An Analysis of the Biomechanics of Arm Movement During a Badminton Smash

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Abstract

In badminton, it will be of great interest to study the mechanics involved in the overhead smash, particularly, in identifying the key contributors to a powerful smash. This study aims at identifying the contributions of each segmental rotations of the arm in producing the resultant racket head speed. The contribution of the rotations of each segment of the arm was computed using three dimensional kinematic method algorithm presented by Sprigings et al. (1994). A set of orthogonal unit vectors for each of the three segment of upper limb was established for computing the anatomical rotational velocities. Reflective markers were attached to the subjects during the execution of the smash. The smashing movement was then recorded on video. The data obtained for the analysis was based on 7 subjects. The results obtained indicated that the contribution of the upper arm internal rotation is the most significant followed by the contribution of the internal rotation of forearm. The hand flexion makes the third contribution. The difference in the measured value of the resultant racket head speed and calculated speed was small.

Keywords: angular velocity, arm segment rotation, racket head speed, kinematic

Introduction

In badminton, the most commonly used stroke is the overhead smash. It is the standard of execution of this stroke that determines the advantage of a player over another. Badminton is one of the most popular racket sports in the world. However, there is still a lack of scientific research done on this sport as compared to other sports such as swimming or soccer. There are relatively little scientific investigations on how a badminton smash is executed. It will be of great interest for sports scientists or badminton coaches to study the mechanics involved in the overhead smash. This would provide information that will enhance the performance of smashes in badminton.

There are a few descriptive studies on the overhead badminton smash. The earlier biomechanical analyses of the badminton smash are usually qualitative in nature, whereby cinematography was used to analyze the performances of the athlete. Tang, et al. (1995) and Tsai and Huang (1998) were among the pioneers to analyze this movement using Direct Linear Transformation (DLT) on images recorded by high-speed cameras. Both studies examined the pronation/supination angle at the radio-ulna joint, flexion angles at the wrist joint, and racket angle (the angle between the forearm and racket shaft). The two studies concluded that pronation of the radio-ulna joint were the most significant with the largest range and the shortest time among the three rotations of the upper limb. Tsai and Huang (1998) also compared the performance of the smash between elite and collegiate players. They found that the shuttlecock velocities were significantly higher for the elite players. They also reported that the flight trajectory of shuttlecock in smashes were significantly steeper for the elite players as compared to the collegiate players. They concluded that the elbow angular velocity might have an influence on the faster shuttlecock velocity of the elite player. However they did not provide information describing the contributions of the longitudinal rotation of the arm segments to the resultant speed of the shuttlecock. They have only specified one point at each articulation, thus making it impossible to obtain the contributions of the rotation of the arm segments along the longitudinal axis to the resultant speed of the shuttlecock. Hence, the longitudinal rotations of different arm segments as well as the differences in the angles of each segment's rotation were not explored.

Sprigings et al. (1994) have developed a kinematic model for determining the effectiveness of the arm segment rotation along the longitudinal axis in producing racket head speed. In their model, they have located two points at each articulation. They have chosen tennis to illustrate the methodology. They found that the upper-arm internal rotation contributed most to the resultant speed of the racket head. They also found that wrist flexion has an effect of the racket head speed but it was to a lesser extent than the internal rotation.

Elliot et al. (1995) and Elliot et al. (1996) also investigated on the contribution of segment rotations. However, these studies are applied to racket sports such as tennis and squash. Elliot et al. (1995) used Sprigings' algorithm to compute the contributions of segmental rotations in tennis serve. They found that the internal rotation velocity of the upper arm has produced the greatest contribution (54.2%) to the racket head velocity. The hand flexion contributed about 30.6% to the racket head velocity. Elliot et al. (1996) also applied Sprigings' algorithm to squash forehand stroke and they found that the internal rotation of the upper arm contributed 46.1% of the resultant racket head speed and the hand flexion contributed 18.2%.

Although the swing pattern for racket sports may be generally similar in nature but there are a number of factors that can contribute to a difference in results in the different racket sports. For example, the nature of the ball used, the tension of the string of the rackets and the method of executing the movement in the different racket sports. In tennis, the impact of a fast moving two-ounce ball on a heavy fifteen-ounce racket needs a locked wrist. Not so with a featherweight shuttle. The contribution of the wrist movement to the final racket head speed in badminton should differ from that in tennis.

The main purpose of this study is to identify the key contributor to the speed of the shuttlecock in badminton overhead smash. In order to identify the key contributor the movement of the arm in badminton overhead smash must be systematically observed and described. The rotation of the upper and lower arm and its contributions to the speed of the racket and the shuttlecock must be accurately quantified.

Methods

This investigation uses mainly a kinematic approach. There will be no consideration to the amount of force that is exerted by each player. The subjects chosen for the study are female members of Singapore national badminton team. To observe the arm movement of the badminton smash reflective markers were placed on the skin at key locations on subjects' arm. The locations of the reflective markers are shown in

Figure 1 and listed in Table 1. A, B, C, D, E, F, G, H are surface landmarks on the three segments. However, surface landmarks are not the best way to describe the movement of the segments, as it is the skeleton that acts as the center of the leverage system. Therefore, it is necessary to compute the midpoints between the surface markers. W, X, Y, Z, K are the computed midpoints. Anatomical position was defined at fundamental position. This position resembles to the military ‘stand to attention’ position. The anatomical position is similar to fundamental position except that the forearm has been supinated from the neutral position of the fundamental position so that the palm of the hand is facing forwards.

For the upper arm, the origin of the axis system is located at the shoulder joint. The three unit vectors are first defined at distal end of the humerus based on the assumption that the rotation of the upper arm through the axes with origins at the distal end of the humerus fits most closely to the rotation of the upper arm about a parallel axis through the shoulder joint and subsequently translated to the shoulder joint.

The first unit vector $\mathbf{P_{1L}}$ is defined to be along the longitudinal axis. It is represented by:

$$\mathbf{P_{1L}} = \frac{\mathbf{r_{X/W}}}{|\mathbf{r_{X/W}}|} \tag{1}$$

The second unit vector $\mathbf{P_{1AA}}$ is constructed perpendicular to $\mathbf{P_{1L}}$. At the anatomical position, the unit vector $\mathbf{P_{1AA}}$ represents the direction of the rotation axis for abduction and adduction of the upper arm.

$$\mathbf{P_{1AA}} = \frac{\mathbf{P_{1L}} \times \mathbf{r_{D/X}}}{|\mathbf{P_{1L}} \times \mathbf{r_{D/X}}|} \tag{2}$$

The third unit vector $\mathbf{P_{1FE}}$ is orthogonal to both $\mathbf{P_{1L}}$ and $\mathbf{P_{1AA}}$. It represents the rotation axis of the extension and flexion of the upper arm at the anatomical position.

$$\mathbf{P_{1FE}} = \frac{\mathbf{P_{1AA}} \times \mathbf{P_{1L}}}{\left|\mathbf{P_{1AA}} \times \mathbf{P_{1L}}\right|} \tag{3}$$

$\mathbf{P_{1AA}}$ and $\mathbf{P_{1FE}}$ are fixed to the segment but they are located at the humeral-ulna joint. One can define these two axes through the shoulder joint but due to the complexity of the shoulder joint and also difficulty in attaching the reflective markers, these 2 axes are located at humeral-ulna joint.

Having defined the three axes on the upper arm, we find the relative velocity of point D from point X, $\mathbf{V_{D/X}}$ can be calculated from the digitized data. Then the component of the velocity tangential to $\mathbf{r_{D/X}}$, $V_{t(D/X)}$ can be found by taking a dot product of $\mathbf{V_{D/X}}$ with unit vector $\mathbf{P_{1AA}}$.

$$V_{t(D/X)} = \mathbf{V_{D/X}} \bullet \mathbf{P_{1AA}} \tag{4}$$

Then the magnitude of longitudinal angular velocity of the upper arm, ω_{1L} can be found.

$$\omega_{1L} = V_{t(D/X)} / \left|\mathbf{r_{D/X}}\right| \tag{5}$$

And the vector is

$$\boldsymbol{\omega}_{\mathbf{1L}} = \omega_{1L} * \mathbf{P_{1L}} \tag{6}$$

Let $\boldsymbol{\omega}_{\mathbf{1}}$ be the total absolute angular velocity of the upper arm as

$$\boldsymbol{\omega}_{\mathbf{1}} = \omega_{1AA} * (\mathbf{P_{1AA}}) + \omega_{1FE} * (\mathbf{P_{1FE}}) + \omega_{1L} * (\mathbf{P_{1L}}) \tag{7}$$

Using the relationship of

$$\mathbf{V_{X/W}} = \boldsymbol{\omega}_{\mathbf{1}} \times r_{\mathbf{X/W}} \tag{8}$$

$$\mathbf{V}_{\mathbf{X/W}} = \omega_{1AA} * (\mathbf{P}_{\mathbf{1AA}} \times \mathbf{r}_{\mathbf{X/W}}) + \omega_{1FE} * (\mathbf{P}_{\mathbf{1FE}} \times \mathbf{r}_{\mathbf{X/W}}) + \omega_{1L} * (\mathbf{P}_{\mathbf{1L}} \times \mathbf{r}_{\mathbf{X/W}}) \tag{9}$$

Next, take the scalar product of the above equation with unit vector $\mathbf{P}_{\mathbf{1AA}}$. An expression of $\boldsymbol{\omega}_{\mathbf{1FE}}$ will be obtained as

$$\boldsymbol{\omega}_{\mathbf{1FE}} = \frac{\mathbf{P}_{\mathbf{1AA}} \bullet \mathbf{V}_{\mathbf{X/W}}}{\mathbf{P}_{\mathbf{1AA}} \bullet (\mathbf{P}_{\mathbf{1FE}} \times \mathbf{r}_{\mathbf{X/W}})} * \mathbf{P}_{\mathbf{1FE}} \tag{10}$$

And taking the scalar product with unit vector $\mathbf{P}_{\mathbf{1FE}}$ will yield an expression for $\boldsymbol{\omega}_{\mathbf{1AA}}$ as

$$\boldsymbol{\omega}_{\mathbf{1AA}} = \frac{\mathbf{P}_{\mathbf{1FE}} \bullet \mathbf{V}_{\mathbf{X/W}}}{\mathbf{P}_{\mathbf{1FE}} \bullet (\mathbf{P}_{\mathbf{1AA}} \times \mathbf{r}_{\mathbf{X/W}})} * \mathbf{P}_{\mathbf{1AA}} \tag{11}$$

The directions of the two vectors $\boldsymbol{\omega}_{\mathbf{1AA}}$ and $\boldsymbol{\omega}_{\mathbf{1FE}}$ are coincident with the abduction/adduction axis and flexion/extension axis through the shoulder joint.

For the forearm, the origin is located at the humeral-ulna joint. The three unit vectors are defined as similar to the upper arm. $\mathbf{P}_{\mathbf{2FE}}$ is defined as the unit vector through the elbow and fixed to the distal end of the humerus while $\mathbf{P}_{\mathbf{2L}}$ is fixed onto the forearm.

$$\mathbf{P}_{\mathbf{2L}} = \frac{\mathbf{r}_{\mathbf{Y/X}}}{|\mathbf{r}_{\mathbf{Y/X}}|} \tag{12}$$

$$\mathbf{P}_{\mathbf{2VV}} = \frac{\mathbf{P}_{\mathbf{2L}} \times \mathbf{P}_{\mathbf{1FE}}}{|\mathbf{P}_{\mathbf{2L}} \times \mathbf{P}_{\mathbf{1FE}}|} \tag{13}$$

$$\mathbf{P}_{\mathbf{2FE}} = \frac{\mathbf{P}_{\mathbf{2VV}} \times \mathbf{P}_{\mathbf{2L}}}{|\mathbf{P}_{\mathbf{2VV}} \times \mathbf{P}_{\mathbf{2L}}|} \tag{14}$$

Next, the angular velocities at the respective axis are calculated using the methods similar to the upper arm.

$$\omega_{2L} = \frac{V_{t(F/Y)}}{|\mathbf{r}_{\mathbf{F/Y}}|} \tag{15}$$

where

$$V_{t(F/Y)} = \mathbf{V_{F/Y}} \bullet \mathbf{P_{2FE}} \tag{16}$$

Thus, rotation through longitudinal axis is

$$\boldsymbol{\omega}_{\mathbf{2L}} = \omega_{2L} * \mathbf{P_{2L}} \tag{17}$$

It was assumed that valgus/varus rotation at the elbow joint is negligible as

$$\boldsymbol{\omega}_{\mathbf{2VV}} = \mathbf{0} \tag{18}$$

The flexion/extension is

$$\boldsymbol{\omega}_{\mathbf{2FE}} = \frac{\mathbf{P_{2VV}} \bullet \mathbf{V_{Y/X}}}{\mathbf{P_{2VV}} \bullet (\mathbf{P_{2FE}} \times \mathbf{r_{Y/X}})} * \mathbf{P_{2FE}} \tag{19}$$

The movements allowed at the wrist joint are flexion/extension and abduction/adduction. For this segment, the axis system is fixed at the distal end of the forearm. This is possible as practitioners interpret flexion/extension and abduction/adduction as motion of the hand with respect to the styloid processes of ulna and radius (Sprigings et al. 1994).

The three unit vectors, $\mathbf{P_{3L}}, \mathbf{P_{3FE}}, \mathbf{P_{3UR}}$ are defined in similar manner as the previous unit vectors used in the other segments. $\mathbf{P_{3L}}$ is set equal to $\mathbf{P_{2L}}$ since the hand is not able to rotate along the longitudinal axis itself. The second vector, $\mathbf{P_{3UR}}$ defined as a unit vector through the axis is responsible for abduction/adduction. It is represented by

$$\mathbf{P_{3UR}} = \frac{\mathbf{P_{2L}} \times \mathbf{P_{3FE}}}{\left|\mathbf{P_{2L}} \times \mathbf{P_{3FE}}\right|} \tag{20}$$

where $\mathbf{P_{3FE}}$ is first approximated by

$$\mathbf{P_{3FE}} = \frac{\mathbf{r_{E/F}}}{\left|\mathbf{r_{E/F}}\right|} \tag{21}$$

The final unit vector, $\mathbf{P_{3FE}}$ defined as unit vector representing the axis of flexion/extension is computed by

$$\mathbf{P_{3FE}} = \frac{\mathbf{P_{3UR}} \times \mathbf{P_{2L}}}{\left|\mathbf{P_{3UR}} \times \mathbf{P_{2L}}\right|} \tag{22}$$

Using the equations similar to the upper arm and forearm section, the angular velocities of the hand segment are as follows:

Longitudinal:

$$\boldsymbol{\omega}_{3L} = \boldsymbol{\omega}_{2L} \tag{23}$$

Flexion/extension:

$$\boldsymbol{\omega}_{3FE} = \frac{\mathbf{P_{3UR}} \bullet \mathbf{V_{Z/Y}} - \mathbf{P_{3UR}} \bullet (\boldsymbol{\omega}_{2L} \times \mathbf{r_{Z/Y}})}{\mathbf{P_{3UR}} \bullet (\mathbf{P_{3FE}} \times \mathbf{r_{Z/Y}})} * \mathbf{P_{3FE}} \tag{24}$$

Ulna/radial deviation:

$$\boldsymbol{\omega}_{3UR} = \frac{\mathbf{P_{3FE}} \bullet \mathbf{V_{Z/Y}} - \mathbf{P_{3FE}} \bullet (\boldsymbol{\omega}_{2L} \times \mathbf{r_{Z/Y}})}{\mathbf{P_{3FE}} \bullet (\mathbf{P_{3UR}} \times \mathbf{r_{Z/Y}})} * \mathbf{P_{3UR}} \tag{25}$$

After obtaining all the angular velocities of the respective segments, the next step is to determine their contributions to the final racket head speed.

Given the assumption that the racket is being held firmly such that there are no relative rotations between the racket and the hand, the velocity of the middle of the racket head can then be expressed as

$$\mathbf{V_K} = \mathbf{V_W} + \boldsymbol{\omega}_1 \times \mathbf{r_{X/W}} + \boldsymbol{\omega}_2 \times \mathbf{r_{Y/X}} + \boldsymbol{\omega}_3 \times \mathbf{r_{K/Y}} \tag{26}$$

w_1, w_2 and w_3 are defined as absolute angular velocities of the three segments. From the known relationships such as

$$\boldsymbol{\omega}_2 = \boldsymbol{\omega}_1 + \boldsymbol{\omega}_{2/1} \tag{27}$$

$$\boldsymbol{\omega}_3 = \boldsymbol{\omega}_1 + \boldsymbol{\omega}_{2/1} + \boldsymbol{\omega}_{3/2} \tag{28}$$

$$\boldsymbol{\omega}_3 = \boldsymbol{\omega}_2 + \boldsymbol{\omega}_{3/2} \tag{29}$$

where $\boldsymbol{\omega}_{2/1}, \boldsymbol{\omega}_{3/2}$ are called relative angular velocity or joint angular velocity, reflecting individual rotations of the forearm and hand segments respectively.

Thus the linear velocity of the racket head can be alternatively expressed by the individual segment rotations:

$$\mathbf{V_K} = \mathbf{V_W} + \boldsymbol{\omega}_1 \times \mathbf{r}_{\mathbf{K/W}} + \boldsymbol{\omega}_{2/1} \times \mathbf{r}_{\mathbf{K/X}} + \boldsymbol{\omega}_{3/2} \times \mathbf{r}_{\mathbf{K/Y}} \tag{30}$$

where $\mathbf{V_W}$ is regarded as the contribution of the legs and torso in the final velocity of the racket head.

Lastly, the following steps will transform the angular velocities into the anatomical coordinate system.

Upper arm:

$$\boldsymbol{\omega}_1 = \boldsymbol{\omega}_{1L} + \boldsymbol{\omega}_{1FE} + \boldsymbol{\omega}_{1AA} \tag{31}$$

Forearm:

Pronation/supination:

$$\mathbf{A}\boldsymbol{\omega}_{2L} = (\boldsymbol{\omega}_{2/1} \bullet \mathbf{P_{2L}}) * \mathbf{P_{2L}} \tag{32}$$

Flexion/extension:

$$\mathbf{A}\boldsymbol{\omega}_{2FE} = (\boldsymbol{\omega}_{2/1} \bullet \mathbf{P_{2FE}}) * \mathbf{P_{2FE}} \tag{31}$$

Valgus/varus rotation:

$$\mathbf{A}\boldsymbol{\omega}_{2VV} = \mathbf{0} \tag{32}$$

Valgus/varus rotation is assumed to be zero.

Thus for the forearm, the total relative rotational velocity is:

$$\boldsymbol{\omega}_{2/1} = \mathbf{A}\boldsymbol{\omega}_{2L} + \mathbf{A}\boldsymbol{\omega}_{2FE} \tag{33}$$

Hand:

Flexion/extension:

$$\mathbf{A\omega_{3FE}} = (\boldsymbol{\omega}_{3/2} \bullet \mathbf{P_{3FE}}) * \mathbf{P_{3FE}} \tag{34}$$

Ulna/radius deviation

$$\mathbf{A\omega_{3UR}} = (\boldsymbol{\omega}_{3/2} \bullet \mathbf{P_{3UR}}) * \mathbf{P_{3UR}} \tag{35}$$

Longitudinal rotation

$$\mathbf{A\omega_{3L}} = \mathbf{0} \tag{36}$$

The equation can be represented in terms of their anatomical coordinate system:

$$\mathbf{V_K} = \mathbf{V_W} + (\boldsymbol{\omega}_{\mathbf{1L}} + \boldsymbol{\omega}_{\mathbf{1FE}} + \boldsymbol{\omega}_{\mathbf{1AA}}) \times \mathbf{r_{K/W}} + (\mathbf{A\omega_{2L}} + \mathbf{A\omega_{2FE}}) \times \mathbf{r_{K/X}} + (\mathbf{A\omega_{3FE}} + \mathbf{A\omega_{3UR}}) \times \mathbf{r_{K/Y}} \tag{37}$$

Since all the angular velocities are vectors, all the vectors will be decomposed in the final forward racket head speed direction to compare and calculate their contributions to the final racket head speed.

For the algorithm presented, the assumptions are made: The constructed orthogonal axes for the three segments closely represent their anatomical axes. The valgus/varus rotation at the elbow joint is assumed as zero. The longitudinal rotation of the hand at the wrist joint is also assumed to be zero. The hand and racket are one single rigid body.

Six female right-handed badminton players from the Singapore National badminton squad were chosen to be the subjects for the testing. The players used their own rackets to ensure comfort during each smash. Reflective markers were attached to the subjects' right arm at the landmarks as shown in Figure 1. Dimensions of the limb of the respective players were also recorded. These are used for calculations later. These dimensions include: girth of deltoid at mid-point, length of upper arm from mid-point of deltoid to the elbow, girth of elbow, length from the elbow to the wrist, girth of wrist and lastly, length from wrist to the mid-point of the index and little finger. The layout of the experiment setup is shown in Fig. 2.

Three high-speed cameras, C5, C6 and C7 operating at 200Hz were used to record the whole experiment. The forward swing sequence, commencing at first forward movement by the arm and finishing at the ball contact, was recorded and digitized manually. The three-dimensional coordinate values for the markers were calculated by PEAK MOTUS. For this experiment, the object space calibration errors are 0.2709%, 0.2254%, 0.2902% in X, Y, Z directions respectively. After the processing of data using PEAK MOTUS, we used MATLAB to assist in the calculations of the data.

Results

The results are based on the data collected from the 6 players. The subject was chosen as the visibility of all the markers on the subject were the best among all. The trials of the subject also provided the best views in all three cameras. From Fig.3, one can see that the measured racket head velocity matches roughly with the calculated one. Although there are some relatively big differences from frames 40 to 63, the two lines share the same trend.

The computed anatomical rotational velocities for the upper arm, forearm and hand during the badminton smash revealed that the highest angular velocity occurs at the ball contact (refer to Fig 4). The upper arm internal rotation has the highest angular velocity of 74rad/s followed by the forearm internal rotation with the angular velocity of 68rad/s. The hand flexion also has a distinguished angular velocity of 14rad/s comparing to that of the other segment rotations at the ball contact. The upper arm extension and abduction have almost the same angular velocity of 5rad/s as the hand radial deviation.

From Fig. 5, 6, and 7, one can observe that the upper arm internal rotation contributes 43 m/s to the racket head speed which is most significant to the final forward velocity. The forearm internal rotation takes the second place by 11m/s. The hand flexion makes about 7m/s contribution to the final velocity. These three movements make the three main contributions to the final racket head speed and account about 66%, 17%, 11% respectively. At the same time, we notice that during the smash there are some arm rotations contribute negatively to the final velocity. One should keep in mind that although some rotations contribute almost zero or negatively to the final velocity, they put other segments in the best position for performing a rapid smash.

Discussion

The study aimed to find the individual contribution of arm rotations to the final racket head velocity during an overhead badminton smash. From this study we can conclude that upper arm internal rotation contributes most to the resultant velocity of the racket head. Among the three arm segments, the contribution of the upper arm internal rotation is the most significant, followed by the contribution of the forearm internal rotation. The hand flexion takes the third place of the contributions to the final racket head velocity. These results correspond slightly to the research paper by Tang, et al. (1995) whereby they have also identified the hand movement at the wrist joint and the forearm movement at the radio-ulna joint seemed to contribute to produce great velocities of the racket head. Our findings also confirm with the studies on the serve in tennis (Elliott, Marshall & Noffal, 1995) and the forehand drive in squash (Elliott, Marshall & Noffal, 1996) which have shown the importance of upper arm internal rotation in contributing to most of the racket head speed in these sports.

By using the algorithm discussed in the research paper by Sprigings, Marshall, Elliott and Jennings (1994) the relationship between the individual rotational velocities of each segment and the final velocity of racket head can be obtained. Although from Fig. 1, one can see that there are still discrepancies between the measured values and the calculated values, there are still many advantages in using this approach. The main advantages include: errors are reduced significantly as only the first derivative of the displacement data is required; joint angular velocities are easier for the coach/athlete to understand as compared to acceleration; the player’s data can be compared to elite players’ and thus able to identify the areas that needs to be improved.

The discrepancies between the measured and calculated values can be partly explained by the raw data collected from the experiment from the start. During the calculations, the mid-point between the two markers at the skin surface for each segment was obtained straightly by taking the average of the positional values of the two markers. In this case, skin marker movement was assumed to be zero, which was not the case in practical sense. Due to skin movement, the marker displaces and this will introduce errors to the raw data (Lu and O'Connor 1999).

Contribution to the error in the raw data also includes digitizing error due to the person carrying out the digitizing of the video data. The error becomes even greater when some of the markers are momentarily hidden from the camera views for the position has to be guessed during the process of digitizing. The situations become even worse when the two markers are near to each other because the vector decided by the two markers absolutely possible to change the direction of the vector if the positions of the markers were digitized wrongly due to poor resolution. Because the vectors are sensitive to the directions, large discrepancy between the calculated and measured racket head speed occurs while trying to calculate $\mathbf{V_K}$ by equation (26) and (37). In our application, the errors make the sum of the final individual contributions of arm segment rotation not equal to the final racket head velocity.

Further studies can be done to reduce the errors in the data in order to produce more accurate and reliable data. Certainly, the discrepancy can be narrowed by adopting protruding markers to make the identification easier on the videotape and looking for a more suitable viewpoint of the cameras to avoid the markers hiding from the camera's view. This will help in minimizing the error involved during digitizing. But protruding markers invite the vibration of the markers thus also invite the errors. Other methods of improving the final results include using 300Hz (or even higher) cameras instead of the current 200Hz cameras used in the experiment. By using a camera of low frequency, some data points may be excluded from the final computed data especially during times whereby a certain velocity is at its maximum but due to the low frequency, the maximum value is cropped off. The low frequency of the cameras also accounts for the abrupt changes in some of the experiment data.

More anatomical points might be located on the subject to reduce the effects of points 'hidden' in the camera views. The torso rotation's contribution might also be calculated by putting markers on the torso. More cameras and more suitable spotlights may also be used to avoid some points being hidden from the camera views.

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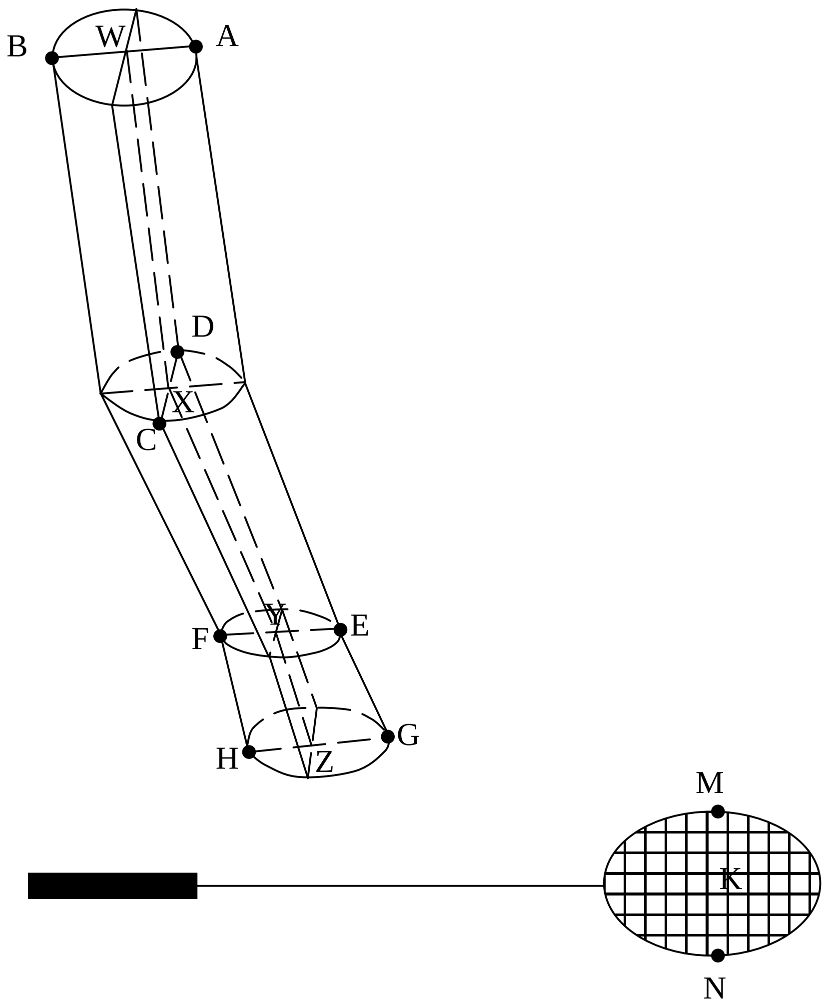

Figure 1: The positions of markers on the arm and the racket head

Marker	Anatomical Position
A	Middle point of deltoid (anterior view)
B	Middle point of deltoid (posterior view)
C	Elbow (at radius proximal)
D	Elbow (at ulna proximal)
E	Wrist (distal end of radius)
F	Wrist (distal end of ulna)
G	Head of index finger
H	Head of little finger
M	Middle point of the left side of racket head
N	Middle point of the right side of racket head

Table 1: Anatomical positions of markers.

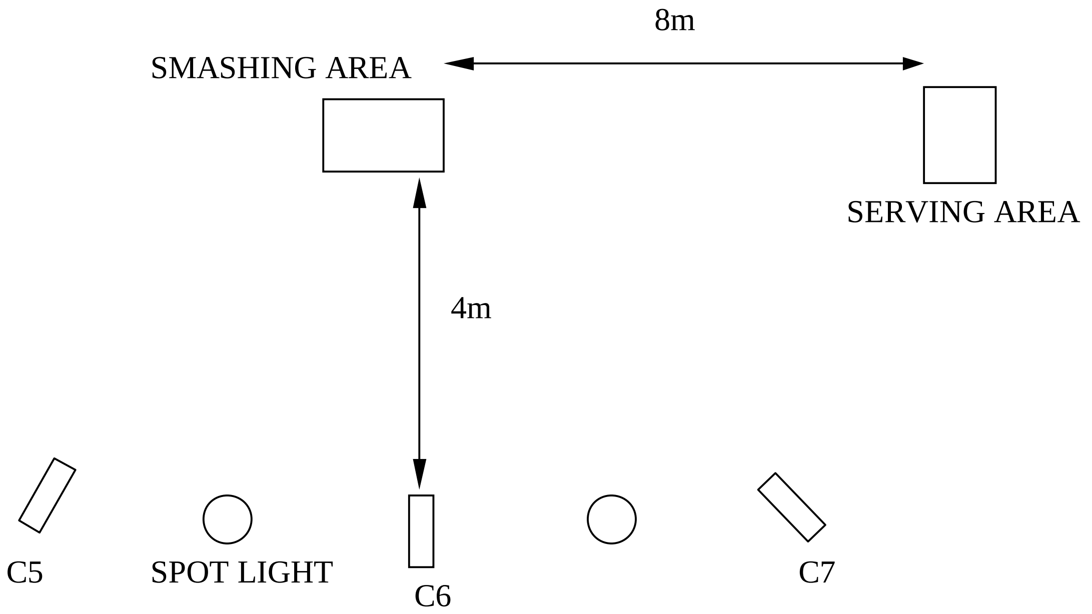

Figure 2: Layout of experiment setup

Glossary

$\mathbf{P}_{ij}$ unit vector of segment i aligned with the anatomical position j, where i=1 (upper arm), 2 (forearm), 3 (hand); j=L (longitudinal), UR (ulna/radial deviation), AA (abduction/adduction), FE (flexion/extension), VV (varus/valgus)

$\boldsymbol{\omega}_{i}$ absolute angular velocity of segment i

$\boldsymbol{\omega}_{ij}$ component of absolute angular velocity of segment i aligned with the unit vector representing anatomical position j

$\mathbf{A\omega}_{ij}$ anatomical rotation j of segment i

$\mathbf{r}_{p/q}$ displacement vector from reference points q to p

$\mathbf{V}_{p}$ absolute linear velocity of reference point p

$\mathbf{V}_{p/q}$ relative linear velocity of reference point p to q

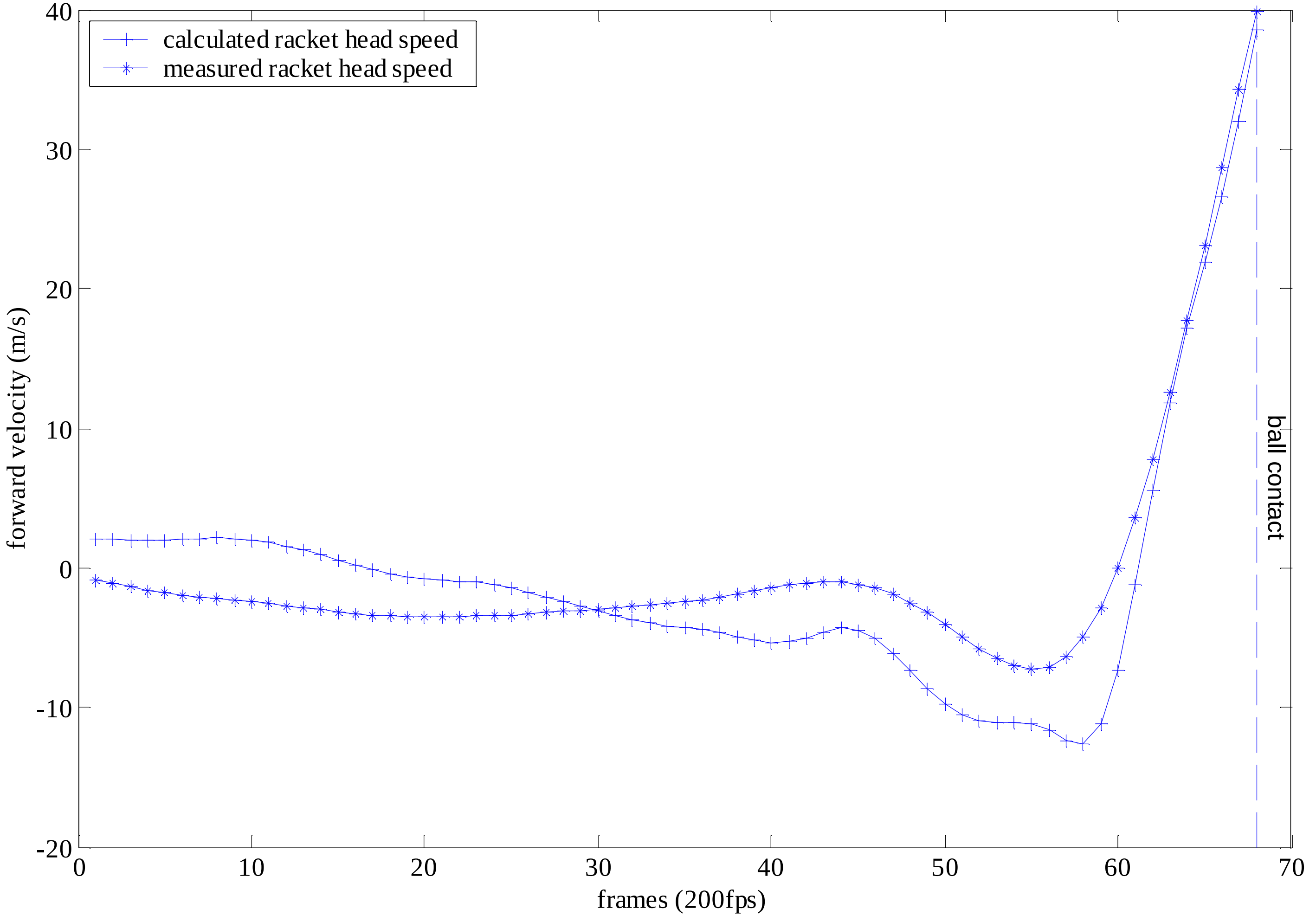

Figure 3: The comparison of calculated and measured racket head speed

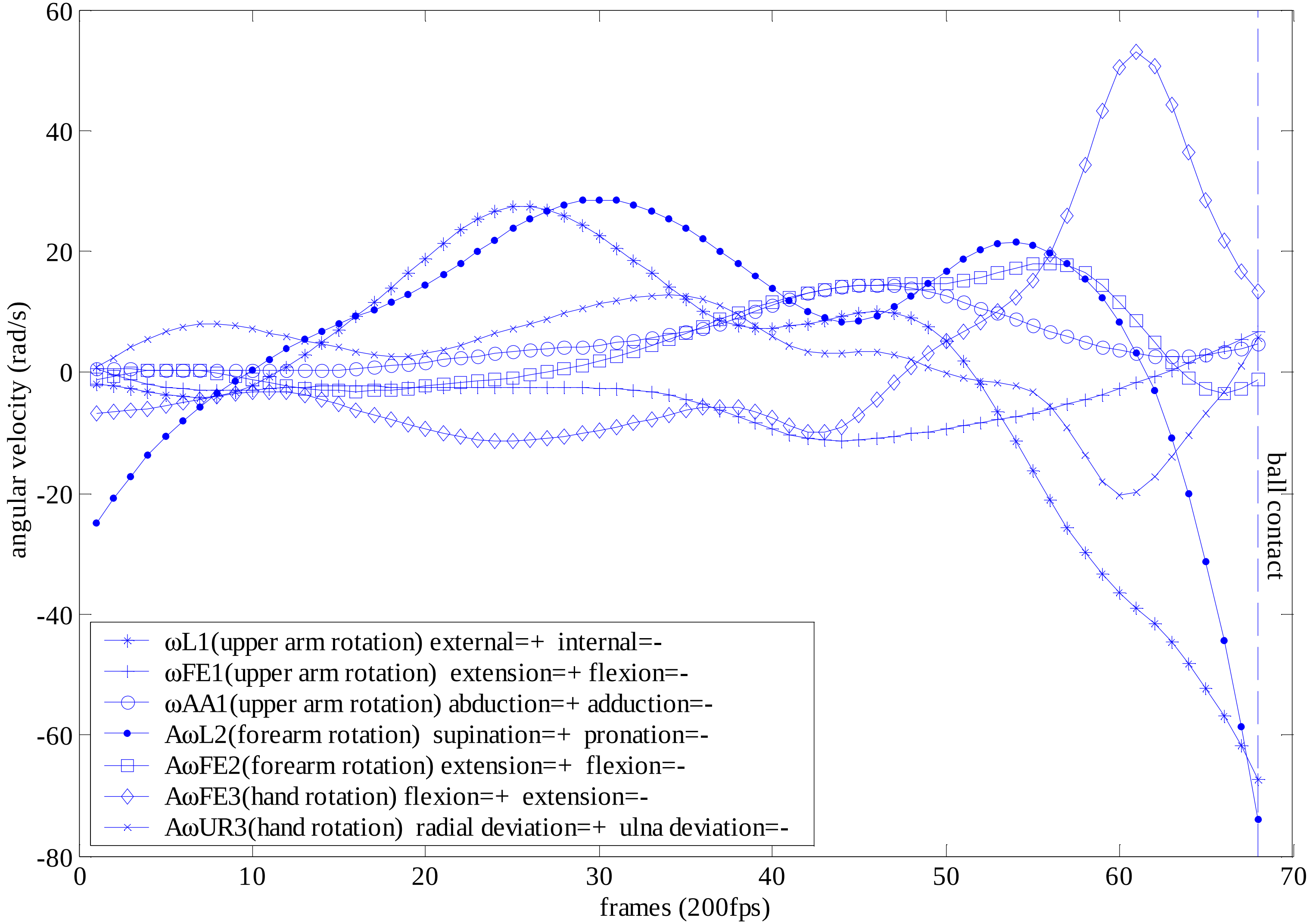

Figure 4: Angular velocity of different arm segment rotation

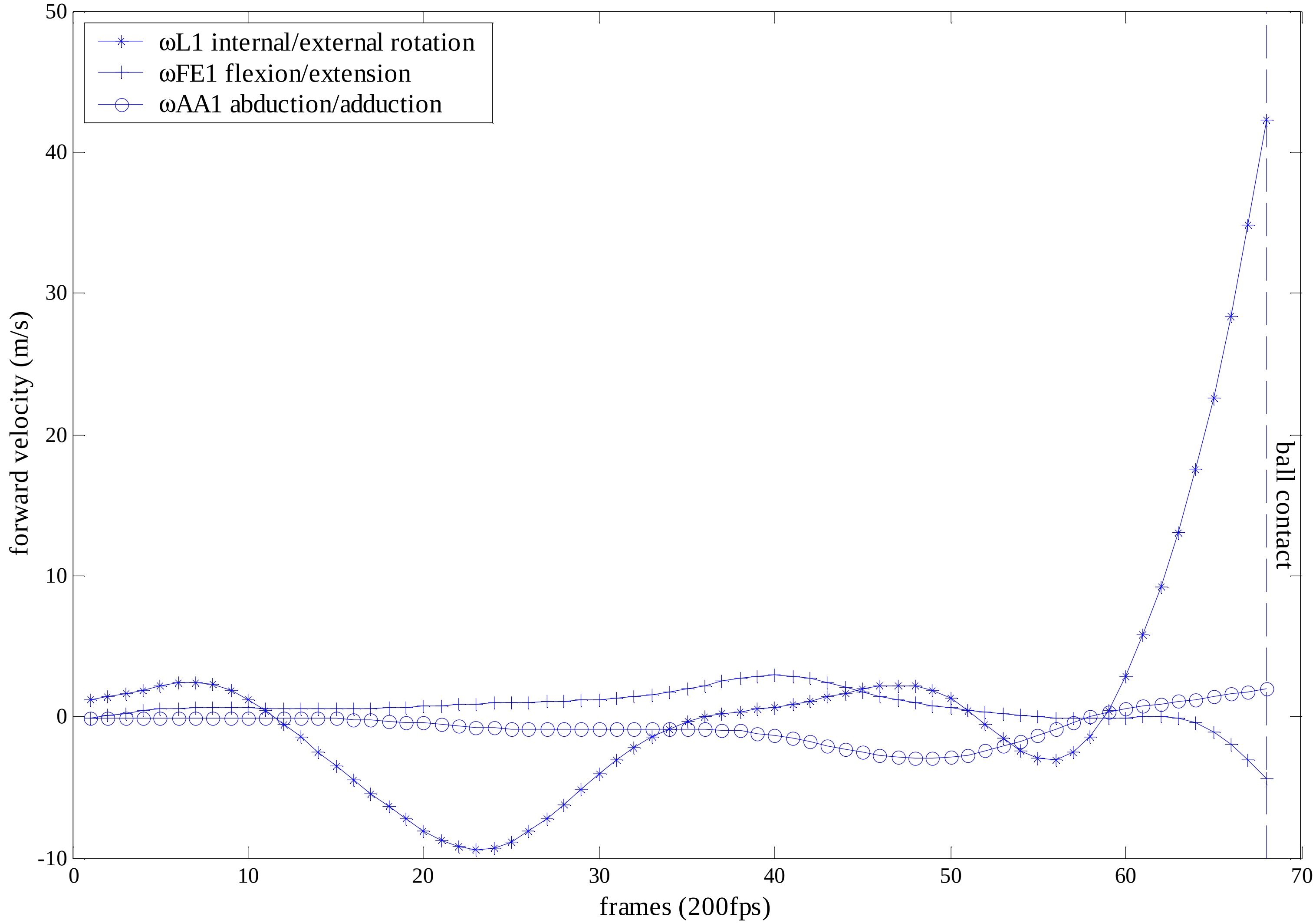

Figure 5: Contribution of upper arm rotation to the forward velocity of racket head speed

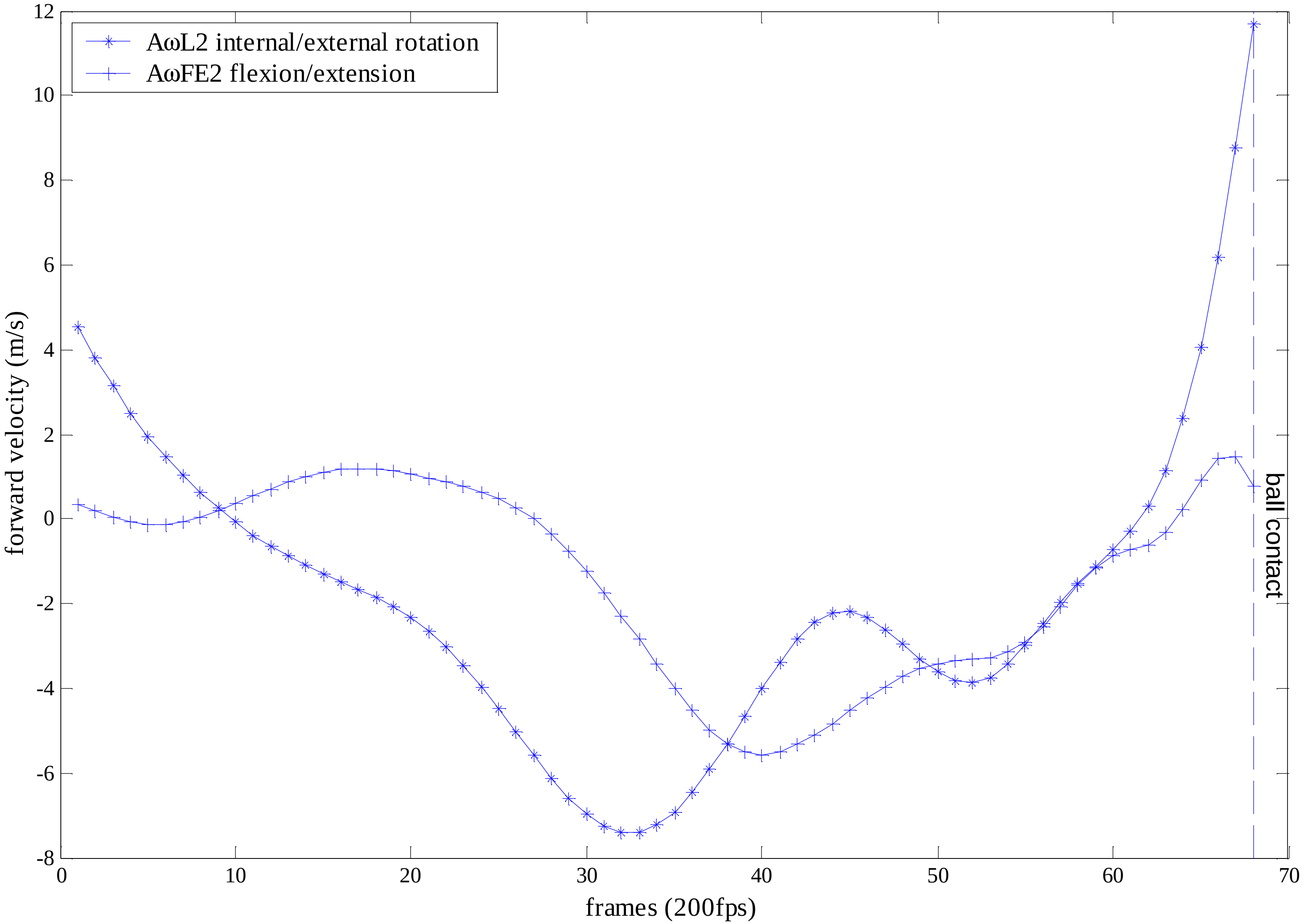

Figure 6: Contribution of forearm rotation to the forward velocity of racket head speed

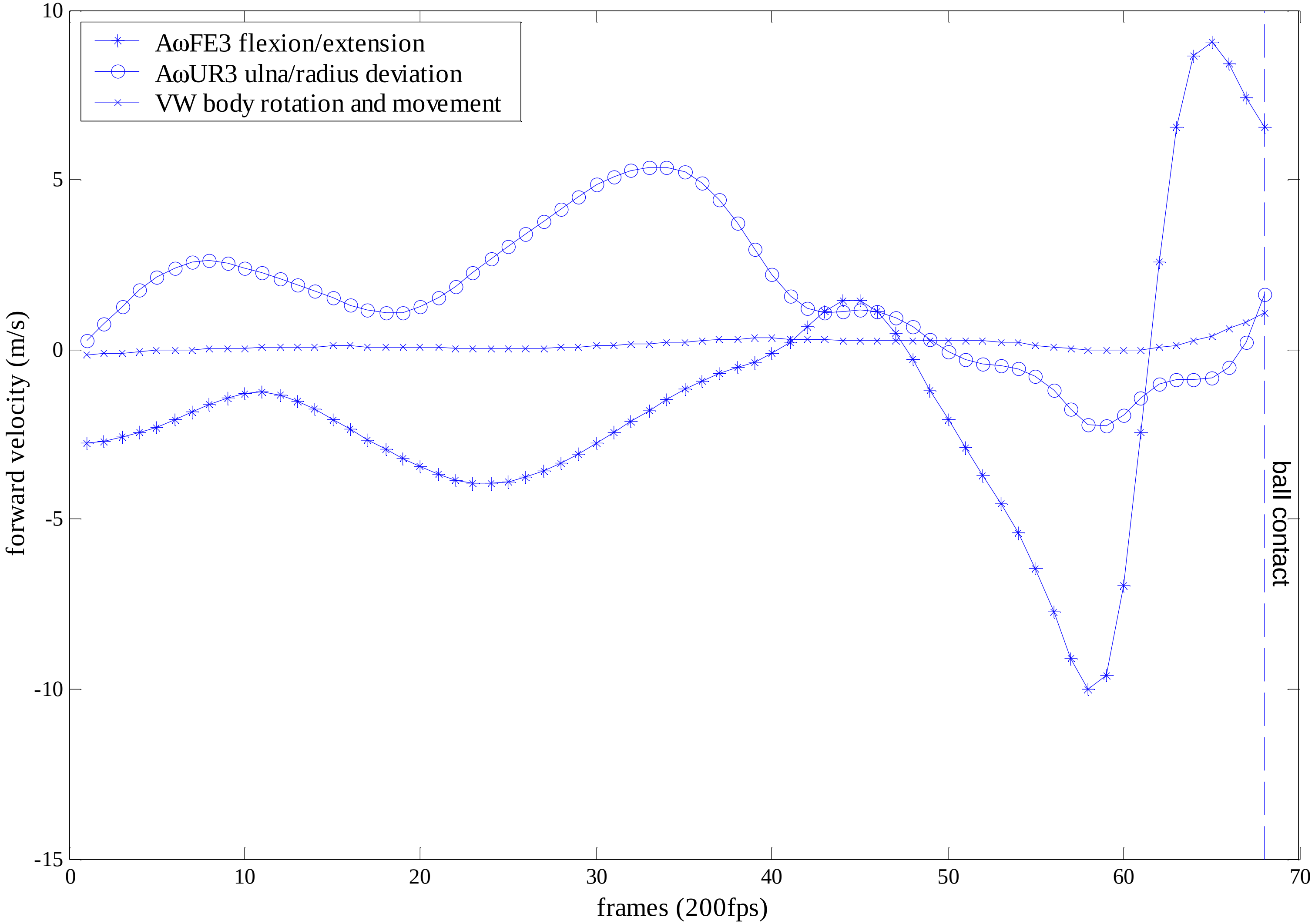

Figure 7: Contributions of the hand and body to the forward velocity of racket head speed.