Optimizing simulation of deficient limb’s strokes in freestyle for swimmers with unilateral transradial deficiency

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Abstract
The present study focused on freestyle swimming by swimmers with unilateral transradial deficiency. It has not been clarified yet whether the deficient limb should move so as to match the tempo of the intact upper limb, or if it should move as fast as possible to produce thrust by itself. The objective of this study was to solve the theoretically ideal deficient limb’s strokes in freestyle for a swimmer with unilateral transradial deficiency by using the optimizing simulation. The method of the optimizing simulation of arm strokes considering muscle strength characteristics was developed in a previous study. This method was utilized to solve the deficient limbs’ strokes in the present study. Actual swimming by a participant was reproduced by simulation first. Since the resultant swimming speed of the simulation was in the range of the experimental speed, the validity of the simulation was confirmed. Next, optimizing simulations were conducted for the case of maximum shoulder joint torque multiplied by 1.0, 0.85 and 0.72. From these results, a significant increase in the swimming speed was found for the optimized cases. It was also suggested that the contribution by the deficient limb to propulsion can be increased by up to 15% of the intact limb. The optimized stroke was found to have a later timing and faster motion than the original stroke. This motion was realized by the principle that more joint torque can be exhibited in adduction than in flexion when the joint angular velocity was high.

Keywords : Swimming, Optimization, Freestyle, Unilateral transradial deficiency, Physical disability, Sports engineering

1. Introduction
Competitive swimming of persons with physical disabilities is becoming popular in recent years. Swimming has been an official event in the Paralympic Games since the first one held in 1960. At present, many competitive swimmers from all over the world are training seriously in order to enhance their performance. In the training and coaching of swimmers with physical disabilities, however, there is little specialized knowledge for physical disabilities. Therefore, swimmers with physical disabilities and their coaches generally have to consider the swimming motion appropriate for their own physical disability through trial and error.

The present study focused on freestyle swimming by swimmers with unilateral transradial deficiency (or amputation). The swimming motion in freestyle with unilateral transradial deficiency is basically not much different from an abled swimmer’s motion. The intact lower limbs perform a flutter kick and the intact upper limb (non-deficient side) also performs a normal stroke. However, there is no established technique for the underwater stroke by the deficient limb. Since there is no hand and the forearm is often very short for the deficient limb, basically only the motion of the upper arm has to be considered. However, it has not been clarified yet whether the deficient limb should move so as to match the tempo of the intact upper limb (not to disturb the intact upper limb’ motion), or if it should move as fast as possible to produce thrust by itself. Indeed, it has not been fully clarified how much thrust the deficient limb can produce for propulsion. There are few previous studies about swimming with unilateral transradial deficiency from a biomechanical...
viewpoint. For example, Osbornough et al. investigated the relationships between the stroke parameters in freestyle for competitive unilateral amputee swimmers (Osbornough et al., 2009), and also investigated the effect of swimming speed on inter-arm coordination as well as leg-to-arm coordination (Osbornough et al., 2010, 2015). Figueiredo et al. (2014) conducted biophysical characterization of a swimmer with unilateral amputation. Lecrivain et al. (2008) constructed a CFD (computational fluid dynamics) model for a swimmer with a lower arm amputation, and investigated the forces generated by the upper arm. Lecrivain et al. (2010) further investigated the effect of body roll and arm rotation speed on propulsive force. Although these previous studies are pioneering works indeed, more biomechanical studies need to be done to answer the above-mentioned questions.

In order to investigate how the upper limb should theoretically move underwater, the method of optimizing simulation of arm stroke considering muscle strength characteristics was developed by Nakashima et al. (2012). By utilizing this method, they investigated the optimal arm stroke for abled swimmers. Nakashima and Ono (2014) further investigated the maximum joint torque dependency of the optimized arm stroke. In addition, an optimizing simulation for swimmers with hemiplegia was recently conducted, and it was found that the optimized stroke effectively utilized the joint torque at the shoulder and elbow to the maximum extent, by selecting more natural positions and a slower stroke cycle (Nakashima et al., 2018). In the present study, this method was utilized to solve the deficient limbs’ strokes. The objective of this study was to solve the theoretically ideal deficient limb’s strokes in freestyle for a swimmer with unilateral transradial deficiency by using the optimizing simulation. This paper is organized as follows. The method of optimizing simulation is described in § 2. The results are shown and discussed in § 3. The conclusions and suggestions obtained in this study are summarized in § 4.

2. Method of Optimizing Simulation

2.1. Outline of the swimming human simulation model SWUM

In order to evaluate the arm strokes in the optimizing calculation, the swimming human simulation model SWUM (Nakashima et al., 2007) was employed. SWUM was designed to solve the six degrees-of-freedom absolute movement of the whole swimmer’s body as a single rigid body by time integration using the inputs of the swimmer’s body geometry and relative joint motion. The swimming speed, roll, pitch and yaw motions, propulsive efficiency, joint torques and so on, are computed as the output data. The swimmer’s body is represented by a series of 21 rigid body segments as follows: lower waist, upper waist, lower chest, upper chest, shoulders, neck, head, upper hip, lower hip, thighs (right and left), shanks (right and left), feet (right and left), upper arms (right and left), forearms (right and left) and hands (right and left). Each body segment is represented by a truncated elliptic cone. The unsteady fluid force and gravitational force are taken into account as external forces acting on the whole body. The unsteady fluid force is assumed to be the sum of the inertial force due to the added mass of the fluid, normal and tangential drag forces and buoyancy. These components are assumed to be computable, without solving the flow, from the local position, velocity, acceleration, direction, angular velocity, and angular acceleration for each part of the human body at each time step. The coefficients in this fluid force model were identified using the results of an experiment with a limb model and measurements of the drag acting on swimmers taking a glide position in the previous studies (Nakashima et al., 2007). As a result of the identification, the fluid force model was found to have satisfactory performance. Many other studies by SWUM, including its validation and application, have been already conducted to date (Nakashima, 2007, Nakashima, 2009, Kiuchi et al., 2010, Nakashima et al., 2010a, Nakashima et al., 2010b, Nakashima, 2010, Nakashima et al., 2013, Nakashima et al., 2018, Nakashima et al., 2019).

2.2. Design variables and objective function

In SWUM, the input swimming motion in one stroke cycle is represented as the time histories of the joint angle. In this study, one stroke was divided into 12 time frames for the upper limbs and 18 for the lower limbs. As the design variables, the joint angles in the five time frames, in which the deficient arm was performing an underwater stroke, were used. This is schematically shown in Fig. 1. The joint angles of three time frames (No. 1–5, in the figure), in which the deficient arm was underwater, were used for the design variables in the optimization. The joint angles between each of the two frames are automatically interpolated using the Spline function. The deficient arm motion was represented by three degrees-of-freedom (DOF) at the shoulder, that is, horizontal flexion/extension, adduction/abduction and internal/external rotation. As a result, the three joint angles at five time frames, in which the arm is underwater, were...
chosen as the design variables. The total number of design variables was 15 (3 DOF × 5 time frames). Note that the elbow joint was not moved (fixed) in the present study since the forearm is often too short to consider in the case of unilateral transradial deficiency.

The objective function in the present study was the swimming speed, which was defined as the one averaged in a stroke cycle.

2.3. Optimizing method

In order to obtain the optimal solution as globally as possible within a reasonable computation time, two-step optimization was employed in this study. In the first step, a simple random search was used for global searching. In this search, 10,000 randomly generated arm strokes were evaluated and the best 20 were employed for the initial candidates of the second step. In the second step, the PSO (Particle Swarm Optimization) algorithm (Kennedy and Eberhart, 1995) was used for fine searching.

2.4. Constraint conditions

In the present study, two constraint conditions were imposed on the optimizing calculation. The first one was related to the adduction angle of the shoulder joint. In the present simulation model, a stroke was basically represented by adduction and abduction at the shoulder joint. In addition, horizontal flexion at the shoulder joint was added to the adduction for underwater stroke, while horizontal extension was added to the abduction for recovery stroke. In such representation, the adduction angle is considered to monotonously increase (the arm moves from the head side to the leg side) during the underwater stroke. Therefore, when the three adduction angles for the five time frames were output from the optimizing algorithm, the order of these joint angles were rearranged so that the adduction angles monotonically increased. This constraint enabled the exclusion of arm strokes that could not be candidates of the optimized solution, such as strokes in which the arm moves back from the leg side to the head side.

The second constraint was related to the maximum joint torque characteristics of the swimmer. The details are described in the next subsection.

2.5. Maximum joint torque characteristics

Since the maximum joint torques are affected by the joint angles and angular velocities, they are not constant in the swimming stroke. Therefore, they were investigated and incorporated into the optimizing calculation in the present study as follows.

To begin with, an experiment using abled participants was conducted in order to experimentally acquire the maximum joint torques for various joint angles and angular velocities. The acquired experimental characteristics, however, were not sufficient for the optimization since the data were obtained only in limited experimental conditions. There were actually numerous combinations of angles and angular velocities of shoulder joints during the swimming stroke. In order...
to solve this problem, a musculoskeletal simulation in which the muscle activations were obtained for numerous combinations of joint angles, angular velocities, and torques was carried out. By using the information obtained in this simulation, it was enabled to calculate the maximum joint torque when a certain muscle was fully activated. Before the simulation, the musculoskeletal model had to be able to reproduce the experimental results. Therefore, the muscle parameters in the constructed musculoskeletal model were adjusted so that the simulation could reproduce the experimental characteristics. The details are described in the reference (Nakashima et al. 2012).

Using the adjusted muscle parameters, the maximum joint torques for various combinations of the angles and angular velocities of the shoulder joint were calculated by the simulation. The results were stored in the computer as a database, which was referred to in the optimizing calculation. The reason for constructing the database was that the musculoskeletal simulation took too much computation time to be directly incorporated into the optimizing iteration. In the optimizing calculation, the maximum joint torques were calculated at each time step in SWUM by the interpolation of the database values. If a joint torque during swimming calculated by SWUM exceeded the maximum joint torque, a penalty term was added to the objective function so that the resultant objective function was reduced.

As described above, the maximum joint torque characteristics in the present study were based on an experiment with abled participants. This was done based on the assumption that a swimmer with unilateral transradial deficiency has the same maximum joint torque characteristics on the deficient limb. Indeed, there is room for discussion on this assumption. It is possible that the shoulder of a deficient limb has different maximum joint torque characteristics from those of abled participants. However, it is out of the scope of the present study to investigate the maximum joint torque characteristics for swimmers with unilateral transradial deficiency. Instead, additional optimizing calculations were conducted in the present study for several different maximum joint torques, as described later.

2.6. Experiment to acquire input data for simulation

In order to acquire the body geometry and joint motion of a swimmer with hemiplegia, an experiment was conducted. One male national class swimmer with unilateral transradial deficiency (year: 24, height: 1.76 m) participated in the experiment. The swimming motion of the participant was filmed by four synchronized cameras (WPN-M43SF, ELMO Co., Ltd., Nagoya). The camera arrangement is shown in Fig. 2. Two cameras were placed for the underwater side views and one for the underwater front view. One camera was placed on land for the motion above the water surface. The participant was asked to swim with full strength for the filming area, whose length was 10 m. In addition to filming the swimming motion, the entire body of the participant was filmed by a still camera from several viewpoints. This experiment was approved by the Ethics Committee of the University of Tsukuba. The procedure was fully explained to the participant in advance, and the written consent of the participant was obtained before the experiment.

From the still images taken of the entire body, the body geometry of the simulation model was firstly determined. The stroke cycle, which is defined as the time for one cycle of the swimming motion, was 1.20 s in the experiment. This one stroke was divided into 12 time frames for the upper limbs and 18 for the lower limbs in the simulation model. For each time frame, the joint angles as the relative body motion were next determined using the filmed swimming motions of the participant. An operator compared the filmed body positions with those in the simulation model on the computer.

Fig. 2 Experimental setup to film the swimming motion of a participant.
screen, and adjusted the joint angles in the simulation model so that both positions became consistent with each other. Examples of the filmed images by the four cameras at one time frame are shown in Fig. 3. The joint angles between time frames were automatically interpolated using the Spline function. Using these input data, a simulation reproducing the experiment was conducted. Twenty cycles were calculated to sufficiently eliminate the effect of initial conditions. The animation images of the simulation are shown in Fig. 4. The red lines emitted from the swimmer’s body represent the directions, magnitudes and points of application of the fluid forces acting on the swimmer’s body. The swimming speed averaged for one stroke in the simulation was 1.70 m/s, while that in the experiment was 1.695 ± 0.015 m/s. Since the swimming speed of the simulation was in the range of the experimental speed, the validity of the simulation was confirmed.

2.7. Analysis conditions

In the optimizing simulations, the stroke cycle was fixed to 1.20 s, which was the same as that in the experiment. In each trial of the optimizing simulation, the swimming movement for five stroke cycles was calculated in order to eliminate the effect of initial condition. The average of the swimming speed for the fourth and fifth cycles was used for the objective function.
The results of swimming speed for the optimizing simulations are shown in Fig. 6. Compared with the actual swimmer’s stroke, significant increases were found for the optimized strokes, even in the case of ULV_0.72. Indeed, the increase from 1.70 m/s to 1.78 m/s corresponds to the time reduction of 2.6 s in a 100 m race. The strokes for the actual
swimmer’s and optimized cases are shown in Fig. 7. It was found that the upper arm became almost vertical at \( t^* = 4.88 \) in the actual swimmer’s stroke, while the upper arm became almost vertical at \( t^* = 4.92 \) in the optimized stroke. It means that the timing of the optimized stroke was later than that of the actual swimmer’s stroke. In addition, although the timing of the optimized stroke was later, the upper arms for both cases took almost the same angle at \( t^* = 4.96 \) s. It means that the deficient limb moved faster in the optimized stroke. In order to examine these tendencies more quantitatively, the time history of the adduction angle, which basically corresponds to the stroke motion, was investigated. The results are shown in Fig. 8. In Fig. 8(a), the adduction angles of the actual swimmer’s stroke, optimized case of ULV_1, and its control points in the optimizing calculation are plotted. From this figure, it was confirmed that the arm stroke started later and stroke itself is faster for the optimized case than the actual swimmer’s stroke. Similar tendencies can be seen in Fig. 8(b) for the other optimized cases (ULV_0.85 and ULV_0.72) as well.

Time averaged thrust by both intact and deficient limbs are shown in Table 1. It was found that the contribution to propulsion of the deficient limb in the actual swimmer’s stroke was only 4.7%, compared to the intact limb. However, the contribution significantly increased in the optimized strokes. The contribution reached over 25% for ULV1. Even for ULV_0.72, it was over 15%. These results suggest that the deficient limb can certainly contribute to propulsion.
Shoulder joint torques during underwater strokes for the optimized cases are shown in Fig. 9. It was found that all the calculated shoulder joint torques reached the corresponding upper limit values around $t^* = 4.9$. This means that the underwater strokes in the optimized cases were performed with the maximum shoulder joint torques for the swimmer. However, it was also found from the figure that the peak shoulder joint torques reached 130 Nm, 110 Nm and 90 Nm for the cases of ULV_1, ULV_0.85 and ULV_0.72, respectively. These values were much higher than 50 Nm, which is the peak shoulder joint torque in Fig. 5, that is, in the case of the actual swimmer’s stroke. This difference was caused by the difference in joint angle. The front views of the swimmer at $t^* = 4.92$ and 4.96 are shown in Fig. 10. From this figure, it was found that the actual swimmer’s stroke was close to the flexing motion at the shoulder, while the optimized stroke was relatively close to the adducting motion. The difference between the flexion and adduction as well as the muscle joint torque characteristics investigated in the previous study are schematically shown in Fig. 11. From this figure, it was found that the maximum joint torque significantly decreases according to the increase in the joint angular velocity for the flexion, as shown in Fig. 11(a) (from the black line to red line, the pale pink arrow). However, the decrease is much smaller for the adduction, as shown in Fig. 11(b). This suggests that more joint torque can be exhibited in the adduction.

Table 1 Simulation results of time-averaged thrust by intact and deficient limbs. The ratio of the thrust by deficient limb divided by that by intact limb is also shown.

<table>
<thead>
<tr>
<th></th>
<th>Thrust by intact limb [N]</th>
<th>Thrust by deficient limb [N]</th>
<th>Ratio (deficient/intact) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual swimmer</td>
<td>37.95</td>
<td>1.78</td>
<td>4.7</td>
</tr>
<tr>
<td>Optimized (ULV_1)</td>
<td>36.80</td>
<td>9.42</td>
<td>25.6</td>
</tr>
<tr>
<td>Optimized (ULV_0.85)</td>
<td>37.64</td>
<td>7.03</td>
<td>18.7</td>
</tr>
<tr>
<td>Optimized (ULV_0.72)</td>
<td>37.75</td>
<td>6.13</td>
<td>16.2</td>
</tr>
</tbody>
</table>

Fig. 9 Shoulder joint torque during underwater stroke. The black lines represent the calculated shoulder joint torque for the optimized strokes. The colored lines represent the upper limit values as the constraints in the optimizing calculations. These joint torques were calculated as composed values of three components of the joint torques about three axes in three-dimensional space, that is, as the absolute lengths of the torque vectors in three-dimensional space.

Fig. 10 Front views of the swimmer.
than in the flexion when the joint angular velocity is high. Indeed, the calculated maximum angular velocities of the shoulder joint were 773 deg/s for the actual swimmer’s stroke and 1177 deg/s for ULV_1, respectively. However, for such high angular velocity, the maximum joint torque characteristics, which were built in the previous study, have not been fully validated yet. Therefore, further investigation about this issue will be an important future task.

4. Conclusion

In the present study, the optimizing simulation of deficient limb’s strokes in freestyle for swimmers with unilateral transradial deficiency was conducted. Actual swimming by a participant was reproduced by simulation first. Since the resultant swimming speed of the simulation was in the range of the experimental speed, the validity of the simulation was confirmed. Next, the optimizing simulations were conducted for the case of maximum shoulder joint torque multiplied by 1.0, 0.85 and 0.72. From these results, a significant increase in the swimming speed was found for the optimized cases. It was also suggested that the contribution by the deficient limb to the propulsion can be increased by up to 15% of the intact limb. The optimized stroke was found to have later timing and faster motion than the original stroke. This motion was realized by the principle that the more joint torque can be exhibited in adduction than in flexion when the joint angular velocity was high.

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