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The key kinematic determinants of undulatory underwater swimming at maximal velocity

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ABSTRACT
The optimisation of undulatory underwater swimming is highly important in competitive swimming performance. Nineteen kinematic variables were identified from previous research undertaken to assess undulatory underwater swimming performance. The purpose of the present study was to determine which kinematic variables were key to the production of maximal undulatory underwater swimming velocity. Kinematic data at maximal undulatory underwater swimming velocity were collected from 17 skilled swimmers. A series of separate backward-elimination analysis of covariance models was produced with cycle frequency and cycle length as dependent variables (DVs) and participant as a fixed factor, as including cycle frequency and cycle length would explain 100% of the maximal swimming velocity variance. The covariates identified in the cycle-frequency and cycle-length models were used to form the saturated model for maximal swimming velocity. The final parsimonious model identified three covariates (maximal knee joint angular velocity, maximal ankle angular velocity and knee range of movement) as determinants of the variance in maximal swimming velocity (adjusted-r^2 = 0.929). However, when participant was removed as a fixed factor there was a large reduction in explained variance (adjusted r^2 = 0.397) and only maximal knee joint angular velocity continued to contribute significantly, highlighting its importance to the production of maximal swimming velocity. The reduction in explained variance suggests an emphasis on inter-individual differences in undulatory underwater swimming technique and/or anthropometry. Future research should examine the efficacy of other anthropometric, kinematic and coordination variables to better understand the production of maximal swimming velocity and consider the importance of individual undulatory underwater swimming techniques when interpreting the data.

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KEYWORDS
Maximum velocity; cycle length; cycle frequency; sport science support

Introduction

The optimisation of undulatory underwater swimming, employed during the underwater phase of the starts and turns of three of the four competitive strokes, is vital to ensure the best possible transition from the glide phase into full-stroke swimming (Mason & Cosser, 2000, 2001). According to Mason and Cosser (2000) the production of an effective underwater kicking action is a fundamental factor with respect to the optimisation of swimming performance, as start and turn times are strongly correlated with overall swim time. However, despite this important role in start and turn performance, there is a relative dearth of quantitative research undertaken to specifically identify the key kinematic factors involved in the production of an undulatory underwater swimming action to maximise swimming velocity.

It has been recognised that undulatory underwater swimming is comparable to an undulatory form of locomotion more commonly associated with aquatic animals (Connaboy, Coleman, & Sanders, 2009; Sanders, Cappaert, & Devlin, 1995; Ungerechts, 1987, 1985, 1982). Ungerechts (1985) highlighted that an exceptional feature of swimmers (animal and human) employing an undulatory form of locomotion in an aquatic environment is that the body motions simultaneously provide the propulsive forces and determine the active drag experienced in one unified motion. Greater undulatory underwater swimming velocities are achieved by increasing the magnitude of the propulsive impulse relative to the active drag experienced, and therefore the same maximal swimming velocity can be attained in a number of different ways. For example the same maximal undulatory underwater swimming velocity can be achieved via large undulatory movements that seek to maximise propulsive impulse production with a correspondingly high active drag (high energy requirement/cost), or via smaller movements that produce a reduced amount of propulsive impulse but simultaneously minimise the active drag experienced. A skilled underwater undulatory swimmer would attempt to maximise propulsive impulse by employing optimal amplitudes of the end-effector. In conjunction, the coordinated amplitudes of the preceding sections of the

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body should be temporally structured in a manner that minimises flow separation (Tokomaru & Dimotakis, 1991; Triantafyllou et al., 2002) and maximises energy reuse from the vortices shed as "body wake" further up the undulating body (Triantafyllou, Triantafyllou, & Gopalkrishnan, 1991; Anderson, Streitlien, Barret, & Triantafyllou, 1998). Unfortunately, these types of kinematic variables are not routinely reported when undertaking biomechanical sports science support for swimmers.

The cycle frequency of the end-effector (tail or terminal limb segment) has consistently been shown to be a strong predictor of undulatory underwater swimming performance (Bainbridge, 1958; Fish, 1984; Hunter & Zweifel, 1971; Long, McHenry, & Boetticher, 1994). However, cycle frequency alone cannot fully explain all the variations apparent in maximum undulatory underwater swimming between performers. Consequently, the relationship between cycle frequency and maximal swimming velocity is not simply governed by the selected cycle frequency, but also by the kinematics used to generate a specific cycle frequency when attempting to maximise undulatory underwater swimming velocity (Anderson et al., 1998; Taneda, 1978; Tokomaru & Dimotakis, 1991). While the relationship among cycle frequency, cycle length and movement velocity is well documented and empirically verified for a variety of forms (rowing, kayaking, running, etc.) of locomotion as Velocity = Cycle frequency × Cycle length (Craig & Pendergrast, 1979), this does not provide sufficient information to identify and understand the relative importance of other kinematic variables commonly measured in the execution and analysis of undulatory underwater swimming performance.

When attempting to analyse swimmers' performance in an applied sports science support setting, the equipment most often available (waterproof video recorder and simple video analysis software) does not generally allow for detailed analysis of the more complex attributes of undulatory underwater swimming. Therefore, the relevance of variables that are relatively easy to determine and utilised within a sports science support setting requires further investigation. The variables most commonly utilised when describing and/or analysing undulatory underwater swimming include: joint centre (vertical linear displacement) amplitudes (Cohen, Cleary, & Mason, 2012; Connaboy et al., 2007a, 2007b; Connaboy, Moir, Coleman, & Sanders, 2010; Elipot, Houel, Hellard, & Dietrich, 2010; Loebbecke, Mittal, Fish, & Russell, 2009a, 2009b) joint angles, ranges of motion and angular velocities (Arellano et al., 2002; Connaboy et al., 2010; Elipot et al., 2010) and the angle of attack of the end-effector (Connaboy et al., 2010; Elipot et al., 2010). Despite the increase in the number of research studies examining undulatory underwater swimming performance, there is still a paucity of understanding as to exactly which variables are the most strongly related to maximal undulatory underwater swimming velocity. Some previous research (Rejman & Borowska, 2008) was undertaken to analyse similar, simple kinematic variables and their relationship to overall undulatory underwater swimming performance. However, this form of undulatory underwater swimming included the use of a monofin. Therefore, further research was still required to understand the relative importance of each of these more easily determined kinematic variables with respect to the production of maximal swimming velocity in the undulatory underwater swimming performed in the competitive swimming strokes.

The purpose of this study was to identify key kinematic determinants of performance for maximal undulatory underwater swimming in skilled swimmers from those routinely analysed when providing sport science support for swimmers. This was accomplished by examining which kinematic variables provided the best predictive models for (a) cycle frequency, (b) cycle length and subsequently (c) maximal swimming velocity.

Methods

Participants

A group of 17 (eight male and nine female) national-level competitive swimmers (males: Mean ± *s*: age 17.6 ± 1.4 years, height 177.6 ± 5.3 cm, mass 72.7 ± 7.9 kg; females: age 16.35 ± 0.8 years, height 164.9 ± 4.1 cm, mass 53.8 ± 3.0 kg) from the "Elite" squad of a local swimming club participated in this study. All participants had a minimum of five years of competitive swimming experience (mean 6.9 ± 1.9 years) and had competed in a national age-group championship final. Ethical approval for the study was granted from the local ethics committee. Informed consent was obtained from each participant, and if a minor (age below 18 years), also from their legal guardian.

Experimental protocol

Seven days prior to data collection, participants performed eight trials of the maximal swimming velocity experimental protocol to familiarise themselves with the requirements of the protocol (Connaboy et al., 2010). The experimental protocol consisted of each swimmer performing three maximum effort undulatory underwater swimming trials, with the swimmer in the prone position and the hands and arms held out in front, consistent with the techniques performed in the starts and turns of the freestyle swimming stroke. A total of six cycles of undulatory underwater swimming data (two cycles per trial) were captured, to ensure that the kinematic data would provide a representative and reliable account of the undulatory underwater swimming kinematics (Connaboy et al., 2010). Prior to undertaking the three trials a standardised (20 min) warm-up was conducted (Connaboy et al., 2010).

Each trial consisted of the swimmer starting from point A (Figure 1) at the left end of the pool, pushing off the wall and swimming underwater using undulatory underwater swimming. The participants attempted to swim as fast as they could, maximising swimming velocity as they swam through the video recording area. The distance from the wall to the start of the recording zone (10 m) was sufficient to ensure that the push-off velocity from the wall had no effect on the maximal velocity attained whilst swimming through the testing area (Arellano et al., 2002). In addition, the participants were instructed to only use the push-off from the wall to

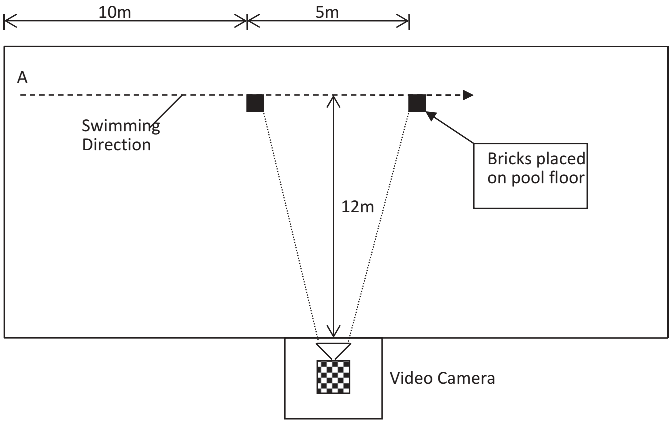

Figure 1. Experimental set-up: showing starting position (A), 10 m section to accelerate and 5 m maximal velocity swimming section.

enable them to achieve the correct orientation and depth rather than as a means to maximise velocity. This was done to ensure that any changes in the performance of the push-off did not have an effect on the undulatory underwater swimming performance through the capture area. A depth of between 0.8 and 1.2 m below the surface of the water was required to exclude the effects of wave drag (Vennell, Pease, & Wilson, 2006). If participants did not swim between these depths, the trial was rejected and then repeated.

The participants were instructed to accelerate over the first 10 m to attain maximum swimming velocity prior to entering the beginning of the recording area, and to maintain that velocity throughout the entire recording zone (Figure 1). No instructions were given regarding the cycle frequency employed. A minimum 5-min rest interval between trials was employed to allow a full recovery (Connaboy et al., 2010). Previous research (Connaboy et al., 2010) has shown that the previously stated protocol provides reliable results and demonstrates no systematic bias as a consequence of either fatigue and/or learning effect.

Data collection and processing

Participants were marked on the skin surface directly over the joint centres of the wrist, shoulder, hip, knee, ankle and 5th metatarsal phalangeal joint of the foot on the right side of the body with a 3-cm-diameter circle of black oil-based body paint. The length of each participant's thigh was measured from the greater trochanter to the lateral epicondyle (on land) and was subsequently used as the scale factor (Clothier, Payne, Harvey, Blanksby, & Benjanuvatra, 2004). Data from Clothier et al. (2004) regarding the efficacy of this method reported mean error in segments lengths of 1 mm, when segment lengths are derived from the video data. The average length of the thigh segment in pixels (per USS cycle) was calibrated against this subject-defined scale factor for each of the respective cycles of undulatory underwater swimming video data (Connaboy et al., 2010; Sanders, Li, & Hamill, 2009), acting to minimise errors associated with extrapolation error, as the participants swam through the data capture area. Horizontal and vertical pixel ratios of the video data were calculated so that the subject-derived scale factor could be scaled appropriately in both horizontal and vertical planes.

A two-dimensional videographic technique was employed to collect position-time data. The participants were video recorded with a stationary underwater camera (KY32 CCD; JVC Corporation, Yokohama, Japan) sampling at 50 fields · s^{-1} (50 Hz), and with a shutter speed of 1/120 s. Every field was digitised, giving an effective digitising rate of 50 Hz. The camera was positioned 12 m from the plane of motion of the swimmer with its optical axis perpendicular to that plane and (Figure 1) 1 m below the surface of the water. The field of view was 4 m in the swimming direction, enabling two complete kick cycles to be captured for analysis for each trial.

A kick cycle comprised a complete upward movement (upbeat) and downward (downbeat) movement identified from the video data as commencing at the frame corresponding to the initiation of an upward movement of the 5th metatarsal phalangeal joint to the frame corresponding to the initiation of the next upward movement. Fifteen additional frames on either side of the observed start and end of the two kick cycles were digitised to enable the accurate identification of the start/end points of each cycle and to provide additional data points to minimise errors near the end of the data set due to the data smoothing process (Vint & Hinrichs, 1996). The segment endpoint data were digitised using an Ariel Performance Analysis System (APAS-2000 Ariel Dynamics, 2000, San Diego, CA).

The raw screen coordinate data output were extracted from the APAS system using a specifically designed Visual Basic (Visual Basic 4.0) program. This enabled the pixel-to-real-world vertical and horizontal ratios to be determined and scale factors adjusted accordingly. These data were then transformed to produce the raw displacement data, using a participant derived two-dimensional linear scale (Clothier et al., 2004). Each individual frame of the collected video data was calibrated with respect to a scale factor determined from a reference structure of known dimension (thigh length) present within each frame of the video data.

To minimise distortion of the data as a consequence of the swimmers swimming "out of plane", the axis of the camera remained perpendicular to the required movement of the swimmer, and any swimming trial that deviated from the required line of swimming was not included in the subsequent analysis. For the purpose of this analysis bilateral symmetry was assumed (Connaboy et al., 2010) and only the side of the body facing the camera (right hand side) was digitised to define a five-segment model of the swimmer's body, comprising the arm, trunk, thigh, shank and foot. The digitised coordinates of the raw two-dimensional segment endpoint data were filtered using a Fourier transform. A cut-off frequency for filtering the data was selected at 7 Hz, as more than 98% of the power in the displacement-time signals was contained within the harmonics up to 7 Hz.

Data analysis

The displacement data were input to a specifically designed MATLAB (Mathworks, Inc) program. The program calculated the first two derivatives (velocity and acceleration) of the displacement data for the wrist, shoulder, hip, knee, ankle and 5th metatarsal phalangeal joint by differentiation using central difference formulae. The start/end points of each kick cycle were then identified based on the four local minima of the *y*-axis coordinates of the 5th metatarsal phalangeal joint position data. These points represent the minimum vertical displacement values of the foot throughout the two cycles.

Using the methods employed by Connaboy et al. (2010), a total of 19 kinematic variables already identified as important in undulatory underwater swimming were calculated for each kick cycle: (1) maximal swimming velocity, (2) cycle frequency, (3) cycle length; joint ranges of movement of (4) shoulder, (5) hip, (6) knee, (7) ankle; maximum angular velocities of (8) shoulder, (9) hip, (10) knee, (11) ankle; vertical joint centre amplitudes of (12) wrist, (13) shoulder, (14) hip, (15) knee, (16) ankle, (17) 5th metatarsal phalangeal joint; (18) maximum angle of attack of the end-effector; and (19) the mean absolute angle of attack of the end-effector.

Statistical analysis

All statistical analyses were performed using SPSS (PASW Statistics 18.0, SPSS Inc., Chicago, IL). The normality of the data distribution for each DV was determined using the Kolmogorov–Smirnov test. Backward elimination (BE) ANCOVA models were utilised to ascertain which individual kinematic variable(s) provided the best predictive models for each of the three DVs for all participants (Draper & Smith, 1998). The BE ANCOVA analysis model was selected because it has the capacity to fit a fixed between-subject indicator variable (n = 17) and enables the estimation of a within-subject source of variation (six cycles) as part of the error structure (Brown et al., 2011; Nevill, Allen, & Ingham, 2011). This enables the ANCOVA analysis to partition the two sources of variation (between and within-subject variations). Participant number was used as a fixed factor to ensure the analysis allowed for individual differences in the respective DVs. With no statistically significant differences ($P < 0.05$) between the sexes for either maximal swimming velocity, cycle frequency or cycle length, and to improve the statistical power of the tests performed, the data from both female and male participants were analysed together.

Through a process of BE a parsimonious or a final (depending on the number of variables retained) model of the determinants of each of the respective DVs was produced. The final model was achieved by a process of iteration, starting with the saturated model containing all the covariates, the least important covariate (as denoted by the largest P-value) was withdrawn from the model and the ANCOVA statistic recalculated. This process was repeated until all the remaining "predictor" variables provided a significant contribution ($P < 0.05$) to the final model (Bridgewater & Sharpe, 1998; Nevill et al., 2010, 2011). Effect size statistics were determined for each variable contained within the final models using partial-Eta^2 ($\eta_p{}^2$) (Brown et al., 2011; Cohen, 1988).

Given the relationship between maximal swimming velocity, cycle frequency and cycle length (maximal swimming velocity = cycle frequency × cycle length) and that the inclusion of cycle frequency and cycle length into a statistical model designed to determine the relationship between kinematic variables and the production of maximal swimming velocity would explain the entire variance in maximal swimming velocity (r^2 = 1.00), separate BE ANCOVA models were used to determine which of the kinematic variables were best able to explain the variation for each of cycle frequency and cycle length from all of the 102 data cycles (17 participants × 3 trials × 2 cycles). Both cycle frequency and cycle length were excluded from the final model (DV = maximal swimming velocity) and the results from the initial series of ANCOVA models for cycle frequency and cycle length were used to determine which variables would be entered into the initial "saturated" ANCOVA model to analyse maximal swimming velocity.

Results

The kinematic data for all the swimmers were determined (Table 1). The data from all participants' six trials were analysed in the BE ANCOVA.

Analysis of covariance: BE models

After the alternate removal of the respective DVs, the remaining kinematic variables were entered as covariates in separate, saturated ANCOVA models for kinematic variables to determine the best predictive models for cycle frequency and cycle length. Through an iterative BE process, the separate saturated ANCOVA models were reduced to parsimonious/final models containing only those covariates that significantly ($P < 0.05$) explained a portion of the variance of the DV (cycle frequency or cycle length) (Table 2).

Table 1. Mean (±*s*) kinematic variable data for skilled age-group swimmers' maximal undulatory underwater swimming performance.

Kinematic variable	Mean		*s*
Cycle frequency (Hz)	2.13	±	0.23
Max *U* (m · s^{-1})	1.20	±	0.13
Wrist amplitude (m)	0.08	±	0.03
Shoulder amplitude (m)	0.08	±	0.02
Hip amplitude (m)	0.13	±	0.03
Knee amplitude (m)	0.27	±	0.04
Ankle amplitude (m	0.46	±	0.06
5th MPJ amplitude (m)	0.61	±	0.07
Cycle length (m)	0.57	±	0.07
Max shoulder angular velocity (° · s^{-1})	180.4	±	37.8
(rad · s^{-1})	3.15	±	0.66
Max hip angular velocity (° · s^{-1})	300.2	±	58.6
(rad · s^{-1})	5.24	±	1.02
Max knee angular velocity (° · s^{-1})	702.7	±	82.9
(rad · s^{-1})	12.26	±	1.45
Max ankle angular velocity (° · s^{-1})	486.1	±	112.5
(rad · s^{-1})	8.48	±	1.96
Shoulder ROM (°)	28.26	±	6.2
Hip ROM (°)	48.27	±	9.1
Knee ROM (°)	89.61	±	6.9
Ankle ROM (°)	53.82	±	8.1
Max AoA (°)	76.85	±	7.6
Mean absolute AoA (°)	43.85	±	2.1

Note: Max U, maximal swimming velocity; ROM, range of movement; AoA, angle of attack; MPJ, metatarsal phalangeal joint.

Table 2. BE ANCOVA models for cycle frequency, cycle length and maximal undulatory underwater swimming velocity.

BE ANCOVA Model	Fixed Factor	Final/Parsimonious Model	P	η_p^2	Adjusted r^2
Cycle frequency	Participant		$P < 0.001$	0.670	0.942
		Shoulder amplitude	$P < 0.001$	0.149	
		Ankle amplitude	$P < 0.001$	0.472	
		Max hip angle velocity	$P < 0.001$	0.184	
		Max knee angle velocity	$P < 0.001$	0.366	
		Max ankle angle velocity	$P < 0.001$	0.317	
		Knee ROM	$P < 0.001$	0.261	
		Mean absolute AoA	$P < 0.001$	0.183	
Cycle length	Participant		$P < 0.001$	0.852	0.941
		Wrist amplitude	$P < 0.01$	0.126	
		Ankle amplitude	$P < 0.001$	0.508	
		Max hip angle velocity	$P < 0.001$	0.151	
		Max ankle angle velocity	$P = 0.01$	0.088	
		Shoulder ROM	$P < 0.05$	0.063	
		Mean absolute AoA	$P < 0.001$	0.229	
Max U	Participant		$P < 0.001$	0.915	0.939
		Max knee angle velocity	$P < 0.001$	0.253	
		Max ankle angle velocity	$P < 0.01$	0.115	
		Knee ROM	$P < 0.01$	0.103	
	None		$P < 0.001$		0.397
		Max knee angle velocity	$P < 0.001$	0.395	
		Max ankle angle velocity	$P = 0.779$	0.001	
		Knee ROM	$P = 0.361$	0.009	

Note: Max U, maximal swimming velocity; ROM, range of movement; AoA, angle of attack.

End-effector cycle frequency

Through the iterative process, the initial saturated model containing all the covariates was reduced to a final model containing only seven covariates (Table 2), all of which contributed to an explanation of the variance of cycle frequency: shoulder amplitude ($P < 0.001$; $\eta_p^2 = 0.149$), ankle amplitude ($P < 0.001$; $\eta_p^2 = 0.472$), max hip angular velocity ($P < 0.001$; $\eta_p^2 = 0.184$), max knee angular velocity ($P < 0.001$; $\eta_p^2 = 0.366$), max ankle angular velocity ($P < 0.001$; $\eta_p^2 = 0.317$), knee range of movement ($P < 0.001$; $\eta_p^2 = 0.261$) and mean absolute angle of attack ($P < 0.001$; $\eta_p^2 = 0.183$). The fixed factor (Participant) significantly contributed to the model ($P < 0.001$; $\eta_p^2 = 0.670$). The adjusted r^2 value was 0.942.

Cycle length

For cycle length the final model for the kinematic variables was reduced to six covariates: wrist amplitude ($P < 0.01$; $\eta_p^2 = 0.126$), ankle amplitude ($P < 0.001$; $\eta_p^2 = 0.508$), max hip angular velocity ($P < 0.001$; $\eta_p^2 = 0.151$), max ankle angular velocity ($P = 0.01$; $\eta_p^2 = 0.088$), shoulder range of movement ($P < 0.05$; $\eta_p^2 = 0.063$) and mean absolute angle of attack ($P < 0.001$; $\eta_p^2 = 0.229$). The fixed factor (Participant) significantly contributed to the model ($P < 0.001$; $\eta_p^2 = 0.852$). The adjusted r^2 was 0.941.

Final model – maximal undulatory underwater swimming velocity

The two initial BE ANCOVA models for cycle frequency and cycle length identified a total of nine covariates as determinants of the variance of these DVs. The BE ANCOVA models conducted to analyse the kinematic variables in relation to cycle frequency and cycle length contained seven and six covariates in their respective final models, with four covariates common to both models (ankle amplitude, max hip angular velocity, max ankle angular velocity and mean absolute angle of attack). The explained variance for each of the respective final models was large (cycle frequency adjusted $r^2 = 0.942$; cycle length adjusted $r^2 = 0.941$). All the variables included in the final cycle frequency final model achieved a large effect-size statistic (as denoted by $\eta_p^2 > 0.1379$; Cohen, 1988; Richardson, 2011). However, for the cycle length final model, only ankle amplitude, max hip angular velocity and mean absolute angle of attack achieved a large η_p^2, with wrist amplitude, max ankle angular velocity and shoulder range of movement achieving a medium effect size ($\eta_p^2 > 0.0588$).

The covariates identified from the resultant final models from the cycle frequency and cycle length BE ANCOVA's formed the initial saturated model to examine maximal swimming velocity. The initial model contained all nine of the covariates (wrist amplitude, shoulder amplitude, ankle amplitude, max hip angular velocity, max knee angular velocity, max ankle angular velocity, shoulder range of movement, knee range of movement and mean absolute angle of attack) identified in the previous BE ANCOVA models.

The final parsimonious model for maximal swimming velocity revealed max knee angular velocity ($P < 0.001$; $\eta_p^2 = 0.253$), max ankle angular velocity ($P < 0.01$; $\eta_p^2 = 0.115$) and knee range of movement ($P < 0.01$; $\eta_p^2 = 0.103$) to account for a large amount of the variance in maximal swimming velocity with adjusted $r^2 = 0.939$. The fixed factor (Participant) significantly contributed to the model ($P < 0.001$; $\eta_p^2 = 0.915$). When the fixed factor (Participant) was removed from the model and the ANCOVA rerun, the explained variance reduced (adjusted $r^2 = 0.397$) (see Table 2). In addition, when the fixed factor (Participant) was removed from the model, max ankle angular velocity ($P = 0.779$; $\eta_p^2 = 0.001$) and knee range of movement ($P = 0.361$; $\eta_p^2 = 0.009$) no longer provided a statistically significant contribution to the model, leaving only max knee angular velocity ($P < 0.001$; $\eta_p^2 = 0.395$).

Discussion

The purpose of this study was to identify key kinematic determinants of performance for maximal undulatory underwater swimming in skilled swimmers from those routinely analysed when providing sport science support for swimmers. This was accomplished by examining which kinematic variables provided the best predictive models for (a) cycle frequency, (b) cycle length and ultimately (c) maximal swimming velocity. Some of the data from the 19 kinematic variables analysed within the present study of skilled swimmers (Table 1) were comparable to data reported in previous research. The maximal swimming velocity values reported (mean maximal swimming velocity = 1.20 ± 0.13 $m \cdot s^{-1}$) within the present study are similar to those reported for the male and female, national standard age-group swimmers (mean maximal swimming velocity = 1.15 $m \cdot s^{-1}$) by Arellano et al. (2002), but lower than those reported by Loebbecke et al. (2009a) and Arellano et al. (2002) for the Olympic level (mean maximal swimming velocity = 1.45 $m \cdot s^{-1}$) and international level (mean maximal swimming velocity = 1.61 $m \cdot s^{-1}$) swimmers, respectively. The cycle-frequency values found within the current study (mean cycle frequency = 2.13 ± 0.23 Hz) are very similar to the international swimmers (mean CF = 2.14 Hz), but higher than those reported for national age-group swimmers (mean cycle frequency = 1.76 Hz) (Arellano et al., 2002). The cycle-frequency values from the current study also closely match the cycle frequency of the male collegiate swimmers (cycle frequency = 2.11 Hz) from Connaboy et al. (2007a) and the male and female Olympic-level swimmers (cycle frequency = 2.18 Hz) analysed by Loebbecke et al. (2009a). The cycle-length data for the skilled age-group swimmers from the present study (mean cycle length = 0.57 ± 0.17 m) are lower than both the international (mean cycle length = 0.76 m) and national (mean cycle length = 0.67 m) level swimmers' cycle-length data reported by Arellano et al. (2002), and the mean cycle length (0.67 m) derived from the mean maximal swimming velocity and cycle-frequency data reported for Olympic-level swimmers (Loebbecke et al., 2009a).

The similarities in cycle frequency and the differences in cycle length and the maximal swimming velocity apparent between the skilled age group swimmers from the current study and the Olympic/international-level swimmers highlight the competing factors that determine the maximal swimming velocity and the manner by which it can be achieved, namely (i) the requirement to simultaneously produce a propulsive impulse and minimise active drag with the same movements (Ungerechts, 1985) and (ii) the different kinematics employed to produce them. The skilled swimmers within the present study were able to attain similar cycle-frequency values, and attain similar or higher amplitudes for the end-effector (0.61 m) compared to the international (0.62 m) and Olympic (0.53 m) swimmers analysed by Arellano et al. (2002) and Loebbecke et al. (2009a), respectively. However, the kinematics that brought about these similarities in cycle frequency and end-effector amplitude ultimately led to a comparatively lower cycle length, and ultimately lower maximal swimming velocity.

The final parsimonious model for maximal swimming velocity demonstrated that three covariates (maximum knee angular velocity, maximum ankle angular velocity and knee range of movement) accounted for a large amount of the variance in maximal swimming velocity (adjusted r^2 = 0.929). When the fixed factor (Participant) was removed from the model and the ANCOVA rerun, the explained variance reduced (adjusted r^2 = 0.397) and only maximum knee angular velocity provided a statistically significant contribution to the model (Table 2). The reduction of the predictive quality of the model from 92.9% down to 39.7% of the explained variance in maximal swimming velocity demonstrates that the individual manner in which the age-group swimmers are achieving maximal swimming velocity may be largely dependent on the participant's own undulatory underwater swimming technique employed and that the individual undulatory underwater swimming technique is an important predictor of maximal swimming velocity. This interpretation of the BE ANCOVA data suggests that the reduction in explained variance with the removal of participant as a fixed factor may be representative of the number of possible solutions to the task (maximise undulatory underwater swimming velocity) in relation to the individual's own organismic constraints (e.g. limb segment lengths) (Newell, 1986). Therefore, the skilled age-group swimmers may be exploiting their own, idiosyncratic organismic constraints to maximise propulsive impulse while simultaneously minimising active drag, in response to those constraints imposed by the task and the environment (Newell, 1986). This can be exemplified from the data of two swimmers with identical mean maximal swimming velocity values (1.18 $m \cdot s^{-1}$). For example, swimmer A has the lowest amplitude of the end-effector (5th metatarsal phalangeal joint) of the entire group (0.52 m) while swimmer B has the second highest (0.69 m). In addition, swimmer A also has the second highest end-effector cycle frequency (2.22 Hz) reported within the group, while swimmer B has the third lowest cycle frequency (1.98 Hz). However, the cycle length for both swimmers (Swimmer A = 0.53 m, Swimmer B = 0.59 m) is relatively close to the mean value reported for the group (group mean cycle length = 0.57 m). These differences in the 5th metatarsal phalangeal joint amplitude and cycle frequency could suggest different movement solutions to the task of maximising undulatory underwater swimming velocity, possibly as a consequence of the differences in organismic constraints such as force production capabilities at specific joints, differences in relative limb/body segment lengths, etc.

The final parsimonious model for maximal swimming velocity shows three covariates providing statistically significant contributions, with either a large effect size (maximal knee angular velocity) or medium/small effect sizes (maximum ankle angular velocity and knee range of movement) depending on whether the participant was included as a fixed factor (Table 2). Of the respective individual relationships between the three identified variables and maximal swimming velocity, only maximum knee angular velocity revealed a substantial positive correlation ($r = 0.63$) with maximal swimming velocity, suggesting that as the maximum knee angular velocity increased, maximal swimming velocity also increased. While both maximum ankle angular velocity and knee range of movement provided a significant contribution to the final ANCOVA model, the individual relationships between them and maximal swimming velocity were 0.08 and 0.15, respectively. Following the removal of "subject" as a fixed factor from the model, only maximal knee angular velocity provided a significant explained variance in maximal swimming velocity, suggesting that maximal knee angular velocity is the primary variable of interest.

However, the reduction in explained variance seen when participant as a fixed factor was removed from the model could also be indicative of the exclusion of important variables (covariates) which were not analysed within the present study. Future research should examine the efficacy of other kinematic, coordination and/or anthropometric variables to better understand the interacting effects of the imposed constraints (organismic, environmental and task) on the production of maximal swimming velocity. Factors such as inter and intra-limb coordination and their respective contributions to the simultaneous production of the propulsive and active drag forces should be considered. Furthermore, subject-specific analyses (i.e. single-subject analyses, Stergiou, 2004) need to be employed to consider the importance of individual undulatory underwater swimming techniques when interpreting the data.

Caution should also be taken when interpreting the results as important limitations should be recognised. For example, the mean angle of attack data from the present study were higher than the 15°–25° range suggested for optimal thrust production (Sfakiotakis, Lane, & Davies, 1999; Videler & Kamermans, 1985; Triantafyllou, Triantafyllou, & Gopalkrishnan, 1993). However, the representation of angle of attack as a discrete variable (mean absolute angle of attack) does not fully explain its behaviour and relevance to undulatory underwater swimming performance. It is understood that the maintenance of a positive angle of attack enables thrust to be produced throughout a larger proportion of the stroke cycle (Fish & Rohr, 1999; Lighthill, 1975; Videler & Kamermans, 1985). The mean value for the angle of attack does not allow an examination of the proportion of the time spent with a positive value for angle of attack or the time within the theoretically optimal range. Therefore, future analyses should look to either incorporate a greater number of discrete measures of data at key points in the movement cycle or combine both discrete and continuous measures of variables such as angle of attack to provide a detailed examination of their relevance on the production of maximal swimming velocity in skilled swimmers.

In conclusion, three covariates – max knee angular velocity, max ankle angular velocity and knee range of movement – were found to explain a significant proportion of the variance in maximal swimming velocity (92.9%). However, the large reduction (53.2%) in explained variance following the removal of participant as a fixed factor suggested that individual swimmers were employing different techniques when attempting to maximise undulatory underwater swimming velocity. However, consistent among all participants was the identified relationship between maximal knee angular velocity and maximal swimming velocity; emphasising the importance of a fast knee extension in the production of maximal undulatory underwater swimming performance.

Alternatively, other important variables not currently analysed were missing from the predictive model, suggesting that the kinematic variables analysed are insufficient for providing a comprehensive assessment of USS performance. Therefore, further analysis is required to establish which constraints are influencing the kinematics employed by skilled undulatory underwater swimmers when attempting to maximise undulatory underwater swimming velocity, incorporating a more comprehensive list of relevant variables. Once a more complete model has been examined and the key determinants of undulatory underwater swimming established, further recommendations can then be made as to which kinematic variables sports scientists should analyse when supporting skilled swimmers.

Disclosure statement

No potential conflict of interest was reported by the authors.

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