Augmented feedback can change body shape to improve glide efficiency in swimming

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Curvatures of the body can disrupt fluid flow and affect hydrodynamic resistance. The purpose of this study was to evaluate the effect of a feedback intervention on glide performance and torso morphology. Eleven male and female national swimmers performed glides before and after augmented feedback. Feedback consisted of self-modelling visual feedback and verbal cuing, to manipulate body curvatures that affect hydrodynamic resistance. Two-dimensional landmark position data (knee, hip and shoulder) were used to enable computation of glide factor and glide coefficient as indicators of glide efficiency; posture (trunk incline and hip angle); and performance (horizontal velocity). Underwater images of the swimmers were manually traced to derive transverse and sagittal diameters, cross-sectional areas, and continuous form outlines (anterior and posterior) of the torso. Maximum rate of change in cross-sectional area and form gradient progressing caudally, were calculated for torso segments: shoulder-chest, chest-waist, waist-hip. Mean velocity, glide factor and glide coefficient values significantly ($p<0.001$) improved due to the intervention, with large effect size (*d*) changes 0.880 ($p=0.015$), 2.297 and 1.605, respectively. Significant changes to form gradients were related to reductions in lumbar lordosis and chest convexity. The study provides practical cuing phrases for coaches and swimmers to improve glide efficiency and performance.

Keywords: Passive drag, visual feedback, verbal cuing, swimming starts and turns, fluid dynamics

Introduction

The glide phase is the time spent without active swimming actions following the start and turn in competitive swimming. The glide is a critical skill for swimmers as glide performance significantly influences overall swimming time (Cossor & Mason, 2001; Guimaraes & Hay, 1985). Elite swimmers spend ~3.7 sec underwater during the start, where the time spent in a glide posture between the head entering the water and initiation of the first undulatory kick is ~1.0 sec (Tor, Pease, & Ball, 2014). Glide performance is determined by the initial velocity from the block start or wall push-off and the ability of a swimmer to minimise deceleration; the latter is known as glide efficiency (Naemi & Sanders, 2008). To minimise deceleration, swimmers strive to maintain a streamlined body position by aligning their upper limbs with the lower limbs and torso, placing one hand on top of the other, and plantarflexing their feet. Glide posture and morphology affect glide efficiency by influencing fluid flow moving in conjunction with the swimmer (boundary layer) and resistive force of the fluid acting on the swimmer in the opposing direction (hydrodynamic resistance) (Naemi et al., 2010). Understanding the effect of body shape on fluid flow characteristics can inform optimal postures to minimise hydrodynamic resistance.

Shape and surface characteristics of a swimmer influence flow characteristics by altering the velocity of fluid flow at different body segments (Pendergast et al., 2006). Body curvatures, such as the head, shoulder, and buttocks, can separate fluid flow from the boundary layer, resulting in turbulence and an increase in hydrodynamic resistance (Mollendorf et al., 2004; Naemi et al., 2010). For example, indentation at the waist and curvature from the lumbar region to the buttocks influences maximum hydrodynamic resistance during a deceleration phase of front crawl swimming (Papic, McCabe, et al., 2020). In addition to the effect of body curvature, anthropometric characteristics such as chest circumference, chest cross-sectional area (CSA), and frontal surface area, are correlated with hydrodynamic resistance (Benjanuvatra et al., 2001; Cortesi et al., 2020; Vilas-Boas et al., 2010). While swimmers are unable to easily alter morphology through training and nutritional strategies, posture in glide and free-swimming phases can change the shape of the body and affect resistive force (Marinho et al., 2009; Morais et al., 2020). Consequently, modifying posture during gliding may affect the magnitude of body curvatures, frontal surface area, and the associated fluid flow characteristics. These hydrodynamic principles could be used to inform technical glide strategies for coaches and swimmers, with the goal of improving glide efficiency.

Coaches and sport scientists commonly use augmented feedback, or extrinsic feedback, to improve an athlete's motor skill acquisition for a given task by providing quantitative and/or qualitative information about their performance (Lauber & Keller, 2014). Augmented feedback can be in the form of kinematic feedback, specific to an athlete's movement characteristics (Lauber & Keller, 2014). For instance, visual and verbal feedback on running technique improved step-frequency and centre of mass displacement in well-trained runners (Eriksson et al., 2011). Visual feedback alone, however, is not as effective for motor skill acquisition without verbal feedback and cuing (Rucci & Tomporowski, 2010).

The most effective method for improving front crawl performance is verbal feedback used in conjunction with self-modelling visual feedback, compared to visually observing an expert model or receiving verbal feedback alone (Giannousi et al., 2017). Visual self-modelling involves a subject viewing video of their own performance, as opposed to viewing an expert model of performance. Self-modelling visual feedback is advantageous for motor skill acquisition as it improves subject attentiveness to the skill and active engagement in the process of identifying areas for improvement (Hodges & Franks, 2002). The effectiveness of feedback methods on task performance is also influenced by the learning capacity of individuals. Humans vary in their in perceptual learning capacities, such as the uptake and response to feedback information, rate of learning, and reliance on the feedback information variables provided (Withagen & Van Wermeskerken, 2009). Inter-individual differences in learning capacity ought to be considered when providing feedback to athletes and when interpreting the effect of feedback strategies on motor skill improvements.

Augmented feedback comprising self-modelling visual feedback and verbal cuing may be useful when modifying posture to improve overall glide performance. The purpose of this study was to evaluate the effect of visual feedback and verbal cuing on: i) glide efficiency and performance; ii) glide posture and torso morphology. We hypothesise that individualised augmented feedback, based on hydrodynamic principles of body curvatures, will improve glide efficiency and performance.

Methods

Participants

Seven male (age: 21.0±2.2 years, height: 185.1±7.8 cm, mass: 82.2±6.6 kg, FINA score: 677.3±44.8) and four female (age: 20.3±2.1 years, height: 172.0±6.4 cm, mass: 69.0±8.6 kg, FINA score: 723.5±85.7) national level swimmers from an Australian swimming club were recruited. FINA point scores were calculated for the swimmers' 100m long course best time within the previous 12 months for their preferred stroke. Swimmers were in mid-season training and four months away from the long course National Championships, completing 7.7±0.9 sessions and 15.9±2.3 hours of swimming training per week. The swimmers were informed via a participant information statement and gave their free written consent to take part in the study.

Experimental and data collection procedures

The experimental procedures were approved by the relevant university ethics committee. Swimming training attire was worn to expose body landmarks for marking. Swimmers adopted a standing streamlined body position on the pool deck while 4 cm diameter circles were marked using waterproof body paint (ProAiir Hybrid, Face Paint Shop Australia) over the following body landmarks on the swimmers' right lateral side: knee joint axis, hip joint axis (greater trochanter), and shoulder joint axis (glenohumeral joint in line with C7). The right side of the body was arbitrarily marked as both sides of the body were assumed to be symmetrical in the sagittal plane during gliding (Elipot et al., 2009). Swimmers were also marked on the front of their body for vertical reference of C7 and the hip during torso shape analysis in the frontal plane: right axilla at C7 and right thigh at greater trochanter level. Landmarks were identified and marked by the same Accredited Exercise Physiologist (Exercise & Sports Science Australia).

Glide analysis was conducted in a ten-lane 25 m pool (3 m depth). Swimmers performed an in-water warm-up administered by their coach of approximately 20 min prior to data collection consisting of free swimming, drills, and underwater glides. Glide, posture and torso shape data were recorded using a single fixed camera ('SwimPro X' SwimPro RJB Engineering, Australia) 3.5 m from the start wall, at 1.0 m depth, and 6.25 m perpendicular to the swimmer's motion. Glide videos were viewed in real-time on a screen on the pool deck by researchers to evaluate glide posture and trajectory. The motion of each swimmer was recorded at 30 Hz with a capture resolution of 1920x1080 pixels, and videos were saved in mp4 format.

Screenshots of vertical and horizontal underwater glides were extracted from 2D video recorded in the frontal and sagittal planes to analyse torso shape characteristics of the streamlined body (see section *Torso analysis*). Given that depth varies throughout the glide, 2D images of the anterior aspect of the torso during horizontal glides are difficult to extract. Consequently, vertical glides from the pool floor toward the water surface were performed to replicate regular glide posture for torso shape analysis in the frontal plane. Swimmers expelled air from their lungs, submerged to 3 m depth, and then performed a vertical push off in the streamlined body position with the anterior torso 6.25 m perpendicular to the underwater camera. Vertical glides were repeated until a glide was achieved in which the swimmer resurfaced without anteroposterior or lateral deviation from the vertical axis of their starting position. Trajectory of the glide was assessed visually by two researchers: one observing real-time footage from the underwater camera in the frontal plane and the other at the start wall observing the vertical glide in the sagittal plane.

Swimmers performed horizontal glides with 2-3 min rest between trials. Approximately 30 s between each swimmer's trial ensured that the water was free of vortices or fluid flow in the wake of the previous swimmer. A summary of the glide feedback protocol is illustrated in Figure 1. Three familiarisation glides were initially performed from the wall under the following instructions (lay terminology was used for the swimmers): i) expel air from the lungs and submerge to the underwater ledge (1.0 m depth); ii) perform a maximal underwater horizontal push-off in a streamlined position in the middle of the lane; iii) maintain a streamlined position without initiating upper or lower limb swimming actions until forward motion stops. During familiarisation, swimmers were given simple verbal feedback on their glide trajectory to help achieve a horizontal glide. After familiarisation, swimmers performed glides until five successful pre-cuing trials were achieved. A glide was deemed successful when the swimmer maintained a horizontal body position and trajectory without lateral deviation from the black lane line, replicating the protocol established in a previous study (Naemi & Sanders, 2008). Each trial was evaluated visually by two researchers.

Figure 1. Glide feedback and cuing procedures

A biomechanist, experienced in technique and performance analysis of Olympic level swimmers, evaluated glide posture during the pre-cuing trials. Evaluation of glide posture was written on a data sheet and verbal feedback provided to the swimmers was recorded using a microphone and mobile phone recording software. The hydrodynamic model of the streamlined body was established with the biomechanist prior to testing, but no specific method of verbal cuing was imposed. A self-modelling visual feedback approach was used in which swimmers viewed recordings of their pre-cuing glide trials and were provided feedback on their performance with technical verbal cues. Feedback and cuing were carried out with the goal of improving body posture and reducing body curvatures that may influence hydrodynamic resistance and glide efficiency. Whilst head position during the glide influences hydrodynamic resistance (Cortesi & Gatta, 2015), specific cuing on head positioning was not provided. Two familiarisation glides were performed after initial feedback and cuing, with additional visual feedback and verbal cuing following each glide to achieve the desired technique. Five successful post-cuing glides were then recorded without any form of feedback.

Data analysis

Camera fisheye distortions were corrected using a checkerboard calibration and the ‘Cinalysis’ software (Elipot et al., 2010), as described in Papic et al. (Papic, Sanders, et al., 2020). The knee, hip and shoulder landmarks in the 2D horizontal glide video were digitised with a neural network trained in DeepLabCut™ (ver 2.1), at the same digitisation accuracy as a human operator (root-mean-square digitisation error ~4-5 mm, ICC>0.99, $p<0.001$) (Papic, Sanders, et al., 2020). A 4.98 m by 1.0 m reference frame with 40 points was used to calibrate the field of interest for glide and torso shape analysis. The digitised x- and y-coordinates of the body landmarks in the horizontal glide videos were converted to real-world position data using a 2D direct linear transformation method. Landmarks that were unidentifiable due obstruction by air bubbles or image blurring were interpolated using a cubic spline filter. Forty-five frames of the glide were analysed, representing 1.5 sec of glide video, starting from the frame that the swimmer's right knee was fully extended after the feet left the wall. A 30-frame buffer was extracted before and after the glide. Interpolated position data were filtered using a 4th order Butterworth filter with a 6 Hz cut-off, ensuring inclusion of the low-frequency movement of gliding.

Glide analysis (horizontal)

Postural and morphological observations recorded by the biomechanist during the pre-cuing glides were organised into common themes and tallied based on their frequency of occurrence in the sample. Specific verbal cuing used to address postural and morphological faults in glide posture were transcribed to text.

Instantaneous horizontal velocities of the hip were derived from 2D position data and used to determine maximum (V_{max}, m/s) and mean glide velocity (V_{mean}, m/s) (Papic, Sanders, et al., 2020). Glide efficiency was assessed using the Hydro-Kinematic Method (Naemi & Sanders, 2008) to derive a glide factor (G_f, m) for each trial. The method involved curve-fitting a logarithmic function, based on inertial and hydrodynamic principles, to the 2D position-time data. The position-time data were defined by the mean x-axis position of the knee, hip and shoulder in each of the 45-frames of filled position data, prior to data smoothing. Glide factor was divided by a glide constant (λ) to derive a glide coefficient (G_c) (Equation 1) for each trial. The glide coefficient is affected by the shape characteristics of the streamlined body position, independent of the swimmers' body size (Naemi et al., 2010). As a result, the glide coefficient enabled assessment of the effect of augmented feedback on glide efficiency of male and female swimmers with different body size and mass. The glide constant was derived using body mass (m, kg), chest CSA (A, m^2), and estimated water density (p, 1000 kg/m^3) (Equation 2). For each trial, chest CSA was derived using underwater images of the swimmer in the frontal and sagittal planes (see section *Torso analysis*).

$$G_c = \frac{G_f}{\lambda} \qquad (1)$$

$$\lambda = \frac{m}{\frac{1}{2}.A.p} \qquad (2)$$

Instantaneous trunk incline and hip angle were calculated using inverse tangent and cosine trigonometric functions from the position of the knee, hip, and shoulder in each frame (Papic, Sanders, et al., 2020). Trunk incline (°) was the angle defined by the shoulder and hip, and the external x-axis, while the internal angle between the torso and the thigh defined the hip angle (°). Mean trunk incline and hip angle were calculated for each trial. Glide trajectory (φ, °) was the angle of the glide with respect to the external x-axis and was calculated from the initial and final x- and y-axis position of the hip (Equation 3). Glide trials with a trajectory greater than 5° were excluded from analysis as the Hydro-Kinematic Method involved a curve-fitting function for x-axis position data, whereby significant y-axis displacement can influence glide factor calculation.

$$\varphi = \left| \frac{180}{\pi} \tan^{-1} \frac{(final_y - initial_y)}{(final_x - initial_x)} \right| \qquad (3)$$

Torso analysis

The 'TorsoShape' program was used to analyse torso morphology (Papic et al., 2019). A screenshot of the swimmer was taken from the vertical glide video and from each pre- and post-cuing trial (Figure 2). Posture during the glide phase was assumed to have negligible effects on the lateral outlines of the torso, as experienced swimmers can align their lower limbs with the torso in the frontal plane. Thus, a swimmer's single vertical glide image was used with each of their horizontal glide images for torso CSA analysis. The horizontal glide screenshot was taken at the instant of median horizontal velocity of the hip. This instant was selected as it represented the glide posture after the initial push off and before the loss of uniform momentum of the body. The outline of the swimmer's torso in the frontal and sagittal planes were manually traced. A single vertical and horizontal glide was randomly selected and manually traced seven times to evaluate intra-rater reliability. The repeated tracings were never performed on the same day to ensure that practice did not affect reliability, similar to previous repeated manual digitisation procedures (Sanders et al., 2015).

Figure 2. Screenshots of vertical and horizontal (image rotated 90° anticlockwise for tracing) glides of a male swimmer used to analyse torso shape characteristics

Coordinates of the torso outline were converted to 2D position data and smoothed, to minimise the effect of random tracing errors, using a 4th order Butterworth filter with a 12 Hz cut-off frequency. This frequency was required to adequately capture rapid changes in torso shape, without having erroneous curvatures due to over-smoothing at lower cut-off frequencies. The program interpolated transverse and sagittal diameters (m) at each millimetre increment progressing caudally from the shoulder to hip. The torso can be modelled as a series of millimetre thick ellipses (Jensen, 1978). Cross-sectional areas at each vertical millimetre increment were calculated by halving the transverse and sagittal diameters (i.e. radii) of the torso and multiplying these radii together and with pi (π) using the formula for the area of an ellipse. The maximum rate of change in CSA (m^2/m) for the following body segment regions were derived in Microsoft Excel using the central difference formula: shoulder-chest; chest-waist; waist-hip.

Distances from a reference line to the outline of the torso in the sagittal plane were output to produce continuous 2D outlines for the posterior and anterior aspects of the torso (Figure 3). The horizontal reference line (*x*-axis in Figure 3) was defined by the markers positioned on the shoulder (C7 height) and hip (greater trochanter). Outlines of the torso in the sagittal plane were used to assess the suddenness of body shape change that may influence the path of fluid flow. Continuous form gradients (m/m) were calculated in Microsoft Excel using the central difference formula for the posterior and anterior torso outlines (Papic, McCabe, et al., 2020). The maximum form gradient was recorded for each body segment region detailed in Figure 3, where body curvature away and toward the reference line represented positive and negative form gradients, respectively.

Figure 3. Torso outlines of an exemplar female swimmer in the sagittal plane with respect to the horizontal reference line between shoulder and hip landmarks (*x*-axis). Maximum form gradients (m/m) were calculated for the body segment regions; posterior shoulder-chest (‘A’ to ‘B’), posterior chest-waist (‘B’ to ‘C’), posterior waist-hip (‘C’ to ‘D’), anterior shoulder-chest (‘E’ to ‘F’), anterior chest-waist (‘F’ to ‘G’)

Statistical analysis

All variables were averaged for pre- and post-cuing trials of each swimmer. Statistical analyses were performed using SPSS (Version 25, SPSS Inc., Chicago, USA), unless otherwise specified. Intra-rater accuracy for repeated tracings was evaluated in Microsoft Excel by calculating the mean of the standard deviations (mean error) of the transverse and sagittal diameters, and anterior and posterior torso outlines, at each vertical increment (mm). Intra-rater reliability for these measures were assessed using intra-class correlation calculations, with an absolute agreement, two-way mixed effects model. Intra-class correlation values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 were indicative of poor, moderate, good, and excellent reliability, respectively (Koo & Li, 2016). The effect of augmented feedback on group mean glide, postural and morphological variables were evaluated using Student's paired t-test and effect size (*d*). To evaluate the effect of the intervention on individuals' glide performance and efficiency, effect sizes (*d*) were calculated for glide velocity, trajectory, and efficiency values of each swimmer by dividing the difference of the pre- and post-cuing mean by the pooled standard deviation (SD). For each variable, an individual pooled SD (Equation 4) were used to account for within subject variability in each swimmer's glide technique. Trivial, small, medium, and large effects were indicated by effect sizes of <0.2, 0.2, 0.5, and 0.8, respectively, (Cohen, 1988). Statistical significance was accepted at p<0.05 for all tests.

$$SD_{pooled} = \sqrt{\left(\frac{{SD_{Pre}}^2 + {SD_{post}}^2}{2}\right)} \qquad (4)$$

Results

'Excellent' intra-rater reliability and low mean errors were found for torso diameter (transverse: ICC=0.999 p<0.001, mean error=3.74 mm; sagittal: ICC=0.998 p<0.001, mean error=2.20 mm) and position data (anterior outline: ICC=0.999 $p<0.001$, mean error=1.68 mm; posterior outline: ICC>0.999 $p<0.001$, mean error=1.36 mm) derived from seven repeated tracings of a swimmer's torso with 676 vertical millimetre increments. Post-hoc review of the digitised body landmarks revealed position errors for the hip landmark of a male swimmer. The swimmer wore swimming briefs with black dots on a light-coloured material, which were of similar size and positioning to the painted hip marker, resulting in errors for automatic digitisation by the neural network in some frames. Corrective manual digitisation of the hip for the incorrectly labelled frames was carried out for this participant using the graphical user interface in DeepLabCut™. Seven glides with an absolute glide trajectory greater than 5° were excluded from analysis. A total of 103 successful glides were analysed, with a minimum of four successful pre- and post-cuing glides for each swimmer.

Visual feedback and verbal cuing significantly improved glide efficiency and performance, with 'large' effect size changes in glide factor, glide coefficient and mean velocity values (Table 1). The effect of the cuing intervention on individual glide performance and glide efficiency results are shown in Table 2 and Table 3, respectively. All but one of the swimmers showed medium-large improvements in their glide factor values in response to the intervention. Furthermore, in glide coefficient values, seven swimmers showed large increases, two swimmers showed moderate increases, and the remaining two swimmers showed trivial-small increases. Observed faults in glide posture, that are susceptible to fluid flow disruption, were: hyper-extension of the hip, lumbar lordosis, chest convexity, shoulder hyperextension, and wrist flexion. The faults, cuing in response to these faults, and the pre- and post-feedback glide factor means for each individual swimmer are presented in Table 4. Frequency of the pre-cuing observations and examples of specific cuing and feedback phrases used to alter glide posture are detailed in Figure 4. The effect of augmented feedback on glide posture and torso morphology is shown in Table 5. Waist CSA increased following the cuing intervention and significant reductions in the maximum form gradient of the anterior chest-waist and posterior waist-hip segments were observed.

Figure 4. Observed glide posture faults and specific cuing intervention phrases used in response to these observations

Discussion and implications

The purpose of this study was to evaluate the effectiveness of visual feedback and verbal cuing on torso morphology and glide efficiency. Glide efficiency improved by ~7% following self-modelling visual feedback and verbal cuing on glide posture. Augmented feedback delivered by the biomechanist primarily focussed on reducing extension of the hips and pelvic alignment using a range of visual and verbal feedback strategies, resulting in significant changes to lumbar lordosis and chest convexity. While postural faults and delivery method of verbal feedback and cuing differed between the swimmers, nine of the eleven swimmers experienced medium-large improvements in their glide coefficient values directly related to changes in their glide posture. The study provides coaches, sport scientists, and swimmers with a hydrodynamic approach to glide feedback and specific phrases that were effective in improving glide posture. The findings have implications for improvements to glide and overall swimming performance.

Glide efficiency and performance

Mean horizontal velocity over a given distance is the most important performance variable of the underwater phase of the start and turn (Sanders, 2002). Relative effort of a swimmer during the push-off and initial velocity, however, can make it difficult to assess differences in mean velocity within and between subjects. Swimmers in the current study significantly improved their mean glide velocity following augmented feedback, without a significant change to initial velocity. ~~Swimmers were able to maintain a greater velocity over 1.5 sec of gliding without significantly altering their relative effort during the wall push off.~~ Whilst not statistically significant, a mean difference in initial velocity of 0.06 m/s from pre- to post-cuing was observed. Evaluation of inter-individual differences in maximum and mean glide velocities (Table 2) revealed that five swimmers incurred large improvements in their mean velocity, whilst showing medium-large increases in their maximum velocity. Individual increases in maximum velocity may influence interpretation of group improvements in mean velocity as a result of the feedback intervention. 'Correcting' for the swimmers' initial velocity using glide factor, however, enabled the effect of augmented feedback on glide efficiency to be assessed. The effect of improvements in glide efficiency on glide performance can be estimated by transposing glide factor values into horizontal distance gained, with known initial velocity and glide time (Naemi & Sanders, 2008). Estimated horizontal distances over 1.5 sec of gliding, with an initial velocity 2.5 m/s, are 2.72 m and 2.76 m for group mean pre- and post-cuing glide factor values of 4.46 m and 4.75 m, respectively. As a result, for the same initial velocity and glide time, postural changes in the sample equated to an average improvement in horizontal displacement of the hip by 4 cm. All swimmers improved their mean glide factor following augmented feedback, indicating that changes in posture reduced hydrodynamic resistance and minimised the body's rate of deceleration.

Investigating the effect of feedback strategies on glide performance is important for developing technical guidelines for coaches and swimmers. To our knowledge, only one other study has assessed the effect of feedback techniques on swimmers' glide efficiency. Thow and colleagues (Thow et al., 2012) evaluated the effect of three feedback interventions on glide efficiency and performance of elite swimmers during dive starts: i) visual feedback; ii) visual and verbal feedback; and iii) visual and verbal feedback, with quantifiable glide performance variables (initial velocity, mean velocity, and glide factor) using the 'GlideCoach' software (Naemi et al., 2008). The swimmers completed four dive sessions over one week with one of the assigned feedback interventions. During the week of training, only the group that received the quantitative feedback from GlideCoach improved. An additional session was carried out a month later where all three groups performed dives whilst receiving verbal feedback and quantifiable glide performance variables. The two groups that had not received quantitative feedback in the first four sessions improved significantly during the additional session. This meant that, overall, quantitative feedback of velocity and glide factor produced significant improvements (Thow et al., 2012). By comparison, large effect sizes in glide factor (d=2.297, p<0.001) were achieved using three short bouts of augmented feedback during a single session in the current study. A focus on optimal glide posture characteristics may be a practical solution for coaches delivering feedback to swimmers in a training setting.

The effectiveness of the feedback intervention on glide efficiency in the current study may be due to the pre-established method of evaluating glide technique. The biomechanist in our study evaluated the swimmers' glide posture based on the aforementioned hydrodynamic principles associated with body curvatures. Verbal feedback and cuing strategies delivered to the swimmers were specific to addressing postural faults that increase body curvatures and turbulent flow. Verbal feedback strategies guided by hydrodynamic principles appeared to be effective in improving glide efficiency, even in the absence of quantifiable performance variables.

Augmented feedback strategies and their effect on posture and torso shape

The most frequent pre-cuing observations that were explained to the swimmers were hip hyperextension, lumbar lordosis, and chest convexity. Verbal cuing was used to instruct swimmers to contract their abdominal muscles during the push-off and maintain muscle engagement throughout the glide. Practice of the desired movement on pool deck was also carried out, where swimmers anteriorly and posteriorly tilted their pelvis to gain proprioceptive feedback on, and awareness of, neutral pelvic alignment. Some swimmers required additional visual observation of their body in a reflective surface to achieve the desired posture. While swimmers received individualised feedback and exhibited different postural changes in response to cuing, technique faults and changes in posture were similar in the sample. Cuing resulted in a reduction of the group mean anterior chest-waist and posterior waist-hip form gradients, indicative of neutralisation of pelvic alignment and reduction of chest convexity relative to the abdominal cavity.

Feedback can be delivered during performance of a motor task or immediately after a task, defining concurrent and terminal feedback, respectively. Concurrent or frequent terminal feedback are effective methods for early learning of a motor skill (Liebermann et al., 2002). Terminal feedback was used in the current study at three instances immediately following glide trials. The effectiveness of terminal feedback hinges on athletes being able to associate their prior performance with the feedback they receive (Sigrist et al., 2013). Given that the swimmers were experienced and visual recordings were used to deliver feedback of prior performances, three bouts of terminal feedback appeared to facilitate skill improvement. However, the ideal frequency of terminal feedback was not assessed. The use of analogy learning techniques are also effective in motor skill improvements in sport (Komar et al., 2014; Liao & Masters, 2001). Analogy learning was used in our study to facilitate improvements in glide technique. The analogies, “imagine an arrow or a spear” and “imagine a rope attached to your hands pulling you toward the opposite wall”, were used to achieve a desired ‘flattened’ body posture.

Analogy learning placed an external focus of attention on the desired technique. External focus of attention, in conjunction with augmented feedback, can not only improve performance of a motor task, but muscular efficiency during the action (Wälchli et al., 2016).

Activation of the ventral and lateral abdominal muscles during the glide phase affects pelvic alignment (Kobayashi et al., 2015). Targeted cuing of torso muscles in our study may have increased activity and contractive force of these muscle groups. For example, cuing of the abdominal muscles was used to posteriorly tilt the pelvis of a male swimmer (P03), resulting in visual changes to lumbar spine curvature and pelvic alignment with respect to the torso (see Figure 5). This change in posture reduced the maximum posterior form gradient (waist-hip) from 0.935m/m in the top image to 0.520m/m in the bottom image in Figure 5. Greater muscle activity of the ventral abdominal muscles is related to increases in muscle CSA (McMeeken et al., 2004). Consequently, greater mean waist CSA from pre- to post-cuing could be due to increases in ventral abdominal muscle thickness with internal focus on activation of these muscles. Our findings support that activation of ventral and lateral abdominal muscles play an important role in maintaining an effective streamline position and that lumbar lordosis during the streamlined body position can occur even in highly skilled swimmers.

Figure 5. Pre- (top) to post-cuing (bottom) example of pelvic neutralisation

A variety of feedback strategies were employed during the intervention phase, including visual and verbal terminal feedback, analogy learning with an external focus of attention, and targeted muscular cuing. The feedback strategies differed between swimmers, which may have reflected previous experiences of the biomechanist, where swimmer responses to the feedback guided the type of strategies implemented. While the effectiveness of each individual strategy and learning capacities of the swimmers are unknown in this context, a combination of visual and verbal feedback interventions to achieve a desired hydrodynamic profile was found to be effective in manipulating the streamlined body.

Torso shape and hydrodynamic resistance

Glide efficiency is dependent upon more than the physical size of the swimmer, but the shape characteristics and posture they adopt (Naemi et al., 2012). Body size characteristics (body mass and CSA) were normalised when calculating the glide coefficient. As a result, improvements in glide coefficient values were due to changes in shape characteristics of the streamlined body. Naemi et al. (Naemi et al., 2012) suggested that hip extension misaligns the streamlined body and creates greater shape-related disturbances to fluid flow than a neutral hip position. Hip extension and/or lumbar lordosis exacerbate the posterior waist-hip form gradient, the curvature from the lumbar spine to the buttocks, which may result in fluid flow separation from the boundary layer and increased turbulence. The combined effect of greater waist CSA and manipulation of pelvic alignment may reduce the suddenness of shape change and subsequent fluid flow deviation at the lumbar spine.

Frontal surface area may have been manipulated from postural changes. Greater lumbar lordosis appeared to be associated with larger chest convexity relative to the abdominal cavity, as shown in the first image in Figure 5. Furthermore, the buttocks were positioned higher in the *y*-axis than the superior boundary of the chest, which would increase the frontal surface area in the transverse plane. Fluid pressure areas are found on the anterior portion of the chest and superior portion of the buttocks during computational fluid dynamics analysis of the streamlined body (Beaumont et al., 2017). Reduction in lumbar lordosis, chest convexity, and hyperextension of the hip positioned the legs and hips within the CSA of the chest, which may reduce the frontal surface area and, consequently, the hydrodynamic resistance acting on the body.

Limitations and future research

Glide characteristics following an underwater wall-push off in this study differ from the glide phase of competitive starts and turns. Swimmers performed a horizontal glide at 1.0 m depth in the current study. In comparison, an optimal glide path following a turn involves a depth of ~0.4 m and horizontal trajectory before deviating toward the water surface and resuming free-swimming actions (Lyttle & Blanksby, 2000), whilst an optimal start involves an entry angle ~46° and a maximum glide depth of ~0.9 m (Tor, Pease, & Ball, 2015). While the predominant flow along the body during gliding is turbulent (Naemi et al., 2010), differences in flow characteristics could exist during gliding after a wall-push off compared with starts and turns. Fluid could settle between each swimmer's glide trials in the current study, compared with turbulent flow characteristics that occur during a start, where the swimmer transitions from the flight phase in the air to the medium of water; and a turn, where vortices are formed in the wake of the swimmer by free-swimming actions prior to reaching the wall. Furthermore, time spent gliding in this study was 1.5 sec, whilst glide posture is held prior to commencing kicking actions during a competitive start and turn for ~1.0 sec (Tor, Pease, & Ball, 2014) and ~0.7 sec (Lyttle & Blanksby, 2000), respectively. To evaluate the effect of postural and body shape related changes on glide efficiency in this study, a constrained glide phase was performed to limit possible confounding effects of calculated glide efficiency values by variable flow characteristics and differences in glide depth and trajectory within- and between-swimmers. As a result, the effect of postural changes in glide technique on the competitive start and turn is unknown. Future research would be advantageous to evaluate the effect of changes in glide posture on global start and turn performance.

While significant improvements in glide efficiency were achieved through three short bouts of augmented feedback, retention of the acquired technique was not assessed. Future research with larger sample sizes could be conducted to explore the causal nature of these findings and compare sex differences in torso morphology between swimmers to tailor individual glide postures. Post-hoc review of the glide footage reveals head positioning faults in some of the swimmers. While feedback on head positioning was not provided, further glide efficiency improvements could be achieved with verbal cuing of head positioning. Given that approximately 20% of breaststroke is performed in a glide position (Seifert et al., 2010), a similar approach to reducing body curvatures could be performed in breaststroke gliding to improve efficiency in the deceleration phases of the stroke.

Conclusion

Analysis of anthropometric and shape characteristics of the streamlined body are commonly performed on land (Cortesi et al., 2020; Naemi et al., 2012). The streamlined body, however, may differ during underwater gliding when subject to resistive force and buoyancy. The methods applied in this study hold significant implications for swimming research, where shape characteristics of the streamlined body during the glide phase and their effect on glide efficiency can be assessed. Skilled swimmers were found to exhibit postural and shape characteristics that increase hydrodynamic resistance during underwater gliding: hip hyperextension, lumbar lordosis and chest convexity. A variety of feedback and verbal cuing strategies were used to instruct swimmers to neutralise the hip angle and alignment of the pelvis, with respect to the thorax. Three bouts of augmented feedback reduced maximum form gradients related to curvature of the lumbar spine and buttocks, and protrusion of the chest. Correcting postural faults based on hydrodynamic principles significantly improved glide efficiency. The feedback strategies used in this study provide practical implications for coaches and swimmers, to improve performance of the underwater phase of the start and turn.

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Tables

Table 1. The effect of augmented feedback on glide efficiency and performance (n=11 swimmers)

Glide variable	Pre-cuing Mean (SD)	Post-cuing Mean (SD)	Mean difference	% change	Effect size (*d*), *p*-value
V_{max} (m/s)	2.52 (0.29)	2.58 (0.28)	0.06	2.38	0.485, 0.139
V_{mean} (m/s)	1.80 (0.16)	1.86 (0.15)	0.06	3.33	0.880, 0.015*
Trajectory (°)	2.08 (1.10)	1.92 (0.93)	-0.16	-7.69	0.125, 0.688
Glide factor (m)	4.46 (0.29)	4.75 (0.29)	0.29	6.50	2.297, <0.001***
Glide coefficient	2.21 (0.22)	2.38 (0.26)	0.17	7.69	1.605, <0.001***

*p<0.05, **p<0.01, ***p<0.001

Table 2. The effect of augmented feedback on individual glide performance (maximum velocity, mean velocity and glide trajectory)

Participant	Sex	V_{max} (m/s)			V_{mean} (m/s)			Glide trajectory (°)		
		Pre Mean (SD)	Post Mean (SD)	*d*	Pre Mean (SD)	Post Mean (SD)	*d*	Pre Mean (SD)	Post Mean (SD)	*d*
P01	F	2.14 (0.24)	2.33 (0.08)	1.08	1.58 (0.13)	1.72 (0.04)	1.54	1.17 (0.60)	1.18 (0.79)	0.03
P02	F	2.26 (0.21)	2.33 (0.02)	0.47	1.67 (0.14)	1.71 (0.02)	0.33	2.30 (1.01)	1.74 (1.02)	-0.55
P03	M	2.69 (0.17)	2.80 (0.09)	0.80	1.89 (0.10)	1.98 (0.04)	1.17	0.99 (0.69)	3.01 (1.90)	1.41
P04	M	2.64 (0.09)	2.82 (0.09)	2.01	1.79 (0.24)	1.99 (0.04)	1.17	2.63 (1.48)	1.08 (1.10)	-1.19
P05	M	2.97 (0.19)	2.74 (0.06)	-1.59	2.00 (0.08)	1.96 (0.04)	-0.54	2.41 (1.13)	3.42 (1.09)	0.90
P06	F	2.57 (0.05)	2.56 (0.05)	-0.14	1.87 (0.02)	1.90 (0.02)	1.31	1.89 (1.15)	0.64 (0.43)	-1.43
P07	M	2.71 (0.18)	2.80 (0.16)	0.52	1.89 (0.07)	1.99 (0.09)	1.28	0.43 (0.53)	0.89 (0.90)	0.62
P08	F	1.99 (0.24)	1.91 (0.16)	-0.37	1.48 (0.19)	1.54 (0.11)	0.40	3.85 (1.14)	2.84 (1.74)	-0.69
P09	M	2.40 (0.18)	2.56 (0.07)	1.14	1.82 (0.06)	1.81 (0.03)	-0.27	3.62 (1.68)	1.92 (0.83)	-1.28
P10	M	2.64 (0.18)	2.72 (0.21)	0.42	1.91 (0.06)	1.92 (0.04)	0.17	2.56 (1.45)	1.85 (0.89)	-0.59
P11	M	2.68 (0.12)	2.76 (0.09)	0.72	1.90 (0.06)	1.94 (0.03)	0.92	1.00 (0.36)	2.54 (1.18)	1.77

Table 3. The effect of augmented feedback on individual glide efficiency (glide factor and glide coefficient)

Participant	Sex	Glide factor (m)			Glide coefficient		
		Pre Mean (SD)	Post Mean (SD)	*d*	Pre Mean (SD)	Post Mean (SD)	*d*
P01	F	4.18 (0.21)	4.65 (0.41)	1.45	2.13 (0.08)	2.53 (0.23)	2.33
P02	F	4.30 (0.20)	4.56 (0.16)	1.40	2.01 (0.15)	2.10 (0.09)	0.78
P03	M	4.28 (0.26)	4.60 (0.15)	1.51	1.97 (0.12)	2.14 (0.10)	1.61
P04	M	4.59 (0.24)	4.77 (0.30)	0.66	2.19 (0.09)	2.36 (0.16)	1.32
P05	M	4.24 (0.29)	4.64 (0.17)	1.70	2.06 (0.15)	2.23 (0.12)	1.20
P06	F	4.94 (0.30)	5.24 (0.15)	1.28	2.53 (0.18)	2.63 (0.12)	0.66
P07	M	4.41 (0.32)	4.82 (0.16)	1.64	2.45 (0.19)	2.70 (0.12)	1.60
P08	F	4.43 (0.55)	4.78 (0.26)	0.79	2.24 (0.25)	2.44 (0.20)	0.85
P09	M	4.91 (0.23)	5.14 (0.21)	1.05	2.42 (0.10)	2.63 (0.16)	1.66
P10	M	4.70 (0.29)	4.84 (0.19)	0.58	2.44 (0.18)	2.51 (0.16)	0.44
P11	M	4.10 (0.25)	4.16 (0.20)	0.30	1.90 (0.16)	1.91 (0.08)	0.10

Table 4. Observed faults, postural cuing provided to each swimmer, and the effect of cuing on mean glide factor values

Participant	**Sex**	**Fault(s)**	**Pre-cuing glide factor (m)**	**Cuing**	**Post-cuing glide factor (m)**
P01	F	hip hyperextension	4.18	neutralise hip angle	4.65
P02	F	↑chest convexity & shoulder hyperextension	4.30	neutralise pelvic alignment ↓chest convexity & neutralise shoulder angle	4.56
P03	M	↑lumbar lordosis ↑chest convexity	4.28	neutralise pelvic alignment ↓chest convexity	4.60
P04	M	↑lumbar lordosis hip hyperextension	4.59	neutralise pelvic alignment neutralise hip angle	4.77
P05	M	↑lumbar lordosis hip hyperextension wrist flexion	4.24	neutralise pelvic alignment neutralise hip angle neutralise alignment of hands	4.64
P06	F	↑lumbar lordosis	4.94	neutralise pelvic alignment	5.24
P07	M	↑chest convexity hip hyperextension	4.41	↓chest convexity neutralise hip angle	4.82
P08	F	↑lumbar lordosis hip hyperextension	4.43	neutralise pelvic alignment neutralise hip angle	4.78
P09	M	hip hyperextension	4.91	neutralise hip angle	5.14
P10	M	hip hyperextension	4.70	neutralise hip angle	4.84
P11	M	↑lumbar lordosis	4.10	neutralise pelvic alignment	4.16

Table 5. The effect of augmented feedback on postural and morphological outcomes (n=11 swimmers)

Postural/morphological outcome	Pre-cuing Mean (SD)	Post-cuing Mean (SD)	Mean difference	Effect size (*d*), *p*-value
Cross sectional area (m^2)				
Chest	0.077 (0.009)	0.077 (0.009)	<0.001	0.377, 0.240
Waist	0.041 (0.004)	0.042 (0.004)	0.001	0.745, 0.033*
Hip	0.063 (0.005)	0.064 (0.005)	0.001	0.202, 0.519
Hip angle (°)	168.20 (4.10)	167.64 (3.98)	-0.56	-0.292, 0.356
Trunk incline (°)	2.92 (2.44)	3.54 (2.76)	0.62	0.238, 0.447
Max ΔCSA† (m^2/m)				
Shoulder-chest	0.330 (0.059)	0.341 (0.051)	0.011	0.432, 0.182
Chest-waist	-0.229 (0.023)	-0.233 (0.028)	-0.004	-0.214, 0.494
Waist-hip	0.256 (0.046)	0.250 (0.046)	-0.006	-0.280, 0.375
Max form gradient (m/m)				
Anterior shoulder-chest	0.794 (0.199)	0.771 (0.134)	-0.023	-0.182, 0.560
Anterior chest-waist	-0.468 (0.171)	-0.394 (0.128)	0.074	0.723, 0.037*
Posterior shoulder-chest	0.328 (0.088)	0.329 (0.119)	0.001	0.010, 0.975
Posterior chest-waist	-0.298 (0.076)	-0.311 (0.090)	-0.013	-0.219, 0.484
Posterior waist-hip	0.964 (0.150)	0.852 (0.189)	-0.112	-0.889, 0.015*

*p<0.05,

†ΔCSA, rate of change in cross-sectional area

Figure legends

Figure 1. Glide feedback and cuing procedures

Figure 2. Screenshots of vertical and horizontal (image rotated 90° anticlockwise for tracing) glides of a male swimmer used to analyse torso shape characteristics

Figure 3. Torso outlines of an exemplar female swimmer in the sagittal plane with respect to the horizontal reference line between shoulder and hip landmarks (x-axis). Maximum form gradients (m/m) were calculated for the body segment regions; posterior shoulder-chest ('A' to 'B'), posterior chest-waist ('B' to 'C'), posterior waist-hip ('C' to 'D'), anterior shoulder-chest ('E' to 'F'), anterior chest-waist ('F' to 'G')

Figure 4. Observed glide posture faults and specific cuing intervention phrases used in response to these observations

Figure 5. Pre- (top) to post-cuing (bottom) example of pelvic neutralisation