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The Longitudinal Mediating Influence of Maturation on the Relationship Between Strength and Performance in Male Youth Swimmers

Shaun Abbott,[1] Wei En Leong,[1] Tom Gwinn,[1] Giovanni Luca Postiglione,[1] James Salter,[2] and Stephen Cobley[1]

[1]Sydney School of Health Sciences, Faculty of Medicine & Health, University of Sydney, Sydney, NSW, Australia;
[2]Swimming Australia Ltd, Sunnybank, QLD, Australia

Purpose: To examine the longitudinal relationships between shoulder internal and external rotation (IR and ER) strength, maturity status, and swim performance (aim 1). To determine whether maturity status mediated (partially/fully) the relationship between shoulder IR/ER strength and performance in age-group swimmers (aim 2). *Methods:* Using a repeated-measures design, anthropometrics, maturity status, shoulder IR/ER strength, and 200-m front-crawl velocity were assessed over 3 competition seasons in $N = 82$ Australian male competitive swimmers (10–15 y). For aim 1, linear mixed models examined longitudinal relationships between assessed variables. For aim 2, causal mediation analyses examined proportional (in)direct contributions of maturity status between shoulder IR strength and swim performance. *Results:* For aim 1, linear mixed models identified a significant relationship between shoulder IR strength and swim performance over time ($F_{1,341.25} = 16.66$, $P < .001$, marginal $R^2 = .13$, conditional $R^2 = .91$). However, maturity status was influential (ΔAkaike information criterion $= -75.8$, $\chi^2 = 19.98$, $P < .001$), suggesting removal of the shoulder IR strength–swim velocity relationship ($F_{1,214.1} = 0.02$, $P = .88$). For aim 2, mediation analyses identified maturity status as fully mediating the shoulder IR strength–swim velocity relationship (92.30%, $P < .001$). *Conclusions:* Shoulder IR and ER strength did not account for variance in longitudinal age-group swim performance independent of maturity status. Interindividual differences in maturity status fully explained the relationship between shoulder IR/ER strength and swim performance. For practitioners, findings promote the need to account for maturation status and question the rationale for upper-limb strength assessment during maturational years.

Keywords: athlete development, interindividual differences, mediation, swimming, maturity, front crawl

Researchers consistently highlight the multifactorial and dynamic process of athletic development.[1,2] Depending on the sport context, numerous physical characteristics commonly underpin or influence performance to a greater or lesser extent over time, including aerobic/endurance capacities, upper-body and lower-body strength, and flexibility.[3,4] However, isolating the contributions of physical performance characteristics from other independent and confounding influences is challenging,[5] potentially affecting the accuracy and interpretation of athlete assessment and subsequent practitioner decision making, such as the design and content of training programs by coaches and sport science support.

Muscular strength is one physical characteristic that is a consistent predictor of performance and is important in sport contexts where force is required for task proficiency.[4,6] In front crawl swimming, shoulder internal rotation strength is required to generate propulsive force and involves several muscles of the shoulder joint (ie, pectoralis major, latissimus dorsi, and anterior deltoid).[7,8] Shoulder internal rotation and arm extension strength are essential during the pull-through phase with such upper body contributions estimated to account for 90% of overall velocity.[9] When assessed in isolation and on dry land, maximal voluntary upper limb strength is consistently correlated with improved front crawl performance (eg, time) in age-group[10] and adult swimmer cohorts.[11] Longitudinal evidence has also verified how upper limb strength predicts front crawl sprint velocity (9–17 y).[12] However,

such relationships may have been interpreted as evidence of causality between upper limb strength and swimming performance. On this basis, it is understandable why practitioners have assessed strength and used such indices to inform programming.[13] Intuitively, dryland training may be implemented to optimize muscular strength in developing age-group swimmers[14] despite showing inconsequential and marginal improvements in swim performance.[12]

Across intervention periods in age-group swimmers, some studies have noted changes in growth but have not appropriately examined its relationship with either strength or swim performance.[9,15] Normative growth and maturation explain how muscle cross-sectional area is strongly associated with muscle strength independent of training intervention during adolescence.[16] Coaches and/or strength and conditioning practitioners, potentially unaware that growth and maturation are influential, may, therefore, inaccurately rationalize the importance of strength-based assessment and training when, actually, a greater proportion of strength gains may be explained by normative growth and maturation. Thus, better consideration of how growth and maturation influence the strength–performance relationship in youth swimming (and other relevant sport contexts) is warranted.

During adolescence, growth is typified by considerable potential interindividual anthropometric differences in height and weight,[6] whereas maturation refers to the relatively rapid change of bodily systems (eg, endocrine and skeletal) during such growth. In normative populations, peak maturational growth (peak height

velocity) typically occurs between 12 and 15 years of age for boys and 2 years earlier in girls.[17] Aligned with growth and maturation, physiological development also occurs. For instance, evidence suggests that peak height velocity precedes peak weight velocity and associated strength gains by approximately 12 to 18 months.[6] Such physiological developments are largely dependent on maturation timing and status and can account for the substantial interindividual performance variations within similar age-group cohorts.[18] Maturation timing and status have been previously associated with strength-based performance gains in, for example, gymnastics and tennis.[19,20] Furthermore, Duarte et al[21] illustrated how maturity-related growth predicted the nonlinear development of knee extension strength in adolescent male soccer players and how strength gains accelerated following peak maturation; greater stature and muscle mass were also independently associated with increased muscular strength over time. Thus, depending on the sport task and assessment time points, maturity status during adolescence could explain strength-based performance differences.

Given the potential direct and indirect influences of maturation status and strength on indices of youth performance, the present study had 2 aims. First, it examined the longitudinal relationships between shoulder internal rotation strength, maturity status, and performance in age-group competitive swimmers (aim 1). Second, it assessed whether maturity status partially or fully mediated the relationship between shoulder internal and external rotation strength and swim performance (aim 2). Findings would explain why researchers identify nonuniform strength–performance development within youth swimmer cohorts. Findings would also identify the extent (partially or fully) to which maturation status explains swim performance development over time. Thus, assessing growth and maturation may be more important per se than assessing strength within youth (prefull maturation) swimming programs and to better understand individual performance trajectories.

Methods

Subjects

Following University of Sydney research ethics approval (App. No: 2017/866), participants were N = 82 male Australian youth swimmers aged 10–15 years ($M_{Baseline}$ = 12.99, SD = 1.41). Participants were registered to (N = 15) swim clubs across New South Wales, Australia, and were included if they were male, were between 10 and 15 years, were free from injury or physical impairment, and competed at state or national age-group level based on respective qualification criteria (ie, qualifying times). Exclusion criteria were boys who were not registered to a club, were outside specified age ranges, or presently had an injury or impairment. On average, participant swim training frequency was between 4 and 8 times per week with session volume averaging approximately 4.95 (SD [0.73]) km. Dryland training frequency was between 2 and 5 times per week, consisting of approximately 20 minutes (SD [7.99]) per session of body weight (eg, push-ups) and plyometric (eg, squat jump) exercises.

Design

A repeated-measures design was applied to examine longitudinal relationships between muscular strength, maturity status, and swim performance. Data were collected on 3 measurement occasions per year, separated by approximately 4 months (M = 3.86,

SD = 1.16). Data collection spanned 3 competition seasons (2018/2019–2020/2021) for a maximum of 8 measurement occasions per participant, with one measurement occasion lost to COVID-19 shutdown. A minimum of 3 repeated measurements per participant were required for inclusion in data analysis (median = 5, range = 3–9).

Methodology

On each measurement occasion, participants completed standardized assessments, including body mass, height, and seated height measurements to determine maturity status. Physical assessment protocols included maximal isometric shoulder internal and external rotation (ie, IR and ER) and 200-m front crawl performance trials. Anthropometric assessments were completed within 5 days (SD = 0.17 d) of the 200-m front crawl time trial, and participants were not blinded to assessment procedures.

Anthropometrics.   Anthropometrics were measured according to the International Society for the Advancement of Kinanthropometry (ISAK) standards and taken in duplicate by the same assessor with averages recorded. If measures differed by 0.4 cm and 0.4 kg, respectively, a third measure was taken with the median value recorded. Body mass was measured to the nearest 0.1 kg using digital scales (Tanita, BC541), height using the stretched stature method, and sitting height (to the nearest 0.1 cm) using a portable stadiometer (Seca, 213, Seca GmbH & Co KG) and standard box (height 44.3 cm). To determine absolute agreement between anthropometric measures, intraclass correlation coefficients (ICCs) were applied using the following criteria: >.90, .75 to .90, .50 to .75, and <.50 indicated excellent, good, moderate, and poor reliability, respectively. Absolute agreement mean ICC_{Mass} > .99, 95% CI, .99 to 1.00; mean ICC_{Height} >.99, 95% CI, .99 to 1.00; and mean $ICC_{Sitting}$ >.99, 95% CI, .99 to 1.00 all indicated excellent measurement reliability.

Maturity Status.   To identify maturity status, Mirwald et al[22]'s noninvasive method, which estimates the chronological distance (in years) to/from peak height velocity (YPHV) with a standard error of 0.59, was used. Specifically, for young boys, the equation included chronological age at measurement, body mass, stature, sitting stature, and leg length:

Maturity offset(years) for boys

$$= -9.236 + (0.0002708 \times [\text{Leg length} \times \text{Sitting height}])$$
$$+ (-0.001663 \times [\text{CA} \times \text{Leg length}])$$
$$+ (0.007216 \times [\text{CA} \times \text{Sitting height}])$$
$$+ (0.02292 \times [\text{Weight by height ratio} \times 100])$$

Shoulder Strength.   A shoulder and arm dynamometer (TTM) was used to assess isometric shoulder IR and ER strength to the nearest 1 kilogram. In all swim strokes, shoulder IR strength is considered an important indicator of swim performance,[23] and handheld dynamometers are a valid,[24] safe, and simple tools[25] for assessing shoulder IR strength in youth swimmers.[26] All participants completed a familiarization session comprising 2 practice trials before an initial assessment. Following a standardized 10-minute warm-up, which included dynamic exercises (eg, dynamic shoulder stretching, elastic band internal rotations, and push-ups),

participants were instructed to stand upright with both arms at 90 degrees elbow flexion and in contact with the side of the body while holding the dynamometer. Participants were instructed to push inward maximally against the dynamometer with both arms for 5 seconds while maintaining an upright position (see Supplementary Material S1 [available online]). Participants completed 1 submaximal warm-up attempt followed by 2 maximal shoulder IR strength attempts separated by approximately 90 to 120 seconds. The maximal attempt with the highest value (kg) was taken forward for data analysis.

Following a 5-minute rest period, shoulder ER strength was assessed using the same procedure as for IR assessment. On this occasion, participants were instructed to pull maximally outward against the dynamometer for 5 seconds while maintaining an upright torso. Shoulder ER strength is not directly involved in swimming arm propulsion; however, it is generally considered an indicator of shoulder stability and injury risk in youth swimmers.[27] In this study, shoulder ER strength was examined to verify IR findings during mediation analysis (aim 2). To determine absolute agreement between shoulder IR/ER strength measures, ICCs were also applied using procedures similar to those reported for anthropometric measures. Excellent reliability was identified between maximal IR and ER dynamometer trial attempts during tracking (mean ICC_{IR} = .96, 95% CI, .95 to .97; mean ICC_{ER} = .94, 95% CI, .93 to .94).

Swim Performance. On each data collection occasion, a 200-m front crawl trial was completed. Front crawl trials were conducted in a standard 50-m swimming pool (water temperature: 25 °C–27 °C). Before each trial, participants performed a 1300-m standard warm-up, including low- to moderate-intensity swimming (see Supplementary Material S2 [available online]). Based on an in-water start, participants were instructed to complete the trial with maximal exertion. Swimming performance was determined by average 200-m velocity measured in meters per second. Average swim velocity was calculated (ie, $\bar{v}_{200} = d_{200}/t_{200}$) using the time taken to complete the 200-m trial. Times were measured by 2 trained researchers to the nearest 0.01 second using digital stopwatches (Hart Sport) and video recorder (GoPro), calibrated to 60 frames per second and 1080 pixels. The recorder was placed perpendicular to the pool, capturing the start and finish of trials. Excellent agreement was found between stopwatch relative to video camera timing methods (mean ICC = .99, 95% CI, .99 to 1.00; $F_{500,500}$ = 225.50; $P < .001$). Video recorded performance times were carried forward for data analysis.

Aim 1: *Statistical Analysis:* Linear mixed models (LMMs) examined longitudinal relationships between shoulder IR strength, maturity status, and swim performance. Data analyses were completed using R statistical software by R Core Team and *nlme* and *lme4* packages.[28,29] Data collection time point (time), shoulder IR strength, and YPHV were included as fixed effects in the LMM with participant ID (intercept) and time (slope) added as random effects. Statistical significance was set at $P < .05$, and marginal and conditional R^2 estimated the variance accounted for by the fixed effects and combined fixed and random effects within each model, respectively. An analysis of variance, change in Akaike information criterion (AIC), and likelihood ratio statistics tested model fit. Model diagnostics were also inspected for normality of residual variance (eg, Q-Q plots), linearity between outcome and predictors and collinearity between time, IR/ER strength, and maturity status. Data met all statistical assumptions (eg, homogeneity of variance in the residuals), whereas variance inflation factor statistics revealed no collinearity between covariates.

Aim 2: *Statistical Analysis:* To identify mediation, LMM relationships between (1) shoulder IR strength and swim performance (model 1), (2) shoulder IR strength with maturity status (model 2), and (3) maturity status with swim performance when adjusted for shoulder IR strength (model 3) were required (aim 1) to permit mediation analysis in line with criteria described by Baron and Kenny.[30] The *mediation* R package for causal mediation analysis was used to examine whether maturity status partially or fully mediated the relationship between shoulder IR strength and swim performance.[31] The package used bootstrapping methods to partition the total variance of shoulder IR strength on swim performance into direct and indirect (via maturity status) contributions toward swim performance. The average direct effects determined the independent effect of shoulder IR strength on swim performance. The average causal mediation effect determined the indirect effect of shoulder IR strength on swim performance through maturity status, whereas the proportion of the effect of shoulder IR strength on swim performance mediated by maturity status was calculated by dividing the average causal mediation effect by the total effect.

Results

Aim 1: Longitudinal Relationships Between Shoulder IR Strength, Maturity Status, and Swim Performance

Descriptive statistics for anthropometrics, maturity status, shoulder IR and ER strength, and 200-m front crawl performance are summarized according to data collection time point in Supplementary Material S3 (available online). An LMM with fixed and random effects identified a significant longitudinal relationship between shoulder IR strength and 200-m front crawl performance ($F_{1,341.25}$ = 16.66, $P < .001$, $\beta = 0.01$, $SE \leq 0.01$, 95% CI, 0.01 to 0.01, marginal $R^2 = .13$, conditional $R^2 = .91$; Figure 1A). Figure 1A illustrates longitudinal differences in swim performance trajectories according to varying progressions in shoulder IR strength as reflected by LMM trend lines for mean (M) shoulder IR strength (9.57 kg [1.0] SD), $M < -1.0$ SD (5.84 kg), and $M > 1.0$ SD (13.31 kg). When accounting for individual differences in swimmer maturity status at baseline, a significant time × shoulder IR strength interaction effect was apparent ($F_{1,157.93}$ = 13.39; $P < .001$; $\Delta AIC = -57.3$; $\chi^2 = 59.26$; $P < .001$; marginal $R^2 = .56$; conditional $R^2 = .93$, and identifying shoulder IR strength level still explained some degree of variance in individual swim performance slopes over time ($F_{1,346.56}$ = 11.64, $P < .001$, $\beta = 0.01$, $SE \leq 0.01$, 95% CI, ≤ 0.01 to 0.01) independent of baseline maturity status ($F_{1,115.60}$ = 79.44, $P < .001$, $\beta = 0.05$, $SE = 0.01$, 95% CI, 0.04 to 0.07). Figure 1B illustrates how baseline maturity status was also associated with performance over time when accounting for shoulder IR strength (interaction effect [time × $YPHV_{Baseline}$]: $F_{1,70.82}$ = 21.16, $P < .001$, $\beta \leq 0.01$, $SE \leq 0.01$, 95% CI, −0.01 to <−0.01; main effect [$YPHV_{Baseline}$]: $F_{1,107.01}$ = 98.95, $P < .001$, $\beta = 0.06$, $SE = 0.01$, 95% CI, 0.05 to 0.08). Figure 1B illustrates longitudinal differences in swim performance trajectories according to baseline maturity status as reflected by generated LMM trend lines for mean (M) baseline maturity status (−0.58 y [1.0] SD), $M < -1.0$ SD (−1.96 y), and $M > 1.0$ SD (0.81 y).

To test whether maturity status variations contributed to the time × shoulder IR strength interaction, a 3-way time × shoulder IR strength × maturity status interaction was added and relationships reexamined. When maturity status was included, shoulder IR strength no longer explained variance in swim performance (3-way interaction: $F_{1,274.88}$ = 0.02; $P = .88$; time × shoulder IR
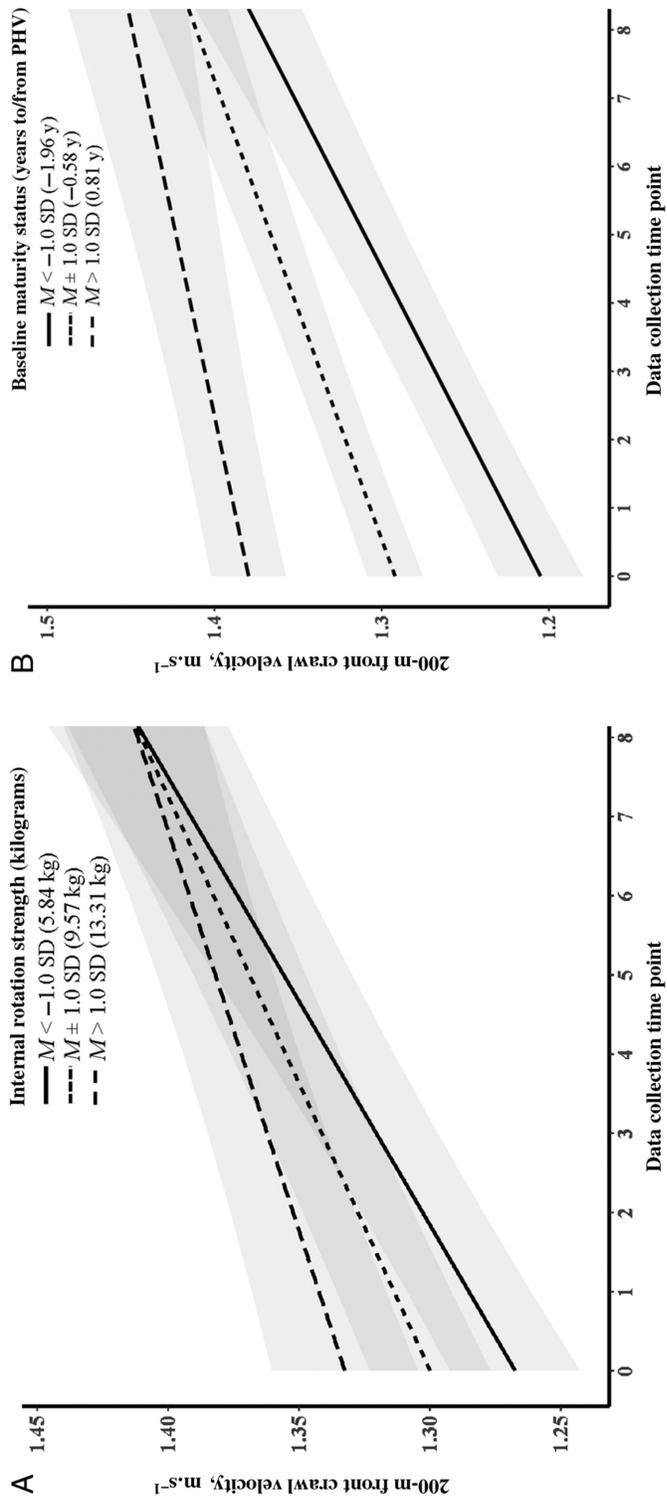
Figure 1 — (A) Longitudinal 200-m front-crawl velocity (in meters per second) performance trajectories according to mean (*M*) (1.0) SD shoulder internal rotation strength (in kilograms) during maximal isometric dynamometer trials. (B) Longitudinal 200-m front-crawl velocity (in meters per second) performance trajectories according to mean (*M*) (1.0) SD maturity status at baseline (years to/from peak height velocity). PHV indicates peak height velocity.

strength interaction: $F_{1,212.94} = 0.41$; $P = .52$, main effect [time]: $F_{1,214.1} = 0.02$; $P = .88$; main effect [shoulder IR strength]: $F_{1,298.99} = 0.71$; $P = .40$). Instead, a time × maturity status interaction ($F_{1,245.37} = 6.00$; $P = .01$) and main effect of maturity status were apparent ($F_{1,299.91} = 29.70$; $P < .001$), suggesting that maturity status accounted for variance in shoulder IR strength and independently explained variance in swim performance with diminishing contribution over time. The removal of longitudinal relationships (main and interaction) between shoulder IR strength and 200-m front crawl velocity when maturity status was included led us to conduct causal mediation analysis (aim 2). Supplementary Material S4 (available online) further summarizes the systematic fitting of LMMs for 200-m front crawl velocity.

Aim 2: Mediation Analysis Between Shoulder IR Strength, Maturity Status, and Swim Performance

Mediation analysis identified no direct relationship between shoulder IR strength and swim performance ($P = .36$, model 3, Figure 2A). Instead, an indirect—fully mediated—relationship between shoulder IR strength and 200-m front crawl velocity via maturity status was identified (average causal mediation effect = 0.02, 95% CI, 0.01 to 0.02, $P < .001$) with the percentage of total mediation influence explained at 92.3% ($P < .001$). Findings indicated that a 1-unit increase in shoulder IR strength was associated with a 0.02 m·s^{-1} increase, which corresponded to a ~3.35 second decrease in a 200-m trial (model 1; Figure 2A), yet this relationship was fully mediated and explained by maturity status. To verify findings, mediation analysis was repeated with shoulder ER strength examined. Again, the relationship was fully mediated by maturity status (ie, 100%, $P < .001$). Figure 2A, B summarizes the path estimates for the indirect and direct effects calculated between shoulder IR/ER strength, maturity status, and 200-m front crawl velocity.

Discussion

Related to aim 1, findings identified a significant linear longitudinal relationship between shoulder IR strength and front crawl velocity. When maturity status was accounted for at baseline, shoulder IR strength still partially explained differences in longitudinal velocity trajectories over time with increases in shoulder IR strength associated with greater swim velocity improvement. That said, such interindividual differences in shoulder IR strength reduced over time. Independently, more progressed maturity status at baseline was also associated with greater 200-m front crawl velocity over time. However, at later data collection time points, there was convergence with individuals with lower baseline maturity status. Longitudinal changes in maturity status also eliminated the main and interaction relationships between shoulder IR strength and 200-m front crawl velocity. Specifically, LMMs suggested that maturity status better explained longitudinal trends in front crawl velocity than shoulder IR strength ($\Delta AIC = -13.9$). Related to aim 2, mediation analyses confirmed that shoulder IR strength was associated with 200-m front crawl velocity in male age-group swimmers. However, when maturity status was introduced as a mediating factor, changes in maturity status fully accounted for the shoulder IR strength–swim velocity relationship. The indirect relationships were also verified when examining shoulder ER strength.

When compared with existing literature, findings from aim 1 uniquely identified that maturity status was potentially more explanatory of swim performance than shoulder IR strength.[9,12,15]

When mediation analyses were conducted (aim 2), findings were also novel as shoulder IR and ER strength gains over time and their relationship with swim performance were fully explained by maturity status during years associated with adolescent growth. Current findings provide greater understanding as to why coaches may rationalize and consider value from strength assessment and training during adolescence. Researchers and practitioners may not have previously recognized how maturation confounds the influence of strength on front crawl performance over time. That said, mediation analyses acknowledged that approximately 8% of the shoulder IR strength–swim velocity relationship was explained by other factors unrelated to maturity status (eg, in-water and dryland training effects).

Related to aim 2, as maturation is associated with multiple bodily structure and system changes (eg, hormonal and neurological), the potential explanations for present findings could be numerous. Specific to muscular strength, differences between children, adolescents, and adults have previously, in part, been explained by progressive maturity-related changes in muscle–tendon architecture and size.[32] During maturation, increasing bone length is associated with muscle length (stretching), which stimulates skeletal muscle growth.[33] Increases in skeletal muscle mass include increased fascicle length and cross-sectional area (eg, myosin heavy chain size and number), which contribute to increased muscular force production over time.[34] Also aligned with aim 2 findings, maturation-related body segment and limb growth (ie, length) may partially explain mediating effects of maturity status on the shoulder IR and ER strength–performance relationship in youth swimmers. For instance, increased hand surface area has been previously associated with improved in-water strength indicators (eg, propulsion) independent of upper body dryland strength (eg, chest press).[9]

Present findings suggest several implications for researchers as well as sports systems and their practitioners (ie, coach, talent development programs manager, and support scientists) alike. Either within research or applied performance settings, a key implication is the need for consideration of maturity status (as part of longitudinal tracking) to better account for the influence of interindividual developmental differences. Practitioners operating within sport contexts and where physical characteristics closely relate to task proficiency need to consider current practices (eg, physiological testing, training programming, and competitive evaluation) where there is potential for growth and maturational confounding. Integrating maturity status assessment could help better explain nonuniform strength- (or physical)-related performance development over time. Current findings also question the rationale for applying strength-based assessment pre and during peak maturational growth. Nonetheless, strength assessment may be important when maturation-associated influences have subsided, again, which will chronologically vary between developing swimmers.

Present findings are not without potential limitations. For instance, we were unable to control for training load influences (eg, in-water and dryland). Such information may have helped further explain findings but, still, may not have been able to override the fully mediating effect of maturity status on the strength–performance relationships. Furthermore, LMM analyses also identified that the remaining interindividual variability (ie, intercepts and slopes) in swim velocity development over time could also be explained by several other factors (eg, biomechanical and technical skill, body shape, and composition) associated with swim performance development. As such, study findings acknowledge the likely (and potentially interrelated) contributions from multiple factors.
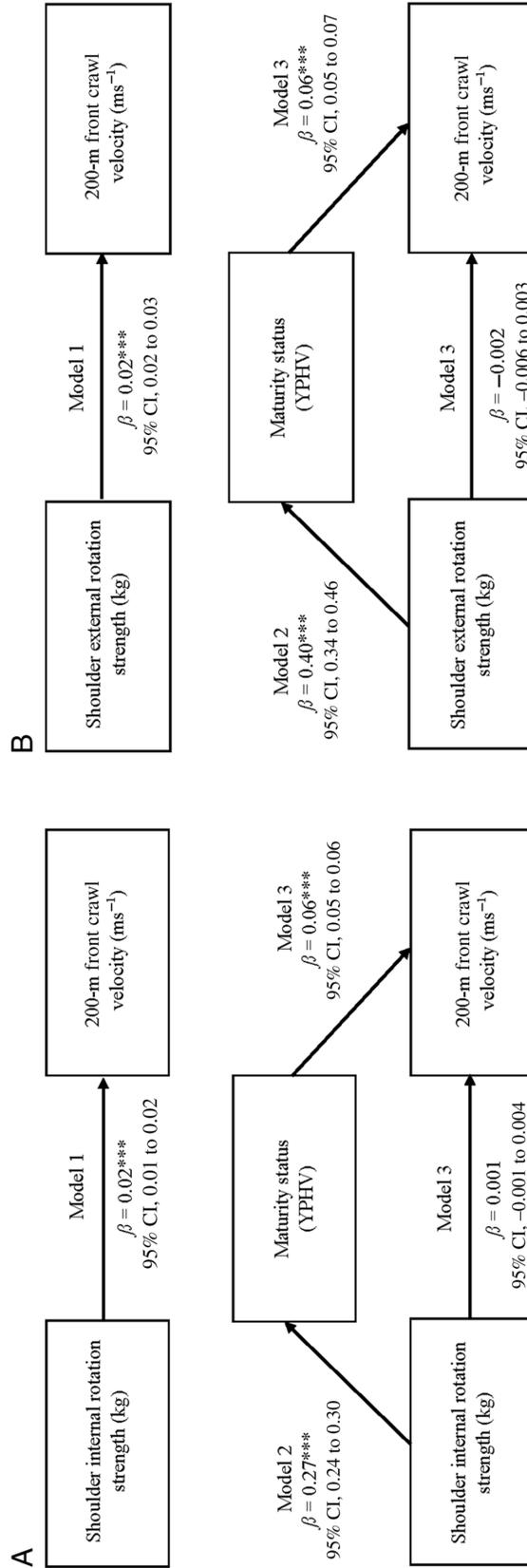
Figure 2 — Longitudinal linear mixed models of relationships between shoulder (A) internal rotation and (B) external rotation strengths (in kilograms) with 200-m front-crawl velocity (in meters per second) mediated by maturity status (YPHV). Note: Models 1 to 3 indicate longitudinal fixed-effect models with random intercepts for participant (ID). β indicates fixed-effect coefficient estimate describing mean relationship (slope); YPHV, years to/from peak height velocity. ***$P < .001$.

Findings highlight key practical applications for swimmer development systems (eg, clubs) and practitioners:

1. As strength gains are likely to be substantially accounted for by maturational development during adolescence, maturity status should be assessed and tracked alongside shoulder IR/ER strength to help accurately distinguish contributions from maturation and, potentially, strength-based training. Findings identify the need for assessing and accounting for maturation status when tracking male youth swimmer performance development.

2. Findings highlight how growth and maturation progression accounts for shoulder IR/ER (isometric) strength-associated performance gains in male youth swimming. Understanding how maturation status relates to other strength characteristics (eg, contraction types and lower limbs) and physical performance indices would help inform the accuracy of swimmer assessment, practitioner decision making, and training programming.

3. From an individual to cohort level, swimming organizations and practitioners (eg, coaches) could benefit from better knowledge of the transient maturity-related influences upon swim performance. Interindividual differences in maturation are associated with performance (dis-)advantages in age-group swimming.

Conclusion

Longitudinal analyses identified linear relationships between shoulder IR strength and maturity status with front-crawl velocity. Importantly, maturity status was more influential, eliminating the independent contribution of shoulder IR strength. Mediation analysis revealed that shoulder IR (and ER) strength was not directly associated with longitudinal performance in age-group swimmers. Instead, shoulder IR strength fully explained swim performance via maturity status in the sample examined.

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