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Original Research

Sport-Specific Neuromuscular Profiles in Male Youth Swimmers and Sailors: A Comparative Analysis

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Abstract

International Journal of Exercise Science 19(1): 1-13, 2026. https://doi.org/10.70252/IJES2026101 Understanding the distinct biomechanical and neuromuscular demands of aquatic sports is key to developing targeted training strategies for youth athletes. This study compared neuromuscular profiles between male youth Thai swimmers and Optimist sailors by examining the Dynamic Strength Index (DSI) in upper and lower limbs. A secondary aim was to assess the relationships between the biological maturity, estimated via 2D:4D digit ratios and predicted peak height velocity (PHV) and neuromuscular performance. Forty male athletes ($n = 20$ per group; mean age: swimmers = 12.9 ± 0.7, sailors = 13.3 ± 0.8 years) completed ballistic (Countermovement Jump, push-up) and isometric (Isometric Mid-Thigh Pull, grip strength) tests. Swimmers showed significantly greater neuromuscular output in both limbs, with higher CMJ peak force (mean diff: 339.78 N; $p < 0.001$, $d = 1.64$) and push-up force (mean diff: 135.26 N; $p < 0.001$, $d = 1.51$), resulting in higher lower-limb DSI (0.86 vs. 0.70; $p < 0.01$, $d = 0.89$). Two-way ANOVA revealed a significant limb effect ($p < 0.001$, $\eta^2_p = 0.631$) and a sport × limb interaction ($p = 0.002$, $\eta^2_p = 0.104$), indicating sport-specific neuromuscular adaptations. Correlational analysis showed positive associations between lower-limb DSI and right-hand digit lengths and a negative relationship with PHV. These results underscore the importance of tailoring strength training to the sport-specific and maturational profiles of male youth athletes.

Keywords: Neuromuscular performance, aquatic sports, age-group athlete

Introduction

Different aquatic sports—such as swimming, sailing, rowing, canoeing and kayaking—impose unique physiological and biomechanical demands that shape neuromuscular development. Investigating these sport-specific adaptations in youth athletes provides critical insight into how training and maturation interact, offering a foundation for more individualized and developmentally appropriate performance strategies.[1,2] In male youth athletes, performance

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enhancement is closely associated with growth and maturation processes, requiring detailed evaluations of neuromuscular profiles to guide age-appropriate training and optimize long-term athletic development.[3,4,5,6]

The 2nd-to-4th digit ratio (2D:4D) and anticipated peak height velocity (PHV) have become recognized as non-invasive measures for evaluating biological maturity. Among maturation indicators, the 2D:4D ratio, which measures the relative lengths of the index (2D) and ring (4D) fingers, has been suggested as a biomarker for prenatal androgen exposure, with lower ratios typically correlating with increased testosterone exposure and enhanced capability in strength and power-oriented sports.[7,8]

Numerous researches have established connections between a reduced 2D:4D ratio and improved performance in swimming and sprinting, hence endorsing its prospective application in talent identification and neuromuscular profiling.[9,10] In sailing, evidence is limited; nonetheless, correlations have been established with coordination and postural endurance abilities that may indicate the special demands of the sport.[11] PHV, characterized as the phase of the most rapid increase in height during adolescence, is regarded as a pivotal indicator for comprehending the time and pace of maturation.[12] Male youth athletes nearing or surpassing peak height velocity experience temporary neuromuscular disturbances, characterized by diminished motor coordination and variations in strength, frequently termed of adolescent awkwardness.[3] These alterations may conceal training adaptations or misleadingly indicate performance plateaus, highlighting the necessity to account for maturation effects when evaluating neuromuscular characteristics such as strength and asymmetry.[13]

Both swimming and Optimist sailing are aquatic activities, but their mechanical and physiological requirements differ.[14,15] High-intensity, intermittent swimming requires full-body coordination and cycle propulsion against water resistance.[16] Performance in short-distance swimming competitions in male youth swimmers mostly relies on the ability to generate explosive power during starts and turns, with both upper and lower limbs being essential for force generation and velocity retention.[17,18] These movement patterns facilitate the enhancement of dynamic strength and rate of force production, particularly in muscles engaged in acceleration and momentum.[19,20]

In contrast, Optimist sailing requires extended submaximal and isometric muscle contractions, especially in the upper body and trunk, where postural stability and endurance are crucial for maintaining hiking positions and adjusting the sail in response to environmental conditions.[21,22] The neuromuscular demands of sailing in male youth sailors prioritize endurance over explosiveness, with performance reliant on upper-limb stability, fine motor control and postural endurance rather than rapid force generation.[23,24] The varied demands of each task likely result in differing neuromuscular adaptations in swimmers and sailors, perhaps creating unique sport-specific profiles of strength expression.[25]

The Dynamic Strength Index (DSI), a ratio of ballistic to maximal isometric force production, serves as a significant tool for assessing these adaptations.[26,27] A high DSI indicates an effective translation of maximal strength into dynamic performance, beneficial for explosive sports, while a lower DSI may signify superior isometric strength without corresponding dynamic conversion.[28] Although DSI has become prominent in profiling athletes in terrestrial sports like football, rugby and basketball its utilization in male youth aquatic sports is still restricted.[29,30] Analyzing DSI in the upper and lower limbs provides insight into sport-specific neuromuscular requirements and may assist in identifying asymmetries relevant to injury risk and performance efficiency.[31,32]

Adolescent male youth athletes experience substantial biological changes, such as growth spurts, hormonal fluctuations and neuromuscular reconfiguration.[12] These developmental characteristics can temporarily impact coordination, force generation, and motor control, therefore affecting performance irrespective of training adaptations. In this context, DSI provides a comprehensive method to differentiate training-related adaptations from maturation effects. Furthermore, assessing limb asymmetry yields essential insights for injury prevention and performance enhancement. Asymmetrical strength profiles are linked to compromised biomechanics, diminished performance and increased injury risk in male youth athletes.[26] In swimming, unilateral dominance in stroke mechanics can result in unbalanced force generation between limbs. In sailing, the continual use of one arm for steering and the preservation of fixed postures may result in asymmetries in postural or grip strength. Comparing ballistic and isometric peak force outputs across limbs, DSI testing can uncover neuromuscular abnormalities that may remain undiscovered in conventional performance evaluations.

Sport-specific training programs strengthen these neuromuscular pathways in male youth athletes. Swimmers frequently participate in dryland training to improve explosive strength, incorporating plyometric exercises and power-focused resistance training.[33] These routines aim to enhance starts, turns and stroke acceleration phases—activities that are advantageous with an elevated DSI. Conversely, Optimist sailors prioritize continuous muscular engagement and grip strength, leading to changes that enhance endurance and isometric force retention.[34,35] The varying training requirements indicate that dynamic and isometric strength capabilities may significantly differ across aquatic sports. Despite existing literature on the energetic and mechanical profiles of swimmers[1,18] and physical fitness indicators in sailors,[21,34] there is a paucity of research directly comparing neuromuscular characteristics between these disciplines, particularly among male adolescent athletes. Furthermore, there is a deficit of comprehension of the differences in DSI-based measurements between the upper and lower limbs in youth athletes, along with the interplay of asymmetry with sport-specific neuromuscular demands during critical phases of physical development.

The primary objective of this study is to compare sport-specific neuromuscular profiles between male youth Thai swimmers and Optimist sailors by examining the DSI in both upper and lower limbs. The study also examines associations between biological maturity indicators including the 2D:4D digit ratio and predicted peak height velocity (PHV) and neuromuscular performance. This study hypothesizes that male youth swimmers will exhibit higher DSI values in both upper and lower limbs compared to Optimist sailors, reflecting greater explosive strength demands. In contrast, sailors are expected to show superior isometric force capacity and lower DSI values due to the endurance and postural demands of sailing. Additionally, it is anticipated that lower 2D:4D digit ratios will correlate with higher DSI values, particularly among swimmers. Predicted PHV is expected to moderate neuromuscular performance, while asymmetry in strength expression will vary between sports based on their distinct unilateral movement patterns.

Methods

Participants

The software G*Power 3.1.9.2 was used to do an a priori power analysis in order to calculate the sample size. Preliminary assumptions included a Type I error rate of 5% and a Type II error rate of 5% (or 95% power). Based on these calculations, a minimum sample size of n = 38 is required to achieve a power of 0.95, an error probability of 0.05, and a high effect size of 0.60.[38] Twenty male youth Thai national swimmers and twenty male youth Thai national optimist sailors (age: 12.9 ± 0.7 vs. 13.3 ± 0.8 years, height: 1.69 ± 0.07 vs. 1.59 ± 0.09 m, body mass: 58.3 ± 9.1 vs. 47.3 ± 11.5 kg, maturity offset: -1.4 ± 0.6 vs. -1.5 ± 0.7 years) volunteered as participants. The criteria for registration are as follows: (i) a minimum of two years of experience in national competitions, (ii) qualification for the Thailand national youth team and (iii) being injury-free for a minimum of six months. Unsuitable health and physical condition with medical issues is excluded. The research complied with the World Medical Association's Declaration of Helsinki as approved by the local University Ethics Committee (code number HS025/2567(C3)). The male youth swimmers, optimist sailors and their guardians were provided with a comprehensive elucidation of the testing methodologies before securing signed agreement for participation. This research was carried out fully in accordance with the ethical standards of the *International Journal of Exercise Science*.[36]

Protocol

This study aimed to investigate sport-specific neuromuscular profiles in male youth Thai athletes through a cross-sectional, single-cohort design. Specifically, the study compared upper- and lower-limb DSI values between competitive swimmers and Optimist sailors to elucidate differences in strength expression attributable to sport-specific demands. DSI was calculated as the ratio of countermovement jump peak force (CMJ-PF) to isometric mid-thigh pull peak force (IMTP-PF) for the lower limbs and the ratio of ballistic push-up peak force to isometric grip strength for the upper limbs. In addition to neuromuscular profiling, the study examined the influence of biological maturity assessed via the 2D:4D and PHV on performance outcomes. The intention of the experiment was to identify the dimension to which maturation status and sport-specific mechanical demands influence neuromuscular asymmetry during adolescence. Additionally, the investigation addressed inter-limb asymmetry in both ballistic and isometric force output.

Forty male youth athletes voluntarily engaged in the study. The data gathering adhered to a standardized three-day testing methodology aimed at minimizing fatigue and improving reliability. On day one, anthropometric measurements, body composition and biological maturation indices (2D:4D and PHV) were evaluated utilizing validated methodologies. Day two concentrated on lower-limb neuromuscular evaluations, encompassing CMJ and IMTP exams to calculate lower-limb DSI. On day three, examinations of the upper limbs were performed utilizing ballistic push-up and isometric grip strength tests to determine upper-limb DSI values. All evaluations were conducted in controlled laboratory settings by qualified individuals utilizing calibrated instruments to guarantee measurement precision. Participants engaged in a familiarization session before testing to reduce learning effects and enhance procedural consistency. Ethical approval was obtained from the institutional review board, and written informed consent was secured from all participants and their legal guardians before the initiation of data collection (Figure 1).

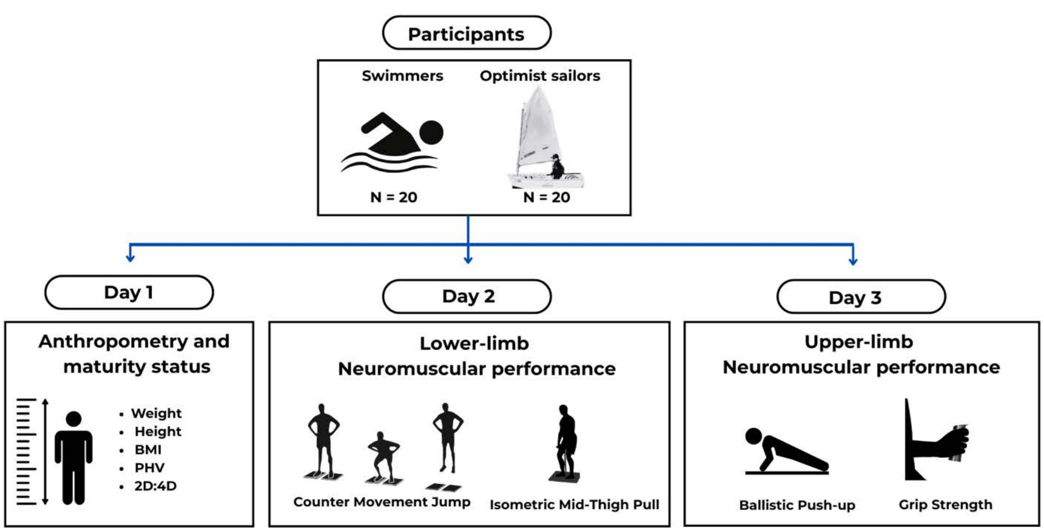

Figure 1. Experimental testing overview

Anthropometric measurements, including body mass, height and body mass index, were acquired using the Body Composition Analyzer: X-CONTACT 357S (Jawon Medical Co., Ltd., South Korea), in accordance with the approval from the International Society for the Advancement of Kinanthropometry.[33] The biological maturity offset was calculated by measuring the age at peak height velocity(age-at-PHV).[12] Weight, height, seat height and gender were all variables in a particular computation. The maturation offset is a quantitative indicator indicating the number of years an individual is from their PHV age. A positive maturity offset (+) shows the number of years a subject has played the activity after PHV, whereas a negative maturity offset (-) indicates the number of years until PHV. The 2D:4D was measured following a standardized anthropometric protocol to ensure high reliability and reproducibility.[8] Participant was seated with their right-hand placed palm-up on a flat surface, as the right hand is reported to show greater sexual dimorphism in 2D:4D values.[8] The lengths of the index (2D) and ring (4D) fingers were measured from the proximal basal crease to the fingertip, with the fingers extended and adducted.[8] Two measurements were recorded per digit, with a third taken if discrepancies exceeded 0.5 mm; the mean of the two closest values was used.[37] The 2D:4D ratio was calculated as the length of 2D divided by 4D.[7]

The lower-limb DSI was calculated from force-time curve data as the ratio of peak force achieved during the CMJ to that during the IMTP.[28,30] The CMJ was performed using a dual force platform system (K-Deltas, Kinvent Physio, Montpellier, France) with a sampling rate of 1000 Hz, ensuring high-resolution kinetic data collection.[39] Sixty seconds after the CMJ, subjects performed the IMTP utilizing the same force platform system. In the IMTP, age-group athletes were directed to exert maximal force on a stationary bar at mid-thigh height while simultaneously pushing their feet against the platform for a continuous duration of 5 s, adhering to recognized isometric strength testing standards.[28] Peak vertical ground reaction forces (N) from both CMJ and IMTP trials were obtained to calculate the DSI (CMJ-PF / IMTP-PF). The asymmetry index was computed to evaluate unilateral strength asymmetry by determining the percentage difference in peak force between the dominant (D) and non-dominant (ND) limbs, utilizing the formula: $[(D - ND) / D] \times 100$, where the dominant limb is identified as the one exerting the higher peak force.[26,31]

The upper-limb DSI was determined by two validated assessments: the ballistic push-up and the isometric grip strength test. Both assessments were performed utilizing high-precision apparatus supplied by Kinvent Physio (Montpellier, France). The ballistic push-up was executed using a K-Deltas dual force platform system, sampling at 1,000 Hz to ensure high-quality kinetic data collection.[28] Participants positioned their hands at shoulder-width on the force plates and performed a regulated eccentric phase until their chest made contact with the platform, subsequently executing an explosive concentric push to achieve hand lift-off, in accordance with established upper-body power protocols.[40] Isometric grip strength was assessed 60 s after the push-up using a calibrated K-Grip Dynamometer (Kinvent Physio, Montpellier, France). Participants executed maximal voluntary contractions for 5 s on each hand, interspersed with a 30 s rest period to mitigate fatigue. Peak force (N) results from the ballistic push-up and grip strength assessments were utilized to calculate the ratio of dynamic to isometric force output for DSI evaluation. The analysis of unilateral strength asymmetry involved computing the percentage difference in peak force between the dominant (D) and non-dominant (ND) limbs using the formula: $[(D - ND) / D] \times 100$, as recommended by Bishop.[26]

Statistical Analysis

All statistical analyses were conducted using SPSS (Version ***25.0***, IBM Corp., Armonk, NY, USA), with a significance threshold established at $p < 0.05$. Descriptive statistics (Mean ± SD) were employed to characterize all continuous variables, including anthropometric features, biological maturation indicators (2D:4D ratio and PHV), peak force outputs, and DSI values for both upper and lower limbs. The assumptions of normality, homogeneity of variance, and sphericity were assessed using the Shapiro–Wilk test, Levene's test and Mauchly's test, respectively. The Greenhouse–Geisser adjustment was used in instances of sphericity violation. A two-way mixed-design analysis of variance (ANOVA) was performed to investigate the primary effects of sport (swimming vs. sailing) and limb (upper vs. lower) on DSI, along with their interaction. Partial eta squared (η^2□) was utilized as an effect size metric, with thresholds classified as small (≥0.01), medium (≥0.06) and large (≥0.14) (Table 2). Independent samples t-tests were employed to undertake group comparisons of DSI and inter-limb asymmetry indices. Cohen's d is utilized to measure effect magnitude for group differences, with established standards of small (0.2), medium (0.5) and large (0.8). The relationships between biological maturity markers (2D:4D, PHV) and DSI variables were evaluated using Pearson's correlation coefficients using JAMOVI software (version 0.9, The Jamovi project, 2019), with correlation strength categorized as small (|r| = 0.1–0.3), moderate (|r| = 0.3–0.5), or strong (|r| > 0.5) (Figure 2).

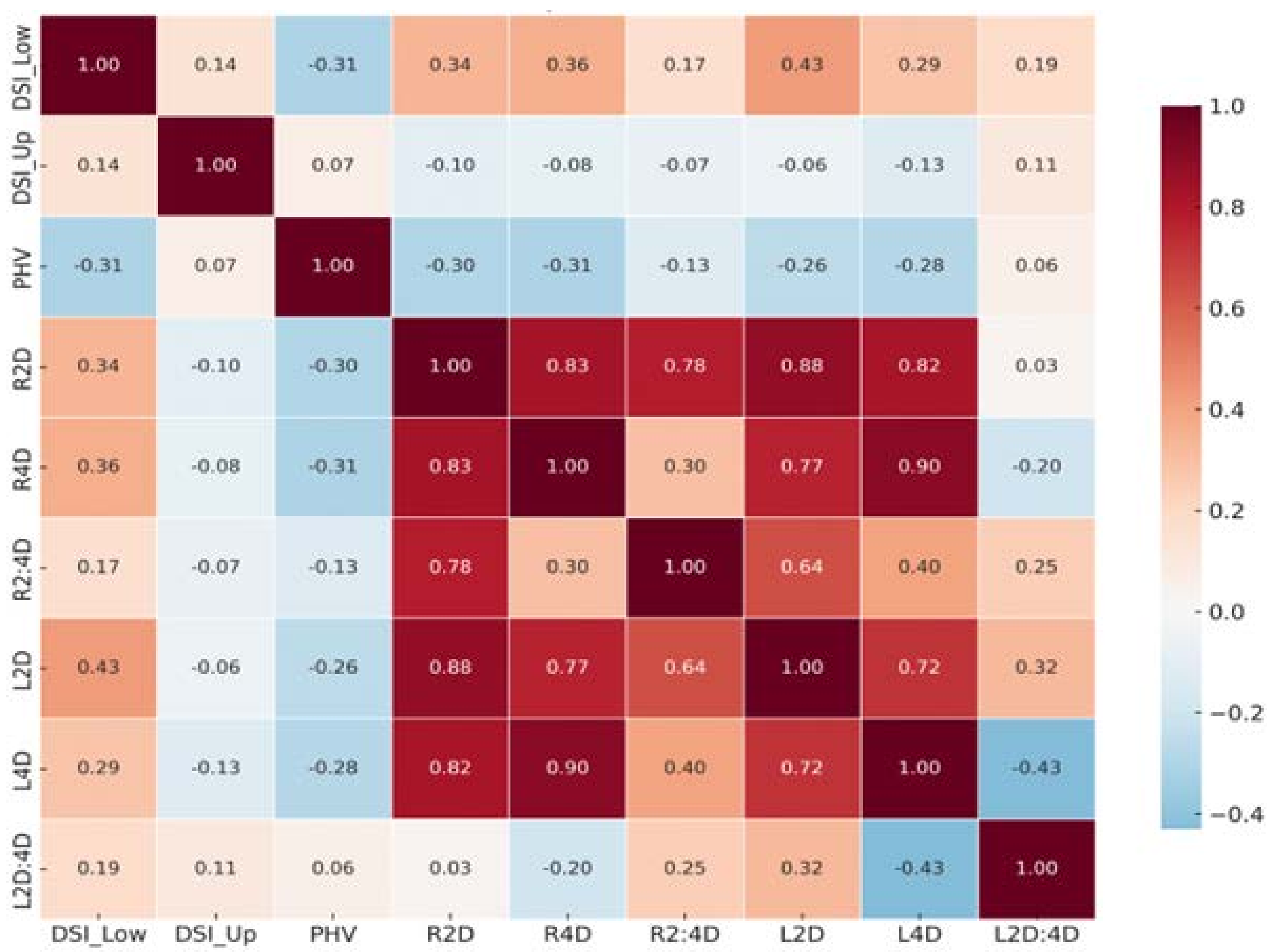

Figure 2. Pearson correlation heatmap illustrating the relationships between dynamic strength indices (DSI_Low and DSI_Up), biological maturation (PHV), and digit measurements including individual finger lengths (R2D, R4D, L2D, L4D) and calculated digit ratios (2D:4D).

Results

The descriptive statistics for all variables are presented in Table 1. The physical advantage in male youth swimmers were found in height (p = < 0.01; d = 1.38; large) and body weight (p = < 0.01; d = 1.04; large). The difference in neuromuscular performance was found in lower limbs DSI with the values from male youth swimmers was higher than from that obtained from male youth optimist sailing (p = < 0.04; d = 0.74; moderate). Male youth swimmers had higher CMJ peak force (p = < 0.01; d = 1.43; large) with no significant difference in IMTP (p = 0.74; d = 0.13; trivia), resulting in a higher DSI (0.88 vs. 0.70 %; 20.54%). For the upper neuromuscular performance, swimmers also had significantly stronger dynamic push-up (p = < 0.01; d = 1.31; large) and isometric grip strength (p = 0.03; d = 0.87; large) and a slightly higher DSI (1.27 vs. 1.20 %; 5.51%), respectively.

Table1. Differences in general characteristics and biological maturation and neuromuscular performance between male youth Thai swimming ad optimist sailing. Mean ± SD values with the respective level of probabilities (p), mean differences, 95% confidence intervals, relative changes (%Δ) and significant effect sizes.

Variables	**Swimmers**	**Optimist Sailors**	**Difference [95%CI]; %Δ**	**p-value**	**Effect size (d)**
General characteristics and biological maturation					
Age (yrs)	12.94 ± 0.61	13.29 ± 0.61	-0.35 [-0.74, 0.04]; 2.70 %	0.07	-0.58
Weight (kg)	58.33 ± 8.51	47.29 ± 9.97	11.04 [5.11, 16.97]; -18.93 %	<0.001	1.19
Height (m)	1.69 ± 0.06	1.59 ± 0.07	0.11 [0.06, 0.15]; -5.92 %	<0.001	1.56
Body mass index (kg□m^{-2})	20.23 ± 2.09	18.56 ± 2.38	1.67 [0.24, 3.11]; -8.26 %	0.02	0.75
Maturity offset (yrs)	-1.45 ± 0.49	-1.55 ± 0.62	0.10 [-0.26, 0.45]; -5.85 %	0.59	0.16
R2D (mm)	76.90 ± 3.60	72.40 ± 9.00	0.45 [0.11, 8.90]; -5.85 %	0.04	0.66
R4D (mm)	80.00 ± 2.64	76.90 ± 6.20	0.31 [0.11, 6.20]; -3.88 %	0.04	0.65
R2D:4D ratio	0.96 ± 0.26	0.94 ± 0.07	0.02 [-0.11, 0.06]; -2.08 %	0.22	0.39
L2D (mm)	76.50 ± 2.10	72.00 ± 7.40	0.46 [1.10, 8.10]; -5.88 %	0.01	0.83
L4D (mm)	80.00 ± 2.50	75. 80 ± 7.80	0.46 [1.00, 8.30]; -5.37 %	0.01	0.77
L2D:4D ratio	0.95 ± 0.02	0.95 ± 0.01	0.00 [-0.04, 0.04]; 0.00 %	0.99	0.01
Neuromuscular performance					
Total CMJ peak force (N) 1,336.16+256.82 1,261.21+289.54 1,406.46+240.00 1,263.07+259.80 1,317.95+265.03	1,393.81 ± 192.94	1,054.03 ± 220.16	339.78 [207.26, 472.30];-24.38%	<0.001	1.64
CMJ asymmetry (%)	6.11 ± 3.52	2.89 ± 1.42	3.22 [1.50, 4.94];-52.70 %	<0.001	1.20
Total IMTP peak force (N)	1,665.81 ± 353.75	1,632.40 ± 536.87	33.41 [-257.62, 324.45];-2.01 %	0.82	0.07
IMTP asymmetry (%)	7.59 ± 4.69	9.57 ± 7.08	-1.98 [-5.83, 1.87]; 26.09 %	0.30	-0.33
Lower limb DSI	0.86 ± 0.18	0.70 ± 0.18	0.16 [0.04, 0.27];-18.60 %	0.01	0.89
Total push-up peak force (N) 1,336.16+256.82 1,261.21+289.54 1,406.46+240.00 1,263.07+259.80 1,317.95+265.03	659.92 ± 71.34	524.66 ± 104.90	135.26 [77.84, 192.68];-20.50 %	<0.001	1.51
Push-up asymmetry (%)	11.29 ± 7.54	20.70 ± 11.26	-9.41 [-15.54, -3.27];83.35 %	0.01	-0.98
Total grip strength peak force(N)	554.83 ± 136.83	447.14 ± 110.12	161.83[105.26, 218.40];-19.41 %	<0.001	1.83
Grip strength asymmetry (%)	9.79 ± 5.47	10.44 ± 7.39	-0.65 [-4.81, 3.52]; 6.64 %	0.78	-0.10
Upper limb DSI	1.09± 0.11	1.20 ± 0.21	-0.11 [-0.21, 0.00]; 10.09 %	0.05	-0.63

Note: R2D, Right 2nd digit length; R4D, Right 4th digit length; R2D:4D ratio, The right 2nd-to-4th digit ratio; L2D, Left 2nd digit length; L4D, Left 4th digit length; L2D:4D ratio, The left 2nd-to-4th digit ratio, CMJ, Counter movement jump; IMTP, Isometric mid-thigh pull; DSI, Dynamic strength index. Cohen's values were calculated and interpreted as follows: small (0.2), medium (0.5), and large (0.8).

Table 2. Two-way mixed-design ANOVA assessing the effects of sport (swimming vs. sailing), limb (upper vs. lower) and their interaction on the DSI. A main effect of limb was found ($F = 196.88$, $p < 0.001$, $\eta^2_p = 0.631$). The interaction between sport and limb was also significant ($F = 6.65$, $p = 0.002$, $\eta^2_p = 0.104$). No main effect of sport was observed ($F = 0.36$, $p = 0.701$, $\eta^2_p = 0.006$).

Source of variance	Sum of squares	df	F	p-value	η^2_p
Sports	0.02	2.0	0.36	0.701	0.006 (small effect)
Limbs	5.20	1.0	196.88	0.000	0.631(large effect)
Sports × Limbs	0.35	2.0	6.65	0.002	0.104(moderate effect)
Total	8.12	120.0			

Note: Partial eta squared (η^2_p) was utilized as an effect size metric, with thresholds classified as small (≥0.01), medium (≥0.06), and large (≥0.14) (Cohen, 1988)

Discussion

This study aimed to examine the sport-specific neuromuscular profiles between male youth Thai swimmers and Optimist sailors by analyzing upper and lower limb DSI and to explore the comparison of biological maturity, assessed through the 2D:4D digit ratio and predicted PHV on neuromuscular performance. The results indicated that male youth Thai swimmers exhibited significantly greater height and body mass than their Optimist sailing counterparts, accompanied by superior neuromuscular performance in both upper and lower extremities. Notably, swimmers demonstrated significantly higher CMJ peak force and dynamic push-up force, contributing to elevated DSI values, particularly in the lower limbs (0.88 vs. 0.70), despite no significant differences in IMTP force.

The analysis demonstrated that DSI values differed notably between upper and lower limbs across both male youth swimming and sailing groups, highlighting the influence of limb-specific demands. Additionally, the difference in DSI between limbs varied depending on the sport, suggesting sport-specific neuromuscular adaptations. However, when considering overall DSI values averaged across both limbs, there was no meaningful difference between swimmers and sailors. These findings emphasize that while limb-specific strength characteristics vary by sport, the combined upper and lower-limb DSI does not distinguish between the two aquatic disciplines. Pearson correlation analysis indicated that lower-limb DSI exhibited a slightly positive association with the lengths of the right second and fourth digits (R2D, R4D), while demonstrating a negative correlation with anticipated PHV. Upper-limb DSI demonstrated negligible correlations with other variables. Overall, the findings partially support the research hypothesis, indicating that sport-specific neuromuscular adaptations and biological maturity associated with variations in lower-limb DSI in this comparative analysis.

Theoretically, growth-oriented neuromuscular adaptation, sport-specific requirements beyond biological maturation significantly influence adolescent strength profiles, so validating DSI as a beneficial tool for personalized and contextually relevant training interventions.[3,8,28,33] Instead, they highlight the critical influence of biomechanical demands and training stimuli unique to each sport. Swimming, characterized by high-intensity, cyclical propulsion and explosive force application during starts and turns, appears to foster greater dynamic strength output ,[16,17,19] as reflected in elevated CMJ and push-up peak forces. In contrast, sailing emphasizes sustained isometric contractions and postural endurance,[21,22] which may not translate effectively to high DSI values.

In the present study, the results highlight significance of sport-specific neuromuscular adaptations in male youth aquatic athletes, using the DSI as a sensitive metric for evaluating explosive capabilities. Male youth Thai swimmers exhibited consistently higher DSI values than Optimist sailors, especially in the lower limbs, despite similar biological maturity as indicated by maturity offset. These findings challenge traditional assumptions that strength and power development in adolescents are primarily driven by maturation ,[3,6,12] emphasizing instead the influence of biomechanical demands and training specificity. Importantly, this study is the first to compare upper and lower-limb neuromuscular performance using the DSI between male youth swimmers and Optimist sailors, specifically within the pre-pubertal to pubertal age range (11–14 years), during which growth and biological maturation are known to significantly influence athletic performance.[6,12] The current study finding that male youth Thai swimmers exhibited a higher mean lower limb DSI (0.88) than both youth optimist sailors (0.70) and previously reported male youth Brazilian soccer players (0.76).[29] This study corroborates the idea that higher DSI in swimmers reinforces the concept that the dynamic expression of force, or the capacity to apply strength rapidly, is significantly influenced by the demands of the swimming.[17,18,33]

In swimming, a powerful leg drive is crucial for starts and turns key performance phases that demand significant force over short durations ,[2,16] while sailing prioritizes isometric strength and postural endurance.[21,22] Consequently, optimistic sailors in this study demonstrated a lower lower-limb DSI, a result that is both expected and informative. This supports the theoretical assertion regrading that prolonged isometric loading may be insufficient to elicit the neuromuscular adaptations required for rapid connectivity force application, especially in youth athletes who continue to develop motor control and explosive strength capabilities.[21,22]

From the perspective of upper-limb DSI, the finding that male youth Thai swimmers exhibited significantly higher dynamic push-up force, isometric grip strength and marginally greater DSI values than their Optimist sailing counterparts suggests that swimming promotes more robust upper-limb neuromuscular development during the pre-pubertal and pubertal years. This aligns with the biomechanical demands of swimming, where repetitive, high-intensity upper-body movements particularly in strokes like freestyle and butterfly require rapid force generation and contribute to superior dynamic strength.[17,33] In contrast, while sailing does involve upper-limb activity, it primarily relies on intermittent and isometric contractions for sail handling and postural stabilization.[21,22,34] The comparatively lower DSI in sailors reflects these unique sport demands, emphasizing control, endurance and balance over explosive power. This distinction highlights the importance of considering sport-specific neuromuscular profiles and challenges the blanket use of performance metrics like DSI across male youth sports.

Another important finding was that the identifying asymmetry patterns, which reflect sport-specific neuromuscular adaptations. Specifically, male youth Thai swimmers exhibited higher CMJ asymmetry (6.11%) compared to Optimist sailors (2.89%), indicating uneven force distribution likely resulting from dominant limb propulsion during ballistic lower-limb tasks consistent with prior swimming biomechanics research.[1,27] In contrast, Optimist sailors exhibited greater asymmetry in upper-body push-up performance (20.70% vs. 11.29%), potentially resulting from the unilateral postural loading necessitated by sail handling and body stabilization during competition.[21,22,34] These findings suggest that while swimmers adapt to symmetrical force production needs through bilateral propulsive movements, sailors are exposed to repetitive unilateral demands that induce chronic force imbalances. Consequently, these asymmetries reflect the neuromuscular specificity of each sport, underscoring the importance of tailored training to balance functional imbalances and enhance performance.

From a theoretical perspective, the development of strength in male youth aquatic athletes is predominantly influenced by sport-specific biomechanical demands and training stimuli rather than completely by biological maturation, as indicated by the complex interplay of these factors.[3,28] Lower-limb DSI had moderate positive associations with the lengths of the right-hand second and fourth digits, indicating that absolute digit lengths may be linked to improved strength expression.

These results correspond with earlier research indicating that digit lengths, irrespective of the 2D:4D ratio, may indicate musculoskeletal development, presumably influenced by prenatal androgen exposure.[7,8] A moderate inverse correlation was noted between the left-hand 2D:4D ratio and the length of the left fourth digit, illustrating the mathematical relationship between the digits and endorsing its application as a non-invasive biomarker of hormonal influences.[8,10,11] Furthermore, lower-limb DSI had a negative correlation with PHV, indicating that adolescents undergoing rapid growth may have a transient decline in neuromuscular coordination, a phenomenon frequently referred to as adolescent awkwardness.[6,12] This underscores the need of correlating neuromuscular evaluations with biological age instead than chronological age.

Finally, while this study provides novel and valuable insight into sport-specific neuromuscular adaptations in male youth aquatic athletes, several limitations must be acknowledged that may influence the interpretation and generalizability of the findings. First, the cross-sectional design limits interpretation to between-group comparisons at a particular time point and limits the assessment of longitudinal developmental changes in neuromuscular performance. Future longitudinal studies are advised to investigate the evolution of neuromuscular profiles during developmental phases and to determine if sport-specific training influences these changes or impacts strength asymmetries. Secondly, variations in training exposure encompassing frequency, intensity, modality and duration were neither standardized nor carefully documented among participants. Athletes that engage more extensively in structured strength or resistance training, particularly apart from their main activity (e.g., dryland conditioning), may have enhanced dynamic strength and DSI values, regardless of the neuromuscular requirements of their individual sport. Third, the findings are not applicable to female youth athletes, who have different growth trajectories, hormonal profiles, and neuromuscular adaptation patterns during adolescence. Future studies should include female swimmers and sailors to investigate sex-specific Dynamic Strength Index profiles and training responses. Finally, the swimmer cohort exhibited markedly greater stature and body mass than the sailor cohort, with substantial effect sizes noted for both anthropometric measures. These physical characteristics presumably provided biomechanical benefits that may have led to enhanced force generation and elevated DSI results, thus complicating sport-related comparisons.

This study highlights the significance of sport-specific biomechanical requirements and training stimuli beyond biological maturation in determining neuromuscular performance in male youth aquatic athletes. Despite swimmers and Optimist sailors displaying comparable biological maturity, swimmers revealed markedly elevated DSI values, especially in the lower extremities, presumably attributable to the explosive propulsion necessitated during starts and turns. These findings challenge the myth that strength development in teenagers is exclusively dictated by maturation and highlight the critical importance of recurrent, high-intensity and sport-specific demands. These data indicate that training strategies must be customized to the neuromuscular characteristics of each specialty. Swimmers may benefit from plyometric and ballistic workouts that improve lower-limb explosive power, whereas sailors may need strength and stability programs aimed at enhancing postural control and rectifying uneven force distributions resulting from unilateral tasks. Furthermore, the DSI functions as a comprehensive and effective instrument for evaluating explosive strength and informing personalized training when analyzed alongside biological maturity status. It is crucial to align neuromuscular development strategies with the physiological stage and biomechanical realities of each activity to optimize male youth performance, foster long-term athletic development and minimize the risk of sport-related imbalances and injuries.

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