

ORIGINAL ARTICLE OPEN ACCESS

Is Warm-Up Preservation Modulated by Biological Maturation and Sex? Effects on Lower Limbs Performance

Francisco Cuenca-Fernández^{1,2}  | Jesús J. Ruiz-Navarro²  | Raúl Arellano²  | Đurović Marko³  | Nikola Stojanović³ 

¹Department of Sports and Computer Sciences, Universidad Pablo de Olavide, Seville, Spain | ²Aquatics Lab, Department of Physical Education and Sports, Faculty of Sport Sciences, University of Granada, Granada, Spain | ³Faculty of Sport and Physical Education, University of Niš, Niš, Serbia

Correspondence: Francisco Cuenca-Fernández (fcuefer@upo.es)

Received: 4 March 2024 | **Revised:** 16 August 2024 | **Accepted:** 6 October 2024

Funding: This study was supported by the Grant PID2022.142147NB.I00 (SWIM III) funded by MICIU/AEI/10.13039/501100011033/ and by ERDF, EU. Funding for open access publishing: Universidad Pablo de Olavide/CBUA.

Keywords: competition preparation | maturation | potentiation | swimming | warm-up

ABSTRACT

Children and adults may react differently to warm-up preservation due to different physical characteristics. This study aimed to: (i) assess the impact of different rewarm-up routines in swimmers during a transition phase (20–25 min), including passive rest (SWU) or dynamic activities (RWU), on countermovement jump and swimming start performances, and (ii) explore potential RWU adaptations considering maturity offset (peak height velocity—PHV) and sex. Performance was analyzed using mixed effect ANCOVA, considering protocol, maturity offset (pre-PHV, mid-PHV, post-PHV, and adv. post-PHV), and sex. Results favored RWU over SWU with substantial magnitudes for jump height: pre-PHV (min-20, ES = 1.21; min-25, ES = 1.65), mid-PHV (min-20, ES = 1.23; min-25, ES = 1.14), post-PHV (min-20, ES = 1.37; min-25, ES = 0.73), and adv. post-PHV (min-20, ES = 1.03; min-25, ES = 0.65). Significant interactions at 25 min ($p = 0.033$, 0.047) showed that RWU outperformed SWU, especially in younger groups (pre-PHV, mid-PHV). RWU was superior to SWU for the reactive strength index at 20 min ($p = 0.042$) and 25 min ($p = 0.047$), with females having lower RSI than males at 20 min ($p = 0.008$, $p = 0.015$) and 25 min ($p = 0.049$) in later developmental stages. The flight distance ($p = 0.009$) and horizontal hip velocity ($p = 0.014$) revealed significant three-way interactions, with the male adv. post-PHV group responding better to RWU. Knee angular velocity was also higher after RWU, with male adv. post-PHV group showing more pronounced improvements ($p = 0.016$). These results suggest that though RWU had higher influence in male adults, it is a valuable approach for varying ages athletes.

1 | Introduction

In the context of swimming events, participants grouped by age, sex, and strokes compete in multiple races scheduled over several hours. As these events may occur in facilities equipped with only one swimming pool, both warm-up periods and competition races are often accommodated in the same venue. Consequently, athletes need the ability to generate high-power output at various times throughout the day, often with considerable passive intervals after the warm-up period [1]. This pose a challenge, as research consistently

highlights that, after a passive rest period of 15–20 min, muscle temperature can rapidly decrease, diminishing the benefits derived from an active warm-up [2]. In this context, the effectiveness of adding dryland activities as form of rewarm-up to benefit from postactivation performance enhancement (i.e., PAPE) has been demonstrated in swimming [1] and other sports [3]. Specifically, research recommends a short active general warm-up (~10 min), gradually increasing intensity (~60%–85% of maximum heart rate) to rise muscle temperature. Meanwhile, proper recovery (~5 min; phosphocreatine [PCr] restoration) and the use of heated garments soon after

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial-NoDerivs](https://creativecommons.org/licenses/by-nc-nd/4.0/) License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2024 The Author(s). *Scandinavian Journal of Medicine & Science in Sports* published by John Wiley & Sons Ltd.

the warm-up combined with short bouts (~2 min) of sprints or jumps are essential to prevent a decay of muscle temperature and avoid the return of vascular and metabolic adaptations to baseline [4, 5], thus maintaining explosive performance [3, 6, 7].

The combination of warm-up followed by conditioning activities has been frequently tested in the swim start (SS) performance, attributing the short-term enhancement in the kinetic and kinematic variables of SS to PAPE effect [1]. In this context, most of the studies have targeted this phenomenon by adding high-load conditioning exercises to warm-up in very specific experimental conditions. However, swimmers have difficulties to carry out these protocols during actual competitions due to the limited access to specific weight equipment in the call room. On the other hand, while this empirical evidence is exclusively reported in adults, the early involvement of children in competitive activities prompt coaches and professionals to design appropriate warm-up routines considering possible maturational constraints. In this regard, literature has shown that children exhibit lower muscle development and smaller percentage and size of fast fibers compared to adults (from 35% at the age of 5 years to approximately 50% at adulthood) [8, 9], suggesting that higher resistance may not significantly impact higher threshold motor units in them [10, 11]. Moreover, there may also be a very low limit to the frequency of motor neuron impulses in the motor cortex during youth, possibly favoring the activation of type I motor units over type II that might compromise performance in physical test requiring explosive demands (e.g., jumps, acceleration, or change of direction) [8]. Therefore, it may be expected that children might be less responsive to warm-ups including intense or high-load stimuli [8, 9]. In contrast, this reduced ability to voluntarily activate type II motor units could make children attain less fatigue during low-intense dynamic activities and thus respond better to rewarm-up protocols due to their faster recovery capacity and PCr restoration compared to adults [12]. This, in turn, would offer a wider range of possibilities while in the call room.

Maturation's complexity arises from the interdependence and interrelation of growth and chronological age [13], leading to individuals being at different maturation stages (e.g., early- or late-maturing individuals). For instance, current literature in youth indicates that peak power improvements often coincide with the period of peak height velocity (PHV) [14, 15], which denotes the phase of maximum growth rate in stature during adolescence [13]; however, rapid growth occurs in the early stages of the pubertal growth spurt [16], necessitating examination of both pre- and mid-PHV samples. Specifically in swimming, performance assessed in the upper limbs can be influenced at these stages if changes in body anthropometrics (i.e., arm span, muscle area) result from these biological changes [17, 18]. Meanwhile, physiological changes entailed with maturation may either underpin changes in body size observed around the period of PHV, post-PHV, or advanced PHV [13], or also act independently of them, leading to concurrent development of strength and power [16, 19], potentially influencing stroke parameters. In addition, during the pubertal growth spurt, boys

may experience substantial increases in testosterone [13, 20], essential for enhancing muscular hypertrophy associated with increased strength and power [16, 19], peaking approximately 1–2 years post-PHV, while girls may experience these changes before, around mid-PHV or PHV [21–23]. Hence, research examining explosiveness and power in youth should encompass a broad age range around the pubertal period (e.g., 11–18 years) to comprehensively assess changes across all maturational phases.

Considering the previous rationale, factors focusing on the lower limbs would be welcome. In this regard, research has shown that various lower limbs exercises relate to SS, with the counter-movement jump (CMJ) being particularly significant [1, 24]. The CMJ test reflects an athlete's explosive power and lower body strength, essential for a powerful SS. It demonstrates strong correlations ($r=0.7$ – 0.9) with performance, helping coaches tailor training to improve start effectiveness and race outcomes [24]. Therefore, this study had a dual focus: first, to assess in a sample of swimmers the impact of different routines during the transition phase, including passive rest or dynamic activities (walking and jumping) on CMJ and SS performance, and second, to elucidate potential underlying mechanisms modulated by the maturity offset of the participants and sex. Our hypotheses were that a transition phase including dynamic activities would help preserve muscle function without causing fatigue, thus maintaining the warm-up effects, and second, the dynamic and low-intensity nature of the rewarm-up activity could preserve these responses in both males and females regardless of their maturity offset, considering their intrinsic adaptations to warm-up mechanisms.

2 | Methods

2.1 | Design

A counterbalanced crossover design compared lower limb neuromuscular performance in CMJ and SS performance variables between two competition transition phases. Each protocol commenced with a 10-min dryland warm-up consisting of dynamic stretches, leg swings, lunges, and short sprints to activate lower limb muscles. After the warm-up, participants were outfitted in tracksuits to standardize conditions for thermal control. The experimental group engaged in intermittent activities, such as walking and jumping for 20 min, while the control group remained inactive, simulating the typical transition phase between warm-up and competition. The potentiation effects of CMJ, mainly when performed at high velocities, are known to be transient, typically subsiding within 6 min [3]. Hence, the intermittent rewarm-up activities (at 5, 10, and 15 min) were crucial for extending these effects, which are pivotal for peak SS performance. Both groups underwent baseline assessments of neuromuscular performance at 10 min postwarm-up, documenting pre–post changes in function, as noted previously [4]. Follow-up tests were conducted 20 and 25 min after the initial warm-up to observe the enduring effects of the protocols. Due to logistical constraints, SS performance variables were only assessed at the baseline and again at 25 min. Including tracksuits and informed awareness about

their thermal benefits aimed to control for any placebo effects related to perceived warmth, ensuring that any observed differences in performance could be attributed more directly to the physical activities of the experimental design rather than psychological influences.

2.2 | Participants

A sample of 84 young trained swimmers (49 boys and 35 girls), aged 10–18 years and engaged in national or regional competitions for at least 3 years, participated in this study. To be included, participants needed to be medically healthy, without any injuries for at least 6 months, and obtain parental consent (for those under the age of 18). Additionally, their participation had to be voluntary. Further *inclusion* criteria included consistent training attendance, with swimmers averaging at least four sessions per week over the past year and no extended training breaks longer than two consecutive weeks. Participant data by sex and maturity-offset group were presented in Table 1. All procedures performed in the study were by the ethical standards of institutional committee and with the Helsinki Declaration. The study was approved by the local ethics institutional board.

2.3 | Procedures

On testing day, participants engaged in a 10-min dryland warm-up, featuring a variety of drills, joint mobility exercises, dynamic activities, and dynamic lower limb stretching. Following a 10-min rest, participants performed five consecutive repetitions of CMJ on a force platform, with each jump followed by a 30-s rest interval. After completing the jumps, participants performed a SS. After a 20-min passive rest, the CMJ series were repeated, and 5 min later, both the CMJ series and SS were repeated. This protocol served as the control situation (SWU), with participants instructed to maintain clothing throughout to prevent temperature loss during transition periods. On a different day, the warm-up protocol and baseline CMJs and SS were

replicated, replacing the 20-min of passive rest with two sets of 1-min walks (at minutes 5 and 15) and a set of 3 × 5 CMJ (at minute 10). This was considered the rewarm-up condition (RWU), and participants were advised to maintain clothing. The test order was reversed to mitigate the “fatigue/learning” effect.

2.4 | Measurements

2.4.1 | Anthropometric Measurements

Prior to testing, anthropometric measurements were conducted using a stadiometer/scale (Seca 799) to assess participants' height, body mass, and sitting height. Additionally, a flexible meter was used to measure arm span. All data were measured by the same experienced researcher to ensure consistency throughout the data collection process.

2.4.2 | Biological Maturity

Considering that a series of events that characterize biological maturation, such as endocrine, neurological, and musculoskeletal changes, can occur in a delayed, synchronized, or accelerated manner among different youths of the same age [25], biological maturity was calculated using established maturity offset method by Mirwald et al. [26]. This noninvasive approach utilizes anthropometric measurements and chronological age to estimate PHV timing. Maturity offset values, indicating the years since reaching PHV, are obtained by subtracting the offset from the chronological age. The participants were grouped into pre-PHV, mid-PHV, post-PHV, and advanced post-PHV based on their maturity offset values. The maturity offset formulas for each gender are:

$$\begin{aligned} \text{Girls: Maturity offset (years)} = & -9.376 + (0.0001882 \times [\text{Leg Length} \times \text{Sitting Height}]) \\ & + (0.0022 \times [\text{Age} \times \text{Leg Length}]) + (0.005841 \times [\text{Age} \times \text{Sitting Height}]) \\ & - (0.002658 \times [\text{Age} \times \text{Weight}]) + \left(0.07693 \times \left[\frac{\text{weight}}{\text{height}} \times 100 \right] \right) \end{aligned}$$

TABLE 1 | Anthropometric and maturity characteristics of boys and girls across different PHV stages.

	Pre-PHV	Mid-PHV	Post-PHV	Adv. post-PHV
Boys (<i>n</i>)	11	17	13	8
Height (cm)	150 ± 5.67	168 ± 7.04	176 ± 4.99	182 ± 7.31
Body mass (kg)	43.6 ± 7.23	56.4 ± 6.76	67.3 ± 7.21	73.9 ± 7.04
Age (years)	10.7 ± 0.79	13.5 ± 0.87	15.9 ± 0.996	17.6 ± 0.52
Maturity offset	−2.29 ± 0.44	0.32 ± 0.52	2.11 ± 0.60	3.8 ± 0.54
Girls (<i>n</i>)	9	9	12	5
Height (cm)	141 ± 5.59	155 ± 9.09	166 ± 6.76	165 ± 1.48
Body mass (kg)	34.9 ± 4.41	42.2 ± 7.87	57 ± 8.37	59.4 ± 4.45
Age (years)	10 ± 0.58	11.2 ± 0.83	14.2 ± 0.62	18.4 ± 1.95
Maturity offset	−1.56 ± 0.50	−0.17 ± 0.57	2.05 ± 0.44	4.46 ± 1.02

Boys: Maturity offset (years) =

$$-9.236 + (0.0002708 \times [\text{Leg Length} \times \text{Sitting Height}]) \\ + (-0.001663 \times [\text{Age} \times \text{Leg Length}]) + (0.007216 \times [\text{Age} \times \text{Sitting Height}]) \\ + \left(0.02292 \times \left[\frac{\text{weight}}{\text{height}} \times 100 \right] \right)$$

Group assignments were as follows: pre-PHV for offsets between -3 and -1 , mid-PHV for offsets higher than -1 to 1 , post-PHV for offsets higher than 1 to 3 , and advanced post-PHV for offsets exceeding 3 [27]. The advanced post-PHV group (denoted as adv. post-PHV), comprising participants with a maturity offset exceeding 3 , is distinctly considered to address these late-maturing adolescents' unique developmental, physiological, and performance characteristics. This separation ensures focused analysis on athletes who, having considerably surpassed their peak growth velocity, may exhibit distinct physiological responses to training and competition compared to their less mature counterparts.

2.4.3 | Countermovement Jump

The CMJ assessed lower limb neuromuscular performance. Participants executed five maximal CMJ attempts on a force plate (Dinascan/IBV, Biomechanics Institute of Valencia, sampling at 1000 Hz), with a 30 -s interlude between attempts and the option for an additional attempt if improperly executed. Excluding the highest and lowest values, the average CMJ height of the remaining three jumps served as the performance outcome for each participant, with swimmers maintaining consistent arm positioning by placing their hands on their hips during jumps. Before initiating the CMJ, participants stood still on the force plate for over a second to accurately measure their body mass in Newtons (N), as McMahon et al. [28] described. Raw ground reaction force (GRF) data underwent a smoothing process using MATLAB software (MATLAB, R2018a; The MathWorks, Inc., Natick, MA) and a low-pass Butterworth digital filter with a designated cut-off frequency of 50 Hz, as Barker et al. [29] recommended. Filtering GRF data removes high-frequency noise, allowing for precise velocity calculations essential for assessing jump height (JH). Movement phases, including braking, concentric, and overall contact time, were delineated based on established methodologies [28]. The primary outcome variables (Table 2), JH and reactive strength index (RSI), demonstrated high reliability across trials and subjects, reflected by mixed model intraclass correlation coefficients (ICC) of 0.98 .

2.4.4 | Swimming Start Performance

Kinematic measurements (Table 2) were carried out according to Cuenca-Fernández, López-Contreras, and Arellano [30], employing two digital video cameras (Casio, HS Camera 100 Hz) with a sampling rate of 100 Hz. One camera, positioned on a tripod and focused on the starting block, recorded block-phase variables like knee extension angular velocity ($V\omega K$), along with flight-phase variables including flight distance (FD) and horizontal hip velocity (VxH). $V\omega K$ was computed by determining the angular difference of the front

knee at the moments of maximum extension and flexion, divided by the time taken for the extension performance (in radians per second). Flight distance measured the horizontal distance covered by the hip from the last foot contact on the block to the initial finger contact with the water (in meters), while VxH represented the velocity from the last block contact to the first finger-water contact (in meters per second). The second camera, fixed poolside, recorded the underwater swim phase up to 10 m (T10m). Both cameras were placed perpendicular to the direction of swimming and synchronized with the starting signal emitted by the starting system (Signal Frame, Sportmetrics), utilizing an audible signal and strobe flash. Video files underwent analysis by two researchers using Kinovea software (version $0.7.10$), yielding interobserver ICC of 0.98 (95% CI: 0.97 – 0.98).

2.5 | Sample Size

We conducted a preliminary power analysis using G*Power [31] for our two-way mixed model ANCOVA involving eight groups based on treatment type (RWU or SWU) and maturity stage (pre-PHV, mid-PHV, post-PHV, and adv. post-PHV). With a set numerator degree of freedom at two, alpha of 0.05 , power threshold of 0.80 , and expected moderate effect size ($f=0.35$), the analysis indicated a necessary sample size of 82 participants for the study.

2.6 | Statistical Analyses

All statistical analyses were conducted using RStudio (version $2023.09.1 + 495$, Spotted Wakerobin, Boston, MA, USA), with a significance level set at $p < 0.05$. Preliminary checks ensured adherence to multivariate regression assumptions, including assessing the linearity of predictor–outcome relationships. Mahalanobis distance identified multivariate outliers using a significance threshold of 0.001 , and these outliers were subsequently excluded. Descriptive statistics, mean, and standard deviation were calculated for outcome variables (JH, RSI, $V\omega K$, FD, VxH , and T10m). Percentage changes in performance ($\% \Delta$) were computed using the formula $\% \Delta = [(\text{MeanB} - \text{MeanA}) / \text{MeanA}] \times 100$. One-way repeated measures ANOVA, with Mauchly's sphericity test, assessed time effects (baseline, 20 , and 25 min) on each protocol's outcome variables. Mixed effect ANCOVA models, considering protocol (SWU vs. RWU) and maturity stages (pre-PHV, mid-PHV, post-PHV, and adv. post-PHV) as fixed effects and subject ID as a random factor, were employed for most outcome variables. We incorporated subject ID as a random factor in our mixed effects ANCOVA models to address the nested data structure inherent in our study, where multiple measurements were taken from the same subjects. This approach ensures that the correlations and dependencies within repeated measures from individual participants are appropriately accounted for, enhancing the robustness of our statistical analysis. However, the analysis indicated minimal variance associated with specified random effects, allowing us to streamline our approach and apply a two-way ANCOVA without the random factor for specific outcomes like T10m, $V\omega K$, and FD. The interaction term examined potential protocol effects across maturity levels. The

Benjamini–Hochberg correction controlled false discovery rates, enhancing inferential robustness [32]. As documented, this approach's merits suggest its superiority over more strict correction methods, potentially revealing genuine effects that might remain undetected. Effect sizes (ES) were interpreted according to Hopkins et al. [33], with criteria ranging from <0.2 for trivial effects, 0.2–0.6 for small effects, 0.6–1.2 for moderate effects, 1.2–2.0 for large effects, and >2.0 for very large effects.

3 | Results

The data presented in Table 3 represent the differential effects of the two postwarm-up protocols (RWU and SWU), examined

TABLE 2 | Calculation of outcome variables.

Variable	Calculation
Jump height (JH)	$(\text{Takeoff velocity})^2 / (2 \times 9.81)$
Reactive strength index (RSI)	$(\text{Jump height}) / (\text{Jump time})$
Knee extension angular velocity (V ω K)	$(\alpha_1 - \alpha_0) / (t_1 - t_0)$
Flight distance (FD)	$(d_1 - d_0)$
Horizontal velocity of the hip during the flight (VxH)	$(d_1 - d_0) / (t_1 - t_0)$
Time to 10 m (T10m)	$(t_1 - t_0)$

through repeated measures ANOVA. Notably, the RWU protocol showed a consistent improvement in performance variables, with JH exhibiting a gradual enhancement from baseline to 25 min. The marginal decrease in RSI between the 20- and 25-min intervals suggested that the benefits accrued up to the 20-min mark were better retained in JH. The FD (assessed at 25 min) increased after RWU, while V ω k, VxH, and T10m followed trend improvements in the RWU condition. In contrast, the SWU protocol displayed a decline in JH and RSI, showing a statistically significant drop from baseline to 20 and 25 min. Similarly, all SS variables exhibited a downward trend at 25 min in SWU.

Employing a mixed effects ANCOVA model, our analysis indicated no significant interactions for JH at 20 min, with RWU consistently outperforming SWU across all PHV stages (see Figure 1A). Additionally, there were no significant sex effects observed for JH at both 20 and 25 min. At 25 min, significant interaction estimates ($p=0.033$ and 0.047) for JH reveal that while RWU consistently outperformed SWU across all stages, younger groups like pre-PHV and mid-PHV responded better under RWU, highlighting the impact of the protocol on these development stages (see Figure 1C). The analysis of RSI at 20 and 25 min provided insights into the influence of sex and developmental stages on performance in RWU. At 20 min, two significant interactions ($p=0.008$ and 0.015) indicated that females in the post-PHV and adv. post-PHV stages had significantly lower RSI than males in the same maturity groups. A similar sex interaction effect ($p=0.049$) was observed at 25 min, with females in the post-PHV stage exhibiting significantly lower scores than males, but with males being better respondents to RWU than

TABLE 3 | Descriptive statistics and percentage change in performance for rewarm-up (RWU) and control (SWU) protocols.

	Baseline	Post 20 min	Post 25 min	Δ Baseline vs. 20 min (%)	Δ Baseline vs. 25 min (%)	Δ 20 min vs. 25 min (%)
RWU						
JH (m)	0.23 ± 0.08	0.24 ± 0.08	0.24 ± 0.08	3.14***	2.02*	−1.09
RSI	0.30 ± 0.09	0.31 ± 0.09	0.30 ± 0.08	3.51	2.39	−1.09
T10m (s)	5.69 ± 1.05		5.65 ± 1.07		−0.81	
FD (m)	1.01 ± 0.35		1.04 ± 0.37		3.69*	
VxH (m/s)	3.79 ± 0.5		3.83 ± 0.51		1.14	
V ω K (rad/s)	544.94 ± 155.01		554.69 ± 152.53		1.79	
SWU						
JH (m)	0.23 ± 0.07	0.22 ± 0.07	0.22 ± 0.08	−4.27***	−4.63***	−0.38
RSI	0.29 ± 0.09	0.28 ± 0.08	0.28 ± 0.09	−5.21**	−5.04***	0.18
T10m (s)	5.67 ± 1.12		5.68 ± 1.11		0.14	
FD (m)	1.07 ± 0.33		1.03 ± 0.32		−3.34	
VxH (m/s)	3.93 ± 0.67		3.70 ± 0.57		−5.90*	
V ω K (rad/s)	549.45 ± 140.04		534.64 ± 147.98		−2.70	

Note: The “Baseline” represents preprotocol measurements, while the “post 20 min” and “post 25 min” mark recordings taken 20 and 25 min postprotocol, respectively. Δ illustrates percentage changes in performance between time intervals. *, **, and *** next to a value underscores statistical significance <0.05, <0.01, and <0.001, respectively.

Abbreviations: FD, flight distance; JH, jump height (m); RSI, reactive strength index; T10m, swim start performance at 10 m (s); VxH, horizontal velocity (m/s); V ω K, knee angular velocity (rad/s).

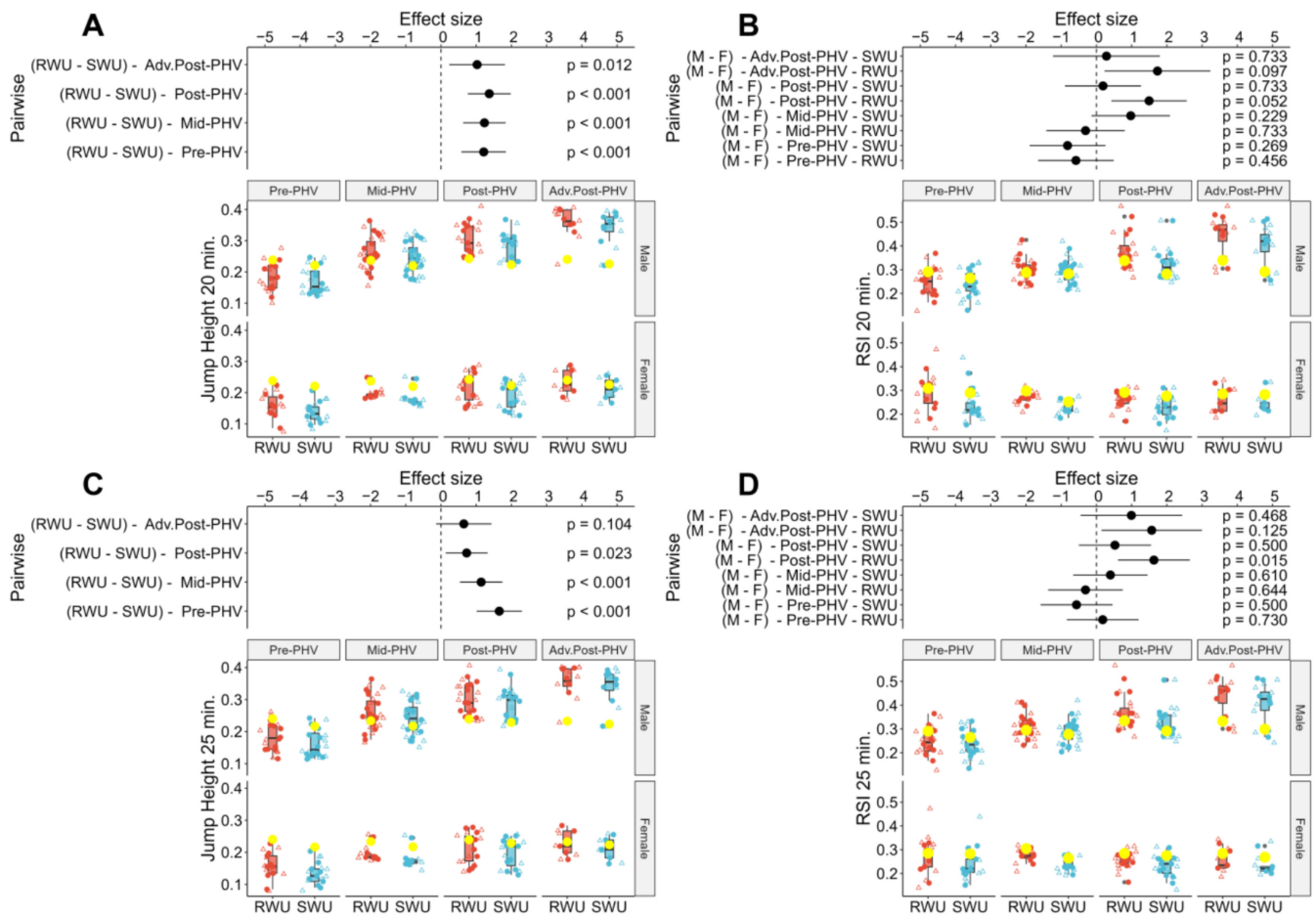


FIGURE 1 | The ANCOVA box plots display the treatment effects of rewarm-up (RWU) and control (SWU) protocols on jump height (JH) and reactive strength index (RSI) at two distinct time intervals postwarm-up, adjusted for the baseline measurement, and introducing interaction effect between maturity stage (pre-PHV, mid-PHV, post-PHV, and advanced post-PHV), sex, and protocol. (A, C) depict JH 20 min and 25 min postwarm-up, while (B, D) represent RSI, respectively. Each outcome variable's data are segmented into pre-PHV, mid-PHV, post-PHV, and advanced post-PHV groups. Individual data points are scattered along each box plot, capturing the variability and distribution of measurements. Yellow dots on each box plot signify the adjusted means after considering baseline measurements. Error bars highlight the variability within the data. Circles represent predicted values, while triangles signify the actual values.

females ($p=0.015$). Nonetheless, the RWU protocol consistently demonstrated superior efficacy compared to SWU, with the SWU main effect linked to significantly lower RSI at 20 and 25 min ($p=0.042$ and 0.047).

For T10m, the main effects for the protocol and developmental group stages were not significant, indicating no discernible differences in performance between the RWU and SWU protocols or across different PHV stages. The FD and VxH revealed significant three-way interactions ($p=0.009$ and 0.014 , respectively). These interactions highlight that male swimmers in the adv. post-PHV group respond better to the RWU than females for both outcome measurements. At the same time, the responses to SWU follow a consistent pattern of sex-specific responses (see Figure 2B,C). The V_{0k} demonstrated that the RWU protocol generally yielded higher effectiveness than SWU, underscored by significant main effects. Notably, the adv. post-PHV group showed a substantial improvement in performance with a significant increase ($p=0.016$) compared to the pre-PHV group. However, pairwise comparisons between the RWU and SWU protocols across different PHV stages did not reveal significant

differences (see Figure 2D). Furthermore, interaction terms between protocol and group stages were not statistically significant, indicating consistent protocol effects regardless of developmental stage.

4 | Discussion

The first aim of this study was to assess the impact of different routines during the transition phase, including passive rest or dynamic activities, on CMJ and SS performance in a sample of swimmers of varying maturity offset. The hypothesis was that a transition phase including dynamic activities would help preserve muscle function without causing fatigue, thus maintaining warm-up effects. The RWU protocol demonstrated to be effective not only in preserving the performance outcomes obtained by the warm-up, but with JH and RSI showing sustained enhancements from baseline to 20- and 25-min mark, indicating potential delayed positive effects during the transition period. These findings align with previous studies using high-load conditioning exercises as the

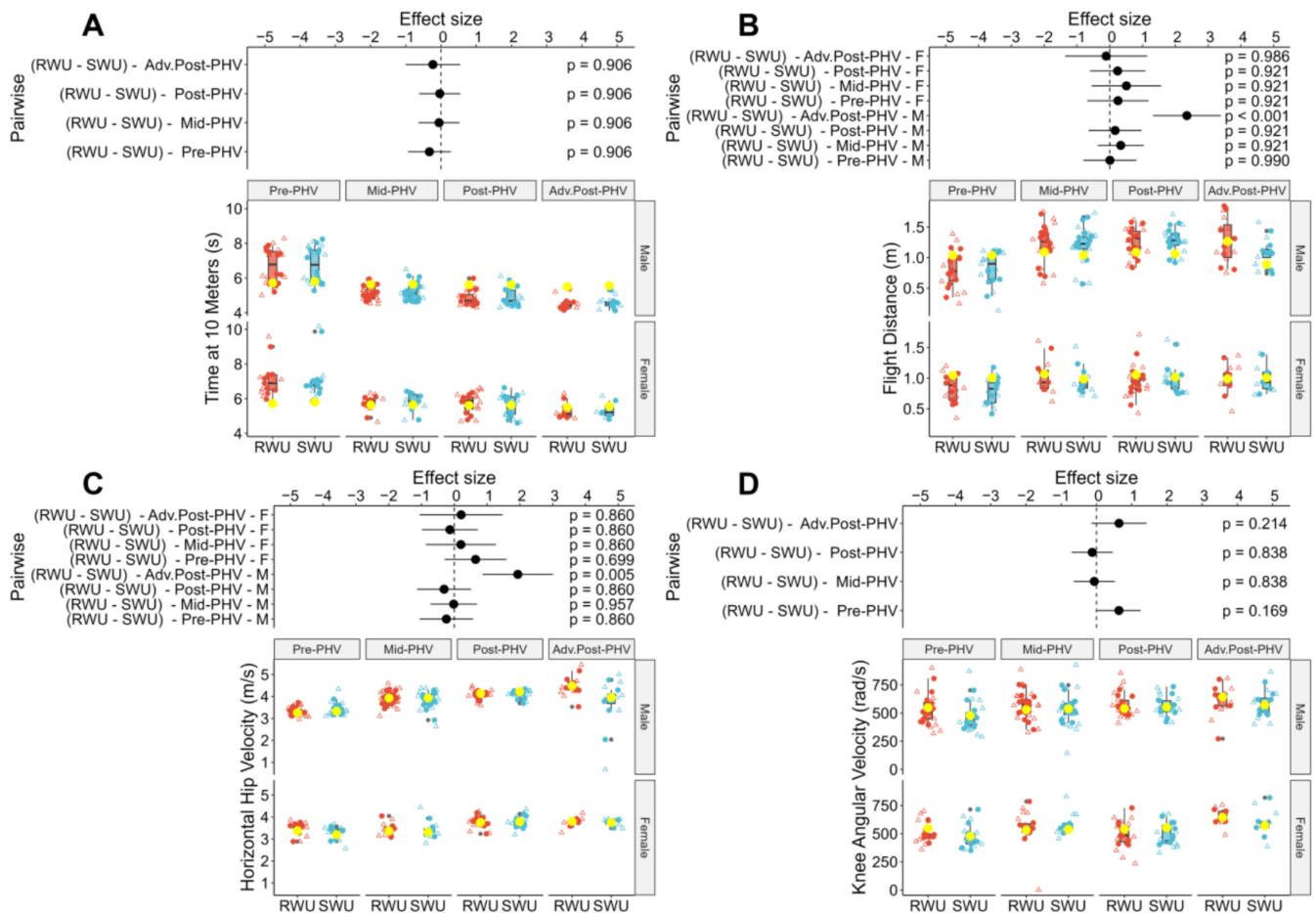


FIGURE 2 | The ANCOVA box plots display the treatment effects of rewarm-up (RWU) and control (SWU) protocols on the swim start at 10 m (T10m), flight distance (FD), horizontal hip velocity (VxH), and knee angular velocity (V ω K) at two distinct time intervals postwarm-up adjusted for the baseline measurement and introducing interaction effect between maturity stages (pre-PHV, mid-PHV, post-PHV, and advanced post-PHV), sex, and protocols. (A–D) depict T10m, FD, VxH, and V ω K 25 min postwarm-up, respectively. Each outcome variable's data are segmented into pre-PHV, mid-PHV, post-PHV, and advanced post-PHV groups. Individual data points are scattered along each box plot, capturing the variability and distribution of measurements. Yellow dots on each box plot signify the adjusted means after considering baseline measurements. Error bars highlight the variability within the data. Circles represent the predicted values, while triangles signify the actual values.

one by Vargas-Molina et al. [34], with CMJ height increases (ES = 0.24, 3.1%) after two sets of three back squat reps at 75% RM. Notably, the present research achieved similar improvements without resorting to loaded conditioning exercises, as supported by previous studies like Hilfiker et al. [35] adding drop jumps to warm-up. The RWU condition exhibited a noteworthy increase in V ω K compared to SWU. Particularly, the significant deterioration at minute 25 in SWU ($\Delta = -2.70\%$) compared to RWU ($\Delta = 1.79\%$) highlighted a key competitive advantage in terms of power output. Regarding FD and VxH, both variables showed improvements after RWU and decline in SWU, indicating well-maintained muscular capacity in lower limbs [4]. Although not statistically significant, the marginal enhancement in T10m over 25 min after RWU condition was also noteworthy (Table 3). The increased FD might suggest a shift in swimmers' trajectory toward a flatter entry in RWU-posttest, making further exploration necessary to understand the impact on variables like VxH (covering a superior distance may imply higher flight time) and T10m (flatter entry compromising underwater trajectory) [36, 37]. In any case, the obtained findings hold significance in the context

of swimming, particularly in scenarios where the call-room introduces limitations in terms of time, space, and equipment for the induction of very specific exercise [1]. Based on the current results, an interesting outcome was that warm-up effects were well maintained with easy activities such as jumping and walking for a considerable long time frame (up to 25 min), possibly due to the transient carry-over effect of the RWU activity in the cardiovascular and neuromuscular factors triggered by warm-up, as observed in the PAPE phenomenon [3, 5].

The second objective of this study aimed to explore potential adaptations to RWU considering maturity offset of participants and sex, areas with inconclusive findings. The hypothesis theorized that the low-intensity nature of the RWU activity could be effective for preserving these responses in both males and females regardless of maturity offset considering their intrinsic adaptations to warm-up mechanisms. About JH, the results uncovered substantial effect magnitudes across different maturity phases, underscoring the advantageous impact of RWU over SWU regardless of maturity state (Figure 1A,C). Surprisingly, at 25 min, RWU demonstrated superiority across

pre-PHV and mid-PHV groups ($ES = 1.65-0.65$; $p < 0.001$), with diminishing but still substantial benefits in post-PHV ($ES = 0.65$), but no significant effects for adv. post-PHV. These results partially align with expectations in younger participants on the basis that PCr restoration is faster in them after dynamic exercise [8]. Nevertheless, possibly younger children, with a larger surface area relative to their mass, could not maintain their core temperatures as well as older participants [7]. Consequently, a young child would be more exposed to temperature losses during SWU, requiring a relatively larger proportion of their metabolically active mass to produce more heat and maintain thermal equilibrium [38]. This was probably counteracted during RWU, which support the efficacy of rewarm-up in preserving muscle temperature and function in the youngest groups. The lower RSI values obtained by females in the post-PHV and adv. post-PHV groups was expected as females possess lower percentage of type II fibers than males [21]. Interestingly, post-PHV males at 25 min were better respondents to RWU than females ($p = 0.015$), while similar trends were also obtained for adv. post-PHV ($p = 0.097$) and post-PHV at 20 min ($p = 0.052$). These findings are in contrast with those obtained by Pääsuke, Ereline, and Gapeyeva [39], which reported that postpubertal boys had similar twitch force-generating capacity as the young boys. Meanwhile, Arabatzi et al. [40] documented age-dependent warm-up effects mainly manifested in adults, with a pre-post RFD-peak responsiveness observed for both men ($d = 0.71$) and women ($d = 0.86$), and in teens males ($d = 0.45$) and teens females ($d = 0.86$), but with no effects in children irrespective of sex. Considering RSI as a measure of the force generation speed to transition rapidly between eccentric and concentric muscle phases, it is possible that male older participants, presumably with a higher proportion of type II fibers [41], exhibited more responsiveness after RWU for this variable. However, it cannot be discarded that the strategic application of force and the ability to modulate technique is typically developed over years of practice and feedback, which older, more experienced athletes would have accumulated.

Concerning SS variables, a significant benefit of the RWU protocol on FD and VxH was particularly noted for male swimmers in the adv. post-PHV group (Figure 2B,C). There may be two possible reasons for the increase in FD and VxH, including changes in flight trajectory or enhanced impulse against the block [1]. About the former, despite the lack of significant interactions in VwK between RWU and SWU across different PHV stages, the males adv. post-PHV group also showed a substantial improvement in performance ($p = 0.016$) compared to the pre-PHV group, which could support the argument behind the enhanced impulse against the block due to RWU [30]. These results agreed with the higher effect sizes obtained in RSI for the post-PHV and adv. post-PHV groups (Figure 1C,D), and reflect a superior lower limbs muscle responsiveness in male adults as a function of time (i.e., rate of force development). In contrast, despite females were also under RWU conditions and follow instructions to maintain clothing, they did not show insights of superior responsiveness in the oldest PHV stages. Possibly, as the thermal dependence of fast-twitch fibers (ATPase reaction appears to be temperature sensitive) favors muscle cross-bridge production [7], this could play a key role in warm-up modulation. Females possess different body fat percentage and

distribution [22], with thicker adipose tissue in the extremities for better temperature insulation. However, this can be disadvantageous during passive rest conditions with greater relative heat flow convection from the trunk to extremities to avoid cooling [42]. In addition, females also possess lower percentage of type II fibers that make them to have lower muscle strength and explosiveness than males [21, 22]. Actually, noteworthy sex interactions showed faster T10m in males compared to females regardless of the protocol or developmental stage used ($p = 0.010$). Therefore, to the best of our knowledge, even though RWU was applied in all groups, the higher muscle development of male adults and the superior frequency of activation of fast-twitch fibers compared to females and children [8, 9] could make temperature-related changes more pronounced in them when involved in activities of high-speed nature, such as the SS, potentially impacting the force-velocity relationship [6]. Therefore, it is reasonable to argue that, despite RWU seeming to be more effective than SWU for maintaining (or improving) muscle capacity in a SS, these findings emphasize the nuanced impact of biological maturation and sex on the responsiveness to the protocols.

This study presented some limitations. First, participants did not perform a water-based warm-up, but previous research supports the effectiveness of dryland warm-up in maintaining SS by increasing muscle temperature and neuromuscular activity in the lower limbs [1]. Additionally, the age and maturational growth of participants are significant factors influencing skill performance [43], especially in a complex movement like the SS. Therefore, younger participants may not only lack the musculoskeletal development cultivated over years of practice, but also exhibit limited expertise and motor control, leading to higher intertrial variability that could potentially mask the nuanced impacts of different warm-up protocols. Despite these limitations, they were duly acknowledged as factors influencing the development of fast-twitch fiber proportion [25], aligning with the hypothesis of this study.

5 | Conclusion

The study provides comprehensive insights into the distinct effects of dynamic or passive transition phases on CMJ and SS performance, emphasizing the consistent superiority of rewarm-up, particularly in JH and RSI. The nuanced examination of maturity stages refines our understanding of protocol efficacy, suggesting that improvements may be more pronounced in more mature participants. This contributes to the discourse of athletic warm-up protocols, emphasizing the need for individualized approaches based on developmental phases for optimal performance outcomes. Furthermore, our results indicated that SS performance 25 min postwarm-up is similar or improved when rewarm-up activities are included during the transition phase, contrasting with deteriorations observed with passive rest. These changes in performance appeared to be thermal dependent and more pronounced in male adults due to the higher responsiveness of their muscle mass to such muscle temperature preservation. Additionally, the study suggests that allowing both children and adults some activity during the transition phase, rather than keeping calm, could help preserve muscle capacity and enhance performance.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. F. Cuenca-Fernández, D. Boulosa, Ó. López-Belmonte, A. Gay, J. J. Ruiz-Navarro, and R. Arellano, "Swimming Warm-Up and Beyond: Dryland Protocols and Their Related Mechanisms—A Scoping Review," *Sports Medicine Open* 8, no. 1 (2022): 1–44.
2. D. Bishop, "Warm Up I," *Sports Medicine* 33, no. 6 (2003): 439–454.
3. L. M. Silva, H. P. Neiva, M. C. Marques, M. Izquierdo, and D. A. Marinho, "Effects of Warm-Up, Post-Warm-Up, and Re-Warm-Up Strategies on Explosive Efforts in Team Sports: A Systematic Review," *Sports Medicine* 48 (2018): 2285–2299.
4. F. Cuenca-Fernández, I. C. Smith, M. J. Jordan, et al., "Nonlocalized Postactivation Performance Enhancement (PAPE) Effects in Trained Athletes: A Pilot Study," *Applied Physiology, Nutrition, and Metabolism* 42, no. 10 (2017): 1122–1125.
5. A. J. Blazeovich and N. Babault, "Post-Activation Potentiation Versus Post-Activation Performance Enhancement in Humans: Historical Perspective, Underlying Mechanisms, and Current Issues," *Frontiers in Physiology* 10 (2019): 1359.
6. S. Racinais, S. Cocking, and J. D. Périard, "Sports and Environmental Temperature: From Warming-Up to Heating-Up," *Temperature* 4, no. 3 (2017): 227–257.
7. S. Racinais and J. Oksa, "Temperature and Neuromuscular Function," *Scandinavian Journal of Medicine & Science in Sports* 20 (2010): 1–18.
8. R. Dotan, C. Mitchell, R. Cohen, P. Klentrou, D. Gabriel, and B. Falk, "Child—Adult Differences in Muscle Activation—A Review," *Pediatric Exercise Science* 24, no. 1 (2012): 2–21.
9. J. Lexell, M. Sjöström, A. S. Nordlund, and C. C. Taylor, "Growth and Development of Human Muscle: A Quantitative Morphological Study of Whole Vastus Lateralis From Childhood to Adult Age," *Muscle & Nerve* 15, no. 3 (1992): 404–409.
10. R. Dotan, C. Mitchell, R. Cohen, D. Gabriel, P. Klentrou, and B. Falk, "Child—Adult Differences in the Kinetics of Torque Development," *Journal of Sports Sciences* 31, no. 9 (2013): 945–953.
11. V. Armatas, E. Bassa, D. Patikas, I. Kitsas, G. Zangelidis, and C. Kotzamanidis, "Neuromuscular Differences Between Men and Prepubescent Boys During a Peak Isometric Knee Extension Intermittent Fatigue Test," *Pediatric Exercise Science* 22, no. 2 (2010): 205–217.
12. O. Eriksson and B. Saltin, "Muscle Metabolism During Exercise in Boys Aged 11–16 Years Compared to Adults," *Acta Paediatrica Belgica* 28 (1974): 257–265.
13. R. M. Malina, C. Bouchard, and O. Bar-Or, *Growth, Maturation, and Physical Activity* 2nd ed. (Champaign, IL: Human kinetics, 2004).
14. S. Copley, J. Baker, N. Wattie, and J. McKenna, "Annual Age-Grouping and Athlete Development: A Meta-Analytical Review of Relative Age Effects in Sport," *Sports Medicine* 39 (2009): 235–256.
15. R. M. Philippaerts, R. Vaeyens, M. Janssens, et al., "The Relationship Between Peak Height Velocity and Physical Performance in Youth Soccer Players," *Journal of Sports Sciences* 24, no. 3 (2006): 221–230.
16. J. Bojsen-Møller, S. P. Magnusson, L. R. Rasmussen, M. Kjaer, and P. Aagaard, "Muscle Performance During Maximal Isometric and Dynamic Contractions Is Influenced by the Stiffness of the Tendinous Structures," *Journal of Applied Physiology* 99, no. 3 (2005): 986–994.
17. M. Oliveira, R. S. Henrique, D. R. Queiroz, M. Salvina, W. V. Melo, and M. A. Moura dos Santos, "Anthropometric Variables, Propulsive Force and Biological Maturation: A Mediation Analysis in Young Swimmers," *European Journal of Sport Science* 21, no. 4 (2021): 507–514.
18. M. D. N. S. Oliveira, D. D. R. Queiroz, M. S. F. da Costa, and A. Oliveira, "Body Segments and Biological Maturation to Estimate the Propulsive Force of the Arm in Young Swimmers," *Revista Brasileira de Cineantropometria & Desempenho Humano* 22 (2020): e74881.
19. A. J. Blazeovich, "Effects of Physical Training and Detraining, Immobilisation, Growth and Aging on Human Fascicle Geometry," *Sports Medicine* 36 (2006): 1003–1017.
20. A. Viru, J. Loko, M. Harro, A. Volver, L. Laaneots, and M. Viru, "Critical Periods in the Development of Performance Capacity During Childhood and Adolescence," *European Journal of Physical Education* 4, no. 1 (1999): 75–119.
21. P. H. Yagüe and J. M. De La Fuente, "Changes in Height and Motor Performance Relative to Peak Height Velocity: A Mixed-Longitudinal Study of Spanish Boys and Girls," *American Journal of Human Biology: The Official Journal of the Human Biology Association* 10, no. 5 (1998): 647–660.
22. J. M. Round, D. A. Jones, J. W. Honour, and A. M. Nevill, "Hormonal Factors in the Development of Differences in Strength Between Boys and Girls During Adolescence: A Longitudinal Study," *Annals of Human Biology* 26, no. 1 (1999): 49–62.
23. R. L. Matchock, L. D. Dorn, and E. J. Susman, "Diurnal and Seasonal Cortisol, Testosterone, and DHEA Rhythms in Boys and Girls During Puberty," *Chronobiology International* 24, no. 5 (2007): 969–990.
24. S. Thng, S. Pearson, and J. W. Keogh, "Relationships Between Dry-Land Resistance Training and Swim Start Performance and Effects of Such Training on the Swim Start: A Systematic Review," *Sports Medicine* 49 (2019): 1957–1973.
25. P. Almeida-Neto, G. G. de Assis, B. R. do Carmo Silva, and R. Medeiros, "Contribution of Biological Maturation and Power of Upper and Lower Limbs to Crawl Swim Performance in Adolescent Athletes," *Human Movement* 24, no. 1 (2023): 85–93.
26. R. L. Mirwald, A. D. Baxter-Jones, D. A. Bailey, and G. P. Beunen, "An Assessment of Maturity From Anthropometric Measurements," *Medicine & Science in Sports & Exercise* 34, no. 4 (2002): 689–694.
27. M. C. Rumpf, J. B. Cronin, J. Oliver, and M. Hughes, "Kinematics and Kinetics of Maximum Running Speed in Youth Across Maturity," *Pediatric Exercise Science* 27, no. 2 (2015): 277–284.
28. J. J. McMahon, T. J. Suchomel, J. P. Lake, and P. Comfort, "Understanding the Key Phases of the Countermovement Jump Force-Time Curve," *Strength & Conditioning Journal* 40, no. 4 (2018): 96–106.
29. L. A. Barker, J. R. Harry, J. S. Dufek, and J. A. Mercer, "Aerial Rotation Effects on Vertical Jump Performance Among Highly Skilled Collegiate Soccer Players," *Journal of Strength and Conditioning Research* 31, no. 4 (2017): 932–938.
30. F. Cuenca-Fernández, G. López-Contreras, and R. Arellano, "Effect on Swimming Start Performance of Two Types of Activation Protocols: Lunge and YoYo Squat," *Journal of Strength and Conditioning Research* 29, no. 3 (2015): 647–655.
31. F. Faul, E. Erdfelder, A. Buchner, and A. G. Lang, "Statistical Power Analyses Using G*Power 3.1: Tests for Correlation and Regression Analyses," *Behavior Research Methods* 41, no. 4 (2009): 1149–1160.
32. Y. Benjamini and Y. Hochberg, "Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing," *Journal*

of the Royal Statistical Society: *Series B: Methodological* 57, no. 1 (1995): 289–300.

33. W. Hopkins, S. W. Marshall, A. M. Batterham, and J. Hanin, “Progressive Statistics for Studies in Sports Medicine and Exercise Science,” *Medicine & Science in Sports & Exercise* 41, no. 1 (2009): 3–12.

34. S. Vargas-Molina, U. Salgado-Ramírez, I. Chulvi-Medrano, L. Carbone, S. Maroto-Izquierdo, and J. Benítez-Porres, “Comparison of Post-Activation Performance Enhancement (PAPE) After Isometric and Isotonic Exercise on Vertical Jump Performance,” *PLoS One* 16, no. 12 (2021): e0260866.

35. R. Hilfiker, K. Hübner, T. Lorenz, and B. Marti, “Effects of Drop Jumps Added to the Warm-Up of Elite Sport Athletes With a High Capacity for Explosive Force Development,” *Journal of Strength & Conditioning Research* 21, no. 2 (2007): 550–555.

36. J. J. Ruiz-Navarro, F. Cuenca-Fernández, R. Sanders, and R. Arelano, “The Determinant Factors of Undulatory Underwater Swimming Performance: A Systematic Review,” *Journal of Sports Sciences* 40, no. 11 (2022): 1243–1254.

37. X. Xie, L. Wei, J. Shi, and Y. Cheng, “Swimming Start Model and Determination of the Optimal Breakout Position,” *Sports Biomechanics* 23 (2021): 1–21.

38. H. Hensel and K. Schafer, “Thermoreception and Temperature Regulation in Man,” in *Recent Advances in Medical Thermology* (Boston, MA: Springer, 1984), 51–64.

39. M. Pääsuke, J. Ereline, and H. Gapeyeva, “Twitch Contraction Properties of Plantar Flexor Muscles in Pre-and Post-Pubertal Boys and Men,” *European Journal of Applied Physiology* 82 (2000): 459–464.

40. F. Arabatzi, D. Patikas, A. Zafeiridis, et al., “The Post-Activation Potentiation Effect on Squat Jump Performance: Age and Sex Effect,” *Pediatric Exercise Science* 26, no. 2 (2014): 187–194.

41. R. Vandenboom, “Modulation of Skeletal Muscle Contraction by Myosin Phosphorylation,” *Comprehensive Physiology* 7, no. 1 (2011): 171–212.

42. G. S. Anderson, “Human Morphology and Temperature Regulation,” *International Journal of Biometeorology* 43 (1999): 99–109.

43. E. Lätt, J. Jürimäe, K. Haljaste, A. Cicchella, P. Purge, and T. Jürimäe, “Longitudinal Development of Physical and Performance Parameters During Biological Maturation of Young Male Swimmers,” *Perceptual and Motor Skills* 108, no. 1 (2009): 297–307.