A METHOD OF QUANTIFYING TORSO SHAPE TO ASSESS ITS INFLUENCE ON RESISTIVE DRAG IN SWIMMING

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Torso shape characteristics such as cross-sectional area, curvatures and indentations influence the pressure distribution of fluid flow around the torso. The purpose of this study was to introduce a new method of quantifying torso shape using photographic imaging. The contours of the torso in the frontal and sagittal planes were obtained by tracing photographs of the swimmers. Anterior, posterior and lateral flow lines were interpolated to samples spaced at 1mm vertically and used to determine continuous form gradients of four elite male swimmers. The maximum rate of change in cross-sectional area was estimated from chest-waist and waist-hip by modelling each vertical sample of the torso as an ellipse. The method provides implications for discussion with coaches and athletes and future research to determine the role of torso shape in talent identification and swimming performance.

KEYWORDS: fluid dynamics, anthropometry, hydrodnamic resistance

INTRODUCTION: The relationship with hydrodynamic resistance and body shape is commonly analysed using broad morphological outcome measures such as body height and mass (Benjanuvatra, Blanksby, & Elliott, 2001) and whole-body surface area (Takahashi, Nomura, Yoshida, & Miyashita, 1983). The influence of the torso on hydrodynamic resistance has been investigated but has focused predominantly on singular anthropometric measures; breadths, circumferences and cross-sectional areas (CSA). For example, chest circumference and the largest CSA of a swimmer have been shown to have moderate positive correlations with passive drag force, that is, the resistance encountered by a swimmer when in a streamlined position without swimming actions (r = 0.50 – 0.70) (Clarys, 1979).

Marine animals and hydrofoils exhibit shape characteristics that minimise hydrodynamic resistance. Dolphins minimise hydrodynamic resistance through the maintenance of laminar fluid flow around their bodies when moving through water (Webb, 1975). One characteristic that aids a dolphin in maintaining this flow pattern is an optimal form gradient (Fish & Hui, 1991). Form gradient refers to the rate of change in body shape when progressing caudally. A lesser form gradient allows the flow to remain laminar for a longer length of flow than a greater gradient. The influence of body curvatures on water flow becomes apparent when comparing the hydrodynamic resistance of male and female mannequins, based on the body shape characteristics of elite level swimmers (Pease & Vennell, 2011). The female mannequin showed approximately 10% greater passive drag force than the male mannequin when fully submerged in the streamlined position thought to be due to the differences in water flow direction around curvatures of the body. A three-dimensional (3D) laser scanner was used successfully to analyse CSAs of the mannequins and informed the approach in the current study.

Given the physical size and cost of a 3D laser scanner, widespread use in swimming is difficult. The purpose of this paper is to introduce a method of quantifying torso shape using photographs of swimmers taken from front and side views of swimmers. Furthermore, the paper discusses future research direction and implications of the method to determine the influence of torso shape characteristics on hydrodynamic resistance in swimming.

METHODS: Digital images of four elite male Scottish front crawl specialists were used from data previously collected by McCabe (McCabe & Sanders, 2012). The four swimmers had body masses within a ~3kg range (body mass: 71.0 ± 1.2kg) and were selected to demonstrate the ability of the method to detect differences in torso shape characteristics of swimmers with similar body mass. Two 35mm cameras were positioned on tripods at a height of 1.0m and with their axis aligned horizontally and perpendicular to the swimmers' frontal and sagittal planes. The swimmers were photographed in the anatomical position wearing regular swimming trunks. In both the anterior and lateral image, the swimmer's arms were positioned such that the torso was clearly visible for analysis.

The torso segment was defined as the mass between the level of C7 vertebrae and the greater trochanter of the femur, marked with black 4cm diameter circular marks (actor's waterproof makeup). The arms were truncated at the axillary line during tracing. Immediately after photographing each swimmer, photographs were taken of a calibration frame positioned where the swimmer had been, to align closely with the swimmer's mid frontal and mid-sagittal planes. The images are input into a bespoke MATLAB 'TorsoShape' program adapted from the 'eZone' program (Deffeyes & Sanders, 2005) (Mathworks, Inc). After calibrating by digitising the images of the calibration frame the user traces, using a mouse and cursor, the outlines of the torso from the front and side views. The tracings extend beyond the C7 and greater trochanter landmarks to eliminate endpoint distortion in subsequent low-pass filtering. The program has a zoom function to ensure accuracy during the calibration and tracing of the swimmer's torso. The program interpolates the sampled points to yield the two dimensional coordinates of the tracings with the vertical (Z) coordinates being 1mm apart, smooths the data at 12 Hertz using a Butterworth 4th order digital filter and aligns the 1mm samples of the four tracings to a common vertical reference. The program automatically outputs the coordinates of each tracing for the frontal plane (X, Z) and for the sagittal plane (Y, Z) and the difference between the X coordinates at each Z sample and the Y coordinates at each Z sample.

Cross-sectional areas: The torso is modelled as a series of 1mm thick vertically stacked ellipses (Jensen, 1978) using the differences in X and Y coordinates as the diameters of each ellipse. Transverse and sagittal diameters are initially converted to radii (a and b respectively). The area of an ellipse formula ($CSA = \pi \cdot a \cdot b$) was used to estimate CSAs moving caudally along the torso. The largest CSA between C7 vertebrae height and the waist was defined as 'chest CSA' (m^2), the smallest CSA as 'waist CSA' and the CSA at the greater trochanter as 'hip CSA'.

Rate of change in cross sectional area: Previous research compared the maximal rate of change in CSA between a male and female mannequin (Pease & Vennell, 2011). Using Microsoft Excel, the change of the CSA values between adjacent vertical increments (0.001 m) were calculated and represented the rate of change in CSA moving caudally along the swimmer's torso. The greatest rate of change in CSA between chest-waist and waist-hip ($m^2 \cdot m^{-1}$) was calculated for each segment. A negative rate of change indicates that CSA is reducing, whilst a positive value indicates that CSA is increasing.

Form gradients: The form gradient ($m \cdot m^{-1}$) for the anterior, posterior and lateral (left and right) aspects of the torso were calculated in Microsoft Excel from the coordinate values in the frontal (X,Z) and sagittal plane (Y,Z). Each form gradient was separated into chest-waist and waist-hip segments. A negative form gradient indicated that the portion of the torso was narrowing, whilst a positive form gradient indicated that the torso was widening.

RESULTS: Chest, waist and hip CSAs and the maximal rate of change in CSA of the swimmers are summarised in Table 1. The form gradients of the swimmers are summarised in Table 2. It is to be noted that the left and right lateral form gradients in Table 2 were calculated from a front view of the swimmers.

Table 1: Cross sectional areas (CSA) (m^2) and rate of change in CSA ($m^2 \cdot m^{-1}$) of the swimmers

Swimmer	Chest CSA	Waist CSA	Hip CSA	Change in CSA	
				Chest-waist	Waist-hip
1	0.074	0.043	0.063	-0.20	0.18
2	0.067	0.043	0.060	-0.19	0.21
3	0.065	0.048	0.069	-0.13	0.23
4	0.064	0.047	0.062	-0.12	0.19

Table 2: Form gradients ($m \cdot m^{-1}$) of the swimmers

Swimmer	Anterior		Posterior		Lateral (left)		Lateral (right)	
	Chest-waist	Waist-hip	Chest-waist	Waist-hip	Chest-waist	Waist-hip	Chest-waist	Waist-hip
1	-0.21	0.16	-0.28	0.50	-0.41	0.32	-0.42	0.29
2	-0.18	0.27	-0.28	0.36	-0.24	0.27	-0.36	0.35
3	-0.11	0.17	-0.31	0.76	-0.22	0.47	-0.27	0.34
4	-0.13	0.01	-0.19	0.84	-0.16	0.41	-0.27	0.08

DISCUSSION: This paper has introduced a new approach of analysing body shape characteristics of elite swimmers by quantifying the rate of change in torso shape. From the preliminary findings presented the method appears to be sensitive enough to detect small differences in torso shape between individuals. While the four swimmers had a body mass within ~ 3kg of one another, they exhibited small differences in body CSAs, but more notable differences in the rate of change in CSA and form gradients. A notable shape variability across the four swimmers is that of the posterior form gradient waist-hip (Table 2). Swimmer 4 revealed a smaller chest CSA than Swimmer 2, but exhibited a posterior form gradient waist-hip more than double that of Swimmer 2, revealing a greater rate of change in shape to the buttocks. This finding highlights the advantage of the method over the use of singular outcomes measures such as maximum CSA when assessing the relationship between morphology and hydrodynamic resistance. Notable within subject differences existed between the lateral (left and right) form gradients of Swimmers 1-3. Differences in form gradients may have been due to contralateral differences in muscle mass between the dominant and non-dominant sides of the swimmers. Surveying swimmers in future research to determine their dominant side may give insight into the cause of contralateral differences in the lateral aspects of the torso.

As the water flows past the chest of a swimmer, the indentation at the waist and the bulge at the buttocks may affect the direction of water flow and result in turbulence and increased hydrodynamic resistance. Quantifiable differences in torso shape among the four swimmers presented in this paper have informed the future direction of the project.

Applications and future directions: Two studies will be conducted to investigate the influence of form and flow line gradients on hydrodynamic resistance during free swimming and in the streamlined body position. In the first study the ‘TorsoShape’ program will be used in conjunction with 400 m front crawl intra-cyclic velocity data to determine the influence of torso shape on an outcome measure of hydrodynamic resistance, coefficient of drag force. The coefficient of drag force will be determined by rearranging the equation embodying Newton’s second law of motion to obtain the total drag force (Equation 1). Therefore, coefficient drag force (C_d) (Equation 2) will be a function of the swimmer’s body mass (m), cross-sectional area (A), velocity (v^2) and acceleration (α), as well as fluid density (ρ). Acceleration will be calculated at the time point of least propulsive force production, given that swimmers commonly exhibit a lag phase between the propulsive phases of each upper limb during 400 m front crawl swimming distance. In the absence of upper limb propulsive force production, deceleration of the body is largely associated with form drag, the resistive force caused by the shape and orientation of the body. A step-wise regression analysis of torso shape outcome measures detailed in this paper will be conducted on a greater sample size of swimmers to determine their relationship with the coefficient of drag force during 400 m front crawl swimming.

$$\mathrm{F}d = \mathrm{m} \cdot \alpha = \frac{1}{2} \cdot Cd \cdot \rho \cdot A \cdot \nu^2 \text{ (Equation 1)}$$

$$Cd = \frac{(\mathrm{m} \cdot \alpha \cdot 2)}{(\rho \cdot A \cdot \nu^2)} \text{ (Equation 2)}$$

The aim of the second study is to assess the relationship between torso shape characteristics and passive drag force. Passive drag will be quantified using a mathematical model (Naemi, Easson, & Sanders, 2009). Swimmers will be photographed on land in an unweighted streamlined position by holding onto a bar above their head, to more accurately model the glide phase. The relationship between passive drag force derived from the mathematical model and torso shape characteristics will be explored using a step-wise regression analysis.

CONCLUSION: 'TorsoShape' is a novel tool that can be used to analyse torso shape characteristics of swimmers and appears to be sensitive enough to detect small differences in body shape between individuals. The method described will be used in two future studies to develop a more thorough understanding of the effect of the morphology of the torso on resistive drag of human swimmers. The method provides implications for discussion with coaches and athletes and future research to determine the role of torso shape in talent identification and overall swimming performance.

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