EFFECTIVE TIMING OF EXERTING JOINT TORQUES TO OBTAIN BASEBALL BAT HEAD SPEED

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The purpose of this study was to quantify the effective timings of exerting joint torques for obtaining a large bat head speed at the ball impact in baseball batting motion. Twelve baseball batters performed hitting a teed ball as strongly as possible. The whole-body segments with bat were modelled as a system of sixteen-rigid linked segments. The kinematic and kinetic data were measured with the motion capture system with 3 force platforms and an instrumented bat. The major contributors were calculated using the equation of the whole-body motion considering the generating factors of the motion-dependent term. Since the instances when the individual contributions show peak values differ among the contributions of the major positive contributors, effective timings of exerting large joint torques exist for obtaining a large head speed at the ball impact.

KEY WORDS: induced speed analysis, motion-dependent term, cumulative effect, closed loop problem, instrumented bat, equation of whole-body motion

INTRODUCTION: In high-speed swing motions; such as, soccer kicking (Putnam, 1993), baseball pitching (Naito & Maruyama, 2008; Hirashima et al., 2008), and tennis serve motion (Koike & Harada, 2014), articulated joint motion is induced not only by joint torques but also motion dependent term (MDT) consisting of centrifugal force, Coriolis force and gyro moment. The contribution of joint torque term shows instantaneous effects to the generation of bat head speed, meanwhile the contribution of the MDT show cumulative effects caused by time-history inputs of joint torques because the MDT is constructed of the product sums of angular velocities of individual segments. Although baseball batters utilize this cumulative effects to obtain large bat head speeds, previous studies mainly focused on kinematics for investigating the skill for obtaining large head speeds. The purpose of this study was to quantify effective timings of exerting joint torques to obtain large bat head speed at the ball impact considering the cumulative effects of joint torques in the generation of the motion-dependent term.

METHODS: Twelve male collegiate baseball players (height: 1.73±0.04 m, mass: 71.2±6.1 kg) were instructed to hit a teed ball in the pitcher's direction as strongly as possible. Kinematic data (47 markers on the body; 6 markers on the bat) were captured with a motion capture system (VICON-MX; 12-camera; 250 Hz). Kinetic data of the individual hands were measured with an instrumented grip-handle (28 strain gauges; 1000 Hz), which has a similar structure to the instrumented bat (Koike et al., 2004). Kinetic data of the individual feet were measured with three force platforms (9281 [× 2], 9287, Kistler Inst.; 1000Hz). A forward swing phase was defined as a period from the start of bat swing to the ball impact. The time history of data was normalized by the period of the forward swing phase as 0 to 100%.
The whole body with a bat was modelled as a system of sixteen-rigid linked segments. A virtual joint, named torso joint, is assumed to be between the upper and lower trunk segments. The bat is assumed to be connected to each hand by a virtual joint with 0 degree of freedom. Each lower limb is assumed to be connected with the ground via a virtual joint at the center of pressure (COP) of the foot (Koike et al., 2007). Anatomical constraint axes (e.g. varus/valgus axis at elbow and knee joints; internal/external rotation axis at wrist joint) are considered in the modeling (Koike et al., 2004).
With use of a generalized velocity vector, $\boldsymbol{V}$, which consists of linear and angular velocity vectors of all segments, the equation of motion for whole body with a bat can be written in

the following expression as:

$$\begin{aligned}\dot{V} &= \text{(joint torque term)} + \text{(gravitational term)} \\ &\quad + \text{(motion-dependent term: MDT)} + \text{(modeling error term)}\end{aligned} \tag{1}$$

where $\dot{V}$ denotes the generalized acceleration vector, which is the time derivative of the generalized velocity vector. This equation shows the contribution of the individual terms: such as, the joint torque term, the gravitational term, the MDT and the modelling error term, to the generation of the generalized acceleration vector.

The MDT can be expressed as the product of the coefficient matrix $\overline{A}_V$ and the generalized velocity vector as:

$$\text{MDT} = \overline{A}_V V \tag{2}$$

Supposing the vector Λ_V as the sums of the following terms,

$$\Lambda_V = \text{(joint torque term)} + \text{(gravitational term)} + \text{(modeling error term)} \tag{3}$$

the equation of motion for the whole body with a bat system is expressed by the following form:

$$\dot{\boldsymbol{V}}(k) = \boldsymbol{\Lambda}_V(k) + \overline{\boldsymbol{A}}_V(k)\boldsymbol{V}(k) \tag{4}$$

The generalized acceleration vector can be expressed by a difference approximation using the time interval Δt of the discretized system shown by the following equation.

$$\dot{V}(k) = \frac{V(k+1) - V(k)}{\Delta t} \tag{5}$$

Substituting eq.(5) into eq.(4) yields a recurrence formula with respect to the generalized velocity vector as follows (Koike & Harada, 2014).

$$\boldsymbol{V}(k+1) = \Delta t \boldsymbol{\Lambda}_V(k) + \boldsymbol{\Psi}_V(k)\boldsymbol{V}(k), \quad \boldsymbol{\Psi}_V(k) = \boldsymbol{E} + \Delta t \overline{\boldsymbol{A}}_V(k) \tag{6}$$

Eqs. (3) and (6) provide us with the information about the contributions of the input terms Λ_V (i.e. the joint torque term, gravitational term, and modeling error term) at the time *k*, to the generation of the generalized velocity vector at the time *k*+1 in the discrete-time system.

By using eq.(6), one can quantify the contribution of time history of Λ_V , expressed by eq.(3), to the generation of the generalized velocity vector at the time k as shown below:

$$\boldsymbol{V}(k) = \Delta t \sum_{h=1}^{k-1} \left[\left\{ \prod_{j=k-h}^{k-1} \boldsymbol{\Psi}_V(j) \right\} \boldsymbol{\Lambda}_V(h-1) \right] + \left\{ \prod_{j=0}^{k-1} \boldsymbol{\Psi}_V(j) \right\} \boldsymbol{V}(0) \tag{7}$$

where the function Π denotes the factorial function. This equation shows the cumulative effect of the inputs to the generation of the generalized velocity vector at the time *k*.

By extracting the linear and angular velocity vectors of the bat segment from the generalized velocity vector for calculating the bat head speed, the time-history contributions of the individual terms to the generation of bat head speed at the ball impact can be obtained as follows:

$$S_{\text{bat,H}}(k_{\text{impact}}) = C_{\text{Trq}} + C_{\text{gravity}} + C_{\text{err}} + C_{V0} \tag{8}$$

where $S_{\text{bat,H}}(k_{\text{impact}})$ denotes bat head speed at the ball impact, C_{Trq} , C_{gravity} , C_{err} and C_{V0} show the time-history contributions of the joint torque term, the gravitational term, the modeling error term and the initialized velocity term, respectively. Furthermore, the contribution of the joint torque term can be decomposed into the contributions of the individual joint torque terms (Koike & Harada, 2014).

RESULTS AND DISCUSSION: Figure 1 shows the mean and SD values of the contributions of the joint torque term and the motion-dependent term (MDT) to the generation of the bat head speed at the ball impact. These values were calculated from the time integration of eq. (1). The MDT is the largest contributor to the bat head speed. The contribution of the gravitational term was negligible small.

Figure 2 shows the contributions of the individual joint torques to the generation of bat head speed at the ball impact considering the generating factors of the MDT. The positive and negative contributors to the bat head speed at the impact are expressed with red and blue bars, respectively. The knob-side shoulder adduction/abduction torque was the largest contributor to the bat head speed at the impact. Although most of the major contributors show positive values, the flexion/extension axial torque at the knob-side elbow joint showed a large negative contribution. Thus, the role of the knob-side elbow joint torque was not obtaining the bat head speed but adjusting timing and positioning of the bat head into the hitting point.

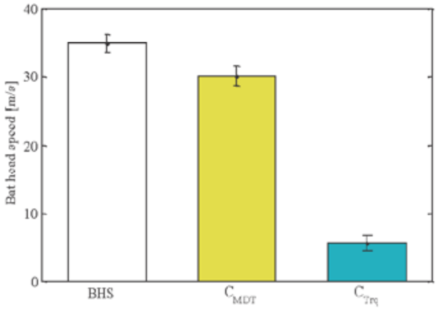

Figure 1: The contributions to the generation of impact bat head speed. BHS: measured bat head speed at the impact, C_{MDT}: contribution of MDT, C_{Trq}: total contribution of joint torques.(n=12)

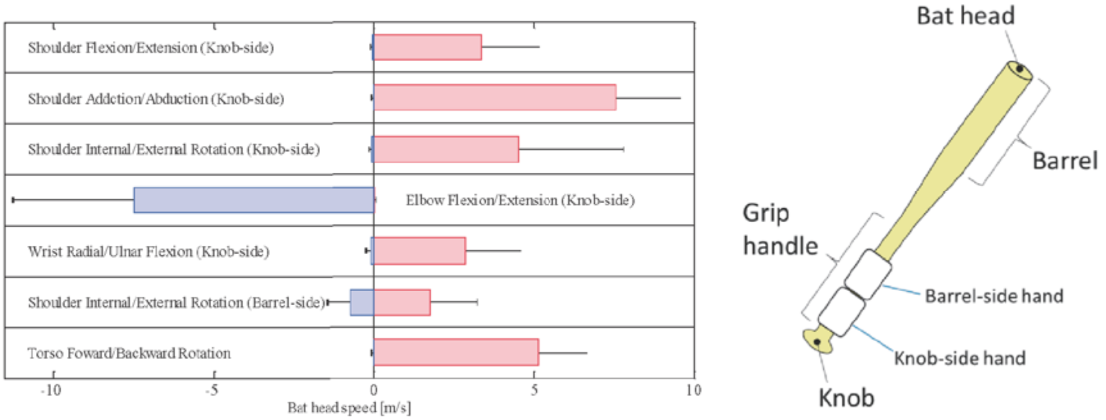

Figure 2: Mean and SD (n=12) contributions of the joint torques to the generation of bat head speed at the impact with consideration of the generating factors of the MDT.

Figure 3 shows the time curves of contributions of the major positive contributors during the forward swing phase (0.2±0.02 sec) to the generation of the bat head speed at the ball impact. The shaded regions show the standard deviation. The total contribution of the individual joint torques in the whole body is expressed with black dotted line in the all graphs. The time curves of the positive contributions of the individual joint torques showed single peak patterns. The individual time curves of the contributions also show how large the individual joint torque at each instance contributes to the generation of the bat head speed at the ball impact. The time curves of the individual contributions of (a) total joint torque, (b) knob-side shoulder flexion/extension torque, (c) torso forward/backward rotation torque, (d) knob-side shoulder internal/external rotation torque, (e) knob-side shoulder abduction /adduction torque and (f) barrel-side shoulder internal/external rotation torque showed their peak values at 50%, 25%, 30%, 45%, 55% and 80% normalized time, respectively. Small contributions of major contributors before the ball impact indicate that joint torques just before the impact do not contribute to increase bat head speed but to maintain large head speed. Since the instances when the individual contributions show peak values differ among the contributions of the major positive contributors regardless of the magnitudes of the individual torques, effective timings of exerting large joint torques exist for obtaining a large head speed at the impact. Although the magnitudes of the joint torques show large values just before the ball impact due to the large centrifugal force exerting along the longitudinal axis of the bat, the torques do not contribute to increasing the bat head speed at the impact.

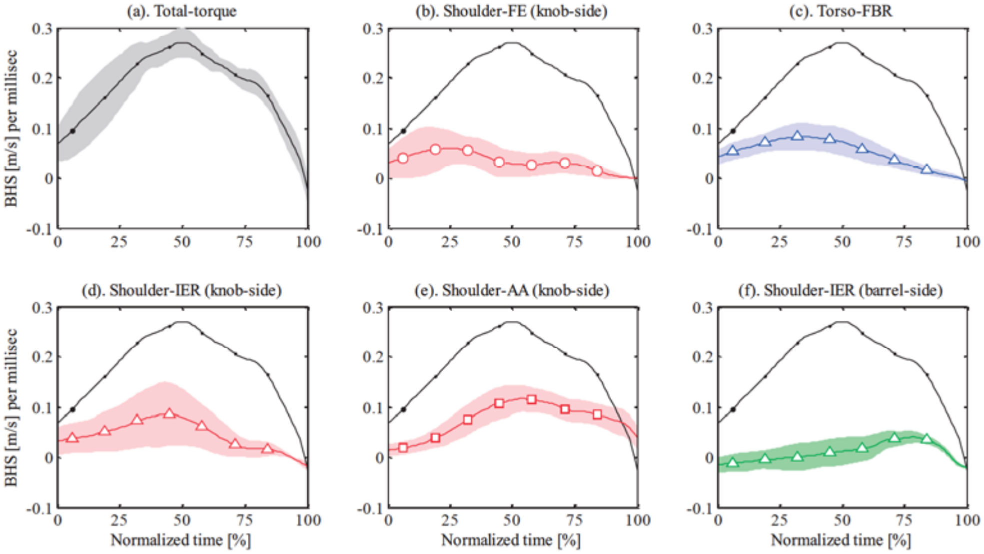

Figure 3: Mean and SD (n=12) time curves of contributions of the major positive contributors to the generation of the bat head speed at the impact. (a): total contribution of all joint torques, (b): knob-side shoulder flexion/extension, (c): torso forward/backward rotation, (d): knob-side shoulder internal/external rotation, (e): knob-side shoulder adduction/abduction, (f): barrel-side shoulder internal/external rotation. Each player shows high consistency.

CONCLUSION: This study has tried to quantify the effective timings of exerting joint torques for obataining a large bat head speed at the ball impact in baseball batting motion. The results are summarized as follows:

(1) The time curves of the positive contributions of the individual joint torques in the forward swing phase to the generation of the bat head speed at the impact showed mostly single peak patterns, where the time curves of each player showed high consistency.
(2) The joint torques exerting just before the ball impact do not contribute to increasing the bat head speed at the ball impact but to maintaining the large head speed.
(3) The effective timings of exerting large joint torques differ among the major contributor joint axes.

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