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An Approach to 3D Gyro Sensor Based Motion Analysis in Tennis Forehand Stroke

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***Abstract*—This paper describes a new measuring model of human body motion using 3D gyro sensors. Proposed model is applied to measure forehand swing motion of tennis players, and swing behaviors are captured. With proposed model, body motion and flow of energy between tennis players are compared. This method can be applied to various motion research with small cost.**

***Index Terms*—gyro sensor, tennis, motion analysis**

I. Introduction

Aging society and lower birthrate have become big issues in Japan. These issues cause increase of aging population who need medical care, and decrease of productive population who give nursing care of aging population. It can be also considered that increase of burden of care will become issue for current child generation, and even grandchild generation. In addition, with lack of a nursing facility and care staff, the elderly people may not be taken enough care. As a result, some of elders may die in loneliness. According to the Old White Paper, number of elders living alone is showing increase trend recently. The solutions towards these issues include improvements of healthy life expectancy. Healthy life means the period when a human can live daily life without a limit of the movement.

Sport exercises are effective to extend healthy life and to expand its communities. It is known that the risk of death from cardiovascular disease and cancer will decrease, if people play sport exercises more than 5 hours a week. According to the report of ”the physical activity standard for health” that Ministry of Health, Labor and Welfare published in 2013, risk of a lifestyle-related disease and the functional decline can be decrease with enough exercise. For the people between 18 years old and 64 years old, more than 3 Metabolic Equivalents (METs) strength exercises for 60 minutes a day is considered as enough exercise. For the people of more than 65 years old exercises at any strength for more than 40 minutes (that is equivalent to 10 METs hours per week) is considered as enough exercise. METs is an index to express strength of the exercise. However, inappropriate exercise load may cause an injury. Generally, there are differences of exercise load between beginners and an experts. Then, the evaluation index of exercise load to guide suitable excise motion is required to prevent an injury.

From these backgrounds, the movement analysis of sport exercises and development of the quantitative evaluation index applicable to anyone are significant. The purpose of this research is to make an environment that helps people begin sports by using the evaluation index. The tennis motion is selected as an example of the target analysis, because tennis can be played by any generation and it requires whole body movement, including running, throwing of services, and twisting of body for racket swing.

There are many approaches to measure the motion of the body. One of the approaches uses the goniometer by attaching to a body directly for joint angle measurement[1]. The following are advantages of this approach: One goniometer is generally cheap, it is easy to transform recorded output signal to suitable parameter, and it can measure the rotation directly in the motion plane regardless of an exercise plane of the body joint. On the other hand, there are two disadvantages: First, it takes a lot of time to set the goniometer to the body because of the complex structure. Secondly, straps and cables limit movement of subject when a lot of goniometers is used. As other approach, direct linear transformation (DLT) method using the picture information by the high-speed video camera is used often[2]. In this method, an attention point is photographed by several cameras. Then translational motion and rotational motion are calculated by photographed movement data. The following are advantages of DLT method: Firstly, the numbers of markers have no limit. Secondly, dates of interest can be obtained simultaneously. Thirdly, the video can be used for evaluation of the movement. As disadvantages of DLT method, it take a time to attach the attention point, it requires multiple expensive high-speed camera, and it is impossible to measure rotation motion because attention point become hidden.

The approach using inertial measurement unit sensor (IMU sensor: gyro sensor and acceleration sensor) exist. It is easy to attach by small and low-weight characteristic, and able to measure 3D motion without limiting human motion. Then, data can be obtained much cheaper than optical motion capture, like using camera. In this research, the angular velocity of each link is measured by attaching IMU sensor directly to body. Then swing model applied measurements is developed to propose evaluation index.

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II. MODELING

This section describe the modeling of the human upper body.

A. Kinematics

The model of human upper body is shown as Fig. 1. In Fig. 1, red circles describe gyro sensors that are attached to upper body. The direction of gyro sensors is shown as Fig. 2.

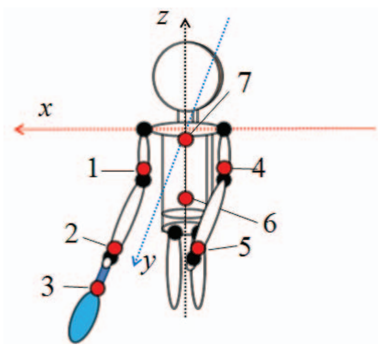


Fig. 1. Modeling of upper body

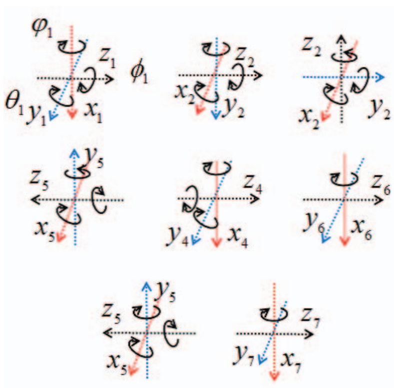


Fig. 2. Local coordinate

Firstly, the angular velocity obtained by gyro sensors must be transformed into roll-pitch-yaw angles which represent rotations in world coordinates. This is because gyro sensors only measure angular velocity between a certain sampling time and next sampling time. This transformation is shown as eq.(1)[3].

$$\begin{bmatrix} \dot{\phi}(t) \\ \dot{\theta}(t) \\ \dot{\psi}(t) \end{bmatrix} = \begin{bmatrix} 0 & \frac{S\psi}{C\theta} & \frac{C\psi}{C\theta} \\ 0 & C\psi & -S\psi \\ 1 & S\psi\frac{S\theta}{C\theta} & C\psi\frac{S\theta}{C\theta} \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \quad (1)$$

C indicates $\cos$ and S indicates $\sin$. Roll-pitch-yaw angles are obtained by integration shown as eq.(2). In this paper, roll angle ϕ represents a rotation around the z axis, pitch angle θ represents a rotation around the y axis and yaw angle ψ represents a rotation around the x axis.

$$\begin{bmatrix} \phi(t) \\ \theta(t) \\ \psi(t) \end{bmatrix} = \int \begin{bmatrix} \dot{\phi}(t) \\ \dot{\theta}(t) \\ \dot{\psi}(t) \end{bmatrix} dt + \begin{bmatrix} \phi(t-1) \\ \theta(t-1) \\ \psi(t-1) \end{bmatrix} \quad (2)$$

Homogeneous transformation matrix ${}^{i-1}\boldsymbol{T}_i$ which is seen from $i-1$ link to i link represents position and attitude in generally manipulator. Homogeneous transformation matrix ${}^{i-1}\boldsymbol{T}_i$ is obtained by product of rotation matrix ${}^{i-1}\boldsymbol{R}_i$ and translation matrix ${}^{i-1}\boldsymbol{Tr}_i$ as eq.(3).

$$ {}^{i-1}\boldsymbol{T}_i(t) = \boldsymbol{R}_i(t) \cdot {}^{i-1}\boldsymbol{Tr}_i \quad (3)$$

Rotation matrix $\boldsymbol{R}$ in eq.(3) is expressed by product of rotation matrix of each axis as eq.(4). Translation matrix $\boldsymbol{T}$ is shown as eq.(5).

$$\boldsymbol{R} = \boldsymbol{R}(\phi) \cdot \boldsymbol{R}(\theta) \cdot \boldsymbol{R}(\psi) \quad (4)$$

$$\boldsymbol{Tr} = \begin{bmatrix} 1 & 0 & 0 & l_x \\ 0 & 1 & 0 & l_y \\ 0 & 0 & 1 & l_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

Elements of homogeneous matrix is shown as eq.(6). Therefore, position of i link are derived as eq.(7).

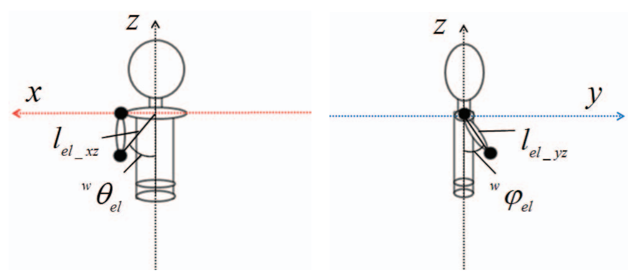
$$ {}^{i-1}\boldsymbol{T}_i = \begin{bmatrix} a_i & b_i & c_i & d_i \\ e_i & f_i & g_i & h_i \\ i_i & j_i & k_i & l_i \\ m_i & n_i & o_i & p_i \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = \begin{bmatrix} d_i \\ h_i \\ l_i \end{bmatrix} + \begin{bmatrix} x_{i-1} \\ y_{i-1} \\ z_{i-1} \end{bmatrix} \quad (7)$$

B. Dynamics

The velocity and energy of each link are calculated from position derived in previous subsection.

1) Derivation of Velocity: Fig. 3 shows the position of right elbow seen from xz and yz plane.



(a) xz-plane (b) yz-plane

Fig. 3. Position of right elbow

After using $\arctan$ for the position of each part seen from xz and yz plane, position coordinates are re-expressed as eq.(8).

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = \begin{bmatrix} l_{i\_xz} \mathrm{S}^{\mathrm{w}}\theta_i \\ l_{i\_yz} \mathrm{S}^{\mathrm{w}}\psi_i \\ l_{i\_xz} \mathrm{C}^{\mathrm{w}}\theta_i \end{bmatrix} \quad (8)$$

Next, the velocity is gotten by pseudo differential of the re-expressed position coordinate. In making this calculation, the caution point is that ${}^{\mathrm{w}}\theta$, ${}^{\mathrm{w}}\psi$, l_{xz} and l_{yz} are variable.

$$\begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{z}_i \end{bmatrix} = \begin{bmatrix} \dot{l}_{i\_xz} \mathrm{S}^{\mathrm{w}}\theta_i + l^{\mathrm{w}}_{i\_xz}\dot{\theta}_i \mathrm{C}^{\mathrm{w}}\theta_i \\ \dot{l}_{i\_yz} \mathrm{S}^{\mathrm{w}}\psi_i + l^{\mathrm{w}}_{i\_yz}\dot{\psi}_i \mathrm{C}^{\mathrm{w}}\psi_i \\ \dot{l}_{i\_xz} \mathrm{C}^{\mathrm{w}}\theta_i - l^{\mathrm{w}}_{i\_xz}\dot{\theta}_i \mathrm{S}^{\mathrm{w}}\theta_i \end{bmatrix} \quad (9)$$

2) Derivation of Energy: Any parts of Human body and racket have mass. However in this paper, assumption is made mass is concentrated in the point of the link. Therefore translational energy in absolute coordinates is represented as eq.(10), rotational energy in absolute coordinates is represented as eq.(11). In this research, position energy is not considered since position energy is much smaller than translational and rotational energy. Thus all energy is represented as sum of translational and rotational energy, as eq.(12).

$$E_{i\_tr} = \frac{1}{2} m \left(\sqrt{\dot{x}_i^2 + \dot{y}_i^2 + \dot{z}_i^2} \right)^2 \tag{10}$$

$$E_{i\_rot} = \frac{1}{2} I \dot{\psi}_i^2 \tag{11}$$

$$E_{i\_total} = E_{i\_tr} + E_{i\_rot} \tag{12}$$

In addition, translational energy on xy-plane is shown as eq.(13).

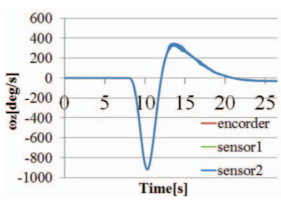
$$E_{i\_xy} = \frac{1}{2} m \left(\sqrt{\dot{x}_i^2 + \dot{y}_i^2} \right)^2 \tag{13}$$

III. Preliminary Experiment

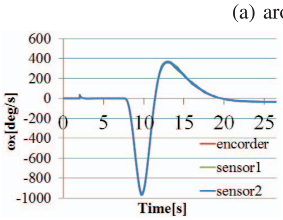
In this section, the performance of 7 gyro sensors and accuracy of developed model are tested.

A. Experiment of Sensor Performance

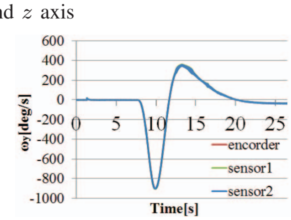
The measurements in each axis are compared between encoder and gyro sensor through preliminary experiment using experimental machine which rotates only one axis. Fig. 4 shows experimental result of sensor 1 and 2.



(a) around z axis



(b) around x axis



(c) around y axis

Fig. 4. Experimental result of gyro sensor

From Fig. 4, the measurements of all axes of gyro sensor are consistent with measurements of encoder. Since same results are confirmed by encoder and sensors, the high performance of gyro sensors is validated.

B. Evaluation of Constructed Model

Applying measurements of simple motion to developed model, the evaluation of developed model is conducted. Table I represents parameters used in preliminary experiment. Initial position is shown as Table II, and right wrist is risen up to shoulder height in revolving 90 deg. However, it is hard to reach desired position because of human motion. Then, the same experiments is carried out 8 times, and gotten the average of position coordinate, shown as Fig. 5. In Table III, DP indicates desired position, EP indicates experimental position, RE indicates right elbow and RW indicates right wrist.

TABLE I
PRELIMINARY EXPERIMENTAL PARAMETER

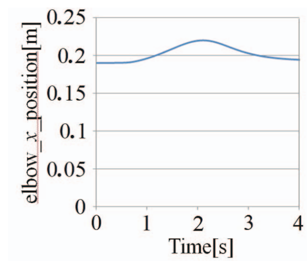
name	unit	value
l_{sh}	m	0.19
l_{ua}	m	0.26
l_{fa}	m	0.28

TABLE II
INITIAL POSITION

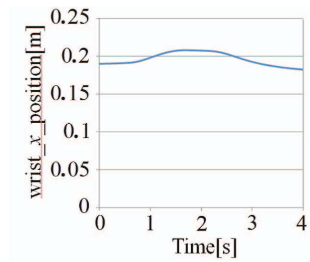
name	unit	description	value
${}^{ini}x_{el},{}^{ini}y_{el},{}^{ini}z_{el}$	m	right elbow	0.19,0.0,-0.26
${}^{ini}x_{wr},{}^{ini}y_{wr},{}^{ini}z_{wr}$	m	right wrist	0.19,0.28,-0.26

TABLE III
EXPERIMENT RESULT

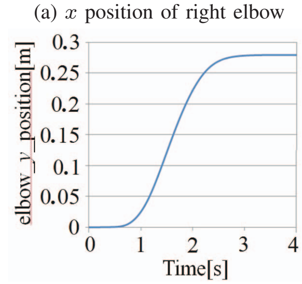
name	unit	description	value
x_{el},y_{el},z_{el}	m	DP of RE	0.19,0.28,0.0
x_{wr},y_{wr},z_{wr}	m	DP of RW	0.19,0.54,0.0
${}^{ex}x_{el},{}^{ex}y_{el},{}^{ex}z_{el}$	m	EP of RE	0.1930,0.2795,0.006
${}^{ex}x_{wr},{}^{ex}y_{wr},{}^{ex}z_{wr}$	m	EP of RW	0.1798,0.5334,0.049



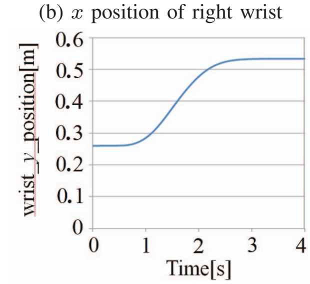
(a) x position of right elbow



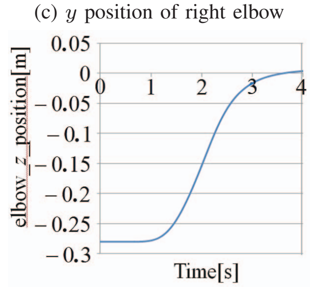
(b) x position of right wrist



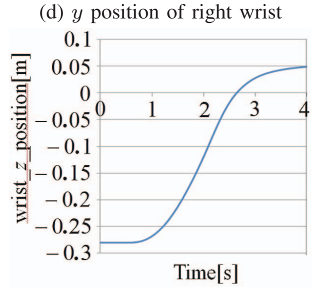
(c) y position of right elbow



(d) y position of right wrist



(e) z position of right elbow



(f) z position of right wrist

Fig. 5. Position of right elbow and wrist

In Table III, maximum error between desired position and experimental position is under 5 cm. There are three reasons to be considered: Firstly, human arm is not straight line. Secondly, thickness of link is not taken into account.

Finally, human motion is hard to reach to desired position. Therefore, resulting error is relatively small, and the accuracy of developed model is confirmed.

IV. Experiment

A. Summary of Experiment

In these experiments, subjects take initial position, and swing two kinds of forehand stroke, open stance and close stance. Position and energy of each link is calculated from developed model. Firstly, experiments were carried out by 3 people. In addition, the close swing of subject 3 was re-measured again with condition based on the consideration of previous experiment results. Their careers of tennis are shown in Table IV, and experimental parameters are shown in Table V. In these parameters, each link of mass is calculated in eq.(14) to eq.(17), and inertia moment is calculated in eq.(18) to eq.(21)[4].

Fig. 6. Initial position

TABLE IV
CAREER OF TENNIS

subjects	career
1	over 5 years
2	under 2 yaers
3	no experience

TABLE V
EXPERIMENTAL PARAMETER

name	unit	value(subject1 $\rightarrow$ 3)
l_{sh}	m	0.19,0.18,0.18
l_{ua},l_{lua}	m	0.26,0.25,0.24
l_{fa},l_{lfa}	m	0.28,0.25,0.22
l_{ra}	m	0.57
m	kg	63.0,60.0,50.0

$$m_{ua} = 0.016m \tag{14}$$
$$m_{fa} = 0.028m \tag{15}$$
$$m_{ra} = 0.006m + 0.35 \tag{16}$$
$$m_{pos} = 0.497m \tag{17}$$
$$I_{ua} = (0.16/2\pi)^2 m_{ua} \tag{18}$$
$$I_{fa} = (0.23/2\pi)^2 m_{fa} \tag{19}$$
$$I_{ra} = 0.0196 m_{ra} \tag{20}$$
$$I_{pos} = (0.9/2\pi)^2 m_{pos} \tag{21}$$

B. Experimental result

First, 4 phases of swing was defined from calculated position: initial position, take back, swing & hit and follow through.

1) Definition of Swing: Racket trajectories of close and open swing in skilled person were shown in Fig. 7 and Fig. 8.

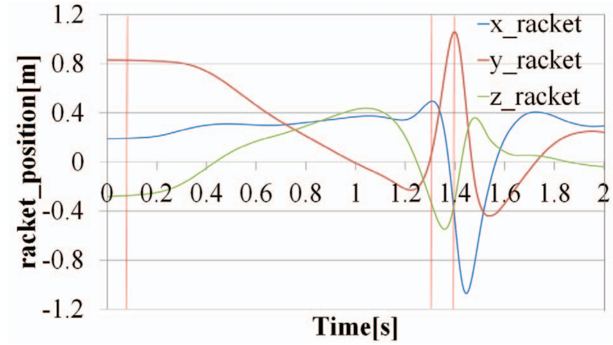


Fig. 7. Racket position of close swing by subject 1

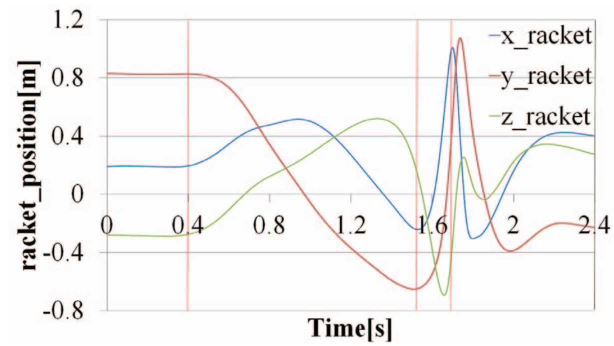


Fig. 8. Racket position of open swing by subject 1

From Fig. 7 and Fig. 8, the time of take back start t_1, swing start t_2 and hit t_3 were decided. Then the condition of each time t_i were defined as below.

$t_1 : |\dot{x}(t) \cup \dot{y}(t) \cup \dot{z}(t)| > 0.1$
t_2(close):$t > t_1 \cap \max x(t)$
t_2(open):$t > t_1 \cap \min y(t)$
t_3(close):$t > t_2 \cap \max y(t)$
t_3(open):$t > t_2 \cap \max x(t)$

2) Energy Transition: In this research, it was assumed that kinetic energy on xy plane make a ball to fly in forward direction and kinetic energy on z axis affect spin rate of the ball, then kinetic energy on xy plane of each link is compared. For energy in posture and shoulder, rotational energy is utilized. From Fig. 9 to Fig. 14 show energy transition of subject 1, 2 and 3. Red lines in figure represent the start of take back, swing and hit.

C. Consideration

In Fig. 9 and Fig. 12, results of most experienced subject, the similar tendency can be seen in both of open and close swing. Firstly, the energy of all parts rises just after take back start, and decreases before and after swing start. Next, the energy of left elbow, left wrist, body and shoulder reaches their peaks at almost same time. Then the energy peaks occur in order of right elbow, right wrist and racket. And finally, energy of right wrist increase for a moment again before swing is finish. From this result, in the swing of subject 1, it can be

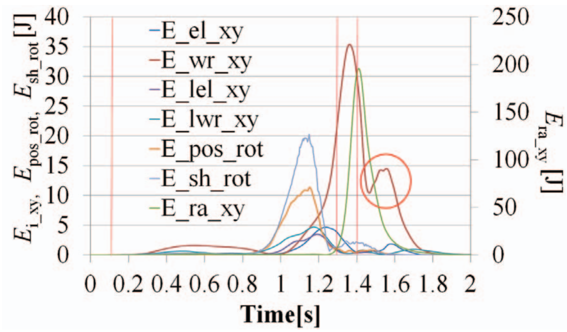


Fig. 9. Energy transition of close swing by subject 1

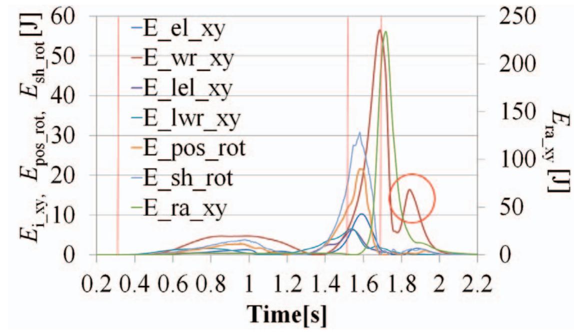


Fig. 12. Energy transition of open swing by subject 1

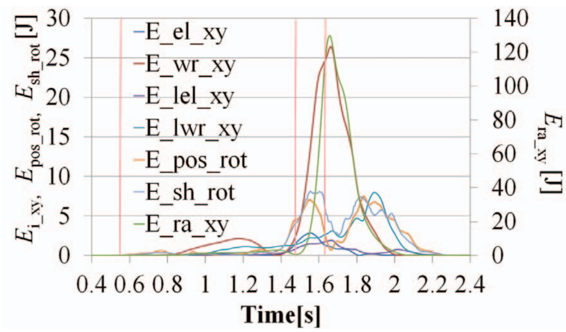


Fig. 10. Energy transition of close swing by subject 2

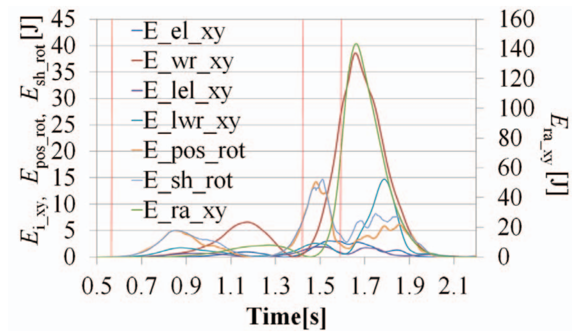


Fig. 13. Energy transition of open swing by subject 2

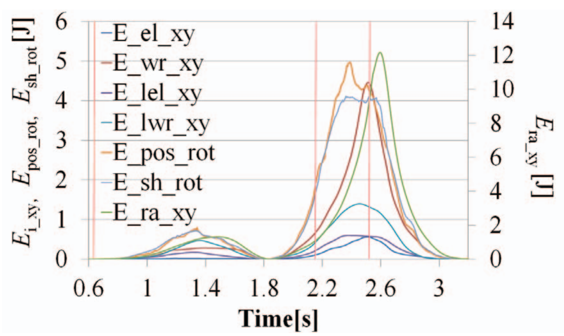


Fig. 11. Energy transition of close swing by subject 3

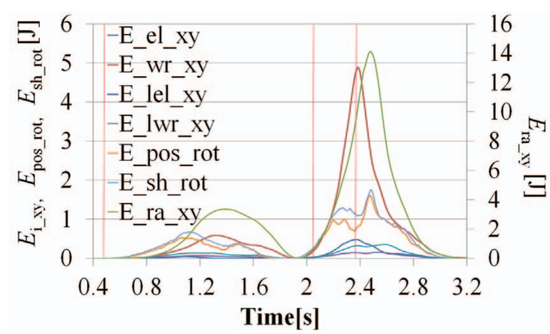


Fig. 14. Energy transition of open swing by subject 3

seen that energy transmit in order of left wrist, left elbow, body, right elbow and right wrist so that the energy in racket becomes biggest just before the hit. In this paper, it is assumed that appropriate swing, which all parts of upper body is used effectively and energy is transmitted effectively, has particular tendency like swing of subject 1. Thus, if energy displacement like subject 1 is observed in other subjects, their swing is appropriate forehand swing.

Then, in Fig. 10 and Fig. 13, the result of subject 2, the energy peaks of right elbow, body and shoulder are seen approximately at the same time at first. Afterwards, the energy peaks of right wrist and racket are seen approximately at the same time. And finally, the energy of left wrist reaches its peak. Therefore, it is confirmed that subject 2 can transmit the energy of body to right elbow, right wrist, racket. However, comparing the result of subject 1 and 2, the energy peaks of left elbow and left wrist are behind subject 1. From this results, subject 2 is not using left part of body well and not transmitting enough energy from left arm to body.

Finally, the result of subject 3 in Fig. 11 and Fig. 14 are considered. The energy of all parts reaches their peaks at almost same time. So subject 3 is not transmitting the energy from the left arm to body and also from body to right arm.

Next, it is considered that the motion lead to the increase of right wrist energy just before swing finish in the result of subject 1. However this is not seen in results of subject 2 and 3. The position and posture of human right wrist are affected by the movement of elbow joint and arm rotation. Fig. 15, Fig. 16, and Fig. 17 are shown about the position and rotation angle of right wrist in close swing. In Fig. 15, Fig. 16, and Fig. 17, there is only slight difference in the position of right wrist. However the rotation angle of right wrist between red line are difference. In Fig. 15, yaw angle turns over 180 degrees. In Fig. 16, yaw angle turns to only 60 degrees. In Fig. 17, yaw angle hardly turns. Therefore based on a supposition that the rotation angle of right wrist after hit cause the energy increasing just before swing finish, the close swing of subject 3 was re-measured again.

Fig. 18 and Fig. 19 are shown as re-measured close swing result of right wrist and energy transmit in subject 3. In Fig.

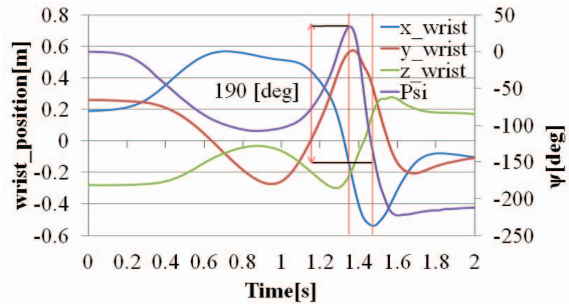


Fig. 15. Right wrist motion of close swing by subject 1

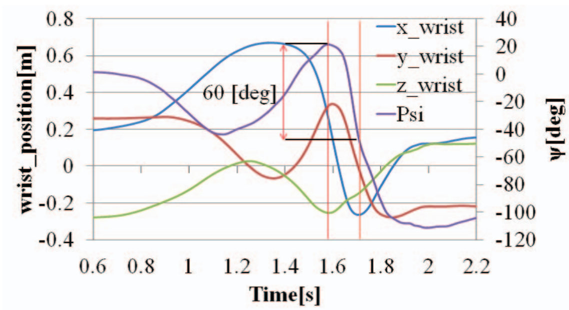


Fig. 16. Right wrist motion of close swing by subject 2

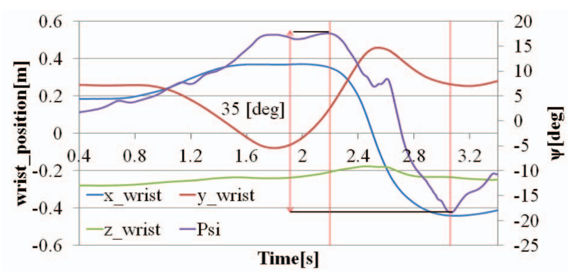


Fig. 17. Right wrist behavior of close swing by subject 3

18, yaw angle between red line is about 135 degrees. In Fig. 19, the energy of right wrist just before swing finish increase. Therefore twisting right wrist after hit increases the energy of right wrist just before swing finish.

V. Conclusion

In this research, forehand swing of tennis was measured with gyro sensors attached to upper body. Difference of energy displacement in xy plane between skilled and non-skilled person was confirmed through comparing the experimental results of forehand swing. Then, motion accounted for increase of the energy in right wrist just before swing finished was found. However the quantitative evaluation index about the energy rise in right wrist is not developed. For further research, analysis of motion accounted for increase for the energy is considered. Then, the quantitative evaluation index for forehand swing, which is evaluated by presence of motion, will be developed. In this paper, swing is evaluated only with energy in xy plane. However, energy in z axis and rotational energy must be considered in future research.

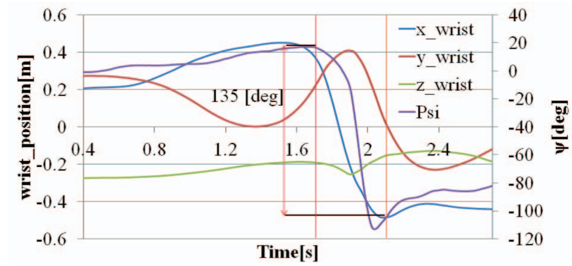


Fig. 18. Right wrist motion of re-mearsured close swing by subject 3

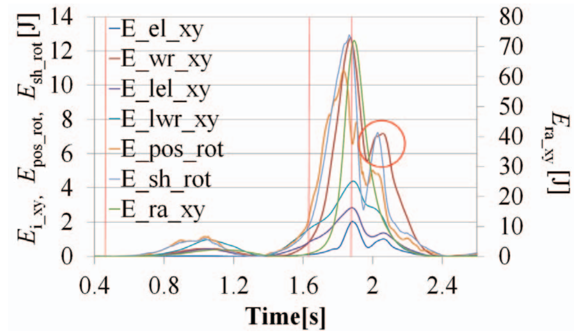


Fig. 19. Energy transition of re-mearsured close swing by subject 3

VI. Acknowledgments

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