Kinetic Analyses on Increase of Bat Head Speed in Baseball Batting

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The purpose of this study was to identify mechanisms to increase bat head speed in baseball batting, from the viewpoint of kinetics. The batting motion of ninety-nine amateur baseball players was recorded with a motion capture system, and the kinematics and kinetics of the bat were analyzed. The bat’s rotational power increased with the torque exerted on the bat’s grip. However, torque and rotational power declined just prior to impact. It can be interpreted that these declines arise from a decrease in torque exerted by the wrist’s periarticular muscles as the bat’s rotational velocity increases (muscle force-velocity relationship). On the contrary, the bat’s translational power increased just prior to impact. Judging from the relationship between the force exerted on the bat’s grip in the direction of the bat’s long axis and the bat head speed, the bat’s translational power seems to depend on the bat’s grip velocity in the direction of the bat’s long axis. It was revealed that the bat’s energy, by the application of rotational and translational power at different times, contributes to an increase in bat head speed in baseball batting.

Keywords: biomechanics, inverse dynamics, grip force, grip torque, radius of curvature

1. Introduction

In baseball, the principal goals for the batters are improvement of batting average and an increased number of home runs. To do so, it is necessary for the batters to accurately contact the pitched ball with the bat, and to increase the bat head speed at impact.

In previous studies of baseball batting, a number of kinematic analyses were reported (Race, 1961; McIntyre and Pfautsch, 1982; Welch et al., 1995; Szymanski et al., 2007; Escamilla et al., 2009; Inkster et al., 2011). According to these reports, the knee joint angle, torso rotational velocity, elbow extension velocity and other factors were discussed as important motions to increase bat head speed. However, the kinematic variables above are only part of the batting motion sequence, and are not the direct factors in acceleration of the bat head.

Unlike kinematic studies of baseball batting, studies investigating bat dynamics are limited (Messier and Owen, 1984; Koike et al., 2004; Milanovich and Nesbit, 2014). Messier and Owen (1984) calculated bat head speed, bat rotational velocity, bat’s kinetic energy in softball batting, and compared the batting motions of baseball and softball. Koike et al. (2004) developed a bat instrumented with strain gages under the bat grip, and directly measured the forces and torques exerted on the bat during the swing. Milanovich and Nesbit (2014) analyzed softball batting biomechanically, and calculated the mechanical energy of the bat, and the forces and torques exerted on the bat grip during the swing. In the results, the bat’s kinetic data were shown three-dimensionally. The basic mechanism to swing the bat was clarified in these studies. However, the mechanisms to improve practical performance in baseball batting (e.g. the increase of bat head speed) remain insufficient. Bat head speed at impact of the bat and ball is an important factor in evaluating the batter’s performance in baseball batting. Szymanski et al. (2009) gave three direct benefits of increasing bat head speed, an increase in decision time, decrease in swing time, and increase in batted-ball velocity. In particular, an increase in batted-ball velocity may lead to improvement in on-base percentage. This is
because defense becomes more difficult, as the batted-ball travels faster and farther. Therefore, the purpose of this study was to identify mechanisms to increase bat head speed in baseball batting, from the viewpoint of kinetics.

2. Methods

2.1. Subjects

Ninety-nine amateur male baseball players (body height: 1.73 ± 0.06 m, body weight: 70.3 ± 8.0 kg, age: 19.0 ± 1.9 years) participated in this study. There were fifty-five right-handed batters and forty-four left-handed batters. The experiment conducted in this study was approved by the ethics committee of Chukyo University. Prior to conducting the experiment, the purpose of the study and the experimental protocols were explained to the subjects. Written informed consent was obtained from all subjects.

2.2. Experimental Protocols and Data Collection

A variety of locations was equipped with retro-reflective markers or tape. These included the bat (two points: bat head, bat grip), subject body landmarks (38 points: vertex, tragus, seventh cervical spine, xiphoid process, anterior superior iliac spine, posterior superior iliac spine, acromion, medial epicondyle of humerus, lateral epicondyle of humerus, ulnar styloid process, radial styloid process, third metacarpal head, greater major trochanter, medial condyle of femur, lateral condyle of femur, medial malleolus, lateral malleolus, base of the first metatarsal, calcaneus) and the ball (six points). The subjects were asked to perform a toss batting with maximal effort. For each subject, the experimenter tossed the ball from a place 3.2 m away from the subjects, using a steady rhythm and aiming at the center of the strike zone. The bat used in this study was a wooden bat (length: 0.84 m, mass: 0.90 kg) and the ball (diameter: 70 mm, mass: 20 g) was made of sponge. The trajectories of the retro-reflective markers were recorded at 250 Hz using a motion capture system (Vicon MX, Vicon Motion Systems, UK).

For each subject, this data collection process was repeated until three trials satisfying the subject were obtained. Then, unsuccessful trials (the posture of batter was lost, the tossed ball was out of strike zone and the bat did not accurately contact the tossed ball) were excluded. Of these three, the trial in which the bat head speed at impact was maximal was selected for further analysis. Impact was defined as one frame prior to the moment where bat head acceleration shows a negative value.

2.3. Bat Kinematics and Kinetics

Bat head speed and angular velocity were calculated by differentiating the bat head displacement and the angular displacement of the bat with respect to time, respectively. The radius of curvature of the bat head was calculated by dividing the displacement of the bat head by the angular displacement of the velocity of the bat head.

The local coordinate system of bat was defined in Figure 1. Bz is defined as the unit vector from the bat head to the bat grip. Bx is defined as the unit vector product of the bat head velocity and the unit vector Bz. By is the unit vector product of Bz and Bx. The force (grip force) and the torque (grip torque) exerting to bat grip were calculated using the inverse dynamics (Winter, 2009). The point of application of grip force and torque was defined as the midpoint of both third metacarpal heads. The center of mass of the bat was measured, and found to be at the position 33.3% along the vector from the bat head to the bat grip. The moment of inertia of the bat was calculated from the period of the bat’s pendulum motion. The moment of inertia of the bat around long axis was $2.025 \times 10^{-4} \text{ kg} \cdot \text{m}^2$, and that around short axis was 0.047 kg\cdot m$^2$.

The bat power as a function of both the grip force and torque was calculated to evaluate the increase and decrease of the bat’s mechanical energy.
(Gordon et al., 1980).

2.4. Data Reduction

In baseball batting, the impact between bat and ball is well known to produce rapid deceleration of the bat head, which causes serious distortion of data near the time of impact when the data are filtered. Therefore, in this study, the methods used in a previous study, which analyzed the soccer kicking motion (Nunome et al., 2006), were adapted to filter the data eliminating the effect of impact. All variables were calculated from the raw three-dimensional coordinate data, and each signal was extrapolated to a time just prior to impact. In addition, the signals were smoothed using a fourth-order Butterworth low pass filter, with a cut off frequency of 25 Hz.

The time period from the moment the bat head speed exceeded 1 m/s to the moment of impact was normalized to 100% (Figure 2).

2.5. Position and Speed of the Tossed Ball

The possibility was considered that dispersion of position and speed of the tossed ball may cause changes in the batting motion. This possibility was considered because a toss batting was used as the experimental method to collect the data. Therefore, the position of the tossed ball relative to the center of gravity (COG) of the batter, as well as speed of the tossed ball at impact were calculated, and these dispersions were assessed three-dimensionally. The position of the COG was calculated using the inertia properties of body segments for Japanese athletes (Ae et al., 1992).

2.6. Statistical Analysis

Pearson’s product-moment correlation coefficient between the bat head speed at impact and the kinetic variables at each instance were calculated. The level of significance was set at $p < 0.001$.

3. Results

The position of the tossed ball relative to the COG of batter at impact was $0.61 \pm 0.07$ m in the outside direction, $0.71 \pm 0.17$ m in the pitcher direction, $0.11 \pm 0.10$ m in the vertically downward direction. The speed of the tossed ball at impact was $2.25 \pm 0.79$ m/s.

Figure 3 shows the change in average value ($\pm$SD) of bat head speed and the bat’s angular...
velocity (left side), as well as the acceleration and the radius of curvature of the bat head (right side). The bat’s head speed at impact was $33.8 \pm 2.0 \text{ m/s}$. The bat’s angular velocity showed a change similar to the bat head speed, and reached the maximum value ($2349.2 \pm 146.7 \text{ deg/s}$) at time equals 85%. The radius of curvature of the bat head showed a constant increase, and reached the maximum value ($1.89 \pm 0.11 \text{ m}$) at impact.

**Figure 4** shows the change in average value ($\pm \text{SD}$) of the grip forces (left side) and grip torques (right side). In addition, the changes in correlation coefficient of the bat head speed at impact and the grip forces and grip torques at each instance were shown. Significant level was the range filled with gray. The grip force in the $B_z$ direction increased from time equals 60% and reached the maximum value ($642.1 \pm 87.4 \text{ N}$) at impact. Just prior to impact (time equals 90-100%), this grip force showed a significant correlation to the bat head speed at impact. Conversely, the grip forces in the $B_x$ and $B_y$ directions were small and hardly showed a significant correlation to the bat head speed at impact throughout the swing. The grip torque around the $B_x$ axis showed a positive value after time equals 50%, and reached a peak value at time equals 75-80%. However, this torque showed a tendency to decrease after time equals 80%, and turned negative at impact. The grip torque around the $B_y$ axis showed a negative value after time equals 50%. These grip torques hardly showed a significant correlation to the bat head speed at impact throughout the swing.

**Figure 5** shows the change in average value ($\pm \text{SD}$) of the bat power as a function of grip force and torque. In addition, the changes in correlation coefficient of the bat head speed at impact and the bat power as a function of grip force and torque at each instance are shown. Significant level was the range filled with gray. The bat’s translational power rapidly increased after time equals 75% and maintained the positive value until time equals 100%. Just prior to impact (time equals 90-100%), the bat’s translational power showed a significant correlation. The bat’s rotational power showed a positive value from time equals 50%, but turned negative at
Figure 5  Bat powers as a function of grip forces and torques and correlation coefficient with the bat head speed at impact.

Figure 6  Relationship between bat head speed and grip force impact. Throughout the swing, the bat’s rotational power hardly showed a significant correlation.

Figure 6 shows the relationship between the bat head speed and the grip force in the Bz direction, in the time period from time equals 30% to before impact (time equals 70-100%). The square of the bat head speed was proportional to the grip force in the Bz direction, and the coefficient of correlation was extremely high ($r = 0.989$, $p < 0.001$, $n = 693$).

4. Discussion

The purpose of this study was to identify mechanisms to increase bat head speed in baseball batting. The batting motion of ninety-nine amateur baseball players was analyzed, and the bat kinematics and kinetics were calculated.

Taking the size of the strike zone into consideration, the standard deviations of the position of the tossed ball relative to batter’s COG were distributed in the strike zone. The standard deviation of tossed balls speed was below 0.8 m/s. In addition, the analysis data used in this study was taken from a trial with which the subject was satisfied. These results suggest that the dispersion of tossed ball did not cause a significant change in batting motion.

The grip torque around the Bx axis showed a positive value after time equals 50% and reached the peak value at time equals 75-80%, and then showed a tendency to decrease (Figure 4). The bat’s rotational power showed a change similar to grip torque around the Bx axis (Figure 5). It seems that the bat’s rotational power is strongly dependent on the grip torque around the Bx axis. Then, it is logical that the inflow of mechanical energy by the grip torque into the bat contributes to increase in the bat’s rotational kinetic energy and the bat’s angular velocity from the middle swing phase until just prior to impact (time equals 50-90%). However, the grip torque around Bx axis and the bat rotational power did not show the significant correlation with the bat head speed at impact (Figure 4 and 5). Morishita et al. (2015) investigated the contribution of the grip forces and torques to the bat head speed using the forward dynamics approach. The previous study reported that the grip torque produced approximately 30% of the bat head speed at impact. Therefore, it is considered that the correlations between the bat head speed at impact and the kinetic variables of rotation are not high.

The grip torque around the Bx axis showed a tendency to decrease after time equals 80%, and then turned negative at impact (Figure 4). A previous study analyzing the female softball swing also reported a rapid decrease of torque exerted on the bat grip just prior to impact (Milanovich and Nesbit, 2014). In this previous study, the reason dis-
cussed for the inability of the batter to maintain torque was the rapid increase in bat speed. The bat also rotated at high speed in the current study, exceeding 2000 deg/s just prior to impact (Figure 3). Based on the force-velocity relationship of skeletal muscles (Hill, 1938), the torque exerted by each wrist joint is quite small even though the wrist joints rotate at a high bat speed. Therefore, it is reasonable that the grip torque around the Bx axis after time equals 80% declined because of the physiological limitation of both wrist joints. Moreover, the negative grip torque around the Bx axis at impact is assumed that the resistance of eccentric contraction on skeletal muscles of both wrist joints is estimated as the negative torque. This suggests that the force-velocity relationship of skeletal muscles holds for not only the motion of a simple joint, but also for the motion of parallel two joints.

The exertion of negative torque around the By axis was evident from the middle swing phase on (after time equals 45%). It is assumed that this torque is exerted in order to maintain the appropriate bat angle, by preventing the bat head from dropping. The previous study analyzing the female softball swing also reported a similar result (Milanovich and Nesbit, 2014).

The grip force in the Bz axis direction increased after time equals 55% (Figure 4). Generally speaking, the centripetal force (or the centrifugal force) is inversely proportional to the radius of rotation in rotational movement. Therefore, the acceleration of rotating objects is also inversely proportional to the radius of rotation. In addition, the centripetal force is proportional to the square of velocity. The grip force in the Bz axis direction was proportional to the square of bat head speed during the time from 70 to 100% (Figure 6). However, the radius of curvature of the bat head showed a constant increase, regardless of the change in bat head acceleration (Figure 3). Conversely, previous study of hammer throw reported that the acceleration of hammer head was increasing during the time period when the radius of curvature of the hammer head was shortened (Dapena and Feltner, 1989; Bandou et al., 2006). Hence, it is considered that the acceleration mechanism was different between baseball batting and hammer throw, although these sports were similar in terms of rotational motion. In addition, it is safe to say that the magnitude of the grip force in the Bz axis direction is not enough to shorten the radius of curvature of the bat head and the force is exerted only to counteract the centrifugal force of the bat.

The bat’s translational power rapidly increased after time equals 75%, and demonstrated a positive value until impact (Figure 5). In addition, the bat’s translational power had a high correlation with the bat head speed just prior to impact. It is logical that the exertion of this power contributes to increasing the bat’s translational velocity. The translational power is expressed as a product of force and velocity. Previous study reported that the grip force in the bat long axis direction produced approximately 70% of the bat head speed in baseball batting (Morishita et al., 2015). However, the results of this study revealed that the grip force in the Bz axis direction is exerted to counteract the centrifugal force of bat (Figure 6). Therefore, it is expected that the bat’s translational power is dependent on the bat grip velocity. In particular, it is assumed that the bat’s translational power is strongly dependent on the bat’s grip velocity in the Bz direction, because the force exerted on the bat grip was primarily grip force in the Bz direction. Taking the golf driver shot as an example, Miura (2001) investigated the mechanism of parametric acceleration, similar to parametric excitation, using an emulation of model unfixed rotation axis. The results showed that the energy of the club was increased if the rotational axis is moved in the direction opposite to the centrifugal force. Furthermore, it is reported that the increase in energy is the result of mutual interaction between the centripetal force and the velocity of the rotational axis, and the power of the model is dependent on the velocity of the rotational axis. The author anticipated the application of this mechanism to other sports (e.g. tennis, baseball and hockey). This study also suggests that the bat’s translational power depends on the bat’s grip velocities in baseball batting. Additional kinematic study to analyze motions that increase grip velocities in the direction of the bat’s long axis is required to understand the association between the mechanism and the actual baseball batting motion.

In this study, the magnitude of the grip forces and torques exerted to the bat grip by each hand is not clarified because the closed loop is formed by the upper extremity in baseball batting. It should be noted that the kinetic results of this study are the net forces and torques exerted to the bat grip by
both hands. Therefore, the limitation of this study is the point that the role of each hand during the bat swing is unclear.

5. Conclusion

In this study, mechanisms to increase bat head speed in baseball batting were analyzed from the viewpoint of bat kinetics. After the middle of the swing, the bat’s rotational power was increased by the exertion of grip torque. However, the grip torque and the bat’s rotational power decreased with an increase in the bat’s angular velocity just prior to impact. On the other hand, the bat’s translational power increased just prior to impact. In addition, it is concluded that the magnitude of the bat’s translational power depends on the bat’s grip velocity. From the results of this study, it is clear that the bat’s energy, by the application of power at different times, contributes to an increase in bat head speed in baseball batting. Therefore, to increase the bat head speed at impact, baseball batters are required to exert the grip torque around the axis perpendicular to the swing plane from the middle of the swing. Moreover, from just prior to impact, the increment of the bat grip velocity in the bat long axis direction contributes to increasing the bat head speed at impact.

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