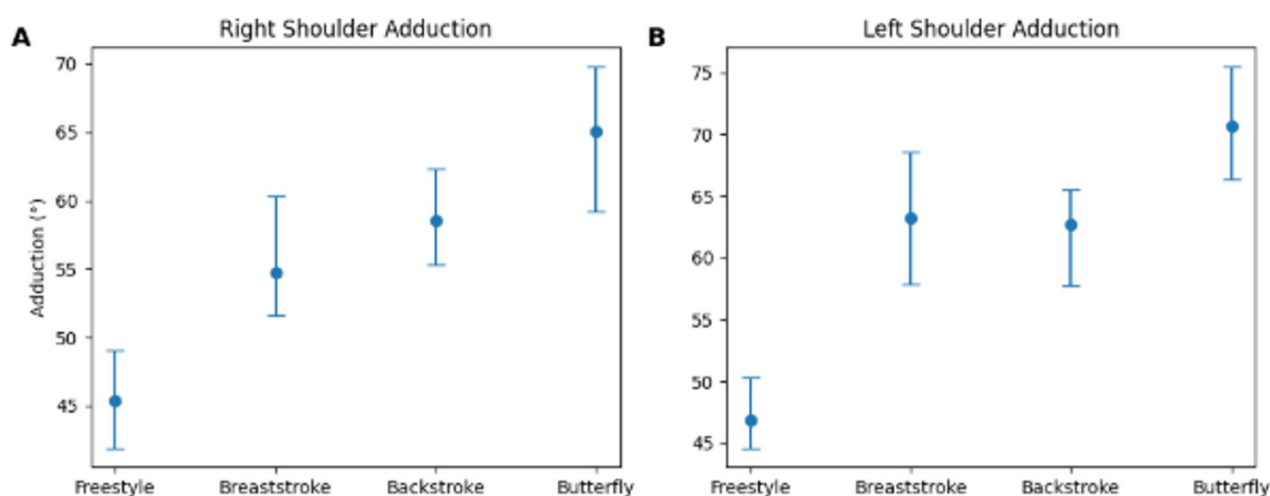


Fig. 1 Shoulder adduction range of motion by swimming stroke. **A** Right shoulder adduction and **(B)** left shoulder adduction across swimming strokes. Points represent median values, and vertical bars indicate the interquartile range (IQR). Significant between-stroke differences were observed for both right and left shoulder adduction (Kruskal–Wallis test; right: $p = 0.003$, left: $p = 0.008$)

groups, whereas breaststroke swimmers exhibited higher BMI values. These differences highlight stroke-specific anthropometric profiles among competitive swimmers and underscore the importance of controlling for anthropometric variables in subsequent analyses.

Shoulder range of motion values by swimming stroke are presented in Table 3. Values are reported separately for each of the six movements across three anatomical planes (sagittal: flexion/extension; frontal: abduction/adduction; transverse: internal/external rotation), measured from the anatomical neutral position (0°). No between-stroke differences were observed for shoulder flexion, extension, abduction, internal rotation, or external rotation on either the right or left side (all $p > 0.05$).

In contrast, shoulder adduction demonstrated clear stroke-specific differences bilaterally. Both right adduction ($p = 0.003$) and left adduction ($p = 0.008$) differed

among the four swimming strokes. Freestyle swimmers exhibited the lowest adduction angles, whereas butterfly swimmers showed the highest adduction values, with backstroke swimmers also demonstrating greater adduction compared with freestyle.

As shown in Fig. 1A and B, shoulder adduction range of motion differed significantly among swimming strokes on both sides. Freestyle swimmers exhibited lower adduction angles, whereas backstroke and butterfly swimmers demonstrated greater adduction values.

Muscle oscillation frequency values adjusted for age, body height, body mass, and training experience are presented in Table 4 as ANCOVA-estimated marginal means $\pm$ SE. To allow comparison with the adjusted results, unadjusted (raw) descriptive values are noted within the text where stroke-specific differences are significant; for non-significant outcomes, the adjusted

Table 4 Muscle oscillation frequency (F, Hz; muscle tone) across the four swimming-stroke groups

Muscle (bilateral mean)	Freestyle (n = 8)	Breaststroke (n = 9)	Backstroke (n = 8)	Butterfly (n = 7)	F (stroke)	p value	Partial η^2
Upper trapezius	15.6 ± 0.9	16.1 ± 1.0	16.4 ± 1.1	16.8 ± 1.2	1.42	0.258	0.11
Middle trapezius	14.3 ± 0.8	14.9 ± 0.9	15.1 ± 1.0	15.5 ± 1.1	1.67	0.193	0.13
Lower trapezius	13.2 ± 0.7	13.7 ± 0.8	14.0 ± 0.9	14.3 ± 1.0	1.81	0.169	0.14
Anterior deltoid	17.9 ± 1.0	18.4 ± 1.1	18.8 ± 1.2	18.6 ± 1.1	1.96	0.145	0.15
Middle deltoid	16.7 ± 0.9	17.1 ± 1.0	17.4 ± 1.1	17.6 ± 1.1	1.88	0.156	0.14
Posterior deltoid	16.1 ± 0.9	16.5 ± 1.0	16.9 ± 1.1	17.2 ± 1.1	1.73	0.182	0.13

Values are estimated marginal means ± standard error from ANCOVA adjusted for age, body height, body mass, and training experience. The upper, middle, and lower trapezius and the anterior, middle, and posterior deltoid were assessed. The F statistic, p value, and partial η^2 are reported for each muscle

* $p < 0.05$; *** $p < 0.001$

Table 5 Muscle dynamic stiffness (S, N/m) across the four swimming-stroke groups

Muscle (bilateral mean)	Freestyle (n = 8)	Breaststroke (n = 9)	Backstroke (n = 8)	Butterfly (n = 7)	F (stroke)	p value	Partial η^2
Upper trapezius	302 ± 12	314 ± 13	319 ± 14	326 ± 15	1.98	0.141	0.15
Middle trapezius	284 ± 11	292 ± 12	298 ± 13	304 ± 14	2.11	0.126	0.16
Lower trapezius	261 ± 10	268 ± 11	274 ± 12	279 ± 13	2.23	0.113	0.17
Anterior deltoid	341 ± 14	352 ± 15	358 ± 16	356 ± 16	2.36	0.098	0.18
Middle deltoid	325 ± 13	334 ± 14	339 ± 15	343 ± 15	2.28	0.108	0.17
Posterior deltoid	318 ± 13	327 ± 14	332 ± 15	336 ± 16	2.14	0.122	0.16

Values are estimated marginal means ± standard error from ANCOVA adjusted for age, body height, body mass, and training experience. The upper, middle, and lower trapezius and the anterior, middle, and posterior deltoid were assessed. The F statistic, p value, and partial η^2 are reported for each muscle

* $p < 0.05$; *** $p < 0.001$

Table 6 Muscle logarithmic decrement (D; elastic damping property) across the four swimming-stroke groups

Muscle (bilateral mean)	Freestyle (n = 8)	Breaststroke (n = 9)	Backstroke (n = 8)	Butterfly (n = 7)	F (stroke)	p value	Partial η^2
Upper trapezius	0.86 ± 0.03	0.88 ± 0.03	0.90 ± 0.03	0.89 ± 0.03	1.02	0.398	0.08
Middle trapezius	0.83 ± 0.03	0.85 ± 0.03	0.86 ± 0.03	0.86 ± 0.03	1.19	0.327	0.09
Lower trapezius	0.81 ± 0.03	0.83 ± 0.03	0.84 ± 0.03	0.85 ± 0.03	1.34	0.273	0.10
Anterior deltoid	0.81 ± 0.03	0.85 ± 0.03	0.98 ± 0.03	0.89 ± 0.03	6.31	0.002*	0.34
Middle deltoid	0.84 ± 0.03	0.86 ± 0.03	0.88 ± 0.03	0.87 ± 0.03	1.48	0.232	0.11
Posterior deltoid	0.85 ± 0.03	0.87 ± 0.03	0.88 ± 0.03	0.88 ± 0.03	1.21	0.319	0.09

Values are estimated marginal means ± standard error from ANCOVA adjusted for age, body height, body mass, and training experience. The upper, middle, and lower trapezius and the anterior, middle, and posterior deltoid were assessed. The F statistic, p value, and partial η^2 are reported for each muscle

* $p < 0.05$; *** $p < 0.001$

values adequately represent the group distributions. The ANCOVA revealed no significant main effect of swimming stroke on oscillation frequency for any of the evaluated shoulder muscles, including the upper, middle, and lower trapezius, as well as the anterior, middle, and posterior deltoid (all $p > 0.05$).

Although small numerical increases in frequency were observed from freestyle to butterfly across several muscles, these differences did not reach statistical significance, and the corresponding effect sizes were small to moderate (partial $\eta^2 = 0.11$ – 0.15). Overall, these findings indicate that muscle oscillation frequency is largely independent of swimming stroke, suggesting that this myotonic parameter reflects general neuromuscular properties rather than stroke-specific adaptations.

Adjusted muscle stiffness values by swimming stroke are presented in Table 5. The ANCOVA analysis, controlling for age, body height, body mass, and training experience, demonstrated no significant main effect of swimming stroke on stiffness values for any of the

evaluated shoulder muscles, including the upper, middle, and lower trapezius and the anterior, middle, and posterior deltoid (all $p > 0.05$).

Although a gradual numerical increase in stiffness from freestyle to butterfly was observed across most muscle groups, these differences did not reach statistical significance. The associated effect sizes were small to moderate (partial $\eta^2 = 0.15$ – 0.18).

Adjusted muscle decrement values by swimming stroke are presented in Table 6. The ANCOVA analysis, controlling for age, body height, body mass, and training experience, revealed a significant main effect of swimming stroke on the decrement values of the anterior deltoid muscle ($F = 6.31$, $p = 0.002$, partial $\eta^2 = 0.34$). The unadjusted (raw) median [IQR] anterior deltoid decrement values were: freestyle 0.81 [0.78–0.83], breaststroke 0.85 [0.82–0.88], backstroke 0.97 [0.94–1.00], and butterfly 0.89 [0.87–0.92], consistent with the direction of the adjusted results.

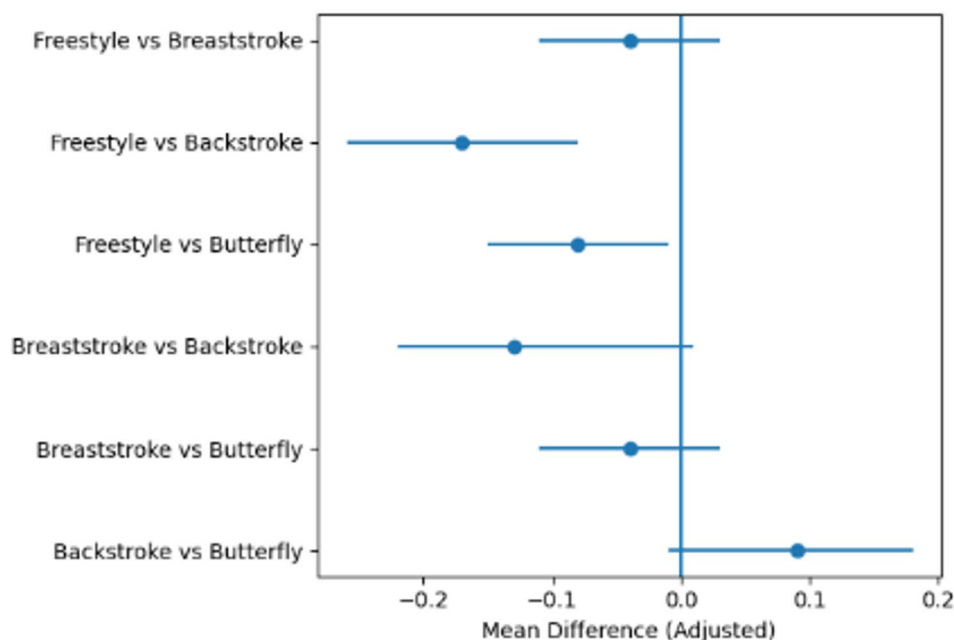


Fig. 2 Bonferroni-adjusted post-hoc comparisons for anterior deltoid decrement (D)

Table 7 Muscle relaxation time (R, ms) across the four swimming-stroke groups

Muscle (bilateral mean)	Freestyle (n=8)	Breaststroke (n=9)	Backstroke (n=8)	Butterfly (n=7)	F (stroke)	p value	Partial η^2
Upper trapezius	19.8 ± 0.7	20.2 ± 0.8	20.5 ± 0.8	20.7 ± 0.9	1.14	0.353	0.09
Middle trapezius	18.9 ± 0.7	19.3 ± 0.7	19.6 ± 0.8	19.8 ± 0.8	1.27	0.305	0.10
Lower trapezius	18.1 ± 0.6	18.5 ± 0.7	18.9 ± 0.7	19.1 ± 0.8	1.39	0.263	0.11
Anterior deltoid	21.4 ± 0.8	21.9 ± 0.8	22.3 ± 0.9	22.1 ± 0.9	1.52	0.229	0.12
Middle deltoid	20.6 ± 0.8	21.0 ± 0.8	21.4 ± 0.9	21.6 ± 0.9	1.41	0.259	0.11
Posterior deltoid	20.1 ± 0.7	20.5 ± 0.8	20.9 ± 0.8	21.1 ± 0.9	1.33	0.278	0.11

Values are estimated marginal means ± standard error from ANCOVA adjusted for age, body height, body mass, and training experience. The upper, middle, and lower trapezius and the anterior, middle, and posterior deltoid were assessed. The F statistic, *p* value, and partial η^2 are reported for each muscle

p* < 0.05; **p* < 0.001

Post-hoc comparisons with Bonferroni correction indicated that freestyle swimmers exhibited significantly lower anterior deltoid decrement values compared with both backstroke and butterfly swimmers (*p* < 0.05), whereas no significant differences were observed between freestyle and breaststroke swimmers.

In contrast, no significant stroke-related differences were found for the upper, middle, or lower trapezius, nor for the middle and posterior deltoid muscles (all *p* > 0.05), with effect sizes remaining small to moderate (partial η^2 = 0.08–0.11).

These findings suggest that, among the evaluated myotonic parameters, decrement of the anterior deltoid demonstrates a distinct stroke-specific pattern, potentially reflecting differences in muscle damping properties associated with stroke-specific shoulder mechanics.

As illustrated in Fig. 2, freestyle swimmers exhibited significantly lower anterior deltoid decrement values compared with backstroke and butterfly swimmers, as indicated by confidence intervals that did not cross zero

after Bonferroni adjustment. No other pairwise comparisons demonstrated statistically significant differences.

Adjusted muscle relaxation time values by swimming stroke are presented in Table 7. The ANCOVA analysis, controlling for age, body height, body mass, and training experience, demonstrated no significant main effect of swimming stroke on relaxation time for any of the evaluated shoulder muscles, including the upper, middle, and lower trapezius and the anterior, middle, and posterior deltoid (all *p* > 0.05).

Although a gradual numerical increase in relaxation time from freestyle to butterfly was observed across several muscles, these differences did not reach statistical significance. The associated effect sizes were small to moderate (partial η^2 = 0.09–0.12), indicating that variability in relaxation time was limited and unlikely to reflect stroke-specific neuromuscular adaptations.

Overall, these findings suggest that muscle relaxation time, as assessed by MyotonPRO, is not strongly influenced by swimming stroke, and may instead represent

Table 8 Muscle creep (C; viscoelastic deformation behavior) across the four swimming-stroke groups

Muscle (bilateral mean)	Freestyle (n=8)	Breaststroke (n=9)	Backstroke (n=8)	Butterfly (n=7)	F (stroke)	p value	Partial η^2
Upper trapezius	1.21 ± 0.05	1.23 ± 0.05	1.25 ± 0.05	1.26 ± 0.06	1.18	0.339	0.09
Middle trapezius	1.18 ± 0.05	1.20 ± 0.05	1.22 ± 0.05	1.23 ± 0.06	1.26	0.306	0.10
Lower trapezius	1.15 ± 0.05	1.17 ± 0.05	1.19 ± 0.05	1.20 ± 0.06	1.34	0.281	0.11
Anterior deltoid	1.27 ± 0.06	1.29 ± 0.06	1.31 ± 0.06	1.30 ± 0.06	1.42	0.256	0.11
Middle deltoid	1.24 ± 0.06	1.26 ± 0.06	1.28 ± 0.06	1.29 ± 0.06	1.37	0.270	0.11
Posterior deltoid	1.22 ± 0.05	1.24 ± 0.05	1.26 ± 0.05	1.27 ± 0.06	1.31	0.289	0.10

Values are estimated marginal means ± standard error from ANCOVA adjusted for age, body height, body mass, and training experience. The upper, middle, and lower trapezius and the anterior, middle, and posterior deltoid were assessed. The F statistic, p value, and partial η^2 are reported for each muscle

* $p < 0.05$; *** $p < 0.001$

general viscoelastic properties shared across competitive swimmers.

Adjusted muscle creep values by swimming stroke are presented in Table 8. The ANCOVA analysis, controlling for age, body height, body mass, and training experience, demonstrated no significant main effect of swimming stroke on creep values for any of the evaluated shoulder muscles, including the upper, middle, and lower trapezius and the anterior, middle, and posterior deltoid (all $p > 0.05$).

Although small numerical increases in creep values from freestyle to butterfly were observed across several muscles, these differences did not reach statistical significance. The corresponding effect sizes were small to moderate (partial $\eta^2 = 0.09$ – 0.11), suggesting that the observed variability in creep parameters reflects general viscoelastic behavior rather than stroke-specific muscular adaptations.

Discussion

The present study investigated the neuromechanical properties of shoulder girdle muscles and shoulder joint range of motion across four competitive swimming strokes in young swimmers. The key finding is that the large majority of shoulder ROM parameters and myotonometric muscle properties did not differ significantly among strokes, with the notable exceptions of shoulder adduction ROM (significantly different across all four strokes) and the decrement value of the anterior deltoid muscle (significantly lower in freestyle compared with backstroke and butterfly). These patterns suggest that most shoulder adaptations in young competitive swimmers reflect the general demands of high-volume aquatic training rather than stroke-specific loading, while adduction mobility and anterior deltoid elastic damping may serve as more stroke-sensitive indicators.

In this study, the mechanical properties of shoulder girdle muscles assessed by myotonometry and the differences in shoulder joint range of motion according to swimming stroke were investigated in young competitive swimmers. The findings showed that shoulder joint range of motion was generally similar across swimming strokes;

however, shoulder adduction range of motion differed significantly according to swimming stroke. In addition, when myotonometric parameters were examined, a stroke-specific difference was identified only in the decrement value of the anterior deltoid muscle, whereas no significant differences were found in muscle tone, stiffness, relaxation time, or creep parameters.

The finding that shoulder joint range of motion was largely similar among swimming strokes may be explained by the bilateral and repetitive upper extremity movements inherent to swimming. Competitive swimmers perform continuously repeated shoulder rotation movements within high-volume training programs. This may lead to long-term adaptations in glenohumeral joint mobility [18]. Since internal and external rotation movements play important roles during the swimming stroke cycle, the continuous repetition of these movements may result in adaptive changes in shoulder joint range of motion [18]. In addition, the similar use of both upper extremities in swimming may explain why marked asymmetries in joint range of motion, commonly observed in unilateral sports, may be more limited in swimmers.

The stroke-specific differences observed in shoulder adduction range of motion in the present study can be explained by the distinct upper extremity mechanics of each stroke. In butterfly, simultaneous bilateral arm entry and the subsequent pull phase require sustained medial movement of the humerus toward the trunk, promoting greater glenohumeral adduction over time. In contrast, the pronounced body rotation in freestyle reduces the duration and magnitude of humerus-to-trunk approximation per stroke cycle, likely resulting in comparatively smaller adaptive increases in adduction ROM. Backstroke swimmers also demonstrated greater adduction compared with freestyle, which may reflect the overhead recovery phase in which the arm crosses near the midline. These findings are consistent with the established principle that joint ROM adapts specifically to the direction and magnitude of repetitive loading [18], and extend this principle to the adduction plane in young competitive swimmers.

Differences in adduction range of motion may further reflect stroke-specific activation patterns of key adductor muscles—particularly the latissimus dorsi and pectoralis major—which are heavily recruited during the pull phase and differ in their temporal activation patterns across strokes. Repeated high-force contractions of these muscles during butterfly and backstroke may induce adaptive remodeling of the glenohumeral capsule and periarticular tissues, gradually expanding the passive adduction arc [9, 10]. Importantly, the adduction differences observed here are unlikely to represent pathological restriction but rather functional, sport-specific adaptations, given that all values fell within or near normative clinical ranges and no pain was reported.

When the myotonometry results were examined, it was noteworthy that muscle tone and stiffness values did not differ significantly according to swimming stroke. This finding suggests that swimming training may produce a sport-specific rather than a stroke-specific adaptation in muscle tissue. Myotonometry is a reliable method for assessing the viscoelastic properties of muscle and allows objective measurement of muscle tone and stiffness in athletes [15, 16, 19]. Studies in different athletic populations have shown that muscle stiffness is mostly associated with general loading level and training intensity. For example, an increase in upper trapezius muscle stiffness has been reported after consecutive climbing sessions in mountaineers [20]. Similarly, changes in muscle stiffness have been reported after exercise, and these changes appear to be sensitive to the characteristics of loading [19]. In this context, although swimming strokes have different movement patterns, it seems likely that the mechanical properties of the shoulder girdle muscles may have developed in a similar direction due to the high-volume nature of swimming training.

The difference observed in the decrement value of the anterior deltoid muscle is one of the most striking neuro-mechanical findings of the present study. The decrement parameter reflects the elastic energy damping capacity of the muscle. The lower decrement value observed in freestyle swimmers suggests that this muscle may exhibit more elastic behavior. In freestyle swimming, the high repetition frequency of shoulder flexion and the faster recovery phase may lead to greater use of stretch-shortening cycles and increased elastic energy recovery. Indeed, studies in tennis players have indicated that muscle mechanical properties are not directly associated with performance, but may vary due to the multifactorial nature of movement patterns [20]. Therefore, the difference in elastic properties observed in the anterior deltoid may be related more to stroke-specific movement patterns than to muscle strength itself.

The literature has shown that the MyotonPRO device is a reliable and valid tool for evaluating muscle properties

in athletes [21, 22]. In addition, scapular position has been shown to affect shoulder muscle tone and function in elite boxers [23]. Similarly, passive stiffness of the periscapular muscles has been reported to be associated with scapular rotation control in swimmers [23]. When considered together with the findings of the present study, these results suggest that the difference in elastic properties of the anterior deltoid muscle may be related to stroke-specific differences in scapular kinematics.

The absence of differences in relaxation time and creep parameters suggests that the viscoelastic properties of muscle may be related more to the repetitive nature of the sport than to stroke differences. In the pathomechanics of swimmer's shoulder, the problem arises mostly from impaired scapular control rather than from muscle stiffness [8]. In addition, the relationship between postural changes and muscle stiffness has been reported to vary across different populations [24–26]. Therefore, focusing only on muscle stiffness parameters may not be sufficient when evaluating injury risk in swimmers.

From a clinical perspective, one of the important outcomes of this study is that shoulder adduction range of motion and the elastic properties of the anterior deltoid muscle may be used as stroke-specific assessment parameters. It has also been reported in the literature that reference ranges obtained by myotonometry may support clinical evaluations [27]. Therefore, the adoption of swimming stroke-specific assessment approaches may be recommended in performance analysis and injury prevention programs.

This study has several limitations. First, because the study had a cross-sectional design, the findings do not allow causal inferences to be made. Although the stroke-related differences observed suggest adaptive changes, it cannot be stated with certainty that these changes are directly caused by swimming stroke. Second, although the sample size was found to be sufficient based on statistical power analysis, all participants were recruited from a single club; this may limit the generalizability of the findings to different age groups or athletes at elite performance levels. Third, an important limitation related to participant selection is that competitive swimmers in real-world settings frequently train and compete across multiple strokes, and proficiency in one stroke does not preclude competence in others. Grouping swimmers by a single dominant stroke may therefore underestimate the true biomechanical heterogeneity within groups and attenuate stroke-specific differences in outcome measures. This classification challenge is inherent to stroke-comparative research and should be considered when interpreting the largely homogeneous results across stroke groups. Finally, training intensity, weekly swimming volume, and dry-land training content were not standardized among participants, which may have

introduced additional within-group variability. Future studies including athletes at different performance levels and using longitudinal designs, multi-stroke classification schemes, and multiple biomechanical assessment methods are recommended.

Conclusion

In young competitive swimmers, shoulder joint range of motion and neuromechanical properties of the shoulder girdle muscles were largely comparable across the four competitive strokes, with two stroke-sensitive exceptions: shoulder adduction ROM (lowest in freestyle, highest in butterfly and backstroke) and the logarithmic decrement of the anterior deltoid (lower in freestyle than backstroke and butterfly). These findings suggest that most shoulder adaptations reflect the general demands of high-volume swim training, while adduction mobility and anterior deltoid elastic behavior may serve as stroke-specific biomechanical indicators relevant to performance evaluation and shoulder injury prevention. Longitudinal studies with larger, multi-club samples are warranted to confirm and extend these observations.

Abbreviations

BMI	Body mass index
(F, Hz)	Oscillation frequency
(S, N/m)	Dynamic stiffness
(D)	Logarithmic decrement
(R, ms)	Relaxation time
(C)	Creep

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Authors' contributions

ÇE: Formal Analysis, Investigation, Writing – original draft, Data curation, Methodology, Supervision, Visualization. KÇ: Writing – original draft, Writing – review and editing, Investigation, Methodology. RM: Writing – original draft, Writing – review and editing, Investigation, Methodology, Supervision, Writing – original draft. SD: Visualization, Methodology, Writing – original draft, Writing – review and editing. GA: Visualization, Methodology, Writing – original draft, Writing – review and editing. EK: Investigation, Methodology, Supervision, Writing – original draft. KBT: Investigation, Methodology, Supervision, Writing – original draft.

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Data availability

The datasets generated and/or analyzed during the current study are not publicly available due to ethical restrictions related to participant confidentiality and the inclusion of sensitive clinical data. However, the data are available from the corresponding authors upon reasonable request, subject to approval by the Scientific Research and Publication Ethics Committee of Kütahya Dumlupınar University.

Declarations

Ethics approval and consent to participate

The study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Ethical approval was obtained from the Scientific Research and Publication Ethics Committee of Kütahya Dumlupınar University (Meeting No: 2025/12; Decision No: 42).

Prior to participation, all eligible participants and their legal guardians were provided with detailed verbal and written information regarding the study procedures, potential risks, and benefits. Written informed consent was obtained from all participants and their parents/guardians before inclusion in the study.

Consent for publication

No.

Competing interests

The authors declare no competing interests.

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