A study on derivation method of motion feature points in sports motion analysis for racket matching

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Abstract
In this study, as part of efforts to assist beginners in sports such as tennis and badminton in selecting the most suitable equipment, an index for objectively evaluating such equipment is proposed. To accomplish this, standard swing trajectory variations are used to create an index from the viewpoint of human motion control. We begin by noting that human body data gained via motion capture are large in number because of the wide variety of equipment types used and due to the significant diversity of human body characteristics. Hence, even though motion capture devices are often used to capture swing motions, the most suitable human body segments for use in equipment evaluations have not yet been clarified. To facilitate this, it is necessary to reduce the overall number of body segments under consideration. In this paper, the method of deriving the feature points in sports motion was examined. More specifically, in order to obtain fundamental findings, tennis stroke and badminton smash motions are used as representative movements, and experiments using a motion capture device are performed. In the motion analysis that follows, we then investigate which markers can most clearly express the relationship between the racket and the human body in order to capture stroke motion characteristics. Then, an index of contribution is adapted to tennis swing and badminton smash motions, the motion feature points in the stroke and smash motion are derived, and the significant markers for motion analysis are identified and discussed.

Keywords: Sports engineering, Human motion, Tennis, Badminton

1. Introduction

Sports have long been deeply embedded in human society, and watching professional sports as entertainment has an extensive history. In modern society, in order to encourage more people of all ages to join and participate in sports actively, it is necessary to ensure they can obtain feelings of enjoyment and satisfaction by such participation. The level of competition is one of the factors that is directly related to such feelings. In sports that use equipment such as rackets, the choice of equipment is largely related to the athlete’s skill level. For example, if a player uses a racket that is not suitable for his or her skill level, the load on the body increases and player may not be able to play as anticipated.

In sports such as tennis, it is empirically known that when a player uses the most suitable racket, his or her swing speed increases, and the impact and rotation speed of the struck ball increase. This indicates that it is possible to increase the skill level by using the most suitable equipment. However, when selecting equipment, the sensation of swinging a racket or the feel that results from hitting a ball are often judged as good or bad based on the user's subjective opinion. Experts who have long familiarity with the handling characteristics of the equipment used in their sports can readily choose the most suitable types based on their experience, but it is extremely problematic for beginners who have just started participating in a new sport to select proper equipment based on their subjective judgment alone.

For this reason, in order to assist beginners in making their equipment choices, an index that can be used to evaluate such equipment objectively is necessary. In our research project, we has proposed an index that facilitates such evaluations by categorizing standard swing trajectory variations from the viewpoint of human motion control (Kawano et al., 2017)(Suzuki and Takehara, 2018)(Sekine et al., 2019). In this study, the trajectory variation of the each body segments of human as a performance of motion control with a racket is indexed using the sum of standard deviations. Then, the relation between this index and the swing speed is investigated. According to these results, the tendency that
the swing speed is higher in the racket with less trajectory variation is obtained. On the other hand, with an extremely heavy racket, the swing speed is high, but the trajectory variation greatly. This result shows that subject cannot be controlled. This indicates that from the viewpoint of racket matching, it is necessary to examine not only factors such as speed of rackets but also accuracy of swing motion. Here, even though motion capture systems are often used to measure swing motions, the optimal human body segments for use in such evaluations have not been clarified from the standpoint of equipment evaluations. This is because motion capture systems collect a wide variety of human body data and because there is significant diversity in human body characteristics. The number of combinations of rackets and each body segment is huge. Accordingly, it is necessary to reduce the number of body segments used when analyzing human motion. In addition, since the trajectory generation is based on the coupled motion of each segment, it is important to select the motion feature points which there is a difference depending on the change of equipments. Then, the cost of experiment and analysis time can be considered to be reduced.

To accomplish this, using tennis and badminton as representative sports that use rackets, we examined the derivation of sports motion feature points in order to obtain fundamental findings. We selected tennis stroke and badminton smash motions as representative movements. The reason for selecting these movements is that many evaluation items are concerned with these movements in psychological estimation of badminton and tennis players on rackets using evaluation grid method (Kasamatsu et al., 2017)(Suzuki et al., 2017). For these motions, experiments using a motion capture device were performed and the obtained three-dimensional coordinate values of the markers on each body part were analyzed.

In a motion analysis involving tennis or badminton strokes, it is necessary to investigate which markers can most clearly express the relationship between the racket and the human body in order to capture stroke motion characteristics. In a separate study involving baseball, Miyanishi proposed an index in which the ratio of the speed obtained by the rotational motion of each joint of the pitcher’s torso and arm contributed to the speed of the pitched ball, thus clarifying how each joint of the body contributes to ball velocity generation (Miyanishi et al., 1996). Koike proposed an equation of motion consisting of a joint torque term, a gravitational term, and a motion-dependent term consisting of centrifugal forces and Coriolis forces. It was shown that the contribution of each term greatly differs depending on which exercise is focused (Koike et al., 2019).

This present study aims to derive the motion feature points using the contribution of each body joint during each movement.

2. Experiment

In our experiment, 12 motion capture cameras (Optitrack, Prime13 and Prime13W) are used to measure tennis stroke and badminton smash motions. Sampling frequency of this camera is 240Hz. This performance is sufficient for swing motion because vibration of racket is not treated in this research. Record information about each part of the body by shooting at 200Hz. 37 markers are attached to subjects' body (Arczewski et al., 2010)(Bryan et al., 1984). The experimental setup is shown in Figure 1. First, the motion capture cameras are placed, as shown in Figure 1. In the tennis experiment, the test subject strikes a ball that is ejected from the automatic tennis ball machine towards the target as measurements are taken. Then the participating test is instructed to swing the racket to the end, the same way every time and aim at the center of the target. Then, the subject switches to a different racket and repeats the same motion. This process is repeated for six racket types, the results of which are taken as one measurement set. Next, the racket trial order is switched, and five more measurement sets are performed.

Similarly, in the badminton experiment, an experimenter throws a shuttle, and the test subject hits a smash toward a target installed at a height of 1.55 m from the floor as measurements are taken. Then, the subject switches to a different racket and repeats the same motion. This process is repeated for three racket types, the results of which are taken as one set. Next the racket trial order is switched and two more measurement sets are performed. Tables 1 and 2 show the rackets used, and Table 3 shows the characteristics of the participating test subjects. In Table 1, the swing weight is one of the important indicators when selecting a racket. The swing weight is calculated using the moment of inertia (Cross and Bower, 2006). The participating test subjects are 4 tennis players(Height: 1.77 ± 0.03m, weight: 62.0 ± 5.0kg, age: 19~45years old) and 12 badminton players(Height: 1.73 ± 0.1m, weight: 68.0 ± 15.0kg, age: 19~39years old). Here, the number of tennis subjects is 4, which is small for examining the generation of sports motion itself. However, 6 types of rackets were used for 4 subjects, and data for 18 trials was acquired for each racket, so the number of samples was 24 and the number of data was 432. For this reason, it is thought that the number of analysis data is enough in terms of deriving feature points for racket matching.
In this paper, one subject about tennis and three subjects about badminton are taken as an example as shown in Table 3, because all subjects have the same tendency about tennis, there are three types of tendency about badminton. This experiment was approved by the Ethics Committee on Sophia University's "Research for Humans" and all test subjects gave informed consent before participating in our experiments.

![Figure 1: Schematic drawing of tennis experiment.](image)

**Table 1** Tennis racket specifications. (Dunlop, 2019) (Wilson, 2019a, 2019b, 2019c) (Yonex, 2019b, 2019c).

|                    | Racket A | Racket B | Racket C | Racket D | Racket E | Racket F |
|--------------------|----------|----------|----------|----------|----------|----------|
| Surface [inch²]    | 100      | 97       | 100      | 100      | 97       | 105      |
| Length [inch]      | 27       | 27       | 27       | 27       | 27       | 27       |
| Weight [kg]        | 0.30     | 0.34     | 0.30     | 0.28     | 0.31     | 0.27     |
| Swing weight [kg • cm²] | 304 | 319 | 304 | 308 | 314 | 302 |
| Gravity center position [mm] | 320 | 305 | 320 | 335 | 310 | 330 |

**Table 2** Badminton racket specifications. (Yonex, 2019a).

|                    | Racket A | Racket B | Racket C |
|--------------------|----------|----------|----------|
| Length [m]         | 0.674    | 0.674    | 0.675    |
| Weight [kg]        | 0.083    | 0.083    | 0.093    |
| Gravity center position [m] | 0.320 | 0.300 | 0.285 |

**Table 3** Test subject characteristics.

| Subject | Height [m] | Weight [kg] | Handedness | Experience [years] | Age [years] |
|---------|------------|-------------|------------|--------------------|-------------|
| 1 (tennis) | 180     | 67          | Right      | 14                 | 23          |
| 2 (badminton) | 165     | 53          | Right      | 13                 | 20          |
| 3 (badminton) | 175     | 65          | Right      | 4                  | 20          |
| 4 (badminton) | 167     | 50          | Right      | 0                  | 22          |
3. Index of feature point contributions

In tennis and badminton swing motions, the energy and speed generated in each human body part are transmitted to the end body part (hand) in order to increase the energy and speed delivered to the racket (Ae and Fujii, 2002). Therefore, in the analysis of stroke motion and smash motion, it is important to clarify the influential motion of each body joint and their effects on swing velocity. In this paper, the index of contributions is adapted to tennis and badminton swing and smash motions. Regarding the contribution, there are basic methods of kinematics, and kinetics methods that requires contributions of a gravitational term and a motion-dependent term in addition to a joint torque term. This study does not focus on the generation of sports movements of the swing itself. In order to examine the difference that occurs when the racket is changed, the contribution is used for the purpose of deriving a point having a characteristic strongly related to the speed of the racket. Therefore, Miyanishi’s method (Miyanishi et al., 1996) is adopted as a method that is easy to derive and has low computational cost (Koike, 2013). Additionally, since the speed of the racket tip is affected by physical properties such as stiffness, this study focuses on the contact point between the human body and the racket, and then obtains the joint motion contribution of each joint on the athlete’s hand speed. In the paragraphs below, we explain the method for calculating the contribution by focusing on tennis strokes (Iino et al., 2008).

First, in order to calculate the angular velocity vector of each segment of an upper limb (torso, upper arm, forearm, and hand), a local coordinate system for each segment was defined using the three-dimensional coordinates of each body point. Figure 2 shows the local coordinate systems of the torso, upper arm, forearm, and hand. In that figure, points i, j, and k represent the unit vectors in each axis direction in the local coordinate system, and the subscripts 1, 2, 3, and 4 represent the torso, upper arm, forearm, and hand, respectively. The positions of the hip (HIP), shoulder joint (SH), elbow joint (EL), and wrist joint (WR) are defined as shown in Fig. 2. Markers are attached to the shoulder joint (SH), elbow joint (EL), and wrist joint (WR). The hip (HIP) is calculated from markers placed on the left and right of the pelvis. The local coordinate system defined for the torso (Fig. 2a) uses the vector from point HIP to point CH as the Z₁ axis and obtains the Y₁ axis from the outer product of this vector and the vector from point HIP to point SH. Then, the coordinate system is defined so that each axis satisfies the orthogonal condition by obtaining the X₁ axis from the outer product of the Y₁ axis and the Z₁ axis. Similarly, in the local coordinate system defined for the upper arm (Fig. 2b), the vector from point EL to point SH is defined as the Z₂ axis, the vector obtained from the outer product of the vector from point EL to point WR and the Z₂ axis is defined as the X₂ axis, and the vector obtained by the outer product of the X₂ axis and the Z₂ axis is defined as the Y₂ axis. In the local coordinate system of the forearm (Fig. 2c), the vector from point WR to point WR₂ is defined as the X₃ axis, the vector from point WR to point EL is defined as the Z₃ axis, and the vector obtained by the outer product of the Z₃ axis and X₃ axis is defined as the Y₃ axis. For the local coordinate system of the hand (Fig. 2d), the vector from point F to point WR is defined as the Z₄ axis, the vector obtained by the outer product of the Z₄ axis and the X₄ axis is defined as the Y₄ axis, and the vector obtained by the outer product of the Y₄ axis and the Z₄ axis is defined as the X₄ axis.

Next, the angular velocity vector of each segment was calculated by differentiating the unit vectors \( \mathbf{i}_l, \mathbf{j}_l, \mathbf{k}_l \) of each segment in time. The following equation (1) is obtained by differentiating the unit vector in each axis direction of the local coordinate system with respect to time.

\[
\frac{d\mathbf{i}_l}{dt} = \mathbf{\hat{ω}}_l \times \mathbf{i}_l \\
\frac{d\mathbf{j}_l}{dt} = \mathbf{\hat{ω}}_l \times \mathbf{j}_l \\
\frac{d\mathbf{k}_l}{dt} = \mathbf{\hat{ω}}_l \times \mathbf{k}_l
\]

(1)

where \( \mathbf{\hat{ω}}_l = \mathbf{\hat{ω}}_{ix} \mathbf{i}_l + \mathbf{\hat{ω}}_{iy} \mathbf{j}_l + \mathbf{\hat{ω}}_{iz} \mathbf{k}_l \). \( \mathbf{\hat{ω}}_l \) is the angular velocity vector in the local coordinate system of segment \( l \).
The component around each axis of the angular velocity vector of segment $l$ can be obtained from equation (2).

$$
\vec{ω}_{lx} = k_l \cdot \frac{dj_l}{dt}
$$

$$
\vec{ω}_{ly} = i_l \cdot \frac{dk_l}{dt}
$$

$$
\vec{ω}_{lz} = j_l \cdot \frac{dl_l}{dt}
$$

Since the angular velocity vector of segment $l$ obtained by equation (2) is the angular velocity vector in the local coordinate system, it was converted to the angular velocity vector in the global coordinate system via a transformation matrix. The transformation matrix can be derived from the unit vector in each axis direction of the local coordinate system (Wadati, 1983). Next, in order to express the angular velocity of each body segment in the global coordinate system as the angular velocity of each joint, the local coordinate system at each body joint was defined. Figure 3 shows the local coordinate systems defined for the hip (HIP), shoulder joint (SH), elbow joint (EL), and wrist joint (WR). $i_{lj}$, $j_{lj}$, and $k_{lj}$ indicate the unit vectors of the local coordinate system at the joint at the bottom of segment $l$. In the local coordinate system defined for the waist (Fig. 3a), the vector from point HIP to point CH is the $Z_{lj}$ axis (reference axis). The $Y_{lj}$ axis was obtained from the outer product of this vector and the vector from point HIP to point SH. In addition, by defining the $X_{lj}$ axis from the outer product of the $Y_{lj}$ and $Z_{lj}$ axes, the coordinate system was defined so that each axis satisfies the orthogonal condition. Similarly, in the local coordinate system defined for the shoulder joint (Fig. 3b), the vector from point EL to point SH is defined as the $Z_{2lj}$ axis, and the vector obtained by the outer product of the $Z_{2lj}$ axis and the vector from point HIP2 to point SH is defined as the $X_{2lj}$ axis. The vector obtained by the outer product of the
The $Z_{2j}$ axis and the $X_{2j}$ axis is the $Y_{2j}$ axis. In the local coordinate system defined for the elbow joint (Fig. 3c), the vector from point WR2 to point EL is defined as the $Z_{3j}$ axis, and the vector obtained by the outer product of the vector from point EL to point SH and the $Z_{3j}$ axis is defined as the $X_{3j}$ axis. The vector obtained by the outer product of the $X_{3j}$ axis and the $Z_{3j}$ axis is defined as the $Y_{3j}$ axis. In the local coordinate system defined for the wrist joint (Fig. 3d), the vector from point F to point WR is the $Z_{4j}$ axis, and the vector obtained by the outer product of the $Z_{4j}$ axis and the vector from point WR to point WR2 is the $Y_{4j}$ axis. The vector obtained by the outer product of the $Y_{4j}$ axis and the $Z_{4j}$ axis is defined as the $X_{4j}$ axis (The Japanese Orthopaedic Association, 1995).

Next, the torso angular velocity vector $\omega_1$ in the global coordinate system, the upper arm relative angular velocity vector $\omega_{2/1}$, the forearm relative angular velocity vector $\omega_{3/2}$, and the hand relative angular velocity vector $\omega_{4/3}$ were obtained by projecting those values onto each axis of the local coordinate system of each joint. As an example, the angular velocity vector of torso region is shown. Projected angular velocity vectors are shown as equation (3).

\[
\begin{align*}
\omega_{(1)x} &= (\omega_1 \cdot i_{1j})i_{1j} \\
\omega_{(1)y} &= (\omega_1 \cdot j_{1j})j_{1j} \\
\omega_{(1)z} &= (\omega_1 \cdot k_{1j})k_{1j}
\end{align*}
\]

(3)

where $\omega_1 = \omega_{(1)x} + \omega_{(1)y} + \omega_{(1)z}$. $i_{1j}$, $j_{1j}$ and $k_{1j}$ are the unit vectors on the local coordinate system of torso joint. The angular velocity vector of each segment of the body in the global coordinate system as the angular velocity of each joint, the local coordinate system for each joint of the body is defined.

Next, based on the Sprigings method (Sprigings et al., 1994), the hand velocity $V_F$ generated by the joint motion of each segment of the lower limb and upper limb is obtained from equation (4).
\[
V_F = V_{HIP} + V_{SH/HIP} + V_{EL/SH} + V_{WR/EL} + V_{F/WR} \tag{4}
\]

\( V \) is the velocity vector, and the subscripts \( HIP, SH, EL, WR, \) and \( F \) are the waist, shoulder joint, elbow joint, wrist joint, and hand, respectively. \( V_{HIP} \) is the velocity vector of the lower end of the torso obtained by the motion of the lower limbs. \( V_{SH/HIP}, V_{EL/SH}, V_{WR/EL}, \) and \( V_{F/WR} \) are the relative velocity vectors of adjacent segments. When each term on the right-hand side of equation (4) is transformed using the angular velocity vector of each segment the angular velocity vector of each segment, equation (5) is obtained.

\[
V_F = V_{HIP} + \omega_1 \times r_{SH/HIP} + \omega_2 \times r_{EL/SH} + \omega_3 \times r_{WR/EL} + \omega_4 \times r_{F/WR} \tag{5}
\]

As an example, \( r_{SH/HIP} \) is the relative position vector of point SH viewed from point HIP. Each relative position vector can be replaced, as shown in equation (6).

\[
\begin{align*}
    r_{SH/HIP} &= r_{F/HIP} - r_{F/SH} \\
    r_{EL/SH} &= r_{F/SH} - r_{F/EL} \\
    r_{WR/EL} &= r_{F/EL} - r_{F/WR}
\end{align*} \tag{6}
\]

Substituting equation (6) into equation (5) and summing up \( r \) yields equation (7).

\[
V_F = V_{HIP} + \omega_1 \times r_{F/HIP} + \omega_2 \times r_{F/SH} + \omega_3 \times r_{F/EL} + \omega_4 \times r_{F/WR} \tag{7}
\]

Equation (7) shows that the hand velocity is the vector sum of the velocity vector generated by the lower limb motion, the velocity vector obtained by the outer product of the angular velocity vector generated by the motion of each joint of the upper torso, and the relative position vector from each joint to the hand. In addition, considering the joint degree of freedom by using equation (3) and expressing equation (7) as the angular velocity vector of each joint allows the following equation (8) to be obtained. Considering the degree of freedom of joints, the joints angular velocities of are not independent of each other. As shown in Fig. 3 (b) and (c), the Z-axis of the shoulder joint coordinate system and the x-axis of the elbow joint coordinate system completely coincide with each other when the elbow joint is 90 deg bent. This indicates that the component becomes zero when \( \omega_{(3/2)} \) is projected onto the x-axis of the elbow joint coordinate system. Similarly, for \( \omega_{(4/3)} \), the component projected onto the z-axis of the wrist joint coordinate system is zero.

\[
V_R = V_{HIP} + (\omega_{(1)x} + \omega_{(1)y} + \omega_{(1)z}) \times r_{F/HIP} + (\omega_{(2/1)x} + \omega_{(2/1)y} + \omega_{(2/1)z}) \times r_{F/SH} + (\omega_{(3/2)x} + \omega_{(3/2)y}) \times r_{F/EL} + (\omega_{(4/3)x} + \omega_{(4/3)y}) \times r_{F/WR} \tag{8}
\]

The velocity component \( V'_l \) in the direction of the combined hand velocity vector is calculated by projecting the hand velocity generated by the lower limb movement and the rotational movement of each upper limb joint in the direction of the combined hand velocity vector. Figure 4 shows a schematic diagram that defines the contribution of each lower and upper limb segment at any moment during the stroke movement. In this study, we focus on the velocity component \( V'_l^+ \) in the positive direction with respect to the resultant velocity vector direction of \( V'_l \). The ratio of \( V'_l^+ \) was defined as a...
“contribution”. The following equation (9) shows the calculation equation for the contribution of each joint to the stroke movement.

\[
\text{Contribution(\%)} = \frac{|V_{l}^{+}|}{|V_{F}^{+}|} \times 100
\]  

(9)

Fig. 4 Schematic diagram of the calculation for the contribution. Schematic diagram of definition of contribution of each segment of lower limb and upper limb at any moment during stroke movement. \(V_{F}^{+}\) is a composite of all positive velocity vectors \(V_{2}^{+}, V_{3}^{+}, V_{4}^{+}, V_{5}^{+}\), and their contributions were calculated using them. \(V_{r}^{+}, V_{l}^{+}, V_{w}^{+}, V_{h}^{+}\) are the velocities obtained from the motions. In this study, we focused on the velocity component \(V_{l}^{+}\) toward the positive direction with respect to the combined velocity vector direction of the hand.

4. Results and Discussion

4.1 Contributions and motion feature points in tennis

In this section, the contributions of each joint to the stroke motion are considered, and the movement feature points are derived. The contribution was calculated from the stroke motion start time to the impact time (the time when the racket hits the ball). The stroke motion start time is the time when the takeback operation (the preparatory operation of pulling the racket backward in order to create the posture needed to swing the racket) is completed, and 0.5 seconds before the impact time.

As an example, Figure 5 shows the time history of the hand speed of Test Subject 1 when using each racket and the hand speed of each joint in the direction of the combined speed vector. Here, it can be seen that the hand speed was generated mainly by the rotational motion of the lower back from around 0.4 seconds immediately after the takeback. After that, it was confirmed that the speed is generated by the rotation of the shoulder joint from around 0.4 seconds. This tendency was found to be common for all test subjects. In addition to the above, our examination of this subject confirms the generation of hand speed due to the rotation of the wrist joint from around 0.45 seconds. In other words, it was found that rotational energy is generated by the torso, which is the center of the body, and that it is transmitted in sequence toward the end of the body (upper arm, hand). In addition, it was found that the experienced subject uses the rotation of the wrist joint immediately before the impact to accelerate the swing speed, but it is very small compared to the rotational movement of the shoulder joint. This tendency is not found in inexperienced subjects. Taking Test Subject 1 as an example, a five-trial average value of the contribution of each joint when using each racket at the impact time is shown in Table 4. Here, it can be seen that, in common with all the other test subjects, the shoulder joint rotational
movement contribution is the highest regardless of the racket used. Then, it is found that the shoulder joint rotational motion is the most important contributor to swing speed near the impact in the tennis stroke motion. Furthermore, since the contribution of the elbow joint rotational motion is very low, the tennis stroke motion can be considered to be an upper limb swing motion centered on the shoulder joint. The characteristic feature of the stroke motion is the wrist, which is located at the end of the upper limb. Moreover, although the contribution ratio of each joint does not change significantly, it is confirmed that there is a difference in the contribution of each racket in each joint. From these results, it is found that one motion feature point for racket matching can be derived by using the contribution.

![Diagram](image)

Fig. 5 Time history of velocity created by the lower limbs and each joint in the direction of the velocity of the right hand (Subject 1). It can be confirmed that the velocity is generated mainly by the rotational movement of the hips from immediately after takeback to around 0.4 seconds, and then from about 0.4 seconds by the rotation of the shoulder joint. The generation of hand speed due to rotation of the wrist joint can be confirmed from around 0.45 seconds. In other words, it was found that rotational energy was generated by the torso, which is the center of the body, and was transmitted in sequence toward the end of the body (upper arm, hand).

| Racket  | Lower limbs [%] | Torso joint [%] | Shoulder joint [%] | Elbow joint [%] | Wrist joint [%] |
|---------|-----------------|-----------------|--------------------|----------------|----------------|
| A       | 6.3             | 35.7            | 42.6               | 1.2            | 14.1           |
| B       | 8.0             | 32.0            | 37.3               | 0.0            | 22.7           |
| C       | 7.3             | 34.7            | 41.0               | 0.7            | 16.4           |
| D       | 7.6             | 32.1            | 40.0               | 2.7            | 17.7           |
| E       | 8.8             | 30.2            | 37.7               | 0.9            | 22.3           |
| F       | 7.6             | 33.3            | 39.4               | 1.2            | 18.5           |

Table 4 Contributions of lower limbs and joints. (Subject 1).
4.1.2 Contributions and motion feature points in badminton

Next, we consider the contribution of each joint to the badminton smash motion and derive the motion feature points. First, the contribution of each joint to the smash movement of an experienced badminton athlete is explained. As an example, Figure 6 shows the time history of the speed of each hand and joint when Test Subject 2 is using each racket. From this figure, it can be seen that the hand speed reaches its maximum just before impact. Next, for each racket, we calculated the five-trial average value of the contribution of each joint at the time when the hand speed was maximum.

The results are shown in Table 5, where it can be confirmed that the contributions of the lower limbs and body are very low, and the upper arm and forearm contributions are high. It can also be seen that although the forearm contributes the most for any swing motion, the flexion and extension of the elbow joint are also important to swing speed generation. The same tendencies were observed for four other experienced subjects, and only Test Subject 3 showed different tendencies. From these results, it can be seen that the motion of the upper arm and the torso contributed significantly to the hand speed. The differences noted for Test Subject 3, who is the least experienced badminton player, are thought to be because he/she was a tennis player before taking up badminton as a sport. In the Sprigings study (Sprigings et al., 1994), it was shown that the flexion and extension motion of the elbow joint did not contribute significantly to the tennis serve action swing speed. From this, we can presume that Test Subject 3’s smash motions were significantly influenced by his previous experience as a tennis player, which led to the results described above. From this, the subject 3 thinks that badminton’s smashing motion had a great influence on the swinging movement that he gained during the tennis player era, and the results are as above.

![Fig.6 Time history of velocity of hand and joints (Subject 2). The velocity of the hand reaches its maximum just before impact. The movement of the upper arm and torso greatly contributes to the velocity of the hand. It was found that the forearm contributes the most to the swing motion, and elbow joint flexion and extension movements are important to generate swing speed.](image)

| Table 5 Contributions of lower limbs and joints. (Subject 2) |
|-------------------------------------------------------------|
| **Lower limbs [\%]** | Torso[\%] | Upper arm[\%] | Forearm[\%] | Hand[\%] |
|----------------------|-----------|---------------|--------------|---------|
| Racket A             | 2.3       | 4.3           | 35.1         | 56.1    | 2.2     |
| Racket B             | 1.0       | 3.3           | 33.7         | 58.1    | 4.0     |
| Racket C             | 1.7       | 8.1           | 26.3         | 62.2    | 1.6     |

| Table 6 Contributions of lower limbs and joints. (Subject 3) |
|-------------------------------------------------------------|
| **Lower limbs [\%]** | Torso[\%] | Upper arm[\%] | Forearm[\%] | Hand[\%] |
|----------------------|-----------|---------------|--------------|---------|
| Racket A             | 2.8       | 19.1          | 55.0         | 19.1    | 4.0     |
| Racket B             | 1.4       | 20.1          | 59.4         | 8.9     | 10.1    |
| Racket C             | 2.5       | 23.5          | 63.7         | 8.0     | 2.4     |
Table 7 Contributions of lower limbs and joints. (Subject 4)

|       | Lower limbs (%) | Torso (%) | Upper arm (%) | Forearm (%) | Hand (%) |
|-------|-----------------|-----------|---------------|-------------|----------|
| Racket A | 2.6             | 31.5      | 40.8          | 14.5        | 10.7     |
| Racket B | 1.5             | 25.2      | 48.9          | 18.4        | 6.0      |
| Racket C | 2.3             | 32.3      | 46.5          | 5.8         | 13.1     |

Next, the contributions of each body part of the inexperienced subjects are discussed. From Table 7, we can see that the upper arm and torso motions contributed significantly to the creation of hand speed for Test Subject 4. The same tendency can be seen when the speed is at its maximum. It can also be seen that the body and forearm motions of Test Subject 4 contributed more to his hand speed than in the case of Test Subject 3. This is because Test Subject 4 is an experienced baseball player and Miyanishi’s study has shown that, during a baseball throwing motion, the contribution of each joint to the ball speed at the time of ball release is highest for the upper arm (Miyanishi et al., 1996), whereas the contribution of the torso is about 20% and the contribution of the forearm is about 18%. The contribution values of Test Subject 4 were found to be almost the same. In fact, all of the inexperienced subjects in this study showed the same tendencies as experienced Test Subject 3 or inexperienced Test Subject 4. Accordingly, the upper arm contribution is calculated to be particularly high in the case of inexperienced subjects.

Based on the above, we found that, in the case of some experienced subjects, the forearm made the highest contribution of the forearm, so the motion feature point is the wrist, which is at the end of the forearm. In contrast, for Test Subject 3 and other inexperienced players, the upper arm contribution is the highest, so the motion feature point is the elbow, which is located at the end of the upper arm. It is found that there is a difference in the contribution of each racket in each joint as well as results of tennis. From these results, it is found that two motion feature points for racket matching can be derived by using the contribution.

5. Conclusion

In this study, focusing on the swing motion differences that result from the use of different rackets, we attempted to derive the motion feature points that most clearly express those differences. By applying an index of contribution, we were able to identify motion feature points related to tennis swing and badminton smash motions. First, in regards to tennis swing movements, the contributions made by the shoulder joint rotational motion were found to be the highest. This indicates that the shoulder joint rotational motion is the most important for producing the swing speed close to impact in the tennis stroke motion. Furthermore, since the contribution of the elbow joint rotational motion is very low, the tennis stroke motion can be regarded as an upper limb swing motion centered on the shoulder joint. Here, it should be noted that the wrist can be cited as one movement feature point of the stroke motion.

In badminton smash motion, although the upper arm and forearm were found to contribute significantly, flexion and extension motions of the elbow joint were also found to be important for generating swing speed. The experienced test subject showed that the most salient motion feature point is the wrist, which is located at the end of the forearm, because the contribution of the forearm is the highest. On the other hand, the highest contribution for inexperienced test subjects was the upper arm, so the movement feature point in those cases is the elbow, which is located at the end of the upper arm. In other words, for badminton, the above two points must be considered in addition to the wrist joint, and it is desirable to investigate their effects on the racket. These results shows that the motion feature points differ depending on each sport and the players’ experience levels, and it is clear that the results reported in this paper may show suitable points for investigating the relationship between sports rackets and human motions.

From the above results, we have shown that by determining the feature points of sports motion using equipment like rackets, the number of segments to be analyzed can be reduced. In other words, it is possible that the influence of the tool on motion control can be easily investigated. This can be said to be a useful result since it indicates the relationship between humans and their tools can be demonstrated by observing just a few feature points, without the need to measure the whole body, even when conducting measurements with motion capture devices. In the future, in consideration of the results obtained from this study, we plan to increase the accuracy of the index creation for tool selection by increasing the number of test subjects.
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