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RELATIONSHIP BETWEEN SELECTED LOAD-VELOCITY PROFILE VARIABLES AND UNDERWATER UNDULATORY SWIMMING PERFORMANCE

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ABSTRACT

BACKGROUND: Load-velocity profiling (LVP) using semi-tethered devices is a validated methodology for quantifying force and velocity capabilities in surface swimming, yet its application to underwater undulatory swimming (UUS) remains unexplored. This study aimed to characterize the LV profiled during UUS, investigate the relationship between the LV profile and UUS performance and anthropometrics, and examine sex-based differences. **METHODS:** Thirty-three competitive swimmers (21 males, 12 females) performed a LV profile test. Individual LV profiles were constructed via linear regression of each trial and the theoretical maximum velocity (V_0), the theoretical maximum load (L_0), and the slope of the regression line (Slope) were calculated. Anthropometric measurements included height, arm span, body mass, sitting height, body length, biacromial and biiliocristal breadths, and derived indices. **RESULTS:** High linearity was confirmed for the LV profile (R^2 = 0.987 ± 0.015, males; 0.981 ± 0.023, females). Except for Slope in males, the LV profile-derived variables were largely to nearly perfectly correlated with UUS performance in both sexes ($p<0.05$). Body mass showed moderate association with L_0 ($r = 0.39$) and Slope ($r = 0.42$) in males and no other significant association between anthropometrics and performance was observed ($p>0.05$). Males exhibited higher V_0 (1.58 ± 0.17 vs. 1.39 ± 0.14 $m \cdot s^{-1}$, $p<0.01$) and L_0 (7.99 ± 2.38 vs. 5.76 ± 1.02 kg, $p<0.01$). Females showed steeper load-velocity Slopes (–0.21 ± 0.05 vs. –0.25 ± 0.03, $p<0.05$). **CONCLUSIONS:** LV profile methodology is applicable to UUS assessment, with limited direct influence of anthropometric factors and clear differences between sexes.

KEYWORDS: Dolphin kick | Semi-tethered swimming | Assessment | In-water forces

INTRODUCTION

Load-velocity (LV) profiling has recently emerged as a standard methodology for evaluating swimming-specific performance capabilities[1,2]. The load–velocity profile is created via semi-tethered swimming, whereby the swimmers propel themselves forward subjected to an external load [1,2]. With the development of advanced resistance systems such as the 1080 Sprint 2, it is now possible to quantify swimming velocity across incremental loads and create an individual LV relationship [1,2]. The stablished profile yields three key parameters: V_0, the theoretical maximal velocity at zero load; L_0, the theoretical load at which velocity reaches zero; and Slope, the steepness of the regression line [1,2]. These three parameters, therefore, provide understandings into swimmers' maximum velocity, ability to produce propulsive forces, and ability to minimize resistive forces[3–5]. In this regard, previous research has explored the association of the LV profile with performance in the 4 swimming strokes[2,6–8]. However, despite this body of evidence for surface swimming, to our knowledge, no study has investigated the LV profile during underwater undulatory swimming (UUS).

The UUS represents a critical phase in competitive swimming, particularly in short-course events, where it may account for up to 60% of the total race distance[9]. Its importance relies from the fact that, except for the dive, the highest velocities in freestyle, butterfly, and backstroke events are achieved during the underwater phase[10]. As such, UUS is regarded as one of the most influential technical components on swimming performance[11]. Biomechanically, UUS relies on whole-body undulatory motion, with propulsion generated primarily by the trunk and lower extremities[12]. This contrasts with surface swimming, where the upper limbs contribute approximately 70% of total propulsion[13]. Given these differences in propulsive mechanics, it remains unclear whether the LV profile during UUS exhibits similar linear characteristics or performance associations as those observed in surface swimming.

The influence of anthropometric characteristics on LV profiling has received relatively limited attention[3]. Although body dimensions are known to affect both hydrodynamic drag and propulsive force generation[14], the specific relationships

between anthropometric variables and LV profile parameters remain largely unexplored, particularly in UUS, where maintaining a streamlined position is essential[12,14]. This consideration is especially relevant when examining sex-related differences, as previous research has reported higher V_0 and L_0 values in male than in female swimmers, likely reflecting greater muscle mass and propulsive surface area[5]. Therefore, this study aimed to: 1) characterize the load-velocity profile during UUS; 2) examine the associations between LV profile parameters and performance and selected anthropometric variables; and 3) compare LV profile parameters between male and female competitive swimmers. It was hypothesized that 1) LV profile relationship during UUS would be highly linear; 2) LV profile-derived parameters would be related to UUS performance and anthropometrics; and 3) Males would exhibit greater V_0 and L_0 with no differences in the Slope.

METHODS

Participants

Thirty-three competitive swimmers (21 males: age 18.0 ± 2.7 years, height 176.9 ± 6.5 cm, body mass 68.9 ± 7.2 kg, performance level 4[15]; 12 females: age 17.1 ± 3.2 years, height 164.3 ± 6.8 cm, body mass 57.9 ± 8.8 kg, performance level 4[15]) volunteered for this study. The protocol was explained to swimmers and their parents (under 18) before obtaining written consent. The study adhered to the World Medical Association's Declaration of Helsinki and was approved by the University of Granada ethics committee (3256/CEIH/2023).

Procedures

During the week prior to the beginning of the testing session, anthropometric variables were taken following standardized techniques adopted by the International Society for the Advancement of Kinanthropometry (ISAK) by an accredited ISAK level II anthropometrist. Variables included: standing height, sitting height, arm span, body mass, body length (streamline position with ankle in plantarflexion) biacromial and biiliocristal breadths, arm length, and leg length (ankle in dorsiflexion). Derived indices included the acromio-iliac index (biiliocristal/biacromial × 100), intermembral index (arm length/leg length × 100), body mass index (BMI), relative arm span (arm span/height), and relative body length (body length/height). Moreover, during the same week, swimmers familiarized themselves with the UUS testing.

On testing day, swimmers performed their standardized dry-land warm-up. That mainly consisted of joint mobility, dynamic stretching, and elastic band pre-activation exercises. Subsequently, swimmers proceeded to the water and performed an in-water warm-up comprising a 400 m swim, a 100 m pull, a 100 m kick, 4 × 50 m increasing speed, 4 submaximal UUS trials, and 200 m easy swim[16]. Five minutes after completing the warm-up, swimmers performed a maximal 12.5 m UUS trial, during which velocity was assessed using the 1080 Sprint 2 (1080 Motion, Lidingö, Sweden), a robotic resistance device in the zero-load mode. Then, swimmers performed a LV profile test, which consisted of three 12.5 m UUS semi-tethered at maximal effort, each separated by 6 minutes of passive recovery[5]. Each trial was performed at 1 m depth beginning with swimmers pushing prone from the wall at 1 m depth to control wave drag effects[17]. Moreover, swimmers were asked to maintain the depth at 1 m throughout the 12.5 m. They were also instructed to start kicking as soon as possible to control the effect of the push-off on the initial kick cycles[18]. The external loads were determined based on pilot testing, with 1, 2, and 3 kg used for males and 1, 2, and 2.5 kg for females. Although some swimmers were capable of displacing greater loads, these values were selected to ensure that all participants could successfully complete the trials under consistent conditions. The loads were applied using the 1080 Sprint 2, which delivers a continuous and controlled resistance via a composite fiber cord attached to a belt secured around the swimmer's waist. This device has been previously used for LV profile testing [1,4–6,19], since it measures the swimming velocity and force simultaneously at a recording frequency of 200 Hz. During testing, the device was secured to the pool wall, with the origin of the cord positioned 0.63 m above the water surface. The cord was then connected to the swimmer's hip and routed through a pulley placed at a depth of 1 m, ensuring that resistance was applied horizontally while minimizing any vertical component. The pulley was mounted on a custom-built structure designed specifically for this purpose.

Mean velocity for each trial was calculated from the 1080 Sprint 2 output during three kicks over the 5 m to 10 m region to ensure steady-state UUS velocity excluding the push-off acceleration phase[19]. Individual LV profiles were constructed by fitting a linear regression between the applied concentric load (kg) and mean velocity ($m \cdot s^{-1}$). The resulting parameters

were: V_0 (Y-intercept, maximal theoretical velocity at zero load), L_0 (X-intercept, theoretical load at zero velocity), and the Slope (rate of velocity decrease per unit of load) [1,4–6,19]. The coefficient of determination (R^2) assessed linearity. All analyses were performed in an own developed script in Python 3.11.

Statistical analysis

Data are presented as mean ± standard deviation (SD) and 95% confidence interval ([95%CI]). Normality of distributions was assessed using the Shapiro-Wilk test. Pearson's product–moment correlation coefficients (r) were used to verify the relationship between the LV profile related variables, UUS swimming performance, and anthropometric. The magnitude of correlations was interpreted as: trivial (<0.10), small (0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), and nearly perfect (≥0.90)[20]. Between-sex comparisons were performed using independent-samples t-tests. Statistical significance was set at $p<0.05$ and all analyses were performed using Python 3.11 with SciPy 1.11 and Pandas 2.1.

RESULTS

Table 1 presents the LV profile descriptive data by sex, with males showing significantly higher V_0 ($p=0.003$) and L_0 ($p=0.001$), and females steeper Slope ($p=0.036$). Individual LV relationships were highly linear across the range of loads tested. For males (n=20, excluding one participant with invalid regression due to equipment malfunction), the mean R^2 was 0.987 ± 0.015[0.98–0.99] for LV profile. For females (n=12), the corresponding value was 0.981 ± 0.023[0.97–0.99].

Table 1. Mean, standard deviation (SD), and 95% confidence interval ([95%CI]) for load–velocity-related variables underwater undulatory swimming (UUS) performance, and anthropometrics variables.

Variable	Males			Females		
	Mean	SD	[95%CI]	Mean	SD	[95%CI]
V_0 ($m \cdot s^{-1}$)	1.58	0.17	[1.51 – 1.65]	1.39	0.14	[1.31 – 1.47]
L_0 (kg)	7.99	2.38	[6.98 – 9.01]	5.76	1.02	[5.18 – 6.34]
Slope	-0.21	0.05	[-0.23 – -0.19]	-0.25	0.03	[-0.26 – -0.23]
UUS performance ($m \cdot s^{-1}$)	1.45	0.17	[1.38 – 1.53]	1.28	0.13	[1.20 – 1.35]
Standing height (cm)	176.69	6.55	[174.15 – 179.69]	164.32	6.82	[160.46 – 168.19]
Sitting height (cm)	94.02	2.10	[93.23 – 95.04]	89.07	4.36	[86.60 – 91.53]
Arm span (cm)	181.90	8.76	[178.31 – 185.62]	167.32	7.53	[163.06 – 171.59]
Body mass (kg)	68.40	7.03	[65.82 – 72.01]	57.89	8.75	[52.94 – 62.84]
Body length (cm)	239.16	12.00	[234.55 – 244.74]	222.56	10.88	[216.40 – 228.72]
Biacromial breadth (cm)	40.86	1.61	[40.28 – 41.73]	37.87	1.49	[37.03 – 38.71]
Biiliocrital breadth (cm)	27.51	1.75	[26.83 – 28.3]	26.72	2.31	[25.42 – 28.03]
Arm length (cm)	70.52	4.27	[68.7 – 72.26]	64.73	3.33	[62.84 – 66.61]
Leg length (cm)	82.66	5.90	[80.31 – 85.26]	75.26	3.22	[73.44 – 77.08]
Acromio-iliac index (%)	67.43	5.16	[65.17 – 69.48]	70.61	5.82	[67.32 – 73.9]
Intermembral index (%)	85.42	3.23	[83.86 – 86.64]	86.04	3.54	[84.04 – 88.05]
Body mass index (%)	21.89	1.68	[21.27 – 22.72]	21.31	1.96	[20.20 – 22.42]
Relative arm spam index (%)	1.03	0.03	[1.02 – 1.04]	1.02	0.02	[1.01 – 1.03]
Relative body length index (%)	1.35	0.03	[1.34 – 1.37]	1.35	0.03	[1.34 – 1.37]

V_0, theoretical maximal velocity at zero load; L_0, theoretical load at which velocity reaches zero; Slope, the steepness of the regression line.

In males, UUS swimming performance was associated with V_0 (r=0.91, p<0.001) and L_0 (r=0.60, p=0.005). However, no significant association was observed with the Slope (r=0.02, p>0.05). Moreover, only body mass correlated moderately with L_0 (r=0.39, p=0.05) and with the Slope (r=0.42, p=0.48). No anthropometric variable correlated significantly with V_0 (p>0.05).

In females, UUS swimming performance was largely correlated with V_0 (r=0.87, p<0.001) and L_0 (r=0.89, p<0.001) and largely correlated with Slope (r=0.53, p=0.05). However, no significant association was observed with any anthropometric variable (p>0.05).

DISCUSSION

This study aimed to characterize the LV profile during UUS, examine the associations between LV profile-derived parameters and both performance and selected anthropometric variables, and compare LV profile parameters between male and female competitive swimmers. Our hypotheses were partially supported. Specifically, the LV relationship during UUS demonstrated a high degree of linearity. Moreover, LV profile-derived parameters were largely to nearly perfectly correlated with UUS performance (except Slope in males). In contrast, anthropometric associations were limited, with only body mass showing moderate association with L_0 and Slope in males and without any other significant association observed. Regarding sex-based differences, males exhibited greater V_0 and L_0, while females showed steeper Slope. Collectively, these findings support the application of LV profiling as a valid method for assessing UUS performance, with limited direct influence of anthropometric factors and clear differences between sexes.

The very high coefficients of determination (R^2>0.98) observed in both sexes confirm that a linear model is appropriate for characterizing the LV relationship during UUS. This finding is indeed consistent with the four swimming strokes[2,6–8]. Notably, the V_0 values obtained during UUS for males (1.52 ± 0.18 $m \cdot s^{-1}$) and females (1.39 ± 0.14 $m \cdot s^{-1}$) were lower than those reported for freestyle in swimmers of similar competitive level[5]. This difference may be partly explained by a comparatively lower technical proficiency in UUS within the present sample[12]. Furthermore, L_0 values were also lower in both sexes, which is expected given that UUS propulsion relies primarily on the trunk and lower extremities, whereas in front crawl the upper limbs substantially contribute to force production[13]. In this regard, despite the lower propulsive output, higher velocities during UUS (compared to surface swimming) are typically achieved due to the substantial reduction in hydrodynamic drag in the underwater phase[10,12]. This is indeed supported by the steeper Slope, which is an indicator of active drag[3], observed in the present study compared with surface swimming in a sample of a similar competitive level.

The strong association observed between V_0 and UUS performance is consistent with previous findings across the four competitive swimming strokes [2,6–8]. This is expected, as V_0 represents the theoretical maximal velocity a swimmer can achieve under free-swimming conditions (i.e., without external load). In contrast, the relationship between L_0 and performance has been less consistent in the literature[21]. This may be explained by the fact that L_0 reflects force-producing capacity; however, the effective translation of this capacity into propulsion in the aquatic environment depends on technical execution and efficiency[21]. In the present study, higher L_0 values were associated with better UUS performance, particularly in females, highlighting the relevance of strength development in UUS. On the other hand, in line with previous research, the Slope was not associated with UUS performance in males and showed lower associations than the rest of the parameters in females[5]. Although Slope has been proposed as an indicator of active drag[3], it does not independently explain performance, given the fundamental role of propulsive force in determining swimming velocity. Therefore, the absence of a direct association with sprint performance does not diminish its relevance but rather suggests that it provides complementary information. For example, an increase in V_0 without a corresponding change in L_0 would result in a steeper Slope, potentially indicating improved efficiency in minimizing resistive forces. This multidimensional interpretation allows coaches to better understand performance changes beyond isolated strength measures[4,22]. Importantly, the LV profile enables the simultaneous assessment of multiple parameters within a single test, offering a more comprehensive evaluation of training-induced adaptations.

Contrary to what it was hypothesized, no anthropometric variable correlated significantly with V_0 in either sex. Thus, UUS velocity appears to depend more on neuromuscular and technical factors than on body dimensions *per se*[12]. This is consistent with the multifactorial nature of sprint swimming performance, where technique and force application

strategy play determinant roles alongside physical attributes[21]. On the other hand, only body mass was associated with L_0 and Slope in males. This might be explained as greater body mass might reflect greater muscle mass and therefore strength levels[23]. However, it could also indicate greater cross-sectional area and therefore greater resistance[14]. Future studies should explore the mediation role of anthropometrics in the LV profile with particular attention to cross-sectional area, given its potential influence on active drag, UUS efficiency, and the reduction of resistive forces.

Limitations

It is important to acknowledge several limitations of the present study. UUS performance was assessed using the 1080 Sprint 2. Although this system includes a zero-load mode, it still imposes a minimal level of resistance, which may have influenced the velocity values obtained, particularly in swimmers with lower strength levels, and may partially explain the lower values observed compared to V_0. Future studies should consider using alternative methods, such as a speedometer or photogrammetry-based approaches, to obtain fully unloaded velocity measurements. Additionally, the smaller sample size in the female group reduced the statistical power of the analyses and may have limited the detection of further associations, as well as precluded us from performing multivariable or hierarchical regression analyses that could provide useful information regarding the independent contribution of anthropometric characteristics. Future research should aim to include larger female samples to better explore these relationships. Furthermore, future studies should seek to combine LV profiling with synchronized video analysis to examine the sequencing of propulsive actions and to identify potential kinematic differences between semi-tethered and free UUS, thereby providing a more comprehensive understanding of performance determinants. Finally, future research may also benefit from broader or individualized loading schemes and from normalizing external loads relative to body mass or other anthropometric descriptors.

Practical Applications

The findings of the present study further reinforce the diagnostic value of LV profiling in swimming, and more specifically in UUS. This approach enables the identification of specific performance limitations by distinguishing between deficits in velocity capacity (V_0), force production (L_0), and the interaction between propulsion and resistive forces (Slope). Such information is highly valuable for coaches and swimmers, as it allows for a more precise characterization of an athlete's performance profile and supports the design of targeted training interventions. For instance, swimmers exhibiting lower V_0 may benefit from velocity- and technique-oriented training, whereas those with reduced L_0 may require a greater emphasis on strength development and its transfer to aquatic conditions. Moreover, monitoring changes in the Slope can provide additional insight into adaptations related to drag reduction and efficiency. Overall, LV profiling offers a comprehensive yet practical tool to guide individualized training prescription, monitor performance adaptations over time, and ultimately optimize UUS performance within competitive swimming.

CONCLUSION

This study demonstrates that load-velocity profiling methodology is applicable to UUS, with high linearity confirmed for the LV relationship in both sexes. LV profile-derived parameters demonstrated large to nearly perfect associations with UUS performance, except for Slope in males. In contrast, the influence of anthropometric characteristics was limited, as only body mass showed moderate associations with L_0 and Slope in males, with no other significant relationships observed. Regarding sex-based differences, males exhibited higher V_0 and L_0 values, whereas females presented a steeper Slope.

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