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Contributions of joint torques, motion-dependent term and gravity to the generation of baseball bat head speed

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Abstract

This study quantifies the dynamic contributions of joint torques, motion-dependent term, and gravity to the generation of baseball bat head speed. Baseball batting is considered one of the most difficult tasks in sports motions. The batter is required to increase the bat head speed within a short time and move the bat into the hitting point with proper timing. Based on multi-body dynamics, a high speed swing motion is caused by not only joint torques and gravity but also motion-dependent term (MDT). The MDT consisting of centrifugal force, Coriolis force and gyro moment shows the dynamic characteristics of multi-segment motion. Five collegiate baseball players participated in this experiment. They performed hitting a teed ball as strong as possible. The whole-body segments with bat were modelled as a system of sixteen-rigid linked segments, and anatomical constraint axes of the elbow, wrist, knee and ankle joints were modelled with geometrical constraint equations in order to consider the degree of freedom (DOF) of the joint. The equation of motion for the whole-body and bat was obtained by considering modelling errors, such as residual joint force and moment, and fluctuations in segment' lengths and joint constraint axes. Kinetic data of each hand and each foot were obtained by using an instrumented bat equipped with 28 strain gauges and 3 force platforms, respectively. The dynamic contributions of the joint moments, the motion-dependent term and the gravity term to the bat head speed were derived from the time integration of the equation of motion for the system. The results show that motion-dependent term is the largest contributor to the bat head speed in the last quarter of the forward swing phase. The contributions of the gravity and modelling error terms show small values. Motion dependent term is main generating factor to the head speed at the ball impact in baseball batting motion.
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Keywords: Baseball tee batting; Cumulative effect; Closed-loop problem; Multi-body dynamics; Kinetic chain; Whip-like effect; Induced speed analysis

1. Introduction

Baseball batting is considered one of the most difficult tasks in sports motions. The batter tries to manipulate the bat with both hands in order to 1) accelerate the bat head to high speed within a short time and 2) adjust the barrel part of the bat into a hitting point accurately with proper timing. A high speed swing motion is caused by not only joint torque but also motion dependent term (MDT) consisting of centrifugal force, Coriolis force and gyro moment, based on multi-body dynamics [1-4]. Since the degree of freedom (DOF) of both hands is totally twelve (3 in force and 3 in moment per each hand) and six DOFs of redundancies exist in kinetics of the hands manipulating the bat, it is impossible to obtain the force and moment exerted by each hand on the bat via the inverse dynamics calculation with use of the only visual information of the bat [5]. This issue is named "Closed-loop problem" [6, 7]. Many previous researches of the upper body in baseball batting motion have focused only on kinematics of the bat and batters [8-12] because of the kinetic redundancies in the upper limbs and bat system. Although Cross (2004) reported a dynamic model of baseball batting [13], it does not consider the closed loop problem and articulated body dynamics of the upper limbs because the model is highly simplified with a 2-dimensional double pendulum model.

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The purpose of this study was to quantify the contributions from the sources of joint torques, gravity and motion dependent term to the generation of bat head speed in baseball tee batting motion by using a whole-body multi-rigid-segment model considering the closed loop problem and modelling errors.

2. Method

2.1. Data collection

Participants were five male collegiate baseball players, who were left-handed batters. They were instructed to hit a teed ball at belt height toward the net placed in the pitcher’s direction as strongly as possible. Three-dimensional coordinate data of the batting motion (body: 47 markers; bat: 6 markers) were captured using a 12-camera motion capture system (VICON-MX, Vicon Motion Systems, UK) operating at 250 Hz. Kinetic data of the individual hands were measured with an instrumented grip-handle equipped with 28 strain gauges operating at 1000 Hz, which has a similar structure to the instrumented bat [5]. Ground reaction forces of the individual legs were measured using three force platforms (9281A [$\times$ 2], 9287B, Kistler Instruments AG, Switzerland) operating at 1000 Hz. The motion capture system, the instrumented bat and the force platforms were electronically synchronized.

2.2. Dynamical model of whole body with a bat

The whole-body segments with a bat were modelled as a system of sixteen-rigid linked segments (Fig. 1). Each lower limb is assumed to be connected with the ground via a virtual joint at the center of pressure (COP) of the foot. Anatomical constraint axes (e.g. varus/valgus axis at elbow and knee joints; internal/external rotation axis at wrist joint), along which the joints cannot rotate freely, are considered. The bat is assumed to be connected with each hand via a virtual joint with 0 degree of freedom.

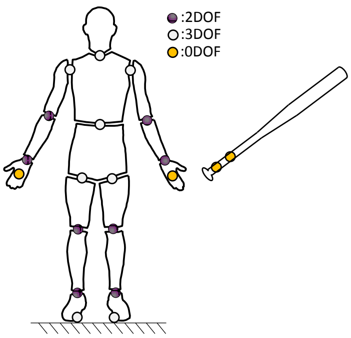

Fig. 1. A schematic representation of whole-body and bat model.

2.3. Equation of motion for the whole body and bat system

The equations of motion for the linear and angular motions of all segments can be expressed in a matrix form as follows:

$$\boldsymbol{M\dot{V}} = \boldsymbol{PF} + \boldsymbol{Q}_\mathrm{a}\boldsymbol{T}_\mathrm{a} + \boldsymbol{Q}_\mathrm{p}\boldsymbol{T}_\mathrm{p} + \boldsymbol{P}_r\boldsymbol{f}_r + \boldsymbol{Q}_r\boldsymbol{n}_r + \boldsymbol{H} + \boldsymbol{G} \tag{1}$$

where $\boldsymbol{M}$ is the inertia matrix, and $\boldsymbol{V}$ is the generalized velocity vector consisting of linear velocity vectors with respect to the center of gravity (CG) and angular velocity vectors for all the segments. $\boldsymbol{P}$ is the coefficient matrix for vector $\boldsymbol{F}$ which contains all joint force vectors and the ground reaction force vectors $\boldsymbol{f}_{\mathrm{COP}}$. $\boldsymbol{Q}$ is the coefficient matrix for vector $\boldsymbol{N}$ which contains all joint moment vectors and the ground reaction free moment vectors $\boldsymbol{n}_{\mathrm{COP}}$. $\boldsymbol{H}$ is the gyro moment vector, and $\boldsymbol{G}$ is the vector due to the gravitational force [4, 14]. $\boldsymbol{P}_\mathrm{r}$ and $\boldsymbol{Q}_\mathrm{r}$ are the coefficient matrices for the compensation vectors $\boldsymbol{f}_\mathrm{r}$ and $\boldsymbol{n}_\mathrm{r}$ set at torso joint obtained via inverse dynamics calculations that started from head and the individual hands and exerting force and moment measured with the instrumented bat.

Assuming that every segment is connected to its adjacent segment at a joint, the geometric constraint for linked segments can be expressed in a matrix form as:

$$\boldsymbol{CV} = \dot{\boldsymbol{\eta}} \tag{2}$$

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