

Undulatory Underwater Swimming Performance and Kinematics: International- vs National-Level Female Swimmers

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Abstract: This study aimed to compare undulatory underwater swimming (UUS) performance and kinematics between international- and national-level female swimmers. Seven international level female swimmers (18.9 ± 3.4 years; 67.2 ± 4.4 kg of body mass; 175 ± 4.8 cm of body height; and 804 ± 35 World Aquatics points) and seven national level female swimmers (17.6 ± 1.7 years; 57.4 ± 4.1 kg of body mass; 166 ± 4.9 cm of body height; and 662 ± 65 World Aquatics points) performed three maximal-effort 15 m UUS trials. Seven body landmarks were auto-digitalized during UUS by a pre-trained neural network and 21 kinematic variables were calculated. The results showed no statistically significant differences across the variables analysed ($p > 0.05$); however, mean and minimum UUS velocities showed a clear trend toward better performance in international-level swimmers ($p = 0.055$ – 0.057 ; $d = 0.91$ – 0.92). In conclusion, there was a tendency for superior UUS performance among international-level swimmers compared to national-level swimmer. Furthermore, variations in UUS technique appear to be more strongly influenced by individual physical and anatomical characteristics than by performance level alone.

1 INTRODUCTION

Aside from the initial dive, the highest velocities in butterfly, backstroke, and freestyle events are achieved during the underwater phase (Ruiz-Navarro et al., 2022). Consequently, this segment is considered one of the most critical for overall performance (Mason & Cossor, 2001). During this phase, swimmers propel themselves forward using undulatory underwater swimming (UUS), a technique characterized by wave-like body movements while maintaining a streamlined position with the arms extended and held together above the head (Connaboy et al., 2010). During each kick cycle, a complete downward (downbeat) and upward (upbeat)

movement of the lower limbs is performed to generate propulsion (Higgs et al., 2016).

Current rules and regulations limit the underwater phase during competition to a maximum of 15 meters. In this regard, the distance covered underwater varies across different performance levels (Pla et al., 2021; Veiga et al., 2016). Race analyses have shown that higher-level performers tend to spend more time underwater, cover longer distances, and achieve higher velocities during this phase (Pla et al., 2021). These factors provide greater advantages in start and turn performance, thereby contributing positively to overall race outcomes (Arellano et al., 1994; Morais et al., 2019).

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Given the increasing importance of UUS, various performance-related variables have been investigated in the literature (Atkison et al., 2014; Higgs et al., 2017; Matsuda et al., 2021). Among the studied variables highlights the joints' amplitude, range of motion, and angular velocities, as well as toe vertical velocity, kick frequency, and kick length (Ruiz-Navarro et al., 2022). These variables are either linked to performance outcomes or used to characterize swimmers' movement patterns (Connaboy et al., 2010; Higgs et al., 2017; Ruiz-Navarro et al., 2022). However, there is currently no up-to-date comparison of these variables across swimmers of different performance levels (Arellano et al., 2002).

Female athletes have historically been underrepresented in sport science research (Meyer & Copley, 2024) highlighting the need for targeted investigations, particularly in swimming, where significant differences in anthropometric and physiological characteristics may influence performance and technique (Janssen et al., 2000; Miller et al., 1993). Thus, this study aimed to compare UUS performance and kinematics between international- and national-level female swimmers. It was hypothesized that international-level female swimmers would exhibit superior performance outcomes compared to their national-level counterparts.

2 METHODS

2.1 Participants

Seven international-level female swimmers (18.9 ± 3.4 years, 67.2 ± 4.4 kg of body mass, 175 ± 4.8 cm of body height, and 804 ± 35 World Aquatics Points (Level 2 (Ruiz-Navarro et al., 2023)) belonging to the same national squad and seven national-level female swimmers (17.6 ± 1.7 years, 57.4 ± 4.1 kg of body mass, 166 ± 4.9 cm of body height, and 662 ± 65 World Aquatics Points (Level 3 (Ruiz-Navarro et al., 2023)) members of the same swimming squad participated in this study. The protocol was explained to the swimmers and their parents or legal guardians (for swimmers under 18 years old) before obtaining their written consent.

2.2 Data Collection

Swimmers were assessed in a single testing session. After anthropometric measurements were taken using a stadiometer (Seca 799, Hamburg, Germany),

swimmers were marked on the right side of the body with a 3-cm-diameter circle of black body paint at the following anatomical landmarks: the styloid process of the ulna, the head of the humerus, the greater trochanter of the femur, the lateral epicondyle of the femur, the lateral malleolus of the fibula, and the 5th metatarsal phalangeal joint of the foot (toe) (Figure 1). These specific points represent the joint centres of the wrist, shoulder, hip, knee, and ankle and the most distal point of the foot, respectively (Naemi & Sanders, 2008). Subsequently, swimmers performed their one warm-up, with special focus on UUS.



Figure 1: Representation of the 6 anatomical landmarks.

Afterwards swimmers performed 3×15 m trials with at least 3 min of total recovery between trials (Higgs et al., 2017). Swimmers were instructed to maintain a consistent depth of 1 m throughout the 15 m to control wave drag effects, otherwise, they would be requested to perform an extra trial (Vennell et al., 2006). Trials were conducted in lane three, 5.2 m from the side wall. All the trials were recorded with one stationary underwater camera (GoPro HERO 9, 60Hz, 2.7K, California, USA) positioned at 7.5 m from the starting wall and 1 m below the surface with the optical axes perpendicular to the swimming direction, recording the area between 5 and 10 m (Ruiz-Navarro et al., 2024). This setup ensured that two complete kick cycles were recorded per trial, with a total of six cycles analysed to provide a representative and reliable assessment of UUS kinematics (Connaboy et al., 2010).

2.3 Data Analysis

The UUS trials were analysed following Papic et al. (2020) procedures, using a pre-trained Neural Network in DeepLabCut™ with a mean test error of 5.5 mm (Ruiz-Navarro et al., 2024). The “Cinalysis” software (Elipot et al., 2010) was used to compute the calibration coefficients by applying a 2D direct linear transformation with a calibration plane (2.05×1.60 m) containing 37 calibration points in Matlab 2016 (MathWorks Inc., Natick, Mass., USA). The calibration error was assessed as the reprojection error, where root-mean-square error (RMSE) of the

reconstructed calibration marker positions were for the x- and y-axis coordinates 0.003 m and 0.002 m, respectively. Two full kick cycles were digitised for each trial, with an additional 15 frames included before and after the start and end points to preserve signal continuity during filtering and time derivative calculation (Vaughan, 1982). A fourth-order low pass Butterworth filter with a cut off frequency of 6 Hz was employed to smooth the data. Finally, the following kinematics variables were calculated using the methods employed by (Connaboy et al., 2010) in Python 3.9: mean, maximum, and minimum undulatory underwater swimming velocity (denoted as mean U, max U, and min U, respectively), cycle length, kick frequency, and vertical joint center amplitudes of the wrist, shoulder, hip, knee, ankle, and fifth metatarsal phalangeal joint. Additionally, joint ranges of motion and mean angular velocities of the shoulder, hip, knee, and ankle, as well as mean and maximum vertical toe velocity, were assessed.

2.4 Statistical Analysis

The data are expressed as mean $\pm$ standard deviation (SD). The normality of all variables was assessed using the Shapiro-Wilk test. An independent t-test was conducted to compare swimmers across performance levels. Effect sizes were calculated using Cohen's d to estimate the magnitude of differences in the analysed variables. The effect size was categorized as follows: small if $0 \leq |d| \leq 0.5$, medium if $0.5 < |d| \leq 0.8$, and large if $|d| > 0.8$ (Cohen, 1988). All statistical procedures were performed using the Jamovi software package version 2.3.28.0 (Jamovi Project 2022, Sydney, Australia, retrieved from <https://www.jamovi.org>) with the level of statistical significance set at 0.05. Subsequently, a post hoc power analysis was conducted for the independent t-test using G*Power version 3.1.9.7 (Universität Düsseldorf, NRW, Germany).

3 RESULTS

Table 1 presents performance level-based mean $\pm$ SD differences for UUS performance and kinematic variables along with corresponding p-values, and effect sizes (Cohen's d). The statistical power ranged from 0.06 to 0.63 across the observed effect size range of 0.03 to 1.12.

Table 1: Performance level-based differences.

Variable	Level 2	Level 3	Diff.	p	d
Mean U (m/s)	1.61 $\pm$ 0.14	1.49 $\pm$ 0.13	0.12	0.057	0.91
Max U (m/s)	1.90 $\pm$ 0.12	1.88 $\pm$ 0.17	0.02	0.384	0.16
Min U (m/s)	1.20 $\pm$ 0.19	1.06 $\pm$ 0.12	0.14	0.055	0.92
Cycle length (m)	0.71 $\pm$ 0.05	0.72 $\pm$ 0.11	-0.01	0.586	0.12
Kick frequency (Hz)	2.27 $\pm$ 0.31	2.10 $\pm$ 0.35	0.17	0.177	0.52
Wrist amplitude (m)	0.06 $\pm$ 0.02	0.07 $\pm$ 0.02	-0.98	0.810	0.49
Shoulder amplitude (m)	0.06 $\pm$ 0.01	0.07 $\pm$ 0.02	-0.75	0.790	0.45
Hip amplitude (m)	0.12 $\pm$ 0.03	0.13 $\pm$ 0.02	-0.82	0.714	0.31
Knee amplitude (m)	0.23 $\pm$ 0.04	0.26 $\pm$ 0.03	-3.23	0.954	0.98
Ankle amplitude (m)	0.37 $\pm$ 0.06	0.41 $\pm$ 0.04	-3.63	0.884	0.67
Toe amplitude (m)	0.51 $\pm$ 0.07	0.54 $\pm$ 0.05	-2.67	0.795	0.46
Shoulder ROM (°)	22.0 $\pm$ 5.6	24.5 $\pm$ 5.3	-2.48	0.796	0.46
Hip ROM (°)	38.6 $\pm$ 8.3	46.7 $\pm$ 6	-8.07	0.971	1.12
Knee ROM (°)	72.2 $\pm$ 9.1	79.5 $\pm$ 3.8	-7.35	0.964	1.05
Ankle ROM (°)	46.1 $\pm$ 9.5	45.0 $\pm$ 7.8	1.06	0.412	0.12
Mean shoulder angular velocity (°/s)	100.8 $\pm$ 25.6	107.4 $\pm$ 20.4	-6.6	0.699	0.29
Mean hip angular velocity (°/s)	168.2 $\pm$ 30.5	200.1 $\pm$ 47.1	-31.8	0.920	0.80
Mean knee angular velocity (°/s)	372.0 $\pm$ 39.8	414.8 $\pm$ 51.4	-42.7	0.946	0.93
Mean ankle angular velocity (°/s)	277.9 $\pm$ 67.8	275.3 $\pm$ 88.6	2.58	0.476	0.03
Mean toe vertical velocity (m/s)	1.14 $\pm$ 0.04	1.11 $\pm$ 0.12	2.42	0.306	0.28
Max toe vertical velocity (m/s)	4.09 $\pm$ 0.28	4.04 $\pm$ 0.31	5.14	0.375	0.17

Abbreviations: U, undulatory underwater swimming velocity; ROM, range of motion.

4 DISCUSSION

This study aimed to compare UUS performance and kinematics between international-level (Level 2) and national-level (Level 3) female swimmers. While no statistically significant differences were observed across the variables assessed, a notable trend emerged in UUS performance and kinematics. Specifically, both mean and minimum underwater swimming velocity demonstrated a large effect size ($p = 0.057$; $d = 0.91$ and $p = 0.055$; $d = 0.92$, respectively; and statistical power $(1 - \beta) = 0.49$, for both) that might indicate differences between performance level.

When compared to previous studies, similar UUS velocity values were observed in a sex-mixed sample of international-level swimmers (Arellano et al., 2002). However, the present study focuses exclusively on female swimmers. In the aforementioned study, significant differences were found between international- and national-level swimmers, with national-level athletes demonstrating notably lower performance (1.25 m/s) compared to those in the current sample (1.49 m/s). Altogether, these findings highlight the increasing importance of the UUS phase in modern competitive swimming and its contribution to overall performance (Pla et al., 2021; Veiga et al., 2016).

With regard to maximum and minimum UUS velocities, a trend toward group differences was observed in minimum velocity. This velocity typically occurs during the upbeat phase of the kick (Arellano et al., 2002), which can be technically challenging due to human anatomical constraints (Loebbecke et al., 2009). Notably, and in accordance to the tendency observed in our results, this phase has been suggested to distinguish the fastest swimmers from their peers, and it is the most responsive to improvement following targeted UUS training interventions in young swimmers (Ruiz-Navarro et al., 2021).

There is an optimal combination of kick frequency and kick length that is specific to each swimmer (Yamakawa et al., 2017). Consequently, the different anthropometric characteristics between swimmers may have led to greater intra-group variability, potentially obscuring differences between them. Moreover, equal velocities can be reached in different ways by increasing the magnitude of the propulsive impulse relative to the active drag experienced (Connaboy et al., 2016). For instance, while some swimmers rely on greater undulations aiming for greater propulsion, they also produce greater resistance, while the opposite may also occur. Thus, the lack of differences in swimming kinematics

may be more indicative of individual differences than to the performance level and therefore, future research should aim to compare swimmers of different performance level within the same cluster.

As observed in elite short-course swimming, consistency in turn performance and control of intra-individual variation appear more indicative of high-level execution than isolated kinematic outputs (Cuenca-Fernández et al., 2022). This highlights the need to consider alternative predictors that may underlie such consistency, such as body shape, passive drag characteristics, and gliding efficiency. Individual anatomical differences, like torso-to-hip ratios or streamline profiles, can substantially influence how force is translated into forward motion and how effectively drag is minimized. These biomechanical and morphological features may explain performance differences even when kinematic metrics appear similar across swimmers. Thus, to enhance our understanding of elite UUS performance, future research should incorporate multidimensional analyses that include anthropometrics, hydrodynamic profiling, and gliding capabilities alongside traditional kinematics.

Another point to consider is that the measurements were not taken in a competitive environment, with swimmers fully rested, unlike during actual races. These measurements are indeed commonly used to characterize swimmers' movements (Connaboy et al., 2010). However, during a race, factors such as physical conditioning and fatigue may affect UUS performance (Taladriz et al., 2015), and differences in UUS between levels might become more pronounced as the race progresses.

Finally, it is important to acknowledge the limitation posed by the relatively small sample size. Although the study successfully included high-level swimmers, who are typically difficult to recruit, the limited number of participants resulted in reduced statistical power, which likely contributed to the absence of statistically significant differences by increasing the risk of a Type II error, thus, the results should be interpreted with caution. Moreover, the high degree of individual variation in technique within each group may have influenced the kinematic outcomes, further masking potential performance-related differences. Additionally, overall swimming performance does not necessarily imply superiority across all phases of the race. As such, specific weaknesses in some international-level swimmers may have aligned with strengths in certain national-level swimmers, potentially contributing to the lack of clear group differences. To better interpret individual performance within specific race phases,

future research should establish benchmarks and corresponding percentiles for key UUS kinematic variables.

5 CONCLUSIONS

In conclusion, the findings suggest a trend toward superior UUS performance—particularly during the upbeat phase—in Level 2 (international) compared to Level 3 (national) female swimmers. However, no clear differences in kinematic variables were observed between groups, which may indicate that variations in UUS technique are more strongly influenced by individual physical and anatomical characteristics than by performance level alone. Our findings should be interpreted as exploratory rather than confirmatory and future studies combining biomechanics, anthropometrics, and hydrodynamics are needed to build on these preliminary results.

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