

AN INNOVATION FOR SWIMMING STROKE MONITORING TRI-AXIAL ACCELEROMETER AND GYROSCOPE DATA LOGGER FOR STROKE ANALYSIS

Yuji Ohgi¹, Hiroshi Ichikawa² and Takeo Nomura³

¹ Faculty of Environmental Information, Keio University, Fujisawa, Kanagawa, Japan, ohgi@sfc.keio.ac.jp

² Doctoral Program of Health and Sport Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan

³ Institute of Health and Sport Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan

INTRODUCTION

In the past, there were three major approaches to analyze swimmer's stroke motion. Those were, the three dimensional motion analysis using cinema or video, the direct measurement of the hydrodynamic force using forearm and hand model and the computational fluid dynamics simulation. The stroke observation by the three dimensional motion analysis using several underwater cameras was most popular and traditional method. Payton and Bartlett (Payton and Bartlett 1995) captured underwater stroke motion of the world top breaststroke swimmers and estimated their propulsive force exerted on the hand using Schleihau's coefficients of the drag and the lift force (Schleihau 1979). Cappaert evaluated the underwater stroke paths of freestyle swimmers in the Barcelona Olympic Men's 100m event by the DLT method and calculated the swimmer's whole body drag (Cappaert et al. 1995). Direct measurement of the hydrodynamic force using the model was begun by Schleihau (Schleihau 1979). He emphasized that the importance of the lift force in swimming. He also described that swimmers should stroke their hand with the angle of attack to the hand velocity vector, not the straight path. This was the world first study of the lift force effect in swimming. Other researchers measured the hydrodynamic force not only on the hand but also on the forearm (Berger et al. 1995, Lauder et al. 2001). The computational fluid dynamic simulation (CFD simulation) has become a popular method in recent years with the increase of the computer power. Tsushima simulated the water flow around the sculling hand model and reported that the resultant force would be different between the thumb opened and closed configurations (Tsushima et al. 1998).

According to both the direct measurement of the hydrodynamic force studies and the CFD simulation studies, it became clear that swimmer's lift force little contribute their propulsive force and the drag force is dominant component of the maximum propulsive force (Ito 2002, Takagi et al. 2002). Ito calculated the maximum thrust force using Schleihau's coefficient of the lift and the drag and recommended that a swimmer should stroke his hand linearly with angle of attack at 42 degree in the front crawl stroke. This swimmer's angle of attack of the hand might be primarily controlled by the forearm pronation and supination.

Among those three major approaches, except the video based motion analysis method, the direct measurement of the hydrodynamic force and the CFD simulation applied a standard human forearm and hand model. Therefore, both methodologies could not apply for each individual stroke motion. In this reason, the videographical motion analysis method had advantage for the analysis of individual swimmer's stroke motion. There are, however, two

difficulties with the underwater three dimensional video analysis. The three dimensional video analysis method requires much time and work for the digitizing process, making it impossible to evaluate a swimmer's stroke motion promptly after he/she has swum at daily training. The other technical difficulty in the underwater videography is air bubbles made by the swimmer's own motion. This sometimes prevents the observation of the underwater stroke.

The authors proposed the acceleration sensor as an alternative to the videographical motion analysis (Ohgi et al. 1999, Ohgi et al., 2000a, Ohgi et al. 2000b). The authors developed a discrimination method between stroke styles using swimmer's wrist acceleration (Ohgi et al. 1999). Then we also reported that each stroke phase could be identified using swimmer's wrist acceleration for both the crawl stroke and the breaststroke (Ohgi et al., 2000b, Ohgi et al., 2003). It is useful for the stroke skill evaluation that the acceleration during swimming event could be identified as each stroke phase without underwater video observation.

Using microcomputer-based acceleration data logger, long duration measurement made possible the continuous accelerometry of the whole training session. The authors examined how swimmers' fatigue would be appeared in their wrist acceleration during intensive training (Ohgi et al., 2002). As a result, swimmer's physiological fatigue caused changes to his wrist acceleration pattern under the intensive interval training. In the upstroke phase, the local maximum of the y-axis acceleration, which was along with the longitudinal axis of the forearm were significantly decreased in his exhaustion. This proved that the acceleration sensor device could be used for not only the skill evaluation but also the physiological monitoring. Thus, some useful knowledge was obtained by the swimmer's wrist acceleration using tri-axial acceleration sensor device.

However, since the acceleration of the swimmer's wrist is measured on the movement coordinate system, we never divide it into each component, such as the horizontal, the gravitational, the centrifugal and the tangential acceleration. Authors used both the three-dimensional video analysis method and the acceleration sensor logger at the same time. Then we synchronized the remarkable acceleration pattern with the swimmer's actual motion and examined it by deductive approach. Unlike an accelerometer, a gyroscope sensor can measure the angular velocity of the object, which is independent from coordinate systems. Therefore, the tri-axial angular velocity of the swimmer's forearm, which is obtained at the wrist joint would be presented the forearm movement in the three dimensional space.

The purposes of this study were as follows; 1) to develop a tri-axial acceleration and tri-axial gyroscope sensor data

logger device, 2) to quantify the swimmer's stroke motion using both the acceleration and the angular velocity.

METHODS

Figure 1 shows the developed acceleration and gyroscope data logger (Prototype II). Table 1 shows the specification of both the tri-axial acceleration data logger (Prototype I) and the tri-axial acceleration, gyroscope data logger (Prototype II).

Prototype I and II are able to measure tri-axial acceleration simultaneously by using two bi-axial acceleration sensor ICs (ADXL210, Analog Devices, Inc.,). In addition, Prototype II has triple gyroscope sensors (ENC-03J, Murata Corp.,). Figure 2 shows the local coordinate system of the data logger. The x-axis, y-axis and z-axis of the data logger corresponds to the ulnar-radial, the distal-proxial and the dorsal-palmar direction of the left forearm respectively. The rotational direction of each axis was also defined as shown in Figure 2. Using this prototype II, we will present the relationship between the swimmer's wrist acceleration, angular velocity and the swimmer's stroke motion.

In order to observe swimmer's underwater stroke motion, the authors developed a remote controlled underwater pan-tilt camera module (Figure 3). A serial controlled camera module (EVI-D30, Sony Corp.,) was waterproofed by the acrylic case. And it can stand at the 5m-depth condition. We could control two underwater cameras simultaneously using RS232C control command from the poolside. We could also control the focusing, zooming, shutter timing and exposure and other settings of each cameras. Two video cameras were equipped to take swimmer's underwater stroke motion. We had set one underwater camera at the bottom of the swimming pool diagonally to left front of the swimmer and the other was set diagonally to left behind the swimmer. The video signals were recorded on the DV camcorders via synchronized video frame counter. The logger was started by the trigger function with connecting the logger to the video frame counter. For the three dimensional motion analysis, calibration markers were set beneath the lane line as shown in Figure 4. The subjects were marked with their left shoulder, elbow and wrist joints. Then we took digitizing process manually for these joint coordinates. The digitized joint coordinates were calculated with respect to the global coordinate system by the DLT method. The square root of the mean squared error of the each axis were $X=6.0\text{cm}$, $Y=4.1\text{cm}$ and $Z=1.9\text{cm}$ respectively.

Five male college swimmers were involved in this experiment. Each swimmer swam front crawl swimming at the three different efforts, such as slow, middle and fast speed. After logger start, the acceleration calibration was done by the gravitation. Then the logger was attached onto the swimmer's left forearm at the wrist joint by taping and bandage.

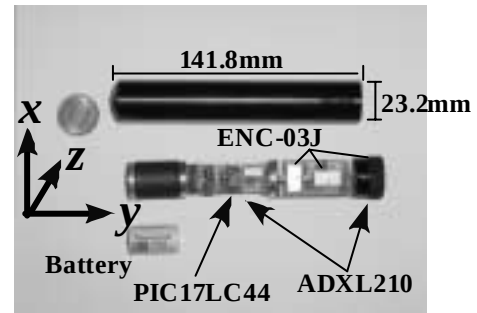


Figure 1: The photograph of Prototype II, the tri-axial acceleration and tri-axial gyroscope sensor logger device.

Table 1: Data logger specifications

	Prototype I	Prototype II
Dimensions	88 × 21 mm	141.8 × 23.2 mm
Weight	50g	78g
Accelerometer	2 × ADXL210	←
Gyroscope	—	3 × ENC-03J
Microcomputer	PIC17LC44	←
Sampling Rate	Up to 128Hz	←
Memory	32Mbit	128Mbit
Battery	CR1/3N	CR2
Duration	1.45h	2.9h

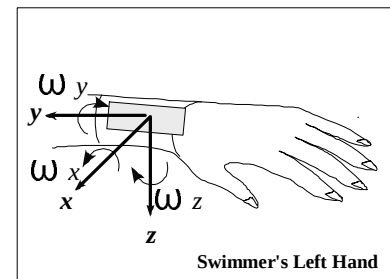


Figure 2: The local coordinate system of the logger

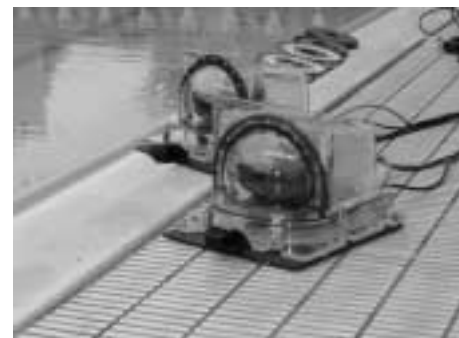


Figure 3: Underwater pan-tilt camera modules

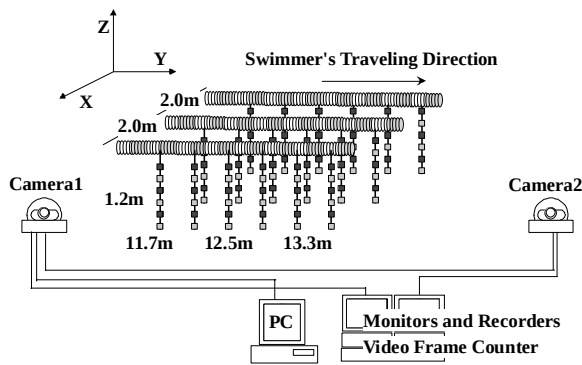


Figure 4: The global coordinate system and the camera configuration for the three dimensional motion analysis.

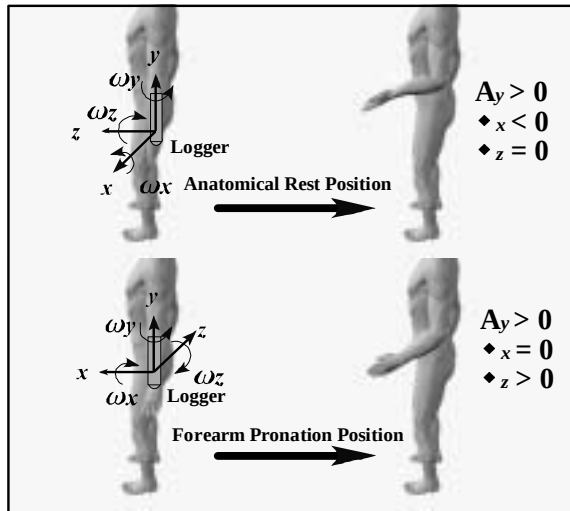


Figure 5: The relationship between the forearm pronation/supination and the angular velocity of the forearm.

RESULTS AND DISCUSSION

Before we discuss the acceleration and the angular velocity of the swimmer's stroke motion, it is useful to understand the effect of the upper extremity's posture configuration to them, especially, the forearm pronation and supination effect to the acceleration and the angular velocity. Figure 5 shows the signs of the angular velocity on both the ω_x and ω_z , which would be changed depending on the forearm pronation or supination configuration. At the anatomical rest position, 1G should be observed in the y-axis acceleration by the gravitation. In this configuration, the palm plane is in parallel with the frontal plane and faces forward. From this configuration, beginning of the elbow flexion motion, the centrifugal component would be observed on the y-axis acceleration by the rotational movement. Thus, in this flexion phase, the x-axis and the z-axis angular velocity changed $\omega_x < 0$, $\omega_z = 0$ respectively. From this anatomical rest position, when we pronate our forearm 90 degree, the palm plane faces our trunk. As same as the anatomical rest position, the gravitational acceleration 1G can be seen on the y-axis acceleration at that time. When we flex our left elbow from this configuration, the y-axis acceleration also outputs centrifugal acceleration component and changes $A_y > 0$. On the other hand, as for the angular velocities, $\omega_x = 0$ and $\omega_z > 0$ would be observed. Therefore, at the elbow flexion stroke phase, it is expected that the forearm pronation/supination

condition could be estimated using the sign and its value of the tri-axial angular velocity.

Maglischo defined the five stroke phases of the crawl stroke (Maglischo, 1993), Entry and Stretch, Downsweep, Insweep, Upsweep, Release and Recovery. Under his phase segmentation, the authors found that each stroke phase could be discriminated by the swimmer's wrist acceleration (Ohgi et al., 2000b). In this study, we will discuss the relationship between swimmer's stroke skill and both the acceleration and the angular velocity under the Maglischo's stroke phase definition.

The whole time series of the acceleration and the angular velocity were extracted as every single stroke pattern using stroke distinctive acceleration by our methodology (Ohgi et al., 2000b). Figures 6 and 8 are the results of Subject A and Subject D on their fast speed trial in the crawl stroke. The left and right graphs show the tri-axial acceleration and the tri-axial angular velocity respectively. In both figures, there are alphabetical symbols from A to F, which are the moments determined by the distinctive local maximum or local minimum of the acceleration. In those figures, section AB corresponds to the stretch phase, BC: the downsweep, CD: the insweep, DF: the upsweep, FA: the recovery, respectively.

Figures 7 and 9 show the coordination of the upper extremity; the shoulder, elbow and wrist on the crawl stroke at the same trial. The symbols A to E are also presented in the stroke path figures. After dividing every single signal pattern into each stroke phase based on our previous discriminative method, we can examine the underwater stroke motion by both the wrist acceleration and the angular velocity.

Entry and Stretch Phase

Before the entry moment, the angular velocity, ω_x and ω_z kept positive during the recovery phase, because of the rotational motion of the upper extremity. At the entry, remarkable impact acceleration was observed in both the x-axis and z-axis acceleration (A). After the entry, the swimmer stretched his forearm forward direction. Then his elbow was fully extended. This is the stretch phase. We can see that there was no rotational movement for the x and z-axis since both the ω_x and the ω_z show nearly zero deg/s. However, ω_y , which was the rotational angular velocity along with the longitudinal axis of the forearm, was positive. It means that the pronation of the forearm was done in this phase. The maximum angular velocity of the ω_y was approximately 250deg/s in this phase.

Downsweep Phase

After the stretch phase, the swimmer's hand began to move downward. This is the downsweep phase. According to the videographical observation of the swimmer's hand motion in Fig. 7 and Fig. 9, the phase from B and C almost corresponds to the downsweep phase. We can see that the angular velocity ω_y was negative during BC. It showed negative (pronation), at the first portion and positive (supination), at the latter portion in the downsweep phase for all subjects. One hand, the angular velocity ω_y of the sub.A changed negative from the beginning of the downsweep phase, when the pronation had been begun at the timing B.

On the other hand, as for Subject D, he began to pronate before the timing of **B**. He started his forearm pronation in the stretch phase.

The downsweep motion was done by the shoulder joint abduction and the elbow joint slight flexion. At the beginning of this downsweep phase, since a swimmer begins to downward stroke motion with his elbow almost fully extended, the centrifugal acceleration would be increased remarkably. Because the distance from the shoulder joint and the hand must be lengthen in this phase. Therefore, because of the centrifugal acceleration component, the y-axis acceleration A_y increased and had a maximum peak at **C**. The timing **C**, it corresponded the end of the downsweep (Figures 7 and 9).

As for the x-axis angular velocity, ω_x decreased in the downsweep phase for all subjects. However, the z-axis angular velocity had different tendency. Although the z-axis angular velocity, ω_z of the Subject A was negative at the beginning of the downsweep phase (**BC**), it increased on subject E from the beginning of the downsweep. Subjects B, C and E also showed same tendency to increase ω_z . This suggests that subject A almost faced his palm plane vertically to the hand velocity direction in the downsweep phase. Others might have some angle of attack with their hand in the downsweep phase. In addition, the positive angular velocity was also observed in the z-axis ω_z . This means that the swimmer's palm had positive angle of attack in this phase.

Insweep Phase

Between **C** and **D**, it was called the insweep phase, when the swimmer sculls his hand toward the trunk. At the end of the insweep phase, since the swimmer finishes his insweep motion by the shoulder abduction and the elbow flexion, the distance from his shoulder joint and the hand would decrease steeply. Because of this motion, the centrifugal acceleration must be remarkably decreased and have a local minimum on A_y at timing **D**. At that time, the x- and y-axis angular velocities, $\omega_x < 0$, $\omega_y = 0$ were observed. And the z-axis angular velocity, ω_z was almost positive in the insweep phase. This means that the swimmers made their inward sculling motion. Then ω_z was changed from positive to negative after the insweep motion.

Upsweep Phase

The swimmer's hand came close to the body center line at the end of the insweep phase. After this maximum elbow flexion, his elbow joint began to extend again. Simultaneously, the abduction at the shoulder joint was still keeping. This is the beginning of the upsweep phase. The upsweep phase is defined as between the maximum elbow flexion and the release of the hand from the water surface. In the experimental results, from the timing **D** and **F** corresponds to the upsweep phase. In the upsweep phase, the x- and z-axis angular velocity, ω_x and ω_z showed almost negative value. As for the y-axis angular velocity, ω_y , showed always positive (supination) for all subjects.

According to the experimental hydrodynamic studies, which were started from late 1970's by Schleihau (Schleihau, 1979), it was believed that the lift force could contribute substantially to the propulsion in swimming. Both the lift

force and the drag force by the sculling motion have been regarded as the swimmer's stroke skill. Especially, the high elbow position should be one of the most important swimmer's skill at the end of the downsweep phase (Counsilman, 1977). A swimmer should bend his arm with his hand at the deep place and his elbow at the shallow place at the high elbow position. In order to accomplish this high elbow position, after stretch phase, it was recommended that a swimmer should stroke with positive angle of attack during the downsweep phase. This leads to the effective lift force production in this phase. According to the observational studies, as was expected, it was reported that an elite swimmer stroke with sweep motion during the downsweep phase. This high elbow position requires swimmer's forearm pronation motion.

Authors propose that the forearm angular velocity, which was obtained by the tri-axial gyroscope, would be useful and effective information for the swimmer's stroke motion. Especially, the forearm longitudinal rotational motion, pronation/supination can be seen by the sign and the absolute value of the y-axis angular velocity, ω_y .

It was impossible to quantify the rotational motion along with the longitudinal axis of the forearm by the videographical motion analysis method without the extra marker sets. However, the gyroscope tells us the forearm rotational movement directly. We could observe the pronation/supination motion of the swimmer's forearm of the crawl stroke in underwater using the microcomputer-based acceleration and gyroscope sensor data logger.

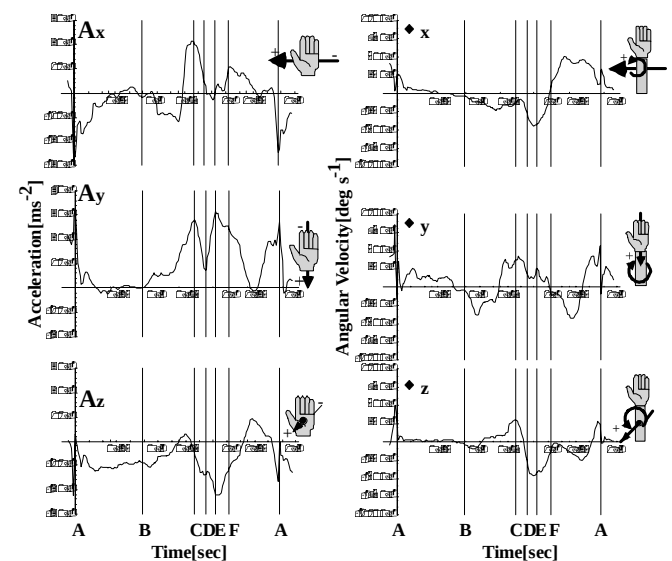


Figure 6: The acceleration and the angular velocity of the forearm in the crawl stroke (sub.A, Fast Speed). **A**=Entry, **AB**=Stretch, **BC**= Downsweep, **CD**=Insweep, **DE**=Upsweep, **FA**=Recovery

SUMMARY

So far, there were many difficulties on the underwater motion analysis method. It happened frequently that a swimmer's motion created water bubbles, which prevents us.

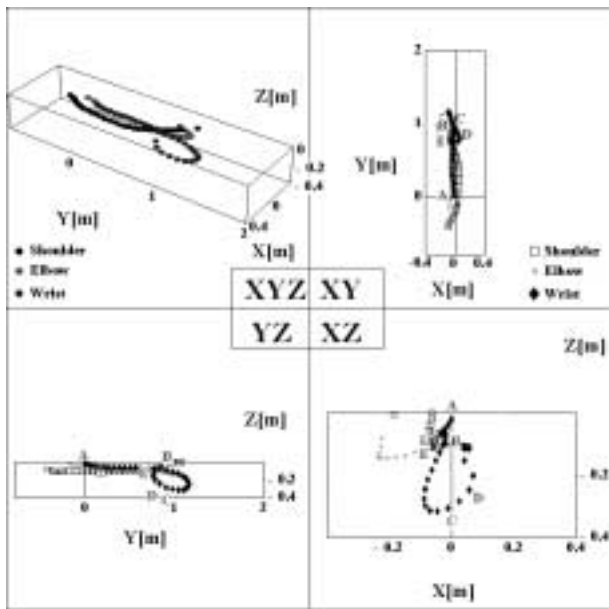


Figure 7: The stroke path of the swimmer's shoulder, elbow and wrist joint in the crawl stroke (sub.A, Fast Speed).

A=Entry, AB=Stretch, BC= Downsweep, CD=Insweep, DF=Upsweep

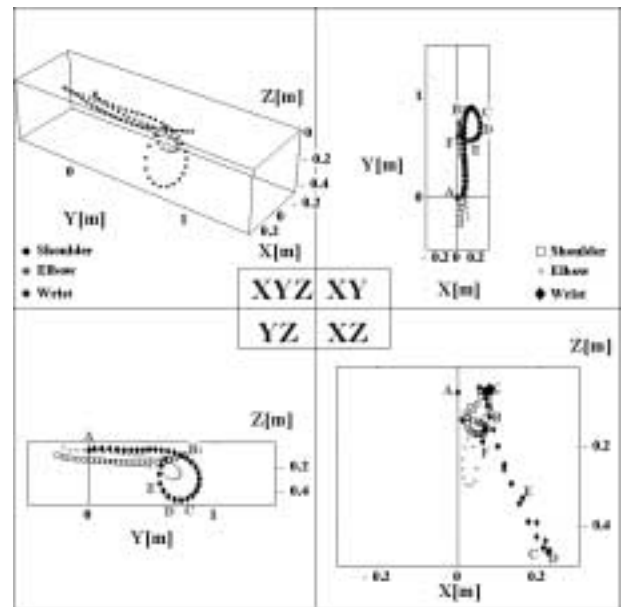


Figure 9: The stroke path of the swimmer's shoulder, elbow and wrist joint in the crawl stroke (sub.D, Fast Speed).

A=Entry, AB=Stretch, BC= Downsweep, CD=Insweep, DF=Upsweep

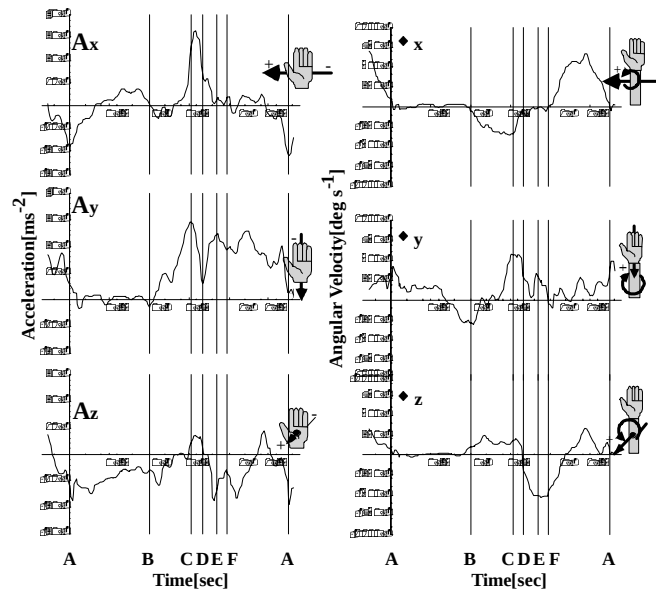


Figure 8: The acceleration and the angular velocity of the forearm in the crawl stroke (subject D, Fast Speed). A=Entry, AB=Stretch, BC= Downsweep, CD=Insweep, DF=Upsweep, FA=Recovery

from observing his motion. In addition, it took much time and work for its digitizing process after video capturing. The stroke phase discrimination method for the crawl stroke was already presented in our former research (Ohgi et al., 2000b). Moreover, in this study, we could propose the availability of the angular velocity using the tri-axial gyroscope sensor for the analysis of the swimmer's stroke motion. The authors examined the swimmer's underwater stroke motion using the tri-axial acceleration and the tri-axial gyroscope sensor data logger. The purpose of our study using the micro-machining inertia sensors was to quantify the swimmer's stroke motion, which was impossible to realize before by the videographic motion analysis method.

The developed data logger device for the stroke monitoring provides us to measure tri-axial wrist acceleration and the tri-axial angular velocity during swimming. This prototype II could quantify the forearm stroke movement directly by the tri-axial angular velocity. Especially, the pronation and supination motion could be quantified by our device without the videographical observation.

REFERENCES

- Adrian, M.J. et al. (1966). *J. Appl. Physiol.*, **21**,1763-1766.
- Berger, A.M. et al. (1995). *J. Biomech.*, **28**(2),125-133.
- Cappaert, J.M. (1995). *J. Appl. Biomech.*, **11**, 03-112
- Counsilman, J.E. (1977). *Competitive Swimming Manual for Coaches and Swimmers*, Counsilman Co. Inc.,
- Hollander A.P. et al. (1987). *Swimming Science V*, 39-43
- Ito S. (2002). *Abst. IXth World Symp. Biomech. Med. Swimming*, 93.
- Lauder, M.A. et al. (2001) *J. Biomech.*, **34**, 31-39.
- Maglischo, E.W.(1993). *Swimming Even Faster*, Mayfield Publishing Company
- Ohgi, Y., et al. (1999). *Biomechanics and Medicine in Swimming VIII*, 77-82.
- Ohgi, Y., et al. (2000a). *The Engineering of Sport*,503-511.
- Ohgi, Y. et al. (2000b). *Jpn. J. Sci. Swim Water Exerc.*, **3**, 35-41.
- Ohgi, Y., et al. (2002). *Int. J. Japan Soc. Mech. Eng.*, **C**, **45**(4), 960-966
- Ohgi, Y., et al. (2003, in press). *Int. J. Sports Eng.*
- Payton, C.J., Bartlett, R.M., (1995). *J. Sports Sci.*, **13**, 447-454
- Schleihauf, R.E. (1979). *Swimming III*, 70-109,
- Takagi, H., Willson, B. (1999). *Biomechanics and Medicine in Swimming VIII*, 101-106.
- Tsushima T. et al. (1998). *Proc. Symp. Sports Eng. Hum. Dynamics*, Japan Soc. Mech. Eng., No.98-31, 268-271