Effect of knee joint motion for the transfemoral prosthesis in swimming

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Abstract
The objective of this study was to investigate the effect of knee joint motion on swimming performance for a transfemoral prosthesis in swimming. A flat spring at the knee joint was introduced into a prosthesis which had already been developed, in order to enable the knee joint to move according to the fluid force acting on the lower limb. A swimming experiment, in which a subject using the prosthesis swam in a pool, was conducted. Five types of flat spring for the knee joint were prepared for the experiment. From the experiment, it was found that there was a proper stiffness of the flat spring from which the subject felt comfortable during swimming. Next, simulations for the flutter kick and crawl stroke were conducted. The validity of the simulation method was confirmed since the simulated joint angles in the simulation of the flutter kick were sufficiently consistent with the experimental ones in respect to the amplitudes and phases for both the knee and ankle. During the simulation of the crawl stroke, it was found that the amplitude of the hip joint torque on the prosthetic leg compared to the healthy leg increased according to the increase in the stiffness of the knee joint. Since this amount was considered to directly correspond with the ‘reaction during kick’ in the VAS evaluation of the experiment, in which the subject evaluated the stiffer knee flat spring as ‘heavier’, the consistency of the tendencies between the simulation and experiment was confirmed. From the simulation results, it was also suggested that the subject in the experiment preferred stiffness at the knee joint which minimized the difference between the amplitude of the hip joint torque on the healthy leg and that on the prosthetic leg.

Key words: Swimming, Prosthesis, Welfare engineering, Sports engineering, Biomechanics

1. Introduction
For people with disabilities, recreational activities such as sports are important for improving the quality of life (QOL) from physical, mental and social aspects (Crawford et al., 2008, Macko et al., 2008, Sporner et al. 2009, Groff et al., 2009, Annesen et al., 2010). Among sports for disabled persons, swimming is widely accepted, especially by persons with lower limb amputations (Kegel et al., 1977, Kegel et al., 1980). One possible reason for this is that persons with lower limb amputation can be released from gravity, which burdens them heavily in their daily life. Another possible reason is that they can start swimming relatively easily compared to other sports because of the many opportunities to observe and participate. Indeed, swimming is a sport suitable for rehabilitation since it is an effectively aerobic and full body exercise. From these backgrounds, swimming is becoming more popular as a sport and rehabilitation for the health enhancement of persons with lower limb amputations.

Persons with lower limb amputations usually swim without their prosthesis (Fergason & Harsch, 2009, Krebs et al. 1991). However, several problems related to swimming without the prosthesis have been pointed out by actual persons with lower limb amputations. For example, balance during swimming is not good (Saadah, 1992), the amputated part is
exposed to other people (Couture et al., 2010, Sjodahl et al., 2004), and movement on land is difficult and accompanied by the danger of falling (Saadah, 1992). In order to solve these problems, a prosthesis for swimming is thought necessary (Kegel et al., 1977). Few developments for the prosthesis for swimming have already been reported. Hashizume (1991) and Betto et al. (1998) developed a transtibial prosthesis for swimming. This prosthesis had an appearance sufficiently similar to a real foot, and walking on land was possible. Colombo et al. (2011) designed a similar prosthesis for swimming and walking. However, the ankles of these prostheses were fixed at the plantar-flexed position during swimming. During the actual flutter kick, the feet should take the plantar-flexed position during the downbeat (in the direction of hip flexion) in order to obtain the thrust. However, during the upbeat (in the direction of hip extension), the feet should not take the plantar-flexed position but should hang loosely from the ankles so that they do not prevent propulsion (Maglischo, 2003). Therefore, in order to realize comfortable swimming, an ankle joint which provides appropriate foot motion is necessary. Saadah (1992) developed a prosthetic fin for persons with transtibial amputation. Although this fin had excellent functionality in which the rigidity of the fin was adjustable, it did not aim to reproduce the appearance of the real foot, and walking on land was difficult.

In order to solve the above-mentioned problems, a prototype of transfemoral prosthesis for swimming was developed by Nakashima et al. (2013). This prosthesis had (i) an ankle joint which provided appropriate foot motion, (ii) the capability of walking by the poolside, (iii) and a foot with an appearance sufficiently similar to an actual one. By an experiment and simulation, it was confirmed that the prosthetic ankle joint moved properly when appropriate spring stiffness was used for the ankle joint. However, the knee joint was fixed at the extended position in that study.

The objective of this study was to investigate the effect of the knee joint motion on swimming performance for the transfemoral prosthesis in swimming. A flat spring at the knee joint was newly introduced into the prosthesis which was previously developed by Nakashima et al. (2013), in order to enable the knee joint to move according to the fluid force acting on the lower limb.

The transfemoral prosthesis used in the present study is explained in § 2. The swimming experiment using the prosthesis is shown in § 3. The simulation to confirm the general validity of the tendencies in the experiment is described in § 4. The main findings obtained in this study are summarized in § 5.

2. Transfemoral prosthesis for swimming

An overall view of the transfemoral prosthesis used in the present study is shown in Fig. 1. It consists of the thigh (socket part), knee joint, shank, ankle joint, and foot. The type of socket was a silicone liner-type with a pin lock system (Iceross® transfemoral, Össur) and the outer thermoplastic socket was partially reinforced with carbon fiber. A schematic view and a photograph of the knee joint are shown in Fig. 2 (a) and (b), respectively. It simply consists of two pyramid adapters and a flat spring, which passively bends according to the external torque acting on the joint. The stiffness of this passive joint can be easily adjusted by changing the thickness of the flat spring. For the shank part, a standard endoskeletal prosthesis was used. With respect to the ankle joint, it has an extension spring at the front part of the ankle joint. When no load is applied to the foot, the ankle joint becomes fully dorsi-flexed, as shown in Fig. 3(a). When the fluid force is applied to the foot during the ‘down’ flutter kick (in the direction of hip flexion), it becomes fully plantar-flexed, as shown in Fig. 3(b). Therefore, the toe never disturbs the ability to walk on land since it keeps the dorsi-flexed position. In the water, on the other hand, the foot can automatically take the plantar-flexed position during swimming. Due to this simple, but effective structure, the user does not need any extra procedure, such as exchanging the foot part, when he/she goes into/out of the water. Note that the ankle joint has two stoppers so that the

Fig. 1 Overall view of the transfemoral prosthesis used in the present study.
foot does not flex more than the fully dorsi-flexed and plantar-flexed positions shown in Fig. 3, that is, the range of motion of the ankle joint was limited between those two positions. The foot is made of silicone resin. The total mass of the prosthesis was 3.2 kg.

3. Swimming experiment using the prosthesis

3.1 Methods

In the experiment, a subject swam with the transfemoral prosthesis attached. The subject was a person with an acquired one-sided transfemoral amputation (male, 46 years old, height: 1.73m and weight: 75kg). He swims frequently and is an experienced swimmer. Before the experiments, the objective and method of the experiments were fully explained to the subject, and his written and oral consent to the experiments was obtained. The experiments were approved by the ethics committee of the Tokyo Institute of Technology. In addition, the experiments were conducted in the presence of a prosthetist. The subject set the liner on the residual limb, and the liner was fixed to the socket of the prosthesis with the pin attached in the end of the liner. The thigh support bandage was used as an adjunct to keep the prosthesis fixed when swimming.

Five types of flat spring for the knee joint were prepared for the experiment, as shown in Table 1. Type A was the softest case in which the thinnest flat spring was used. For Type B, C and D, progressively thicker (stiffer) flat springs were used. Type E was the fixed (rigid) condition, in which two flat springs were fixed with a space in order to avoid bending, as shown in Fig. 2(c). Note that the five types were divided into three groups (soft, intermediate, stiff) for later discussion, as shown in Table 1.

Two kinds of experiments were conducted in the present study. First, the subject performed the flutter kick for 10 seconds holding onto the side wall of the pool. The motion of the subject was recorded by an underwater video camera from the side. The joint angles were computed assuming that the motion was in the sagittal plane. For this purpose, markers were attached to the subject and the prosthesis, as shown in Fig. 4. The attaching positions were at the waist, great trochanter (hip joint), knee joint, ankle joint and toe on each leg.

Second, the subject swam 25m using the front crawl stroke twice. The time records for 25m were carefully
measured. Note that the subject was asked to swim with a constant effort as best as possible.

In addition to those video and time recordings, questionnaires about comfort during swimming were asked using the VAS (Visual Analogue Scale) for evaluation, just after the flutter kick as well as the front crawl swimming. For the flutter kick, ‘reaction during kick’, ‘balance between legs’ and ‘ease of performing the six beat kick’ were asked in terms of absolute evaluations. During the evaluation of ‘reaction during kick’, a score of ‘good’ was 50 (center of the scale), ‘too heavy’ was 100 (right end of the scale), and ‘too light’ was 0 (left end of the scale). During the evaluations of the other two, a score of ‘good’ was 100 (right end of the scale) and a score of ‘bad’ was 0 (left end of the scale). For the front crawl, ‘a feeling of propulsion during kick’ was additionally asked as a relative evaluation. In this evaluation, ‘the same as the case without the prosthesis’ was 50 (center of the scale), ‘better’ was 100 (right end of the scale), and ‘worse’ was 0 (left end of the scale).

### 3.2 Results and discussion

The results of the questionnaires about comfort during swimming are shown in Figs. 5 and 6. The results of the flutter kick are shown in Fig. 5, and those of the front crawl are in Fig. 6. With respect to the reaction during kick shown in Fig. 5(a), it was found that Types B and C (the intermediate group) were right for the subject, while Type A (soft) was too light and Types D and E (stiff group) were too heavy. With respect to the balance between legs and ease of performing the six beat kick as shown in Fig. 5(b) and (c), it was found that Types B and C were very good, while Types D and E were somewhat worse than Types B and C, and Type A was very bad. From Fig. 6(a), (b) and (c), it was found that the results for crawl swimming were almost the same as those for the flutter kick, although Types D and E in Fig. 6(b) and (c) became worse than those in Fig. 5(b) and (c). With respect to the feeling of propulsion during kick as shown in Fig. 6(d), Types B and C performed better than swimming without prosthesis, while Types A, D and E were
all worse. To summarize all these results, the scores for Types B and C (intermediate) were the highest, Types D and E (stiff) came next, and Type A (soft) was the lowest. Therefore, it can be concluded that there was a proper stiffness of the flat spring in which the subject felt comfortable during swimming, and stiffer and softer springs resulted in worse results.

The results of the time records for the 25m front crawl test were shown in Table 2. The average swimming speeds were also shown in the table, which were simply calculated as the length that was swum (25m) divided by the time recorded. Similar to the questionnaires, Types B and C (intermediate) brought the fastest swimming speeds, while Types D and E (stiff) brought slightly worse results, and Type A brought all-around the worst.

The images captured by an underwater camera for the experiment of the flutter kick (Type C as an example) are shown in Fig. 7. From these images, the joint angles were calculated. The results of the joint angles are shown in Fig. 8. In this figure, the positive direction corresponds to the dorsi-flexion for the ankle joint, the extension for the knee joint, and the flexion for the hip joint, respectively. From the curves of the joint angles, the amplitudes of the knee joint were calculated. The results are shown in Table 3. It was confirmed that the amplitudes became smaller when the flat spring for the knee joint became stiffer. Note that the amplitude in Type E (fixed condition) was too small to measure.

4. Simulation to confirm general validity of the tendencies in the experiment

4.1 Objective of simulation

From the experiment in the previous section, it was found that swimming performance as well as the evaluation by
the subject depended on the stiffness of the flat spring at the knee joint, and that there was a proper stiffness where those were maximized. However, it was difficult to prove the validity of those tendencies in the experiment statistically since it was difficult to recruit many subjects for the experiment. Therefore, in this study, the general validity of the tendencies in the experiment was examined by simulation.

### 4.2 Simulation method

For the simulation, the swimming human simulation model SWUM was employed. SWUM was developed for the mechanical analysis of human swimming (Nakashima et al., 2007). In SWUM, the swimmer’s body is represented as a series of 21 truncated elliptic cones. The fluid forces acting on the swimmer are assumed to be computable from the local motion of the swimmer’s body. By inputting body geometry and joint motion, the equations of motion of the swimmer as one rigid body are solved through the means of a time-marching method. As a result, the user can obtain data on the fluid forces acting on the swimmer and characteristics of the resultant swimming movement, such as

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**Table 3** Amplitudes of knee joint (peak-to-peak value).

<table>
<thead>
<tr>
<th>Type</th>
<th>Amplitude [degree]</th>
</tr>
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<tbody>
<tr>
<td>Type A</td>
<td>58.2</td>
</tr>
<tr>
<td>Type B</td>
<td>41.7</td>
</tr>
<tr>
<td>Type C</td>
<td>41.7</td>
</tr>
<tr>
<td>Type D</td>
<td>21.5</td>
</tr>
<tr>
<td>Type E</td>
<td>N/A</td>
</tr>
</tbody>
</table>

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Fig. 7 Images captured by an underwater camera for the experiment of the flutter kick (Type C as an example).

Fig. 8 Joint angles for the experiment of the flutter kick (Type C).

For the simulation in the present study, SWUM was extended to be able to calculate the swimmer’s performance with the prosthesis. The schematic of the simulation model is shown in Fig. 9. The prosthetic shank and foot parts were modeled as two rigid bodies, respectively. They were connected to the swimmer by virtual springs and dampers, as schematically shown in Fig. 10. Since this connection restricted only the relative translational movement at the connecting point, it enabled free rotation at the knee and ankle joints. The stiffness of the virtual springs was determined as being an adequately large value so that the relative displacement between the two parts at the connecting point became sufficiently small.

In addition to this connection, the flat spring at the knee joint of the actual prosthesis was represented as a simple rotational spring whose restoring moment was proportional to the knee joint angle $\theta_k$ shown in Fig. 11(a). The
extension spring at the ankle joint was represented in the simulation model as well. The actual geometrical relationship between the ankle joint and both ends of the spring, which is shown in Fig. 11(b), was reproduced in the model. In order to reproduce the stopper as it is in the actual prosthesis, spring stiffness was assumed to become sufficiently large when the angle of the ankle joint exceeded the range of motion.

4.3 Simulation of the flutter kick for validation

4.3.1 Analysis conditions

In order to examine the validity of the simulation method, a simulation of the flutter kick was carried out. The body geometry in the model was adjusted to match the subject’s. The hip joint motion and the stroke cycle measured in the experiment were put into the model. The absolute movement of the swimmer was not solved by the time-marching method, but instead given as an input, since the swimmer did not propel in the experiment. Among the six degrees-of-freedom of the absolute movements of the swimmer, translational movements in the three directions were assumed to be zero and rotational movements in two directions aside from the roll movement were assumed to be zero as well. For the roll movement, the roll angle measured in the experiment was input into the simulation using an approximated sine curve. Since motion of the upper limbs was unnecessary for this simulation, the upper limbs were fixed in a straight-stretched position. Three stroke cycles were simulated in order to eliminate the effects of the initial condition.

4.3.2 Results and discussion

The swimming motion of the flutter kick in the case of Type C (intermediate) is shown in Fig. 12. In this figure, time \( t \) is the non-dimensional time normalized by the stroke cycle. The prosthetic foot and shank are shown in green and pale blue, respectively. From the figure, it can be seen that the prosthetic foot moves from the dorsi-flexed position to the plantar-flexed position, and vice versa. It was also found that the prosthetic knee joint bends both in the

![Fig. 12  Swimming motion of the flutter kick (Type C).](image-url)
directions of flexion and extension. The results of the simulation for the knee and ankle joint angles of the amputated side are shown in Fig. 13. The simulated values are represented by dashed lines while the experimental values are represented by solid lines. It is noted that the simulated values were not the values put into the simulation, but the ones obtained as outputs of the calculation. From the figure, it was found that the simulated joint angles were sufficiently consistent with the experimental ones in respect to the amplitudes and phases both for the knee and ankle. Similar tendencies were obtained for other cases as well. Therefore, the validity of the proposed simulation method was confirmed.

4.4 Simulation of crawl stroke

4.4.1 Analysis conditions

In order to examine the general validity of the tendencies observed in the experiment, a simulation of the crawl stroke was carried out. In this simulation, a body geometry using average values for 20-29 year-old Japanese males, as well as the standard crawl stroke motion used in the previous studies (Nakashima et al., 2007, Nakashima, 2007a) were put into the model. The stroke cycle in the simulation was determined as 1.6 s based on the actual values found in the experiment. The absolute movement of the swimmer for six degrees-of-freedom was fully solved by the time-marching method in this simulation. Five stroke cycles were simulated in order to eliminate the effect of the initial condition.

4.4.2 Results and discussion

The swimming motion of the crawl stroke in the case of Type C (intermediate) is shown in Fig. 14. In this figure, time $t$ is the non-dimensional time normalized by the stroke cycle, and the period of one kick (about one third of one entire stroke) is shown. It was found that the prosthetic ankle and knee joints worked well also in the crawl stroke. In order to examine the consistency between the simulation and experiment, ‘reaction during kick’ in VAS was focused on. The reaction during the kick was considered to correspond with the hip joint torque. Therefore, the hip joint torques for all cases were calculated in the simulation. Two examples were the hip joint torques in the cases of Type C (intermediate) and Type A (soft) for one stroke cycle as shown in Fig. 15. It was found that the amplitude (peak-to-peak value) of the joint torque on the prosthetic leg (the right leg) for Type A became significantly smaller than that for Type C, although the amplitude on the healthy leg (the left leg) for both types were almost the same. The differences between the amplitude of the hip joint torque on the healthy leg and that on the prosthetic leg are shown in Table 4. These values were calculated by subtracting the amplitude on the healthy leg from that on the prosthetic leg. It was found that the difference increased from Type A to Type E according to the increase in the stiffness of the knee joint. This amount was considered to directly correspond with the ‘reaction during kick’ in the VAS evaluation of the experiment, in which the subject evaluated the stiffer knee flat spring as being ‘heavier’. Therefore, consistency of the tendencies in the simulation and experiment was confirmed. In addition, the absolute value of the difference became minimal for intermediate stiffness of the knee joint (6.5 Nm for Type B and 3.9 Nm for Type C). Since the subject evaluated the intermediate stiffness as the best in the experiment, this simulation result suggested that the subject preferred the stiffness at the knee joint which minimized the difference between the amplitude of the hip joint torque on the healthy leg and that on the prosthetic leg. This preferred stiffness will change according to the subject him/herself, and his/her preferred swimming velocity and swimming forms (especially for the kicking style). Therefore, it is desired that the flat
spring is changeable according to the swimmer’s preference.

5. Conclusions

The effect of knee joint motion on swimming performance for the transfemoral prosthesis in swimming was investigated in the present study. A flat spring at the knee joint was newly introduced into a prosthesis which was...
previously developed, in order to enable the knee joint to move according to the fluid force acting on the lower limb. A swimming experiment, in which a subject wearing the prosthesis swam in a pool, was conducted. In order to confirm the general validity of the tendencies in the experiment, simulations for the flutter kick and crawl stroke were conducted. The findings are summarized as follows:

(1) In the experiment, there was a proper stiffness of the flat spring with which the subject felt most comfortable during swimming. The stiffer and softer springs resulted in worse results.

(2) In the simulation of the flutter kick, the simulated joint angles were sufficiently consistent with the experimental ones in respect to amplitudes and phases for both the knee and ankle. Therefore, the validity of the proposed simulation method was confirmed.

(3) In the simulation of the crawl stroke, it was found that the amplitude of the hip joint torque on the prosthetic leg compared with the healthy leg increased along with the increase in the stiffness of the knee joint. This amount was considered to directly correspond with the ‘reaction during kick’ in the VAS evaluation of the experiment, where the subject evaluated the stiffer knee flat spring as being ‘heavier’. Therefore, consistency of the tendencies in the simulation and experiment was confirmed.

(4) From the simulation results, it was suggested that the subject in the experiment preferred a stiffness at the knee joint which minimized the difference between the amplitude of the hip joint torque on the healthy leg and that on the prosthetic leg.

References


Couture, M., Caron, C.D., and Desrosiers, J., Leisure activities following a lower limb amputation, Disability and Rehabilitation, Vol.32, (2010), pp.57-64.


Table 4 Differences between the amplitude of hip joint torques on the healthy leg and that on the prosthetic leg.

<table>
<thead>
<tr>
<th>Type</th>
<th>Difference [Nm]</th>
<th>Group of stiffness of the knee joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>−44.8</td>
<td>Soft</td>
</tr>
<tr>
<td>Type B</td>
<td>−6.5</td>
<td>Intermediate</td>
</tr>
<tr>
<td>Type C</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>Type D</td>
<td>12.8</td>
<td>Stiff</td>
</tr>
<tr>
<td>Type E</td>
<td>23.4</td>
<td></td>
</tr>
</tbody>
</table>


