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Optimisation of the upper body motion for production of the bat-head speed in baseball batting

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Abstract

The purposes of this study were to 1) develop a simulation model of baseball batting utilising the standard motion (Ae et al., 2007), and 2) explore optimal motions of the upper body to increase the bat-head speed. Twenty-three male collegiate baseball players performed tee batting set at waist height. A ten-segment angle-driven simulation model consisting of a bat and upper body was driven using with the coordinate data of the standard motion. Performance optimisation was conducted to find joint angle time histories of the upper body that increase the maximum bat-head speed. In the evaluation of the simulation model, the root mean square error between the measured and simulation model was 0.19 m/s and 0.98° for the time histories of the bat-head speed and bat orientation angle. Performance optimisation was able to achieve a targeted increase in bat-head speed (35.6 m/s to 40.0 m/s) through greater barrel-side shoulder abduction, knob-side elbow flexion, and torso right lateral flexion around ball impact resulted in the bat accelerating in the hitting direction. It is concluded that the proposed simulation approach can be applied as a tool for further simulation analysis in various complex sporting motions.

Keywords: computer simulation, angle-driven, standard motion, baseball batting, hitting mechanics

Introduction

The task of baseball batting is to hit a ball accurately and forcefully through the swift and skilful manipulation of a bat. Bat-head speed is a major determining factor of batting performance (Sawichi, Hubbard, & Stronge, 2003). Numerous studies of baseball batting have detailed the relationship between generating bat-head speed and the motion of the bat and body (Escamilla, Fleisig, DeRenne, & Taylor, 2009a,b; Dowling & Fleisig, 2016; McIntyre & Pfautsch, 1982; Messier & Owen, 1984; Race, 1960; Welch, Banks, Cook, & Draovitch, 1995). The generation of bat-head speed has been demonstrated to involve using a kinetic chain that transfers mechanical energy from the lower to upper limbs and bat through sequential proximal-to-distal joint motions (Welch, et al., 1995). Investigating the roles of the upper body and limbs associated with the production of bat-head speed would provide insight into potential improvements in batting performance.

Most studies focussing on batting technique have examined the difference in select variables between groups, such as different skill levels and conditions. Escamilla et al. (2009a, b) provided recommendations for the kinematics of the body dependent on different hand position and age groups. Dowling & Fleisig (2016) also compared kinematic patterns between different competition levels. In sports biomechanics research, a theoretical approach (i.e., computer simulation) has the advantage that ideal experiments can be carried out by changing a single variable (Yeadon & King, 2008). That is, the computer simulation would enable us to provide key suggestions and investigate optimal movement patterns in order to improve the performance. For this reason, many studies investigating optimal sporting performance have employed the computer simulation approach (Allen, King, & Yeadon, 2010; Fujii & Hubbard, 2002; Hiley & Yeadon; 2003; Yeadon & King, 2002). However, few previous studies have employed computer simulation for analysis of baseball batting due to the complex three-dimensional nature of the movement. The movement patterns which maximise the bat-head speed could be considered an optimal solution because bat-head speed relates directly to batted ball velocity. Exploring the movements required to generate higher bat-head speed through simulation can provide knowledge of optimal techniques and some important insights as to how batting performance can be improved.

In the teaching and coaching of sports, imitating the motion of skilled performers is a useful and efficient method for unskilled performers or beginners to improve their techniques (Ae, Muraki, & Koyama, 2007). In order to promote such activities through the biomechanical approach, Ae et al. (2007) proposed ‘a standard motion’ created by averaging the motion of many skilled performers. The standard motion represents athletic motions as a template motion displayed as a stick diagram, which is proven to be a useful visualisation in sports biomechanics research. Shimizu, Ae, Fujii, & Koyama (2018) used the model to analyse the motions of elite male long jumpers to classify jumping techniques and to identify biomechanical characteristics of each technique classification. Performing simulation analysis with several participants, not a specific participant, provides a description of a generic movement pattern that could be useful for many athletes who aim to improve their performance through personal adaptation of a movement template. The combination of the simulation approach and standard motion can allow an exploration of the optimal movement patterns originating from the initial movements of several participants. Therefore, the simulation using standard motion in this study can be a useful biomechanical tool and could provide insights into the improvement of batting performance in baseball.

The purposes of this study were to: 1) develop a simulation model of baseball batting utilising the standard motion, and 2) explore optimum motions of the upper body in order to increase the bat-head speed. It was hypothesised that the increase of higher bat-head speed would require noticeably changed motion patterns of the upper body enabling greater generation of mechanical energy.

Methods

Data collection and processing

Twenty-three male collegiate baseball players (age: 19.8 ± 1.3 years; height: 1.74 ± 0.04 m; mass: 74.1 ± 6.2 kg; baseball career: 12.0 ± 2.1 years) who were considered skilled hitters and played regularly in the Tokyo Metropolitan Area University Baseball League 1 participated in this study. The participants consisted of 11 right-handed batters and 12 left-handed batters. All participants gave informed consent to participate in the study, which was approved by the University of Tsukuba Research Ethics Committee. The protocol required the participants to strike a ball positioned on a tee at waist height (0.82 ± 0.02 m) from a self-selected stance position. Participants were instructed to hit the ball straight ahead on a flat trajectory with maximum velocity. A single trial of each participant was selected from the successful trials for the development of the standard motion. The successful trials were judged by several criteria (Ae, Koike, Fujii, Ae, & Kawamura, 2017; Ae, Koike, Fujii, Ae, Kawamura, & Kanahori, 2018; Ae, Koike, & Kawamura, 2020); including hitting the ball in a line drive towards a target (1.4 m × 0.7 m), the highest evaluation score of 4 or 5 (1, poor; 5, excellent).

Fifty-three retroreflective markers, including six placed on the bat, were captured using a motion capture system with 12 cameras (VICON-MX, Vicon Motion Systems, Ltd., Oxford, UK) operating at 250 Hz. Force and moment of the individual hands were measured with an instrumented grip-handle equipped with 28 strain gauges (1000 Hz) that had a similar structure to the instrumented bat proposed by Koike, Iida, Fujii, Kawamura, & Ae (2004). The marker positions were placed according to the method of Ae et al. (2017). A global coordinate system was defined as a right-handed orthogonal reference frame as follows: the positive X direction was from the inside (medial) to the outside (lateral) of home plate for a right-handed batter; the positive Y direction was from the back (posterior) to the front (anterior) of home plate; and the positive Z direction was vertically upwards. The three-dimensional coordinate data were smoothed by a fourth-order Butterworth low-pass digital filter with zero-phase shift at optimal cut-off frequencies (7.5-15 Hz), which were determined by residual analysis (Winter, 2004). Centre of gravity (CG_{sg}) and the inertia parameters of each segment were estimated from the body segment parameters of Japanese athletes (Ae, 1996). The common parameters in the simulation were as follows: bat-head speed was calculated by the magnitude of the bat-head velocity vector, joint angles for the upper body were calculated as the Euler angle between the orthogonal coordinate systems of the proximal and distal segments. The bat-head location was calculated by extrapolating 0.71 m from the midpoint of both hands to the bat-head side along the longitudinal axis of the bat, based upon the actual bat length and average hand position. The z-axis of the individual segmental coordinate systems was defined as the longitudinal direction among the proximal and distal joint centres. All parameters and procedures in this study were computed using MATLAB (The MathWorks Inc., Natick, MA, USA).

Standard motion

The standard motion (Ae et al., 2007) was calculated as averaged coordinate data across all participants by fitting the time series to 101 points and normalising by heights of the participants, as given by the following equations (Ae et al., 2007; Shimizu et al., 2018);

$$\boldsymbol{r}_{i,j} = \boldsymbol{R}_{i,j} - \boldsymbol{R}_{rp,j} \quad (1)$$

$$\boldsymbol{nr}_{i,j} = \frac{\boldsymbol{r}_{i,j}}{h_j} \quad (2)$$

$$\overline{\boldsymbol{r}_i} = \frac{\sum_{j=1}^{n} \boldsymbol{nr}_{i,j}}{n} \quad (3)$$

$$\overline{\boldsymbol{R}_{rp}} = \frac{\sum_{j=1}^{n} \boldsymbol{R}_{rp,j}}{n} \quad (4)$$

$$\overline{\boldsymbol{R}_i} = \overline{\boldsymbol{r}_i} + \overline{\boldsymbol{R}_{rp}} \quad (5)$$

where $\boldsymbol{r}_{i,j}$ is the relative coordinate vector from $\boldsymbol{R}_{rp,j}$ to $\boldsymbol{R}_{i,j}$ (coordinate vectors of landmark *i* and reference point (*rp*) for participant *j* (i.e., Whole body's CG), which were normalised to movement time), $\boldsymbol{nr}_{i,j}$ is the vector normalised to body height (h_j), $\overline{\boldsymbol{r}_i}$ is the mean coordinate vector, *n* is the number of participants, $\overline{\boldsymbol{R}_{rp}}$ is the mean coordinate vector of the *rp*, and $\overline{\boldsymbol{R}_i}$ is the mean coordinate vector of the *i*th landmark). The coordinate data of the standard motion was scaled to the mean movement time for use as input to the simulations, in which the movement time was varied in the performance optimisation. The CG_{sg} and the inertia parameters of the standard motion were calculated in the same manner as calculating those of each participant. Joint angular accelerations were calculated as the second-order differential of the joint angles of the standard motion, which is the relative angle between proximal and distal segments using Euler (Cardan) angle, for use as input to the simulation model. The period of the bat swing was defined as the time from the instant at which the sum of speeds of the bat-head and handle exceeded 3 m/s until one frame before ball impact to avoid distortion of the data (Ae, Koike, & Kawamura, 2013, 2014; Koike et al., 2004).

Simulation model

A ten-segment simulation model consisting of a bat and upper body model (comprising individual hand, forearm, upper arm, head, and two trunk segments) was developed (Figure 1) and driven using the coordinate data of the standard motion. The simulation model had 26 degrees of freedom (DOF). Twenty DOF governed the model configuration at the shoulder, elbow, wrist, torso and neck joints, and six DOF defined the linear and angular position of the lower trunk segment. The elbow varus/valgus and wrist pronation/supination axes were defined as anatomical constraint axes, which allowed no angular displacement. The bat and both hands were constrained with the averaged relative configuration of them for the measured data.

Model parameters, such as CG_{sg} positions and lengths of each segment, were calculated using the standard motion data. Input to the simulation model comprised the linear and angular displacement time histories of the lower trunk segment and the joint angle time histories (i.e., the second-order integral of the varied joint angular acceleration) of each joint in the form of cubic splines. Output from the model included the bat parameters (e.g., bat-head speed and angular velocity) and the joint torque time histories of the upper limbs. In order to calculate the joint torques, inverse dynamics calculations using Newton-Euler equations of motion were performed. In baseball batting, it is not possible to calculate the joint force and torque of the upper limbs due to 'closed loop problem' (Vaughan, Hay, & Andrews, 1982a, b). The force and moment of the individual hands were distributed by the optimisation procedure, dependent on the measured kinetic variables of the individual hands (Ae et al., 2013, 2014; Koike et al., 2004). In order to evaluate the accuracy of the simulation model, a root mean squared error (RMSE) between the measured and simulation model data was calculated for the time histories of bat-head speed, bat orientation angle and joint angles (17 DOFs).

Optimisations

Three optimisations were performed to find the optimal motions of the upper body for the increase of the bat-head speed (performance simulation) and to distribute the force and moment between the individual hands (Figure 2). All optimisation procedures were conducted by varying the values and timings of the time history data (i.e., joint angular acceleration, force and moment of the bat) by using a hybrid function of Simulated Annealing with fmincon (Sequential Quadratic Programming) in MATLAB. The time history data was varied by adjusting the timing and amplitude of nodes fit to the time histories (Figure 3). The nodes were set at the absolute maxima and minima, and zero-crossings of the standard motion data and an interpolating cubic spline function was fitted to the nodes (Fujii & Hubbard, 2002). In order to fit the node parameters more naturally, additional nodes were attached to the midpoints between adjacent nodes (Hiley & Yeadon, 2013). The smoothness of the reshaped joint angle time histories would largely influence the kinetic parameters of the hands and upper joints output from the optimisations, therefore second-order integrals of the joint angular accelerations were calculated and used as the joint angle time history input to perform the angle-driven simulations.

In the first optimisation, the joint angle time histories of the torso, shoulder, elbow and wrist joints were varied to obtain an optimised performance simulation with the aim of increasing the maximum bat-head speed to near 40.0 m/s (approximately 10% greater than the maximum bat-head speed of the standard motion [35.6 m/s]). The translation and rotation of the lower trunk, and neck joint rotation were not varied in the optimisation and were driven by the standard motion data. The criterion (F) was based on minimising the difference in the maximum bat-head speed and the target speed, and the RMSE of the time histories of the bat force ($RMSE_1$) and moment ($RMSE_2$) around the bat handle centre between the measured and optimised performance data (Eq. 6).

$$F = |40 - \|\boldsymbol{V}_{\mathrm{bat-head}}\|| + 0.04 \times RMSE_1 + 0.12 \times RMSE_2 \tag{6}$$

The bounds on the resulting bat Euler angle and optimised joint angles were allowed within ± 2 standard deviations (SD) of the averaged data of all participants to avoid unrealistic movement patterns. In order to constrain the ball impact height and bat trajectory, the angle between the bat-head velocity vectors of the measured and optimised performance data was constrained to be less than 10 degrees, and difference of the impact point of the bat at ball impact less than 0.05 m. The ball impact point of the bat was assumed to be located at 0.15 m from the bat-head (Ae et al., 2018). Simulations exceeding the set bounds of the bat and joint angles and impact parameters were given a large penalty.

In the second and third optimisations, simulations were performed to distribute the force and moment acting on the bat to the individual hands for the standard motion and optimised performance simulation data. The second optimisation distributed the total force and moment acting on the bat in the standard motion between the two hands. The averaged data from the instrumented bat were largely different from the simulated values of the model evaluation. The second optimisation varied the distribution of the force and moment of the simulation model between the two hands and evaluated the differences between total forces and moments on the bat in the simulation and model data. The third optimisation was then conducted by inputting the force and moment data for the individual hands determined in the second optimisation as the initial parameters and varied the distribution of the force and moment of the simulation model between the two hands and evaluated the differences between total forces and moments on the bat in the simulation and optimised performance data.

In the second and third optimisations, a forward dynamics model of the bat was used to compute the motion of the bat from the forces and moments of the individual hands. In the forward dynamics simulation of the bat, the equations of motion for the linear and angular motion of bat segment can be expressed as follows:

$$m_{\mathrm{bat}}\ddot{\boldsymbol{x}}_{\mathrm{bat}} = \boldsymbol{f}_{\mathrm{barrel}} + \boldsymbol{f}_{\mathrm{knob}} + m_{\mathrm{bat}}\boldsymbol{g} \quad (7)$$

$$\hat{\boldsymbol{I}}_{\mathrm{bat}}\dot{\boldsymbol{\omega}}_{\mathrm{bat}} + \boldsymbol{\omega}_{\mathrm{bat}} \times \left(\hat{\boldsymbol{I}}_{\mathrm{bat}}\boldsymbol{\omega}_{\mathrm{bat}}\right) = \boldsymbol{n}_{\mathrm{barrel}} + \boldsymbol{n}_{\mathrm{knob}} + \boldsymbol{r}_{\mathrm{bat},\overline{\mathrm{cg-barrel}}} \times \boldsymbol{f}_{\mathrm{barrel}} + \boldsymbol{r}_{\mathrm{bat},\overline{\mathrm{cg-knob}}} \times \boldsymbol{f}_{\mathrm{knob}} \qquad (8)$$

where m_{bat} is the mass of the bat, $\ddot{\boldsymbol{x}}_{\mathrm{bat}}$ is the position vector of the bat's CG, $\boldsymbol{f}_{\mathrm{barrel}}$ and $\boldsymbol{f}_{\mathrm{knob}}$ are force vectors applied by the hands of the barrel-, near side of the bat-head, and knob-side, near side of the handle-end, $\boldsymbol{g}$ is the gravitational acceleration vector, $\hat{\boldsymbol{I}}_{\mathrm{bat}}$ is the inertia matrix of the bat expressed in the global coordinate system, $\boldsymbol{\omega}_{\mathrm{bat}}$ is the angular velocity vector for the bat, and $\boldsymbol{n}_{\mathrm{barrel}}$ and $\boldsymbol{n}_{\mathrm{knob}}$ are moment vectors applied by the individual hands. The vectors $\boldsymbol{r}_{\mathrm{bat},\overline{\mathrm{cg-barrel}}}$ and $\boldsymbol{r}_{\mathrm{bat},\overline{\mathrm{cg-knob}}}$ with barred subscripts cg-barrel and cg-knob denote position vectors running bat's CG to the estimated points of the individual hands on the bat, which is considered the hand placement for each participant.

By inputting the fitted force and moment of the individual hands to Eq. (7) and (8) with the initial kinematic parameters of the simulation model and optimised performance simulation data, the linear acceleration and angular acceleration of the bat segment was calculated (Koike et al., 2017). The criterions used in optimisation 2 and 3 were based on minimising the difference in the maximum bat-head speed, the RMSEs of the bat-head speed and bat angular velocity time histories, and total bat force and moment. The accuracies of the procedure of force and moment distribution were then assessed by the RMSE of the time histories of the bat-head speed and bat orientation angle as in the evaluation of the simulation model.

Results

The RMSE between the measured data and simulation model was 0.19 m/s, 0.98°, 0.31° for the bat-head speed, bat orientation angle and the joint angles of the upper body (17DOFs) respectively. The second and third optimisations, that distributed the force and moment of the individual hands, achieved RMSEs in the bat parameters of 0.51 m/s and 2.61°, and 0.46 m/s and 1.45° respectively.

The maximum bat-head speed achieved in the optimised performance simulation was 40.0 m/s, predominantly produced by an increase in the Y axis component of its velocity around ball impact (Figure 4). The angle between the bat-head velocity vectors of the measured and optimised performance data was 1.81°, and the difference of the impact point of the bat at ball impact was 0.032 m, which are set to constrain the ball impact. The time histories of joint angles at the barrel- and knob-side upper limbs in the measured and optimised performance simulation data displayed differences in the second half, in particular around ball impact (Table I, Figures 5, 6 and 7). The barrel-side shoulder abduction angle was smaller in the simulated than the measured performance (Figure 6b) and wrist radial flexion angle was smaller in the simulated than the measured performance (Figure 6g). The knob-side elbow flexion/extension and wrist palmar flexion angles were smaller in the simulated than the measured performance (Figure 7d, f). In addition, the right lateral flexion angle of the torso joint was larger in the simulated than the measured performance during in the 0.15 s before ball impact (Figure 8b).

The RMSE of the joint torque time histories of the upper limbs between second and third optimisations was 5.8 ± 5.4 Nm (Table II). The largest discrepancies were observed in the knob-side shoulder adduction/abduction and elbow flexion/extension torques; 22.2 Nm and 11.2 Nm respectively (Figure 9).

Discussion and Implications

The primary purpose of this study was to develop a simulation model of baseball batting using the standard motion. The hitting motion is one of the most complex movements in sports, and few studies have conducted simulation analysis of the movement. The simulation model in this study displayed the capability to reproduce the measured data with high accuracy (RMSE: 0.31°), and thus it was validated for the investigation of optimal technique for the production of increased bat-head speed. In general, the use of torque-driven simulation models requires as input a representation of muscle activation based on participant's specific parameters (Yeadon & King, 2002). Several simulation analyses however developed angle-driven simulation models which monitor the joint torques produced during the evaluation (Hiley & Yeadon, 2003, 2013, 2016). In this study, the joint angle time history data input was calculated by second order integration of the varied joint angular accelerations; this method therefore allows inverse dynamics calculations to evaluate the joint torques of the upper limbs.

The performance simulation to optimise bat-head speed resulted in increased bat velocity in the hitting direction (Y axis) occurring around the time of ball impact (Figure 4). In the moments around ball impact the bat was moving in the horizontal plane in the hitting direction (Y axis). Tabuchi, Matsuo, & Hashizume (2007) suggested that having peak bat velocity at ball impact allowed for the optimal transfer of energy to the ball as well as increased spatial accuracy. In this study, the bat position and bat path at ball impact were constrained within the optimisation procedures. If the ball height and bat path at ball impact are not constrained, the timing and direction of the bat acceleration might differ greatly. Further research investigating different ball heights (high/low) and/or courses (inside/outside) would help to obtain the knowledge of increasing the bat-head speed under other constraints. Additionally, simulation analyses applying strict or non-strict impact constraints can enable assessments of the sensitivity of the optimal technique to changes in impact location.

The secondary purpose of this study was to explore optimal motions of the upper body in order to increase the bat-head speed. The optimised performance simulation was able to increase the maximum bat-head speed by 12% (35.6 m/s to 40.0 m/s). Hence, the changed joint angles of the upper body obtained from the optimised performance play an important role in increasing the bat-head speed. As shown in Table I and Figures 6, 7 and 8, the barrel-side shoulder abduction, knob-side elbow flexion/extension, and torso right lateral flexion angles demonstrated the largest differences between the measured and optimised data. It appears that adjusting the movement patterns at these joints might produce greater bat-head speed for the population studied. For the movements of the upper limbs in baseball batting, previous studies suggested that the adjustment of the knob-side elbow flexion/extension angle helped to alter the bat trajectory around ball impact (Escamilla et al., 2009a; McIntyre & Pfautsch,1982) and also factored into hitting skill level (Dowling & Fleisig, 2016). To actualise the performance simulation requires that the peak knob-side elbow extension torque time history was changed noticeably; the torque was increased and then decreased rapidly around ball impact (Figure 9). Koike & Mimura (2016) revealed through forward dynamic analysis that the knob-side elbow extension torque negatively contributed to generating bat-head speed. Since the upper limbs and bat compose a closed loop system, it could be expected that the adjustment of the barrel-side upper limb motion will also affect the motion of the knob-side limb. Changing the knob-side elbow flexion/extension angle might therefore have a role in the adjustment of the bat movement in order to hit a ball properly in response to the changes in the angles of the barrel-side shoulder and/or torso joints.

Overall, the results obtained from the optimised performance simulation demonstrate that the alterations to the joint angles of the upper body effected an increase in the bat-head speed in baseball batting. In the performance simulation, the adjustments to the joint angles were subtle (Table I, Figure 6, 7 and 8), in particular the knob-side shoulder abduction/adduction angle was not greatly altered; however the knob-side shoulder abduction torque and elbow extension torque were greatly increased around ball impact (Figure 9). The result also supports previous investigations into the kinetic characteristics of the upper limbs in baseball batting (Ae et al., 2014). Prior research has demonstrated that the knob-side shoulder abduction torque exerted around ball impact does not contribute to increases in the bat-head speed due to the large centrifugal force exerted along the longitudinal axis of the bat (Koike & Mimura, 2016). Therefore, it is speculated that the increased knob-side shoulder abduction torque is required to maintain the bat trajectory rather than producing the bat-head speed directly. The knob-side shoulder adduction/abduction and elbow flexion/extension torques displayed substantial differences between the second and third optimisations. Several studies have concluded that the hand force and joint torque of the knob-side were larger than those of the barrel-side in baseball batting (Ae et al., 2014; Koike et al., 2004; Koike & Mimura, 2016). The variation of the joint angles in the optimised performance was allowed within ±2 SD of the standard motion data, and the subsequent RMSE of the joint torques was relatively small (Table II), when compared to the exerted peak joint torques of the upper limbs observed previously (Ae et al., 2014). The results demonstrate that the optimal joint angles to increase the bat-head speed would produce a sufficiently realistic bat swing. The joint angle changes were mostly subtle and occurred around the time of ball impact (Table I, Figure 6, 7 and 8). Although only one ball impact location was investigated, optimal movement patterns for different ball impact locations may result in greater changes of the individual joint angles. The results of this study consequently rejected our hypothesis that to increase bat-head speed would require noticeably changed motion patterns of the upper body.

Angle-driven simulation analysis using the standard motion has demonstrated a highly versatile and useful procedure for improving performance in various sporting motions. In this study, the simulation model was able to accurately represent the motion of both the body and bat, and to assess the kinetics of the upper limbs in baseball batting. The angle-driven simulation approach has proven to be an effective tool to avoid problems in calculation such as re-construction of the body segment motions and optimisation time (Hiley & Yeadon, 2003, 2013, 2016). The results of this study suggest that the simulation model can be applied to baseball batting to investigate the mechanics of the technique and provide an insight into improving performance. In addition, the results obtained from the standard motion could imply more general information for improving performance of many athletes within the population, although the recommendations are not specific to any individual. If simulation analysis is applied to an elite athlete (e.g., Olympic-level athlete), it facilitates insights into high skilled performance, however the information may not be relevant for many athletes such as beginners and recreational athletes. Ae et al. (2007) noted that the standard motion can be used as an example of a good movement pattern or a template of model performance. Knowledge of the standard motion can provide a model motion for these people to improve their performance.

The simulation model in the present study consisted of the bat and upper body, and did not examine the effects of the lower body movements. The movements of the upper body play an important role in the production of bat-head speed and control the bat movement by generating and transferring the mechanical energy (Escamilla et al., 2009a, b; Dowling & Fleisig, 2016; McIntyre & Pfautsch, 1982; Messier & Owen, 1984; Race, 1960; Welch et al., 1995). Determining the optimal movement patterns of the upper body could increase of the bat-head speed whilst maintaining the movement of the lower body. The lower body however contributes to the rotational movement of the body and adjustment of the swing timing (Ae et al., 2017, 2018; Escamilla et al., 2009b; Welch et al., 1995). It is therefore necessary to approach a simulation analysis incorporating the lower body in further research to investigate the optimal movements of the whole body in baseball batting. In the performance simulation, the optimal technique for the increase of bat-head speed was explored within a relatively large range of upper body movements. However, the resulting difference in the ball impact location might be large when compared to the diameter of a bat (0.066 m) and a baseball (0.074 m). In order to consider the relationship between the body motion and the resulting batting performance (i.e., batted ball speed and launch angle), constraining the ball impact location more strictly would lend greater insight into the effects of batting technique on resulting batted-ball characteristics.

Conclusions

The analysis in the present study combined angle-driven simulation with the standard motion model and was able to provide the optimal movement patterns originating from the initial movements of several participants for improving general baseball batting performance, however not for a specific performance. In order to increase the bat-head speed by 12% (35.6 m/s to 40.0 m/s), changes to the barrel-side shoulder abduction, knob-side elbow flexion/extension, and torso right lateral flexion angles were made around ball impact, thus demonstrating an optimal bat swing motion. The result identified that if a batter can suitably adjust their movement patterns, the resulting bat-head speed can be increased and provides a useful insight for improving the hitting motion. Moreover, given that baseball batting is a complex three-dimensional sports motion, the proposed simulation approach can be applied as a tool for further simulation analysis in various similarly complex sporting motions.

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