Microcomputer-based Acceleration Sensor Device for Sports Biomechanics
~Stroke Evaluation by using Swimmer’s Wrist Acceleration~

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Abstract
In order to observe underwater stroke motion in swimming, the author developed a tri-axial acceleration data logger and a tri-axial acceleration/angular velocity data logger. Those sensor devices were attached on the wrist joint of the swimmers. The obtained acceleration and angular velocity in swimming were indicated swimmer’s stroke characteristics. In this study, the author applied (1) the discrimination of the stroke phases and (2) the fatigue estimation by the wrist acceleration during intensive interval training.

Keywords
Microcomputer, Acceleration Sensor, Gyroscope, Swimming, Coaching

INTRODUCTION
The swimmer’s propulsive force mostly depends on his stroke motion. Without exceptions, swimmers and coaches are very interested in stroke motion. Needless to say, the most important phase of the swimmer’s stroke is the underwater phase. However, it is difficult to observe the swimmer’s underwater stroke motion in daily training. Although we could prepare an underwater movie camera and take swimmer’s motion, the air bubbles and swimmer’s own motion sometimes prevent us observing swimmers motion. Therefore, a new methodology of swimming stroke monitoring have been expected.

The author had reported that the wrist acceleration of the sports athletes indicates the characteristics of their movement pattern. As for the swimming, the discrimination of the swimming stroke style was enabled by swimmer’s tri-axial wrist acceleration[2, 3]. And we could obtain the stroke cycle time by their wrist acceleration.

The purpose of this study was to develop a microcomputer-based acceleration/angular velocity data logger device for the swimming research and examine an application for the swimming stroke evaluation.

DATA LOGGER SPECIFICATIONS

PROTOTYPE I
Figure 1 shows a tri-axial acceleration data logger (prototype I). On the basis of author’s former research, the swimmer’s tri-axial wrist acceleration was less than 10G (98.0m/s²). Therefore, two ADXL210 (Analog Devices Inc.) were built in the logger device. These two sensor ICs were mounted on the basal plate flatly and perpendicularly. Thus we could measure tri-axes acceleration.

PROTOTYPE II
Figure 2 shows the prototype II. The prototype II could measure the tri-axial acceleration and the tri-axial angular velocity of the swimmer’s wrist joint. For the measurement of the angular velocity, three ENC-03J (Murata Manufacturing Co. Ltd.) were applied. The technical specifications of both loggers, prototype I and prototype II were explained in Table 1. Both loggers were capsulated by alminium alloy cylinder which allowed the loggers with 200m water resistant. The capacities of the acceleration and gyroscope sensor were ±10G and ±1500deg/s respectively.

The data loggers were tightly attached on the distal of the swimmer’s forearm by taping and bandage (Fig.3). Figure 4 shows the coordinate system of the acceleration data logger. The data logger had a trigger start function which enabled the video timer to start simultaneously. Thus synchronization between the data logger and the videography was achieved. After measurement, connecting the
Table 1. Technical specifications of the data loggers

<table>
<thead>
<tr>
<th></th>
<th>Prototype I</th>
<th>Prototype II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>88 × 21 (mm)</td>
<td>141.8 × 23.2 (mm)</td>
</tr>
<tr>
<td>Weight</td>
<td>50g</td>
<td>78g</td>
</tr>
<tr>
<td>Acceleration</td>
<td>ADXL210</td>
<td>ENC-03J</td>
</tr>
<tr>
<td>Gyroscope</td>
<td>←</td>
<td>←</td>
</tr>
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<td>PIC17LC44</td>
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</tr>
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<td>Sampling</td>
<td>~128Hz</td>
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<tr>
<td>Memory</td>
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<td>128Mbit</td>
</tr>
<tr>
<td>Battery</td>
<td>CR1/3N</td>
<td>CR2</td>
</tr>
<tr>
<td>Duration</td>
<td>1.45h</td>
<td>2.9h</td>
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</tbody>
</table>

Figure 2. The photograph of the prototype II

Figure 3. Logger was attached on the swimmer’s left wrist

DISCRIMINATION OF STROKE PHASE
Maglischo defined the stroke phase of the crawl stroke [1]. The entry, stretch, downsweep, insweep, upsweep and recovery were the crawl stroke phases. As for the breaststroke, outswep, insweep and recovery phases were also defined. Firstly, the discrimination of the stroke phase was examined.

The water flume was used for this study. In this experiment, the prototype I was used. The crawl stroke and breaststroke styles were covered in this experiment. A swimming is a cyclic movement. Same acceleration pattern was measured repeatedly in swimming trial. Therefore, only single stroke acceleration was examined. Figure 5 and figure 7 show the tri-axial wrist acceleration of the crawl stroke and breaststroke respectively. Subjects were both top-level crawl stroke and breaststroke college swimmers. For the observation of underwater swimmer’s stroke motion, four video cameras were equipped from the side and beneath the water flume. Those video cameras were synchronized with the data logger.

There were typical local maximums and local minimums in the swimmer’s wrist acceleration during a single stroke. These local maximums and minimums are illustrated in the Fig. 5 and Fig. 7 as closed circles. As a result, some of these local maximums and minimums of the tri-axial acceleration were corresponded with the transition timing of the underwater stroke phase which were defined by Maglischo.

Acceleration in Crawl Stroke
In the crawl stroke, the impact acceleration occurred at the entry moment, because of collision between the swimmer’s hand and water surface. Especially, this impact acceleration was appeared in the X-axis and Z-axis accelerations. For X-axis acceleration, this impact acceleration appeared as a negative sharp peak. Then we could extract every single stroke duration by this negative peaks. In addition, we could also determine precise stroke time which defined as the duration time of the stroke. Based on this negative peaks, the time series of acceleration in Fig. 5 was extracted. These local maximums and local minimums could be used for the stroke phase discrimination.

Four stroke phases, the entry and stretch (I), downsweep (II), insweep (III) and upsweep and recovery (IV) phase were discriminated by the tri-axial acceleration.

For reasons already stated, X-axis shows negative peak at the entry moment. After entry, Y-axis acceleration decreased and reached 0 m/s². This corresponded with the end of the stretch phase. After
Y-axis reaching 0 m/s², the X-axis increased steeply and took a local maximum. During this phase, swimmer’s hand moved outward and downward. This corresponded to the downswipe phase. At the timing of the X-axis local maximum, the swimmer’s hand was at the most deepest position. Then the swimmer’s hand moved inward between the X-axis local maximum and X and Y-axis local minimums. This corresponded to the insweep phase. After insweep phase, Y-axis increased steeply. This corresponded to the upswipe phase. Because we could not distinguish the release timing by acceleration now, we brought together the upswipe and the recovery phase as phase IV.

In order to understand the orientation of the data logger and the swimmer’s wrist, Fig. 6 shows the relationships between stroke motion and the direction of the acceleration sensor axes.

As for the breaststroke, the stroke motion was divided into three phases, outsweep (I), insweep (II) and recovery (III). Whole stroke phases could be determined only by the swimmer’s wrist acceleration. The outsweep began with the Y-axis local minimum. At the timing of this Y-axis local minimum, the swimmer finished his insweep motion and began his recovery motion. This is the beginning of the recovery phase (I). Thus, we could extract every single stroke duration by the Y-axis local minimums. After forward extension of the upper extremity in the recovery phase, swimmer’s hand moves outward. This corresponds to the beginning of the outswipe phase. During outswipe phase, the swimmer’s hand travels toward negative direction of the X-axis with respect to the forearm sensor coordinate system.

According to the motion analysis, when the X-axis acceleration decreased, then went across zero and changed negative, the swimmer began to spread his arm. His hand was widely spread out at the end of the outswipe phase. When his arm was most widely spread out, the X-axis acceleration had a local maximum at the same time. Then the arm moves toward the swimmer’s trunk. Therefore, we could determine the end of the outswipe phase which equals to the beginning of the insweep phase by the X-axis acceleration. Thus we could determine all stroke phase in breaststroke by only tri-axial wrist acceleration.

**ANGULAR VELOCITY IN SWIMMING STROKE**

The prototype II gives us the acceleration and angular velocity during swimming. Figure ?? shows the tri-axial acceleration and tri-axial angular velocity of the swimmer’s wrist. The transition timing of each stroke phase is illustrated as vertical solid line in the figure. Because we could discriminate the stroke phases by the acceleration, the forearm
movement could be clarified by the angular velocity information. For example, the Y-axis angular velocity indicated the pronation/supination movement of the forearm. The X-axis and Z-axis angular velocity indicated whether or not the palm had an angle of attack for the hand velocity vector. For example, if the X-axis had high value and the Z-axis with low or zero value of the angular velocity during forearm flexion movement with respect to elbow joint, the swimmer’s forearm might move with no angle of attack.

Figure 9 shows the result of the breaststroke fast speed trial. Also the stroke phase of the breaststroke could be discriminated by the acceleration. Let us consider the relationships between the stroke phase and the forearm angular velocity.

In the outsweep phase, a swimmer moves his hand with his hand gradually having a positive angle of attack so that he may make propulsive force during this phase. This movement means the pronation of the forearm. In the first half of the outsweep phase (II), the Y-axis angular velocity shows clear negative peak. This means the swimmer’s pronation movement during the outsweep phase in the breaststroke.

According to the X-axis angular velocity, the X-axis angular velocity was relatively small rather than that of the other two axes'. It must be believed that the forearm had move with some angle of attack constantly in the breaststroke. Thus we could discriminate the underwater stroke phase and estimate the status of its movement.

**Figure 9. Wrist acceleration and angular velocity in breaststroke**

**FATIGUE ESTIMATION**

As a coaching application, we examined the estimation of the swimmer’s fatigue by the tri-axial acceleration. For this purpose, we applied the prototype I in the experiment.

**Experimental Protocol**
Four male and one female triathlon athletes were involved in this experiment. In order to determine each subject’s swimming speed, a three speed test (300m×3) was taken before the main experiment. Then we had estimated onset of blood lactate accumulation (OBLA) speed of each subject and defined 50m target time (OBLAT) at 1st set of the experiment. At the OBLA speed intensity, the blood lactate begins to increase exponentially. So the swimmer’s fatigue also begins to accumulate.

The experimental protocol is illustrated in Fig.10. The subjects had to swim 8 times 50m at their own target time, as possible as they could. The target time of 1st set was calculated from their OBLA speed (OBLAT). Their target time at 2nd and 3rd set were 3 and 6 seconds faster than that of 1st set. It should lead complete exhaustion after 3rd set. The interval was adjusted to 15 seconds in every set. The heart rate was measured immediately after each set. And blood lactate was sampled 3 minutes after each set. We used a LactatePro (Model LT-1710, Arkray Inc.,) for our blood lactate sampling test.

Three Dimensional Motion Analysis

We had also developed a remote controlled underwater pan-tilt camera for the kinematical observation. A remote controlled pan-tilt camera (EVI-D30, Sony Inc.,) was waterproofed by acrylic case (Fig.11). It can stand under the depth of 5m. We can control two underwater cameras simultaneously using RS232C control command on the poolside. The control software configures the camera’s pan-tilt angle and its rotation speed, zooming, focusing, shutter timing and exposure settings. We had set one underwater camera at the bottom of the swimming pool diagonally to the left front of the swimmer and the other was set diagonally to the left behind the swimmer. A frame counter which was synchronized with the data logger overlaid time code on the video frame. The underwater motion was recorded on the digital video recorders. For three dimensional motion analysis, the calibration markers were set beneath the lane line as shown in Fig.12. The subjects were marked with their shoulder, elbow, wrist and metacarpophalangeal joints. Then we took digitizing process manually for these joint coordinates. The digitized joint coordinates were reconstructed with respect to the global coordinate system by the direct linear transformation method.

Fatigue Estimation

Fig.13 shows average swimming velocities and blood lactates of the subjects. All subjects swam almost same time as their target time in each set. We see when they finished final set, they were almost exhausted. Because their blood lactates were between 6.8~14.9mmol/l. Especially, sub.C, D and E finished over 11mmol/l with their blood lactate. The intensity of their interval training were enough to exhausted them.

Figure 13. Change of average swimming velocity and blood lactate
and last trial on the final set. He completely exhausted after last trial of 50m.

A small local maximum (P2) is appeared after global maximum of the Y-axis acceleration (P1). As mentioned before, this local maximum of the Y-axis acceleration, P2 is in the upsweep phase. We see that the P2 on the 8th trial decreased than that of the 1st trial. The end of the insweep motion which equals to the beginning of the upsweep motion, corresponded to this timing (P2). In Fig.15, the timing P2 are explained. The bottom of Fig.14 shows the change of elbow angle (\( \theta_e \)) and its angular velocity (\( \omega_e \)). From these angular parameters, P2 almost corresponded to the maximum elbow flexion timing. Before his exhaustion, it occurred at about 0.93sec. Then it shortened to 0.83sec at the fatigue situation on 8th trial. Usually, a swimmer flexes his elbow joint at the end of the insweep, that is the beginning of the upsweep. The local maximum P2 was probably caused by the centrifugal acceleration component which was made by the elbow extension at the beginning of the upsweep motion. Subject C released his left arm and hand with his elbow angle keeping about 100[deg] at the 8th trial (Fig.14). This fact also explains that the centrifugal acceleration made by elbow extension caused the Y-axis local maximum at P2. The declining of the P2 indicated that the swimmer could not complete his elbow extension during the upsweep phase. It is reasonable suppose that the swimmer’s fatigue was this P2 declining phenomenon.

CONCLUSION

In order to evaluate the underwater swimming stroke, the tri-axial acceleration and acceleration/angular velocity data logger were developed. Using these logger devices, the experiment focused on the observation of the underwater stroke motion in crawl stroke and breaststroke. The stroke phase discrimination could be achieved by the tri-axial acceleration. In addition, the tri-axial acceleration also indicated the evidence of the swimmer’s fatigue and change of the stroke motion. From the tri-axial angular velocity, we could estimate how the swimmer’s forearm moved in the each stroke phase. It is expected that a miniaturization of the acceleration and angular velocity data logger helps our swimming training and coaching.

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REFERENCES