Understanding the Effects of Training on Underwater Undulatory Swimming Performance and Kinematics

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Abstract

In swimming, the underwater phase after the start and turn comprises gliding and dolphin kicking, with the latter also known as underwater undulatory swimming (UUS). Swimming performance is highly dependent on the underwater phase; therefore, understanding the training effects in UUS and underwater gliding can be critical for swimmers and coaches. Further, the development of technique in young swimmers can lead to exponential benefits in an athlete's career. This study aimed to evaluate the effects of a training protocol on UUS and underwater gliding performance and kinematics in young swimmers. Seventeen age group swimmers (boys =10, girls =7) performed maximal UUS and underwater gliding efforts before and after a seven-week training protocol. Time to reach 10 m; intra-cyclic mean, peak, and minimum velocities; and gliding performance improved significantly after the training protocol. The UUS performance improvement was mostly produced by an improvement of the upbeat execution, together with a likely reduction of swimmers' hydrodynamic drag. Despite the changes in UUS and gliding, performance was also likely influenced by growth. The findings from this study highlight kinematic variables that can be used to understand and quantify changes in UUS and gliding performance.

Key words: swimmers, velocity, assessment, Statistical Parametric Mapping, biomechanics.

Introduction

Underwater undulatory swimming (UUS), also known as 'dolphin kick', is a technique used by swimmers to propel themselves forward after the start and turns of the freestyle, butterfly, and backstroke events. In UUS, the swimmer adopts a streamlined position with the arms outstretched and held together over the head while performing body undulations (Arellano, Pardillo, & Gavilán, 2002; Connaboy, Coleman, Moir, & Sanders, 2010). Each kick cycle comprises a complete downward (downbeat) and upward (upbeat) movement of the lower limbs created by a sinusoidal wave that travels caudally along the body. During competition the underwater distance is limited to a maximum of 15 m from each wall in freestyle, butterfly, and backstroke events (FINA, 2013). With the exception of the dive at the start of a race, the underwater phase of the start and turn represent the fastest parts of the freestyle, butterfly, and backstroke events, making UUS one of the most influential variables on race performance (Mason & Cossor, 2000).

Maximisation of propulsive impulse and minimisation of resistive impulse are key variables when assessing technique to optimise swimming performance (Connaboy, Coleman, & Sanders, 2009). Propulsion in UUS is generated by producing a 'body wave' that increases in amplitude as it travels caudally along the body (Gavilan, Arellano, & Sanders, 2006; Ungerechts, 1983), resulting in a leg-dominated technique (Higgs, Pease, & Sanders, 2017). Resistive impulse is greatly affected by wave drag, a resistive force produced by the transfer of kinetic energy from the body to the water. The wave drag represents 50–60% of the total passive drag force at the surface in swimming; nevertheless, as depth increases the wave drag decreases noticeably (Vennell, Pease, & Wilson, 2006). This fact results in the potential for higher swimming velocity in UUS than in surface swimming.

Before executing UUS in the start and turns of a race, swimmers glide in a streamlined position underwater away from the wall. In addition to one's ability to perform UUS, a swimmer's underwater gliding capacity likely plays an important role in swimming performance. A more streamlined body position in underwater gliding helps to minimise hydrodynamic drag (Arellano, 2010), which could improve the performance of starts and turns without increasing physiological cost (Naemi, Easson, & Sanders, 2010). In this regard, swimmers would likely benefit from a training protocol aimed to improve UUS and underwater gliding abilities.

The optimum age for learning swimming technique ranges between 7 and 12 years old (Navarro, Oca, & Castañón, 2003), for this reason previous studies have investigated the effect of specific training protocols to improve UUS and underwater gliding in young swimmers (Collard, Gourmelin, & Schwob, 2013; Helmy, 2013). In a study conducted in swimmers aged 9-10, Collard, Gourmelin, & Schwob, (2013) observed greater improvements in 25 m freestyle times in a group that received UUS-specific training, comprising undulation drills incorporated daily into a standard swimming program, than a group that received a standard swimming program only. The distance covered underwater was larger (6.50 vs. 4.91 m) and improvements in 25 m freestyle time were greater (0.94 vs. 0.36 s) in the UUS-specific trained group than in the control group. Similarly, Helmy (2013) observed improvements in underwater gliding performance, measured as the time to cover 8, 10, 12.5, and 15 m, in swimmers aged 11-13 after a 12-week combined program of land and aquatic exercises designed specifically to improve underwater gliding performance.

In the aforementioned studies, the UUS and underwater gliding performance were assessed as time to cover a given distance (Collard et al., 2013; Helmy, 2013). The information provided was helpful to evaluate the overall performance; however, the factors underlying this performance enhancement are unknown. It is possible that the improvements reported in underwater gliding by Helmy were a consequence of technique changes, strength gains associated with normal growth, or a combination of these factors. Thus, to extend beyond the information provided by the assessment conducted in the studies by Collard and Helmy and colleagues, kinematic data could be used to better understand the biomechanical factors underlying overall UUS and gliding performance improvements after a period of training.

A variety of kinematic parameters have been used to assess UUS performance, such as maximal and minimal velocity, or kicking frequency (Arellano et al., 2002; Atkison, Dickey, Dragunas, & Nolte, 2014; Higgs, Sanders, Pease, 2014). Maximal velocity is achieved near before finishing the downbeat, while minimal velocity is achieved at the end of the upbeat when the knees reach peak flexion (Arellano et al., 2002). Increases in maximal or minimal velocity would produce improvements in average velocity of the kick. Kicking frequency has been proposed as one of the most important factors that can be modified to improve UUS velocity (Arellano, Pardillo, & Gavilan, 2003; Arellano et al., 2002). A comparison between age group swimmers and national and international swimmers showed main differences in kicking frequency: the best swimmers were able to reach higher frequencies with similar amplitudes to achieve better performance (Arellano et al., 2003; Arellano et al., 2002). Calculations of these kinematic variables can be done with a single 2D camera or linear potentiometer and minimal data processing time, making them accessible to sports scientists and coaches.

A variety of tools can be used to evaluate underwater gliding performance. For instance, a new 'TorsoShape' tool has been developed to better understand the effects of torso morphology on resistive drag (Papic, Mccabe, Naemi, & Sanders, 2019; Papic, McCabe, Gonjo, & Sanders, 2020) as a corollary for underwater gliding ability. The Hydrokinematic method is another measurement tool that can be used to predict the exact time that underwater undulatory swimming should be initiated (Naemi & Sanders, 2008). Moreover, in addition to measuring the distance covered during a glide (Helmy, 2013), simple measurements of gliding performance have been proposed, such as distance reached as the swimmers slows to 2 m/s and 1 m/s and the time until which forward movement stops (Arellano, 2010). These simple time and position variables allow a quick and detailed quantitative description of underwater gliding.

The scarcity of knowledge about the effects of training on UUS and gliding kinematics in young swimmers led us to implement a skill-specific training protocol aimed to improve UUS and underwater gliding performance. The purpose of this study was to evaluate the performance and kinematics changes after a period of training in young swimmers. It was hypothesised that UUS and gliding performance would improve following a period of training using our protocol.

Methods

Participants

Seventeen age group swimmers, ten boys and seven girls (11.6 ± 0.2 and 10.6 ± 0.4 years, 1.47 ± 0.01 and 1.45 ± 0.04 m of height, 39.2 ± 1.4 and 38.2 ± 3.6 kg of body mass, and 1.50 ± 0.01 and 1.48 ± 0.05 m of arm span, respectively), volunteered to participate in the current study. All of them were under the supervision of the same coach at five training sessions per week and had at least two years of competitive swimming experience. The protocol was explained to the swimmers and their parents, who were informed about the benefits and risks of participating in the current study prior to signing an informed consent form. The study was conducted according to the Code of Ethics of the World Medical Association (Declaration of Helsinki) and The University of Granada Ethics Committee approved the protocol (project reference: 852).

Experimental Approach

A ‘pre/post testing’ design was conducted with an intervention carried out over eight weeks during the second macrocycle of the season, which started at week 22 of the annual training cycle. The first week of the intervention comprised two familiarization sessions with the pre/post testing procedures that were used to evaluate UUS and underwater gliding performance during the first week (PRE) and after seven weeks (POST) of UUS- and glide-specific training. Swimmers were asked to refrain from intense exercise the day before and the day of testing and to abstain from caffeine and stimulants (e.g. energy drinks) during those days.

Swimmers followed the training program set by their coach throughout the study. Standard methodologies were used to compute and categorise swimming training load using a five-zone system (Mujika et al., 1996). The swimmers trained in zones 1, 2, and 5, which corresponded to general swimming, basic endurance, and speed, respectively. Swimming training load was calculated for each week and expressed in the total volume completed (km) and arbitrary training units (T.U.), which was quantified as:

$$T.U. = (km_{z1} * if_{z1}) + (km_{z2} * if_{z2}) + (km_{z3} * if_{z3}) + (km_{z4} * if_{z4}) + (km_{z5} * if_{z5})$$

Where *km* represents the sum of the total volume swum in kilometres in the respective zone (*z1* = zone 1, *z2* = zone 2, *z3*= zone 3, *z4* = zone 4, and *z5*= zone 5) and *if* was the respective intensity factor for each zone: $if_{z1} = 1$, $if_{z1} = 2$, $if_{z1} = 3$, $if_{z1} = 5$, and $if_{z1} = 8$ (Mujika et al., 1996). The progression of swimming training load (determined by total volume completed and T.U.) was monitored over 11 weeks from the first week of the second macrocycle until the end of the eight-week intervention (Figure 1).

(Insert Figure 1 near here)

Experimental Setup

Height (m) and body mass (kg) were measured using a stadiometer (Seca 799, Hamburg, Germany) and arm span (m) was measured with measuring tape. In order to test the reliability of height and arm span measurements, swimmers were measured by two independent researchers. The standard error between researchers was calculated as 0.012 m for height and 0.011 m for arm span. The final anthropometric values were the mean of the two independent measurements.

UUS and underwater gliding were assessed in a 12.50 m long x 5.94 m wide x 1.20 m depth swimming pool (water temperature = 27 ºC, humidity = 60%). This pool enabled to securely place a vertical barrier fixed to a platform (Supplementary File 1), which allowed placing touchpads of an electronic timing system (ALGE-TIMING, TP1890C Anschlagplatte, Lustenau, Austria) to the start wall and to the vertical barrier. This system allowed to electronically measuring the time to cover 10 m in the UUS trials. Horizontal velocity during USS and underwater gliding were registered using a speedometer cable (linear transducer, Heidenhain, D83301, Traunreut, Germany) attached to the swimmer's hip via a belt.

Training Protocol

The skill-specific training protocol comprised three 30 min sessions per week conducted during regular training sessions. The training protocol was designed according to recommendations of swimming drills designed for teaching youth swimming (Guzman, 2017; Lucero, 2015). Exercises were divided into five groups: 'body awareness', 'gliding', 'gliding + propulsion', 'propulsion', and 'speed'. 'Body awareness' exercises were performed on land and all other exercises were performed in the water. 'Body awareness' and 'gliding' exercises focused on body alignment and body position, respectively, 'gliding + propulsion' and 'propulsion' exercises focused on movement coordination and efficiency, and 'speed' exercises focused on developing maximum velocity (Supplementary File 2). The contents of each session were progressed in difficulty over the seven training weeks (Figure 2). Each exercise was progressed when all swimmers were able to perform them correctly. The swimmers' coach, a Sport and Exercise Science graduate with swimming coach qualifications, qualitatively determined when to progress, based on the exercise description. A researcher accompanied the coach during training sessions to ensure that the training protocol was performed and to assess swimmers' progress. Thus, some exercises were repeated more times than others because some swimmers had more difficulty in learning certain skills than others. These training procedures aimed to help swimmers develop abilities necessary to transfer training effects to UUS and underwater gliding during competition (Navarro et al., 2003).

(Insert Figure 2 near here)

Testing Protocol

Prior to testing, swimmers performed a standardised warm-up of dry-land exercises, aimed to challenge the abdominal muscles to stabilise and control the motion of the pelvis and lumbar region (McLeod, 2009): shoulder, hips, knees, and ankles joint mobility, 2x30 s planks (changing from front plank to right lateral plank and to left lateral plank each 10 s) with 15 s rest, and 2x30 s bird dog with 15 s rest followed by an in-water warm-up in a 25 m training pool: 200 m swim, 50 m dorsal kick, 50 m ventral kick, 2x25 m underwater gliding as far as possible until forward progression stopped then swimming to the wall, and 2x25 m UUS increasing speed. PRE and POST testing comprised two 10 m maximal UUS efforts and two maximal underwater gliding efforts from an in-water push start. Swimmers performed one underwater gliding trial followed by one maximal UUS trial, with 2 min of passive rest, and then repeated the procedure after 15 min of passive rest. For the underwater gliding condition, swimmers were instructed to glide as far as possible while maintaining horizontal streamlined position (i.e. with both arms stretched and held together over the head, body erect, and legs straight and held tightly together) for 3 s after forward progression had completely stopped. Underwater gliding performance was measured as the horizontal distance of the swimmer's head from the start wall to the end of the movement. The maximal UUS and underwater gliding efforts began with the swimmers pushing prone from the wall at 1 m depth to remove wave drag effects (Vennell et al., 2006). A mark on the bottom of the pool was located every 2.5 m. During the UUS efforts, swimmers were asked to maintain the same depth until they reached the third mark (7.5 m from the start wall) and to ascend progressively using UUS until reaching the touchpad on the vertical barrier. UUS performance was measured as the time to cover 10 m from the moment the feet pushed off the start wall to the moment hand contact was made on the touchpad secured to the vertical barrier. The best UUS effort (i.e. lowest time to cover 10 m) and underwater gliding trial (i.e. furthest distance covered) were chosen for analysis.

Data Processing and Analysis

Velocity data recorded by the speedometer were A-D converted (Signal Frame MF020, Sportmetrics, Spain) and exported to MATLAB 2013a (MathWorks Inc., Natick, Mass., USA). The encoder voltage was recorded at 200 Hz. Velocity-time curves were smoothed using a fourth-order low pass Butterworth filter, with a cut off frequency of 6 Hz.

From the velocity-time curves, the kick cycles were identified using methods from Arellano, Pardillo, & Gavilán, (2002). The start of the kick was established as the slowest velocity point of the cycle, which corresponds to the end of the upbeat and the start of the downbeat. Velocity increases from the beginning of the downbeat until reaching its peak value before decreasing just prior to the end of the downbeat. From the beginning of the upbeat, velocity increases again until reaching its peak value (smaller than the downbeat peak), which corresponds to the half of the upbeat. Finally, from the small peak in the upbeat to the end of the upbeat, velocity decreases to its minimum value. Six successive kicks performed during the best maximal UUS trial were identified and chosen for analysis. To avoid effects of the push from the wall (Arellano et al., 2002), the first two kicks were discarded; thus, the first kick analysed was the third kick performed, which took place approximately 2 m from the start wall for all participants. The following 'UUS variables' were calculated for the best UUS effort.

- Time to cover 10 m (Ttime) (s): time spent to reach the final touchpad.
- Average underwater velocity (Uavg) (m/s): mean velocity from each of the six selected kicks recorded using the speedometer.
- Average underwater peak velocity (Upeak) (m/s): mean peak velocity from each of the six selected kicks recorded using the speedometer.
- Average underwater minimum velocity (Umin) (m/s): mean minimum velocity from each of the six selected kicks recorded using the speedometer.
- Kick frequency (Hz): the number of selected kicks (six) divided by the time spent to perform them.

The following variables were calculated for the best underwater gliding trial, defined as 'gliding variables', from the speedometer data:

- Average gliding velocity (Gavg) (m/s): mean of velocity values recorded during the underwater gliding until swimmers slow down to 0.15 m/s.
- Push-off velocity (m/s): highest value obtained from the individual velocity-time curve during underwater gliding.

- Time to reach 2 m/s (T2) (s): time taken to slow down to 2 m/s after pushing off the wall.
- Time to reach 1 m/s (T1) (s): time taken to slow down to 1 m/s after pushing off the wall.
- Time to reach 0.15 m/s (T0.15) (s): time taken to slow down to 0.15 m/s after pushing off the wall.

Statistical Analysis

According to the Shapiro-Wilk test, PRE and POST UUS and gliding variables and the difference between variables scores of these moments were normally distributed, with the exception of T2. Square root transformation of T2 was conducted and therefore, parametric statistical analysis was adopted. The differences in Ttime and UUS and glide variables between PRE and POST were further evaluated using paired-sample *t*-tests. Effect sizes (d) were calculated and interpreted using Cohen, (1988) recommendations (small: $|d| \leq 0.5$, medium: $0.5<|d|\leq 0.8$, and large: $|d|>0.8$). To test the relationship between performance and kinematics variables, Bivariate Pearson's correlation coefficients (r) and linear regression analyses were determined between Ttime and 1) UUS variables and 2) gliding variables for PRE and POST separately. To test the possible effect of anthropometric development on the performance, Pearson's correlation coefficients were also determined between: Ttime change (POST-PRE) and height change (POST-PRE); Ttime change and body mass change (POST-PRE); Ttime change and arm span change (POST-PRE).

To compare PRE and POST data, a curve analysis was performed using Statistical Parametric Mapping (SPM) (Penny, Friston, Ashburner, Kiebel, & Nichols, 2011) in MATLAB 2013a using the 'spm1d' plugin (Pataky, 2012) (http://www.spm1d.org). The average of the six selected kicks was calculated. The velocity-time curve for the average kick and underwater gliding from the PRE and POST trials were normalised to 101 data points. SPM involves four steps. First, at each point of the normalised time series, the paired *t*-test value between PRE and POST are computed. Second, the temporal smoothness of each curve is estimated based on the average temporal gradient of the residuals. Third, the value of a test statistic is calculated from which only 5% of trajectories resulting from a random process equally smooth to ours would occur. Finally, the probability that specific suprathreshold regions (named clusters) could have resulted from an equivalently smooth random process are computed (De Ridder et al., 2013). Technical details are provided elsewhere (Penny et al., 2011). Statistical procedures, with the exception of SPM, were performed using SPSS 24.0 (IBM, Chicago, IL, USA), and the level of statistical significance was set at $p<0.05$.

Results

Height (PRE: 1.46 ± 0.08 m; POST: 1.47 ± 0.08 m), body mass (PRE: 38.8 ± 6.2 kg; POST: 39.4 ± 6.6 kg), and arm span (PRE: 1.49 ± 0.09 m; POST: 1.51 ± 0.09 m) increased during the seven weeks of intervention with moderate to large effect sizes ($p = 0.005$, $d = 0.8$; $p = 0.006$, $d = 0.6$; and $p < 0.001$, $d = 1.3$, respectively). Nevertheless, the change in performance was not correlated with height ($r = -0.130$, $p = 0.630$), body mass ($r = -0.239$, $p = 0.373$) or arm span ($r = 0.157$, $p = 0.561$) change.

Uavg, Upeak, and Umin improved significantly after the training protocol and, consequently, Ttime decreased by almost 8% in the UUS trials (Table 1). Swimmers maintained a similar kick frequency between PRE and POST. For the underwater gliding trials, T2, T1, and T0.15 decreased, while Gavg and push-off velocity did not change significantly (Table 1). Table 2 shows Pearson's correlation coefficients of PRE and POST Ttime vs. UUS and gliding variables. There were significant negative correlations between Ttime and Uavg, Upeak, and Umin in PRE and between Ttime and Uavg, Upeak, and Umin in POST (Figure 3).

(Insert Table 1 near here)

(Insert Table 2 near here)

(Insert Figure 3 near here)

Ttime presented significant negative correlations with T2, T1, and T0.15 in PRE and Ttime presented significant negative correlations with push-off velocity, T2, T1, and T0.15 in POST (Figure 4). Ttime and Gavg were not significantly related in either PRE or POST.

(Insert Figure 4 near here)

SPM analysis showed significant differences between PRE and POST horizontal velocity for the average kick. From the beginning to around 15% of the cycle time, the velocity during POST was significantly higher than in PRE. Moreover, from around 50% to the end of the cycle time, the velocity during POST was also significantly higher than in PRE (Figure 5). The POST gliding velocity was significantly higher than PRE gliding velocity at around 3% of the cycle time of the gliding velocity-time curve (Figure 6).

(Insert Figure 5 and 6 near here)

Discussion and Implications

The purpose of this study was to evaluate the effects of a training protocol on UUS and underwater gliding performance and kinematics in young swimmers. Enhancements in UUS performance, measured by changes in Ttime between PRE and POST, were likely the result of regular swimming training, the UUS and gliding skill-specific training protocol, and growth. Our findings contribute to a better understanding of the changes in UUS and underwater gliding technique underpinning these improvements.

There are two potential reasons for the performance enhancement observed. The first possibility is related to propulsive and resistive forces. When the propulsive forces are higher or lower than the resistive forces (i.e. hydrodynamic drag) the body is accelerated or decelerated and therefore swimming velocity increases or decreases, respectively (Vilas-Boas, Fernandes, & Barbosa, 2011). The larger improvements in Upeak (9.1%) and Umin (40.4%) were therefore a consequence of changes in both the propulsive and resistive forces or only in one of them. As we did not measure hydrodynamic forces, we cannot elucidate whether or not propulsive and resistive forces during UUS changed after the training protocol.

The second probable explanation is related to the downbeat and upbeat execution. While Upeak is obtained near the end of the downbeat, Umin is obtained at the end of the upbeat (Arellano et al., 2002). The upbeat is important for UUS performance since its successful execution can be challenging, setting the fastest swimmers apart from the rest (Atkison et al., 2014). Hence, the larger improvement observed in Umin compared to Upeak is of great interest. Swimmers achieved higher velocity during the beginning of the downbeat and during the whole upbeat (Figure 5). Therefore, the fact that the velocity was significantly higher during the complete execution of the upbeat indicates that UUS performance improvements presented here were mostly produced by a better execution of the upbeat.

Arellano and colleagues (2002, 2003) suggested that increasing kicking frequency could improve UUS performance; however, in the current study, while kicking frequency did not change significantly, improvements were observed in UUS performance and kinematics.

Indeed, performing just several maximal trials at different kicking frequencies can provoke kinematic changes at their preferred kicking frequency; without affecting maximal UUS velocity (Shimojo, Sengoku, Miyoshi, Tsubakimoto, & Takagi, 2014). In other words, training may induce changes in UUS kinematics without affecting the kicking frequency. Therefore, our results suggest that swimmers might have improved their ability to utilise the same kick frequency more effectively after the training.

Underwater gliding performance can be determined by two factors: initial push-off velocity and hydrodynamic drag, where the latter decelerates the swimmer (Lyttle, Blanksby, Elliot, & Lloyd, 1998; Novais et al., 2012). The push-off velocity did not improve after the training, which may suggest that swimmers did not enhance the impulse during the push-off (Lyttle & Mason, 1997). Nevertheless, since the push-off velocity did not increase and T2, T1, and T0.15 were significantly improved, it can be postulated that swimmers reduced their hydrodynamic drag. Hydrodynamic drag may have been reduced by improvements in the ability to hold a more streamlined body position (for example, from the 'body awareness' and 'gliding' exercises). Moreover, since push-off velocity correlated with Ttime in POST and not in PRE, the swimmers likely improved their ability to utilise the push-off velocity more effectively in POST than in PRE. These findings support the need to measure different aspects of underwater gliding to accurately evaluate performance.

The gliding kinematics measured here are easily collected and relate strongly to UUS performance (Table 2), which makes them appropriate for age group swimmers or daily assessment. From a coaching perspective, the time taken to reach surface swimming velocity is likely to be the variable of greatest interest since swimmers should start kicking prior to this velocity to avoid slowing below surface swimming velocity. In the current study, the velocity for T2 was chosen because it is similar to swimming velocity achieved in sprint racing (i.e. 2 m/s equates to 25 s for a 50 m race). On the other hand, T1 may be more suitable to use with swimmers who are not capable to reach higher velocities while swimming. Furthermore, while swimmers inevitably start kicking before slowing to T0.15 and thus this variable may not be as applicable as T2 or T1, the T0.15 measurement provides an understanding of a swimmer's ability to maintain their body position and whether coaches should focus on core stability, which is vital in swimming due to the unstable nature of the water environment (Willardson, 2007).

Improvements observed in the current study might have been influenced by swimmers' training and growth. While UUS performance changes were not correlated with height, weight, or arm span changes, this does not necessarily mean that growth had no effect on performance, because the combined effect of the change in height, weight, and arm span might have had an influence on the outcome. Hence, the findings are limited by the lack of a control group. Yet, the assessment conducted here will allow coaches to identify the effects of training on their swimmers. This assessment will aid to identify weaknesses in specific components of UUS and underwater gliding that can be used to better plan future training and therefore achieve higher performance. Other skill-specific training protocols, such as resistance training, may be complementary to the exercises used in the current intervention. Future research should be conducted to better understand how muscle strength and technique training interact to induce enhancements in UUS performance.

Conclusion

The detailed assessment of UUS and underwater gliding kinematics in the current study contributes to the understanding of training effects on youth swimmers by showing individual changes. Our results showed that after a period of seven weeks, swimmers improved their UUS and gliding performance. The UUS performance enhancement was mostly due to an improvement in the upbeat execution. Since push-off velocity did not change, swimmers may have improved their ability to hold a more streamlined body position, which could have provoked a reduction in hydrodynamic drag that led to improvements in gliding performance. The strong correlations between most of the kinematic variables with performance suggest the use of this assessment protocol in future studies.

Disclosure Statement:

The authors have no conflicts of interest to report.

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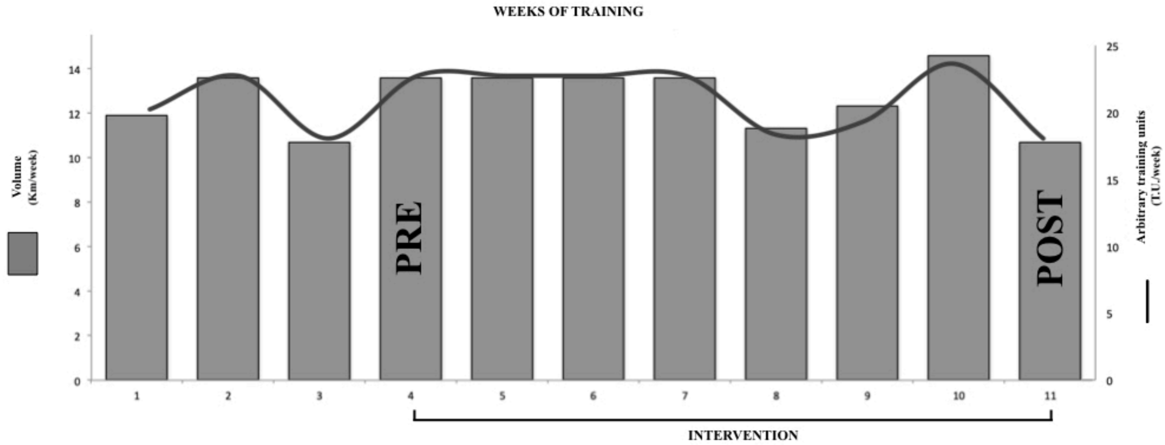

Figure 1. Training volume and units (T.U.) of the monitored 11 weeks, from the beginning of the second macrocycle until the end of the eight-week intervention. PRE: UUS and underwater gliding performance evaluation during the first week of intervention; POST: UUS and underwater gliding performance at the end of the intervention.

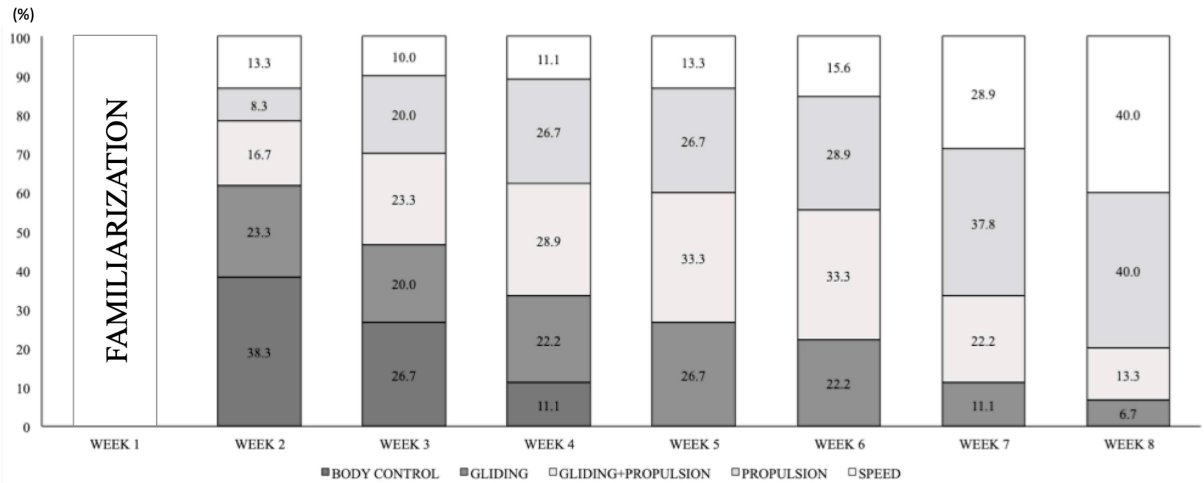

Figure 2. Percentage distribution of the time spent weekly on each content during the underwater training protocol.

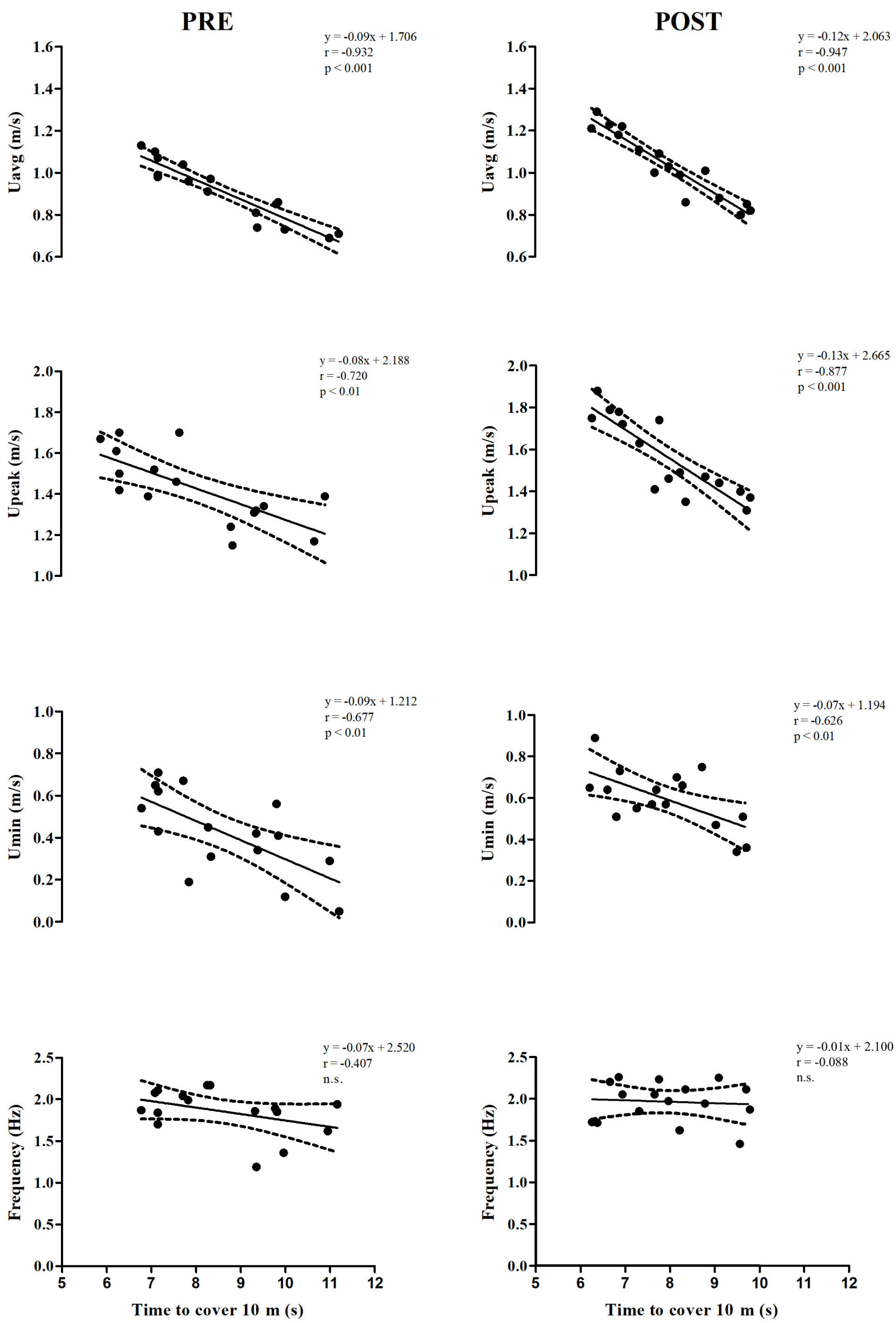

Figure 3. Linear regressions of PRE and POST between time to cover 10 m (s) and UUS parameters. Individual value and 95% confidence lines are represented. Uavg: average underwater velocity; Upeak: average underwater peak velocity; Umin: average underwater minimum velocity.

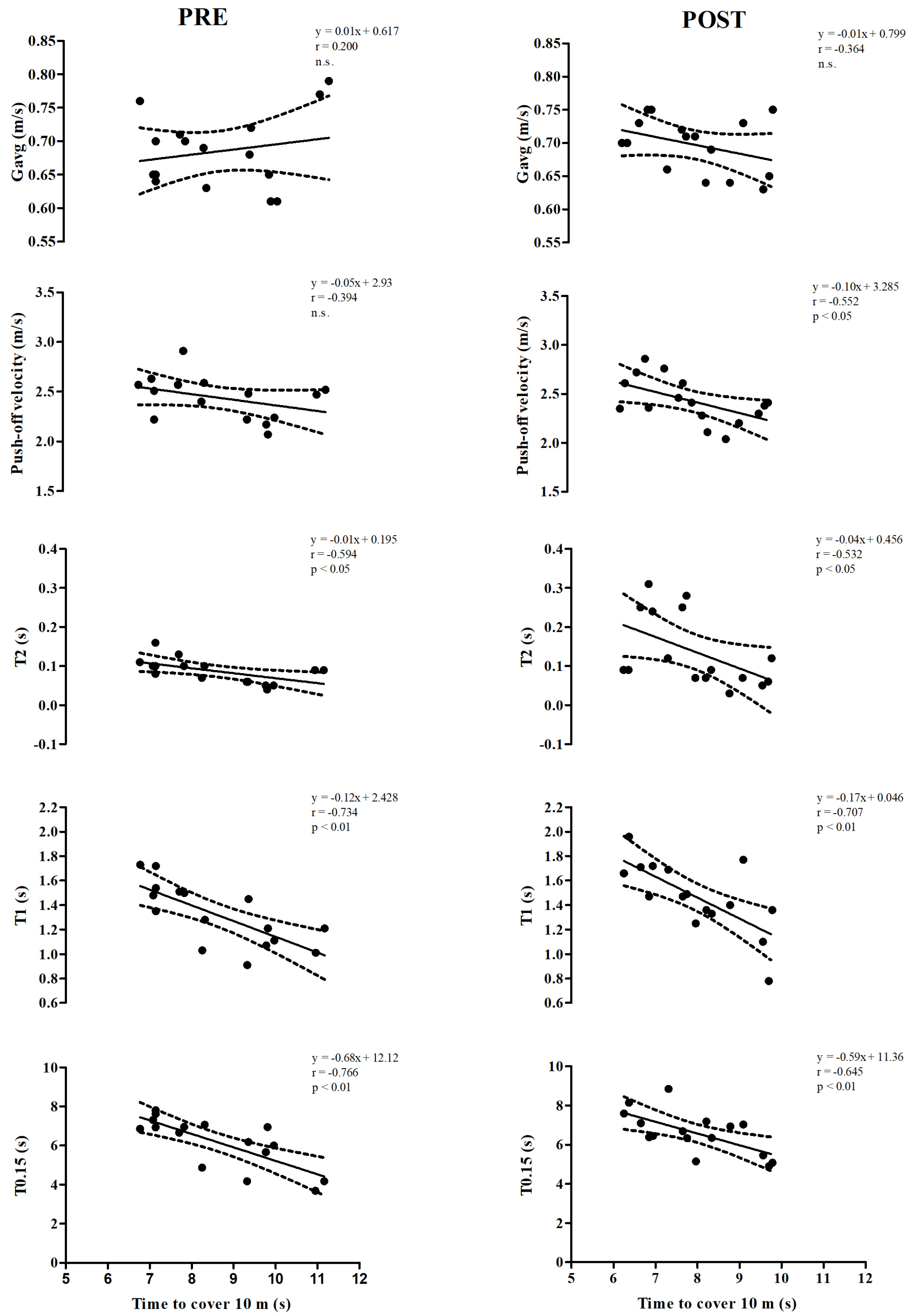

Figure 4. Linear regressions of PRE and POST between time to cover 10 m (s) and gliding parameters. Individual value and 95% confidence lines are represented. Gavg: underwater gliding velocity; T2: time to reach 2 m/s; T1: time to reach 1 m/s; T0.15: time to reach 0.15

m/s. For T2 raw data is presented; however, analyses were conducted with the square root transformation.

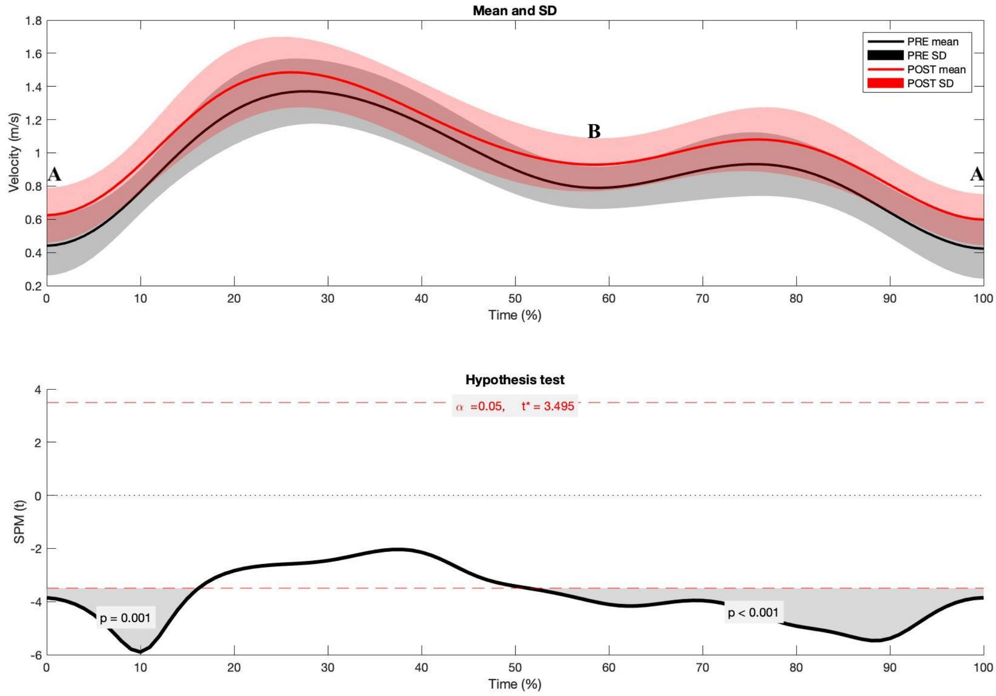

Figure 5. Kinematic comparison between PRE and POST of the average kick velocity-time curve. Above, 'Mean and SD' are mean values kinematic trajectories with SD clouds. Below, SPM results; 'Hypothesis test' is the trajectory Student's t statistic or, equally, the sample-size normalised variance normalising the mean difference curve. The dashed horizontal line represents the critical threshold (p<0.05). A: end of the upbeat – start of the downbeat; B: end of the downbeat – start of the upbeat.

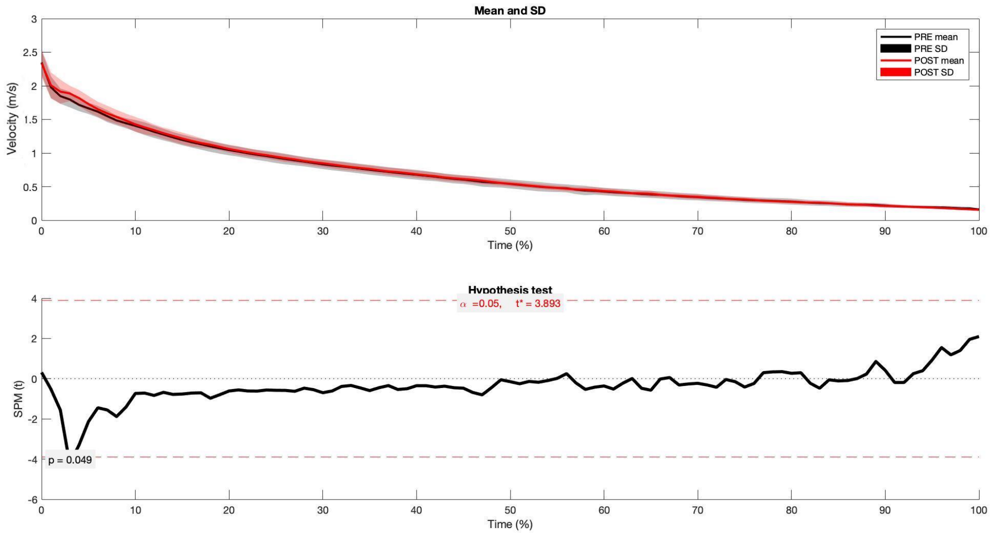

Figure 6. Kinematic comparison between PRE and POST of the underwater gliding velocity-time curve. Above, 'Mean and SD' are mean values kinematic trajectories with SD clouds. Below, SPM results; 'Hypothesis test' is the trajectory Student's t statistic or, equally, the sample-size normalised variance normalising the mean difference curve. The dashed horizontal line represents the critical threshold ($p<0.05$).

Supplementary File 1. Touchpad place in the vertical barrier fixed to the platform.

Supplementary File 2. Exercises performed per content in the specific training protocol. The order of appearance is based on grade of difficulty.

Table 1. Effects of seven weeks of training on UUS and gliding kinematic variables. The PRE and POST mean ± SD values with mean differences between PRE and POST, upper and lower 95% confidence intervals, relative changes (%Δ), statistical probabilities (p-value), and effect sizes are shown.

Variable	PRE	POST	Difference [95%CI]; %Δ	*p*-value	Effect size (*d*)
Ttime (m/s)	8.60±1.45	7.94±1.18	-0.66 [-0.98, -0.32]; -7.6%	0.001**	1.04
Uavg (m/s)	0.91±0.14	1.04±0.16	0.13 [0.08, 0.17]; 13.9%	<0.001***	1.72
Upeak (m/s)	1.43±0.17	1.56±0.18	0.13 [0.07, 0.19]; 9.1%	<0.001***	1.15
Umin (m/s)	0.42±0.19	0.59±0.14	0.17 [0.08, 0.26]; 40.7%	0.001**	0.99
Kick frequency (Hz)	1.85±0.27	1.96±0.24	0.10 [-0.08, 0.30]; 5.8%	0.261	0.29
Gavg (m/s)	0.68±0.05	0.69±0.04	0.01[-0.02, 0.04]; 1.5%	0.523	0.16
Push-off velocity (m/s)	2.44±0.21	2.42±0.23	-0.01[-0.11,0.09]; -0.5%	0.792	0.06
T2[a] (s)	0.08±0.03	0.13±0.09	0.05[0.01, 0.08]; 55.7%	0.028*	0.60
T1 (s)	1.31±0.25	1.46±0.28	0.14[0.05, -0.25]; 11.4%	0.006**	0.80
T0.15 (s)	6.18±1.30	6.60±1.10	0.31[-0.75, 0.11]; 6.8%	0.038*	0.57

Ttime: time to cover 10 m
Uavg: average underwater velocity
Upeak: average underwater peak velocity
Umin: average underwater minimum velocity
[a]Raw data is presented, but square root transformed data was used in the analysis

Gavg: average gliding velocity
T2: time to reach 2 m/s
T1: time to reach 1 m/s
T0.15: time to reach 0.15 m/s

* $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

Table 2. Pearson's correlation coefficient between time to cover 10 m and underwater undulatory swimming (UUS) and gliding variables of PRE and POST test values.

		Uavg	Upeak	Umin	Kick frequency	Gavg	Push-off velocity	T2	T1	T0.15
PRE Ttime	*r*	***-0.932**	***-0.720**	***-0.677**	-0.407	0.200	-0.394	***-0.594**	***-0.734**	***-0.766**
POST Ttime	*r*	***-0.947**	***-0.877**	***-0.626**	-0.088	-0.364	***-0.552**	***-0.532**	***-0.707**	***-0.645**

***$p < 0.05$**
PRE Ttime: time to cover 10 m using pre-test
POST Ttime: time to cover 10 m using post-test
Uavg: average underwater velocity
Upeak: average underwater peak velocity
Umin: average underwater minimum velocity
Gavg: average gliding velocity
T2: time to reach 2 m/s
T1: time to reach 1 m/s
T0.15: time to reach 0.15 m/s