DEVELOPMENT OF A FULL-BODY MUSCULO-SKELETAL SIMULATOR FOR SWIMMING

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INTRODUCTION

There have been no studies of the musculo-skeletal analysis for human swimming since the external force acting on the whole body as the input to the musculo-skeletal model was difficult to measure or estimate. The authors have recently developed a simulation model SWUM (SWimming hUman Model) in order to analyze the mechanics of swimming [1]. The analysis of the crawl stroke [1,2] and the other three strokes (breast, back and butterfly strokes) [3] have been already conducted, and their results indicate the validity of SWUM. Since the unsteady fluid force acting on each part of the whole body can be obtained by SWUM, the analysis of the muscle activity during swimming is realized by integrating SWUM and the musculo-skeletal model. Therefore, the objective of this study was to develop a full-body musculo-skeletal simulator by which the muscle activity for the whole body during swimming can be obtained.

METHODS

SWUM

The simulation model SWUM is designed to solve the six degrees-of-freedom absolute movement of the whole human body as one rigid body, using the inputs of the human body geometry and relative joint motion. Therefore, the swimming speed, roll, pitch and yaw motions, propulsive efficiency, joint torques and so on are computed as the output data. As the external forces acting on the whole body, unsteady fluid force which includes buoyancy and gravitational force are taken into account. The unsteady fluid force, which consists of inertial force due to added mass of fluid, normal and tangential drag forces and buoyancy, is assumed to be computable, without solving the flow, from the local position, velocity, acceleration, direction, angular velocity, and angular acceleration at each part of the human body at each time step. In addition, SWUM has been implemented with GUI as a free software "Swumsuit" [4]. Figure 1 shows an example of simulation by SWUM for the crawl stroke. The red lines from each part of the body represent the direction and magnitude of the fluid force.

Musculo-skeletal model (AnyBody Modeling System)

For the musculo-skeletal analysis, the commercial software "AnyBody Modeling System" [5] (AnyBody Technology, Denmark) was employed. In this software, the min/max criterion [6] is used for the objective function to determine the muscle forces. The various body models and analysis examples are available online [7]. The full-body model with 458 muscles was used for the present study.

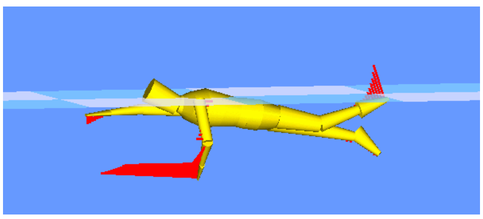

Figure 1: An example of simulation by SWUM (crawl stroke).

Integrating SWUM and AnyBody

Figure 2 shows the whole data flow of the simulator. First, SWUM loads the data of body geometry and joint motion. Then, SWUM outputs the four data categories: body geometry, joint motion, body movement, and fluid force. With respect to the body geometry and joint motion, their definitions in AnyBody are different from those in SWUM. Therefore, these data are converted to the AnyBody format. In the "body movement" data, the time histories of the whole body in six degrees-of-freedom as computed results are described. In the "fluid force" data, the direction and magnitude of the fluid force acting on each part of the whole body are described. These data are also output according to the AnyBody format. In addition, these converting procedures are automatically performed in our software "Swumsuit". Swumsuit outputs the data files of the four categories in AnyScript (programming language used in AnyBody) directly. Therefore, the user does not have to be conscious of the data converting between SWUM and AnyBody at all. The actual operation on Swumsuit will be demonstrated at the symposium.

RESULTS AND DISCUSSION

Figure 3 shows the musculo-skeletal simulation results of the crawl stroke by the developed simulator. The swimming motion was produced based on videos of model swimming by an elite swimmer. The stroke cycle was 1.96s. The swimming speed was 1.18m/s as the computed result by SWUM. The time t in the figure

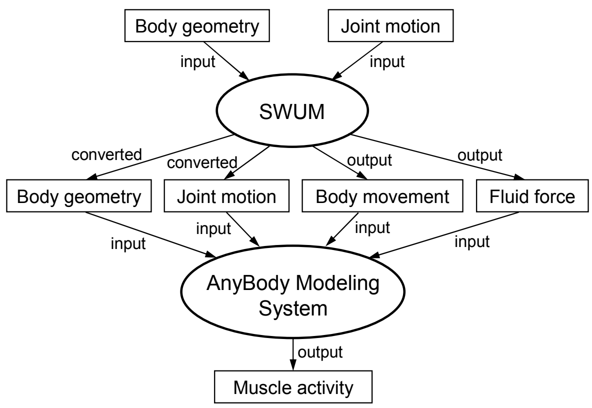

Figure 2: Whole data flow of the musculo-skeletal simulator for swimming.

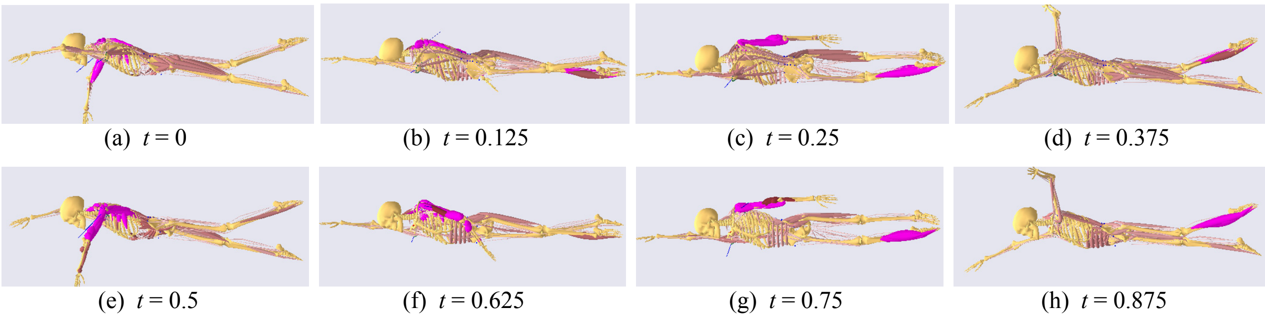

Figure 3: Simulation results of crawl stroke for one stroke cycle. Time t is normalized by the stroke cycle.

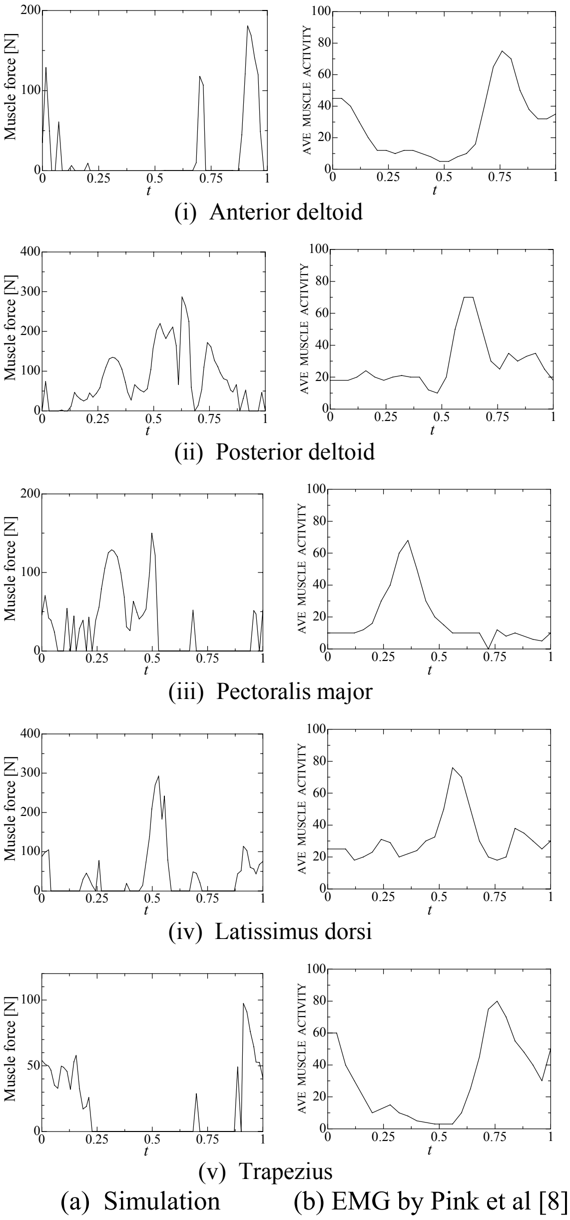

Figure 4: Comparison results between simulated muscle forces and EMG.

is normalized by the stroke cycle, and the moment $t = 0$ corresponds to the left hand entry to the water. The pink thick lines represent muscles with large muscle forces. It is found that the muscles around the left shoulder and upper arm become active when the hand pushes the water ($t = 0.5$, 0.625) and the beginning of the "recovery" phase ($t = 0.75$). With respect to the left lower limb, tibialis anterior is found to become active three times in one stroke cycle ($t = 0.25$, 0.5, 0.875) according to the three flutter kicks.

In order to examine the validity of the simulation in more detail, a comparison between the simulation and EMG was conducted. Pink et al [8] has measured EMG of the muscles around the shoulder of a crawl swimmer. Figure 4 shows the comparison results. From the EMG results, following findings are obtained: (a) Anterior deltoid and Trapezius become active at the beginning of the recovery ($t = 0.75$) and entry ($t = 0$). (b) Posterior deltoid and Latissimus dorsi become active when the hand push the water ($t = 0.5$~0.75). (c) Pectoralis major becomes active when the hand "pulls" the water ($t = 0.25$~0.5). All of them also can be seen in the simulation results, indicating a certain validity of the simulator. However, the swimming motion in the simulation may be different from that in the experiment. In order to discuss more quantitatively, the simultaneous measurement of the swimming motion and EMG will be necessary. The simulation results of breast, back and butterfly strokes will be presented at the symposium.

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