INTRODUCTION

No one can know how baseball players exert forces and moments on the grip handle from the batting motion. Because the bat is manipulated by both hands in batting, the upper extremities and the bat make a closed multiple-segment loop. Therefore it is impossible to determine the forces and moments acting on the bat with only visual information of batting motion. Since the roles of the upper extremities during baseball batting are transfer of the energy generated by the lower extremities into the bat and control the bat to place in a hitting point, the knowledge of the patterns of joint torques of the upper extremities is necessary for an understanding of the batting strategy. Such information is very useful for training and coaching. The only way permit us to know the joints torques is to measure the force and moment acted on the grip handle by each hand. This is why there are few kinetic studies on batting motion of the upper extremities, and previous research on the kinetics of batting has focused only on the lower extremities with use of a force platform system (Messier, 1985; Welch, 1995).

The purpose of this study was to investigate three-dimensional kinetics of the upper extremities using an instrumented bat that measure forces and moments exerted on the bat by hands.

METHODS

Five varsity baseball players volunteered to participate in this study as subjects (Table 1). The subjects performed T-batting, namely, hitting a ball on a tee whose height was same as the height of the hip of them. They hit the ball as strong as they could. The good hits were used for data in this study with accuracy of data collection as shown in Table 1. The positions of markers of the body segment endpoints and the bat were captured with VICON motion analysis system operating at 120Hz. The ball was videotaped with two high-speed VTR cameras operating at 250Hz.

For the purpose of the realization of the kinetic analysis, an instrumented bat was used in the experiments. Figure 1 shows the structure of the bat. The bottom side grip handle was separated from the bat. An aluminum alloy bar with strain gauges attached on its surface was inserted into the grip handles, and connected them. The strain gauges provided force and moment information as 1) torsional moment acting on grip axis between hands, 2) bending moments and 3) tensile and compressive axial forces. The information about the sensed forces and moments was converted into the forces and moments exerted by hands by resolving static equilibrium equations with respect to forces and moments. A personal computer was used to store the strain gauge signals that were amplified through dynamic strain amplifiers. The sampling frequency of the force and moment data was 500Hz. Both the motion and the strain gauge signals collection system were electrically synchronized to begin collection simultaneously.

Table 1: Specifications of the subjects.

<table>
<thead>
<tr>
<th>Subject ID</th>
<th>Weight [kg]</th>
<th>Height [m]</th>
<th>Number of trials in the kinetic analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>78</td>
<td>1.82</td>
<td>7</td>
</tr>
<tr>
<td>B</td>
<td>68</td>
<td>1.69</td>
<td>6</td>
</tr>
<tr>
<td>C</td>
<td>75</td>
<td>1.76</td>
<td>7</td>
</tr>
<tr>
<td>D</td>
<td>79</td>
<td>1.77</td>
<td>9</td>
</tr>
<tr>
<td>E</td>
<td>72</td>
<td>1.75</td>
<td>8</td>
</tr>
</tbody>
</table>

Figure 1: The structure of the instrumented bat.

Several coordinate systems were defined to calculate angles of joints of the upper extremities. The full description of them is in APPENDIX. Torque and power of the joints of the upper extremities in the forward swing were estimated by an inverse dynamics approach with the forces and moments obtained with the instrumented bat. The joint torque powers were calculated as the products of the joint angular velocities and the joint torques.

The coordinate system O-XYZ was defined as the global reference frame as shown in Figure 2. The positive Y-axis defined as the direction from home plate to the pitcher’s plate and was parallel to the batter’s box. The Z-axis lies in the vertical axis, and the X-axis is perpendicular to both the Y and Z axes. The motion of forward swing were analysed from the time when the knee of the step leg was smallest in Y-axis to the time of impact, and the period was divided into three phases as shown in Figure 2, such as:
Figure 2: The phases during batting motion and the average swing time at each phase.

Phase 1 (striding phase): From the time when the knee of the step leg was smallest in Y-axis to the time when the toe of the step leg touched down.
Phase 2 (downswing phase): From the time when the toe of the step leg touched down to the time when the bat was parallel to the Y-axis.
Phase 3 (level swing phase): From the time when the projection of the bat was parallel to the Y-axis to the time of impact.

The forces and moments exerted by hands were expressed by using a plane named as “swing plane” depicted in Figure 3. The plane of an instant was calculated so as to approximately involve the bat axis at the instance, and the axes at 5% time before and after the instant.

RESULTS

Figure 4 shows the swing planes and the orientations of the coordinate system of them during Phases 2 and 3. Figures 5 and 6 show the forces and moments exerted by the bottom and top hands in the expression of the coordinate system of the swing plane. The solid lines and dashed lines designate mean values and standard deviations respectively. These values were normalized by the times of the forward swing phases. The mean values and standard deviations were relatively small during the Phase 1.

The x-axial forces of the hands showed inversion patterns approximately with respect to sign. The x-axial force of the bottom side hand decreased gradually till 240% time, and increased rapidly toward the impact. The y-axial force of the bottom side hand increased toward the impact and reached tremendous large positive values compared to other forces. On the other hand, the y-axial forces of the top hand showed different pattern, and it reached the peak about 240% time and then decreased toward the impact. The z-axial forces of the hands also showed inversion patterns approximately with respect to sign. The force of the bottom side hand decreased gradually till 200% time, and increased toward the impact.

The x-axial moments showed negative values during Phases 2 and 3. The y-axial moments showed small values. The z-axial moment of the bottom side hand increased and reached the peak about 140% time, and then it decreased rapidly toward the impact. Figures 7, 8 and 9 show the torque, angular velocity and torque power of the adduction/abduction, flexion/extension and internal/external joints of the shoulders. The abduction torque of the bottom arm increased gradually toward the impact and reached large values, and the variance of the torque became large during Phase 3. The angular velocities of both arms reached a peak about 180% time, and then these became nearly zero towards impact. Therefore the torque powers of the abduction/adduction joints reached the peak about the same time. The extension torque of the bottom arm increased gradually toward impact, but its magnitude was much smaller than the abduction torque. The peaks of the magnitude of the angular velocities occurred at 150% time. Large angular velocity in the direction of internal rotation occurred during Phase 3, and a large negative torque power by the internal/external joint of the bottom arm occurred during Phase 3.

DISCUSSION

The forces acting through x- and y- axes in the swing plane by both hands showed mainly couple of forces, that is, opposite direction and almost equal magnitude of values. However the forces acting in the y-axis showed completely different patterns between both hands.

The results of the forces and moments exerted on the grip handle by both hands indicated that movement of the bat was mainly caused by the forces of the bottom side hand, and both hands exerted coupled forces onto the bat to rotate forward the bat top and to maintain the bat top motion into horizontal
Figure 4: Stick diagram of the orientations of the bat swing plane coordinate system.

Figure 5: The forces and moments exerted by the bottom hand expressed in the bat swing plane coordinate system.

Figure 6: The forces and moments exerted by the top hand expressed in the bat swing plane.
plane from 150% time to the impact. The y-axial force of the bottom hand mainly accelerated the bat in translational motion, and forces in other axes were mainly coupled forces during the swing.

The z-axial moment exerted by the bottom hand showed negative values during Phase 3, which indicated that the moment reduced the rotational acceleration generated by the couple of forces about the x-axis. The y-axial force of the top hand showed negative values just before impact, and the positive force exerted by the bottom hand would cancel the negative force. From this, we can see that there were some forces and moments that did not cause the movement of the bat.

The abduction torque of the shoulder joint of the bottom arm generated the largest values in the joints of the upper extremities during Phase 3. The large values were due to the large forces in the y-axis. These results indicated that the abduction torque of the left shoulder would keep the bat close to the body just before impact to resist centrifugal force. The magnitude of torques of the flexion/extension joints were not large, because the axis of this joint was approximately parallel to the y-axis of the bat. Hence the large y-axial force in the swing plane was mainly generated by the abduction torque of the shoulder of the bottom arm. The large magnitude of negative torque power of the internal/external joint of the bottom arm showed that the joint mainly controlled the bat into horizontal plane. There were many joints that generated positive work in the bottom arm, and there was no large positive but a small negative work in the top arm.

From the results obtained by this study, the role of the bottom arm is to accelerate the bat, and that of top arm is to modify the bat motion.

**SUMMARY**

To investigate kinetics of the upper extremities during baseball batting, an instrumented bat with strain gauges was used to solve the closed multiple-segment loop problem. From the results obtained by this study, the role of the bottom arm is to accelerate the bat, and that of top arm is to modify the bat motion. These results indicate that some joints would behave as actuators to accelerate the bat and/or to keep the bat close to the body, and some of joints would behave as free joints during the forward swing.

**REFERENCES**


![Figure 7](image1.png)
**Figure 7:** The torques, angular velocities (A.V.) and torque powers in the abduction/adduction joints of the shoulders.

![Figure 8](image2.png)
**Figure 8:** The torques, angular velocities (A.V.) and torque powers in the flexion/extension joints of the shoulders.
Figure 9: The torques, angular velocities (A.V.) and torque powers in the internal/external rotation joints of the shoulders.

Figure 10: Work done at each phase of each joint in the upper extremities expressed as values in J. (AA : abduction/adduction of shoulder. sFE : Flexion/extension of shoulder. IER : Internal/external rotation of shoulder. eFE : Flexion/extension of elbow. SP : supination/pronation of elbow. RU : radial/ulnar deviation of wrist. PDF : palmar/dorsal flexion of wrist.)

APPENDIX

Figure A1 shows the coordinate systems used for kinematic and kinetic analyses of the batting motion with respect to the right arm, and the coordinate systems were defined as follows.

The upper torso coordinate system $\Sigma_{ut}$ (figure A1(a)) : The three unit vectors $(x_{ut}, y_{ut}, z_{ut})$ describing the upper torso coordinate system are directed as follows. The vector $s_{ut}$ lies in the direction from the centre of the shoulder joints (shC) to the centre of the shoulder joints (shC). The vector $x_{ut}$ lies in the direction from the left shoulder joint (shL) to the right shoulder joint (shR). The vector $y_{ut}$ is determined from the cross product of $s_{ut}$ and $x_{ut}$. The vector $z_{ut}$ is obtained by the cross product of $x_{ut}$ and $y_{ut}$.
The shoulder joint coordinate system $\Sigma_{sh}$ (Figure A1(a)): The vector $s_{sh}$ lies in the direction from the elbow joint (elbR) to the shoulder joint (shR). The vector $x_{sh}$ lies in the direction from the shL to the shR. The vector $y_{sh}$ is determined from the cross product of $s_{sh}$ and $x_{sh}$. The vector $z_{sh}$ is obtained by the cross product of $x_{sh}$ and $y_{sh}$.

The second shoulder joint coordinate system $\Sigma_{sh2}$ (Figure A1(b)): The vector $s_{sh2}$ lies in the direction from the shL to the shR. The vector $z_{sh2}$ lies in the direction from the elbR to the shR. The vector $y_{sh2}$ is determined from the cross product of $z_{sh2}$ and $s_{sh2}$. The vector $x_{sh2}$ is obtained by the cross product of $y_{sh2}$ and $z_{sh2}$.

The elbow joint coordinate system $\Sigma_{elb}$ (Figure A1(c)): The vector $s_{elb}$ lies in the direction from the wrist joint (wrR) to the elbR. The vector $z_{elb}$ lies in the direction from the elbR to the wrR. The vector $y_{elb}$ is determined from the cross product of $z_{elb}$ and $s_{elb}$. The vector $x_{elb}$ is obtained by the cross product of $y_{elb}$ and $z_{elb}$.

The second elbow joint coordinate system $\Sigma_{elb2}$ (Figure A1(c)): The vector $s_{elb2}$ lies in the direction from the elbR to the shR. The vector $z_{elb2}$ lies in the direction from the wrR to the elbR. The vector $y_{elb2}$ is determined from the cross product of $s_{elb2}$ and $z_{elb2}$. The vector $x_{elb2}$ is obtained by the cross product of $y_{elb2}$ and $z_{elb2}$.

The wrist joint coordinate system $\Sigma_{wr}$ (Figure A1(c)): The vector $s_{wr}$ lies in the direction that is parallel to the line from the bottom of the bat (batB) to the top of the bat (batT). The vector $z_{wr}$ lies in the direction from the wrR to the elbR. The vector $y_{wr}$ is determined from the cross product of $s_{wr}$ and $z_{wr}$. The vector $x_{wr}$ is obtained by the cross product of $y_{wr}$ and $z_{wr}$.

The palm coordinate system $\Sigma_{palm}$ (Figure A1(d)): The vector $s_{palm}$ lies in the direction from the back of hand (backR) to the wrR. The vector $x_{palm}$ lies in the same direction with the $y_{palm}$. The vector $z_{palm}$ is obtained by the cross product of $x_{palm}$ and $y_{palm}$.

The second palm coordinate system $\Sigma_{palm2}$ (Figure A1(e)): The vector $y_{palm2}$ lies in the same direction with the $y_{palm}$. The vector $z_{palm2}$ lies in the direction from backR to the wrR. The vector $x_{palm2}$ is obtained by the cross product of $y_{palm2}$ and $z_{palm2}$.

The joint angles were defined as follows, and the angular velocities were calculated by differentiating the angles with respect to time:

**Shoulder joint angles**: The flexion/extension angle $\theta_{FE}$ is defined as the angular displacement between the $y_{sh}$ and the $y_{sh2}$ (Figure A2(a)). The adduction/abduction angle $\theta_{AA}$ is defined as the angular displacement between the $x_{sh}$ and the $x_{sh2}$ (Figure A2(b)). The internal/external rotation angle $\theta_{IR}$ is defined as the angular displacement between the $x_{sh}$ and the $x_{sh2}$ (Figure A2(c)).

**Elbow joint angles**: The flexion/extension angle $\theta_{EE}$ is defined as the angular displacement between the $z_{elb}$ and the ($-z_{elb2}$), where full anatomical extension of the elbow joint corresponded to 180 degree while full anatomical flexion of the joint correspond to 0 degrees (Figure A2(d)). The supination/pronation angle $\theta_{p}$ is defined as the angular displacement between the $x_{sh2}$ and the $x_{elb2}$ (Figure A2(e)).

**Wrist joint angles**: The palmar/dorsal flexion angle $\theta_{DF}$ is defined as the angular displacement between the $y_{wr}$ and the $y_{palm}$ (Figure A2(f)). The radial/ulnar deviation angle $\theta_{UL}$ is defined as the angular displacement between the $x_{palm}$ and the $x_{palm2}$ (Figure A2(g)).

In this paper the coordinate systems, angles, torques with respect to the left arm were expressed by using “left handed expression”.

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**Figure A2**: Definition of the joint angles with respect to right arm.