Effect of body roll amplitude and arm rotation speed on propulsion of arm amputee swimmers

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A B S T R A C T

Only a limited amount of research has gone into evaluating the contribution made by the upper arm to the propulsion of elite swimmers with an amputation at elbow level. With assistance of computational fluid dynamics (CFD) modelling, the swimming technique of competitive arm amputee swimmers can be assessed through numerical simulations which test the effect of various parameters on the effectiveness of the swimming propulsion.

This numerical study investigates the effect of body roll amplitude and of upper arm rotation speed on the propulsion of an arm amputee swimmer, at different mean swimming speeds. Various test cases are simulated resulting in a thorough analysis of the complex body/fluid interaction with a detailed quantitative assessment of the effect of the variation of each parameter on the arm propulsion. It is found that a body roll movement with an amplitude of 45° enhances greatly the propulsive contribution from the upper arm with an increase of about 70% in the propulsive force compared to the no roll condition. An increase in the angular velocity of the upper arm also leads to a concomitant increase in the propulsive forces produced by the arm.

Such results have direct implications for competitive arm amputee front crawl swimmers and for those who coach them. One important message that emerges in this present work is that there exists, for any given swimming speed, a minimum angular velocity at which the upper arm must be rotated to generate effective propulsion. Below this velocity, the upper arm will experience a net resistive drag force which adversely affects swimming performance.

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1. Introduction

Front crawl is the fastest of the four competitive swimming strokes. The contribution of the arm action to propulsion in front crawl swimming is estimated to be at least 80% (Deschodt et al., 1999; Toussaint and Beek, 1992). Elite front crawl swimmers with an arm amputation at elbow level are clearly at disadvantage when compared to able-bodied swimmers since they are deprived of an important propelling surface (hand and forearm). Swimmers with this level of impairment compete in the International Paralympic Committee (IPC) S9 classification for front crawl.

The upper arm was not generally assumed to be a propelling surface during able-bodied swimming. Most studies of arm propulsion in front crawl swimming only considered the propulsive effect of the hand and forearm (e.g. Schlehauf, 1979; Berger et al., 1999; Toussaint et al., 2002). Hay and Thayer (1989), using tufts around the hand and arm as well as pressure measurements also observed that arm rotation resulted in enhanced propulsion. Payton and Wilcox (2006) looked at the propelling effect of the upper arm of unilateral amputee swimmers. Findings from their experimental study indicated that the affected limb can generate some propulsion. However, the magnitude of the propulsive force was not quantified. More recently the use of CFD has been implemented to predict athlete’s performance. Bixler et al. (2007) made use of steady CFD to evaluate the passive drag of a submerged swimmer. Results from the numerical simulation were found to be within 4% of the experimentally determined values. Lecrivain et al. (2008) used unsteady CFD to investigate the effectiveness of a partially amputated arm of a competitive swimmer. The unsteady computation of the hydrodynamic forces generated by the upper arm was achieved through the use of a moving/deforming mesh. Results showed that the upper arm motion through the water effectively contributes to the propulsion of the unilateral front crawl swimmer. However, this initial simulation work did not evaluate the influence of body roll, or the effect of changes in the arm rotation speed and average swimming speed, on propulsion. The present research aims to investigate the effect of these parameters on the enhancement of an amputee swimmer’s performance.
There have been some limited attempts to identify how body roll contributes to swimming performance. Hay et al. (1993) modeled the trunk and the arm as rigid segments joined by simple hinge joints. Since the propulsive force produced by the hand is linked to its speed (Payton and Bartlett, 1995), the effect the body roll movement has on the hand propulsion can be assessed qualitatively. Hay et al. (1993) and Payton et al. (1997) both found that body roll contributed to increased hand motion. However, in a later study that used kinematic data derived from three-dimensional analysis of swimmers, Payton et al. (2002) reported no such positive contribution. This outlines the need to investigate this phenomenon further.

Unlike these previous studies which involved the decomposition of the arms into separate segments and their resulting effects on the hand velocity, the CFD model used in this study enables a complete computation of all the hydrodynamic forces involved (Lecrivain et al., 2008). This study aims to investigate the contribution of body roll and of arm rotation speed at different mean swimming speeds. 27 test cases are simulated in all, resulting in a thorough analysis of the complex body/fluid interaction with a detailed quantitative assessment of the effect of the variation of each parameter on the arm propulsion. It is hoped that the results of this study will deliver some improvement advice for generating an enhanced swimming performance.

2. Methods

2.1. CFD model

The participant in this study was an elite female swimmer with an arm amputation at elbow level. Written informed consent was obtained from the participant for the procedures described in this section. The CFD model of the swimmer was derived from the procedure detailed in Lecrivain et al. (2008). They used a laser scanner to accurately capture the geometry of the upper arm. A complex surface CFD mesh of the competitive swimmer was then built. The present paper does not focus on the wave drag acting on the swimmer body but focuses on the hydrodynamic forces generated by the upper arm being pulled underwater. To this effect, the swimmer model was fully immersed in a large cubic volume of water making up the computational domain. The computational domain was discretised into a set of unstructured tetrahedral cells. The inlet boundary of the domain was set to a uniform velocity while the outlet surface boundary was set at a constant atmospheric pressure. The CFD package Fluent was used to carry out the numerical simulations. A Standard k–epsilon turbulence model was used for the simulation and a turbulence intensity of 1% was given at the inlet and outlet boundaries. The choice of the turbulence model and of the turbulence intensity was based on the work of Bixler et al. (2007). A total of about 200,000 cells formed the computational domain. The CFD simulations incorporated a dynamic/moving mesh to reproduce the upper arm movement and the trunk rotation of the swimmer. The movement of the relevant body parts was achieved through the use of user-defined functions (UDF). A UDF is a function programed using the C-programming language and loaded within the CFD software Fluent. The period of time during which the upper arm rotates was divided into 100 time steps. The discretised volume of water forming the CFD mesh was updated at the end of each time step to account for the repositioned arm and trunk. Over the time step, the unsteady flow simulation was solved through an iterative algorithm until convergence of the residuals within 10−4 was achieved.

In the steady case, this convergence criterion was checked to lead to a constant drag coefficient for the swimmer. The upper arm was allowed to move in the plane normal to the shoulder axis (parasagittal plane) and the body oscillated about its long axis. The propulsive effect of the legs and of the contralateral arm was reproduced by providing the swimmer model with an average travelling velocity taken from experimental data (Payton, 2008).

2.2. Arm rotation speed

2.2.1. Experimental data

The swimmer performed front crawl trials at various paces whilst being video-taped below water from the side view using a tracking camera. The data for the arm angular position, relative to the horizontal axis, were determined for average swimming speeds ranging from 1.06 to 1.31 m/s. The angular position of the upper arm during the pull phase (arm entry to arm exit) of a stroke cycle, at three swimming speeds, is shown in Fig. 1. The kinematic data were determined at a sampling frequency of 50 Hz. Towards the end of the pull phase a few values are missing because of the difficulty in measuring the arm angular position as the shoulder comes out of the water. It was found that all curves describing the arm angular position against time showed a similar trend. Following arm entry, the swimmer kept her upper arm horizontal for a short period of time before commencing the downsweep phase (arm angle 0–90°). During this phase the arm initially accelerated and then began to decelerate. The upsweep phase (arm angle 90–180°) was characterised by a deceleration of the upper arm rotation.

2.2.2. Mathematical model

The experimental data of the arm angular position for an average swimming speed of 1.06 m/s were taken as a reference for all the simulations. To eliminate the inherent noise in the series of measurements, a smooth NURBS function was fitted to the arm angle–time data and the first derivative of the function was calculated to obtain the arm angular velocity. The angular position–time data, for the pull phase of an arm amputee's front crawl stroke at three swimming speeds, is shown in Fig. 1. The participant for the procedures described in this section. The CFD model used in this study enables a complete computation of all the hydrodynamic forces involved (Lecrivain et al., 2008). This study aims to investigate the contribution of body roll and of arm rotation speed at different mean swimming speeds. 27 test cases are simulated in all, resulting in a thorough analysis of the complex body/fluid interaction with a detailed quantitative assessment of the effect of the variation of each parameter on the arm propulsion. It is hoped that the results of this study will deliver some improvement advice for generating an enhanced swimming performance.

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3. Validation

To initially validate the CFD model, a set of steady simulations were carried out within the range of typical swimming speeds. The total drag forces computed around the amputee swimmer were compared with experimental values determined for three able-bodied female swimmers (Toussaint et al., 1988). The body mass (65 kg) and height (1.63 m) of the amputee swimmer remained close to the mean values determined for the set of able-bodied participants (mean body mass 65 kg; mean height 1.77 m). Drag forces were calculated for swimmer speeds ranging between 1 and 1.4 m/s with an increment of 0.2 m/s. It can be seen in Fig. 5 that the CFD simulations delivered total body drag values that closely match their experimental equivalents. This initial stage validated the numerical assessment of the hydrodynamic forces during the unsteady CFD simulation. However, to qualitatively validate the hydrodynamic forces generated by the upper arm, a CFD simulation was carried out with the swimmer model fully immersed in a non-moving fluid (i.e. inlet velocity set to 0 m/s) and with no body roll movement. The arm angular velocity remained identical to the normal arm pull experimentally observed. In this particular case, the rotational movement of the upper arm can be considered as a rotating stiff arm. The rotation leads to a velocity gradient along the upper arm, such that the tangential velocity of the upper arm increases from shoulder to elbow. The tangential velocity gradient results in a pressure gradient along the upper arm (Toussaint et al., 2002) which in turn induces a tangential resultant force. Since the resultant force is correlated with the angular velocity of the stiff arm, it is therefore expected that the resultant force reaches maxima simultaneously with the arm angular velocity and gradually diminishes after the peak. As seen in Fig. 6, it is pleasing to see that the profile of the resultant force (Fr) computed on the upper arm surface matches the profile of the arm angular velocity (Fig. 2). Both curves peak when the arm angular position attains the value $\alpha=50^\circ$. The pattern of the vertical force ($F_y$) is also as
expected; the vertical force increases during the downstroke of the arm stroke and becomes negative during the upstroke phase.

4. Results

4.1. Initial swimming speed ($V_s = 1.06 \text{ m/s}$)

4.1.1. Effect of body roll amplitude on propulsive forces
At the start of the simulation, the swimmer model was set in a horizontal position with the upper arm stretched forward. Fig. 7 shows some successive positions of the swimmer body and the upper arm at different times of the stroke.

The contribution of the body roll amplitude was assessed for a swimmer speed of $1.06 \text{ m/s}$ and an arm rotation corresponding to that observed experimentally. The resulting hydrodynamic forces, in each space direction, produced by the upper arm for no body roll movement and for body roll amplitudes of $30^\circ$ and $45^\circ$ are illustrated in Fig. 8. The force components correspond to the propulsive element ($F_x$), to the vertical component ($F_y$) and to the lateral component ($F_z$). The overall resultant force is shown as $F_r$. Results show that the upper arm effectively contributes to the propulsion of the body. It can be seen from Fig. 8 that an effective propulsive force ($F_x$) is generated through most of the pull phase, except towards the end of the upstroke. Fig. 9 shows the effect of body roll amplitude on the propulsive force. An increase in the maximum body roll leads to an increase in the propulsive effect of the affected limb, with a substantial effect when the arm angular position exceeds $70^\circ$. The propulsive forces reach maxima when the arm is at approximately $30^\circ$ and $110^\circ$, corresponding to the time $t = 0.32 \text{ s}$ (44% of the arm stroke) and $0.5 \text{ s}$ (69% of the arm stroke), respectively. Table 1 summarises the increase in arm propulsion that is attributed to the body roll movement. Mean hydrodynamic forces, calculated from the start of the downstroke to arm exit, increased approximately 51% and 73%, for the $30^\circ$ and $45^\circ$ body roll simulations, respectively, relatively to the forces obtained in the no body roll condition.

4.1.2. Effect of arm rotation speed on propulsive forces
As in the previous simulations, a body roll movement of $0^\circ$, $30^\circ$ and $45^\circ$ was used alongside an average swimming speed of $1.06 \text{ m/s}$. The propulsive force was determined for each case. Fig. 10 illustrates the propulsive forces generated by the upper arm for a body roll amplitude of $0^\circ$, $30^\circ$ and $45^\circ$. It can be seen that, at a constant swimming speed of $1.06 \text{ m/s}$, the maximum propulsive force is doubled when the duration of the pull is reduced by 20% and halved when the pull time is increased by 20%. The fast and slow arm pulls do not have a major impact on the propulsive force for arm extension angles beyond $120^\circ$. The rotation of the trunk, similarly to results of the initial simulations previously reported, has an effective propulsive effect for arm extension angles ranging from approximately 70 to $130^\circ$. In this study, the swimmer model was constrained to travel at a constant velocity. The exact amount of propulsion generated by the pull of the affected arm is directly influenced by the intra-cyclic speed of the body at the moment the

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Fig. 6. Force components produced by the upper arm for the CFD model incorporating no body roll movement and a zero-velocity inlet.

Fig. 7. Dynamic mesh at different times ($\alpha$: arm angular position, $\beta$: body roll angle).
pull starts. The results do not reflect the positive net effect of upper arm observed by Payton and Wilcox (2006) but show the influence of the body roll and the arm rotation speed on the propulsive contribution of this latter.

4.2. Results for swimming speeds ranging from 0.8 m/s to 1.2 m/s

To extend and validate the overall trends previously observed, additional scenarios were tested with different swimming speeds, with a set of simulations involving the same changes in the body roll amplitude and in the arm rotation speed. Figs. 11–13 illustrate the propulsive forces computed for swimming speeds of 0.8, 1.06 and 1.2 m/s. As expected, as the average swimming speed was increased, the affected arm was less able to generate effective propulsion. The main effect is observed during the downsweep part of the pull. For arm extension angles above 100°, the change in the propelling effect is relatively small. Results of these simulations also confirm the overall tendency observed when modifying the body roll amplitude and the stroke period. The body roll movement greatly increases the propulsive contribution from the upper arm, as with an increase in the arm rotation speed. However, some caution should be exercised when considering the practical application of these two findings. Yanai (2003) demonstrated that an increase in stroke frequency results in a diminution of the body roll amplitude. He reported that 40% increase in stroke frequency induced a reduction of 20% in the body roll amplitude. This inverse relationship between stroke rate and body roll magnitude indicates that the potential benefits of increasing arm angular velocity, to enhance propulsion, are likely to be moderated by a reduction in the contribution from body roll.

5. Discussion

The hydrodynamic forces found in this work agree closely with previous CFD tests carried out by Lecrivain et al. (2008). By means of a different arm angular profile they found that the mean resultant and propulsive forces in the propelling phase (from the start of downsweep) equaled 7.9 and 3.6 N, respectively. In the current study, the forces (mean and resultant) were estimated at 8.6 and 3.5 N, respectively. As discussed by Payton and Wilcox (2006), swimmers with a unilateral arm amputation have demonstrated that, in the absence of a forearm and hand, it is possible to use the upper arm to increase swimming speed within the front crawl stroke cycle, but not as effectively as with the complete arm. Therefore, hydrodynamic forces acting on the upper arm should be lower than those acting on the hand. Gourgoulis et al. (2008) derived hand forces of front crawl swimmers from experimental kinematic data. They estimated the mean resultant and propulsive forces at 11.9 ± 2.6 and 8.1 ± 1.4 N, respectively, for competitive female swimmers. Such values substantiate the numerical assessment of the upper arm forces.

The results of this study have implications for competitive arm amputee front crawl swimmers and for those who coach them. The most important message that emerges is that there exists, for any given swimming speed, a minimum angular velocity at which the upper arm must be rotated to generate effective propulsion. Below this velocity, the upper arm will experience a net resistive drag force which will adversely affect swimming performance. If the speed of an amputee swimmer increases, either during the course of a race, or over an extended period of time, as a result of training, the upper arm will contribute less to the swimmer’s propulsion unless the arm’s angular velocity is increased proportionally.

Given that arm amputee front crawl swimmers can experience intra-cyclic speed fluctuations of 35%, relative to their mean speed (Payton and Wilcox, 2006), some consideration must be given as to when the pull of the affected arm should be commenced for optimum. As the highest intra-cyclic swimming speed occurs during the upsweep phase of the intact arm, it could be argued that initiating the downsweep of the affected arm at this time...
would be least effective for generating propulsion. Conversely, if the start of the downsweep was delayed until the intact arm was recovering over the water, or even entering the water, the potential for the affected arm to generate propulsion would be enhanced, as the intra-cyclic speed would be lowest. Further work is needed to verify these speculations.

![Fig. 10. Effect of acceleration and deceleration of the arm motion on propulsive forces.](image1)

![Fig. 11. Effect of average swimming speed on propulsion for the accelerated movement of the arm.](image2)

![Fig. 12. Effect of average swimming speed on propulsion for the original movement of the arm.](image3)

![Fig. 13. Effect of average swimming speed on propulsion for the decelerated movement of the arm.](image4)
6. Conclusions

Complex CFD simulations investigating the influence of two variables (body roll and arm rotation speed) at various mean swimming speeds on the arm propulsion of a front crawl swimmer with a single amputation at elbow level were carried out. The hydrodynamic forces were evaluated throughout the underwater pull phase of the stroke. It was found that the body roll movement contributed greatly to the propulsion of the swimmer's body and that a fast arm pull also increased the propulsive forces produced by the arm. This work also showed that the ability of the upper arm to generate propulsion effectively decreased as the overall speed of the swimmer is increased. The results have demonstrated that CFD can be used effectively to gain some fundamental expertise on swimming strategies and to deliver practical recommendations for amputee swimmers. Improvements on the CFD model such as the addition of an extra degree of freedom (the arm abduction angle) would provide further advances in the maximisation of swimming performance.

Conflict of interest statement

The authors do not have any conflict of interest.

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