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Dynamic contribution analysis of badminton-smash-motion with consideration of racket shaft deformation (A model consisted of racket-side upper limb and a racket)

Sekiya KOIKE[a]*and Tomohiro HASHIGUCHI[b]

[a]Faculty of health and sport sciences, Univertsity of Tsukuba, 1-1-1 Tennodai, Tsukuba, 305-8574, Japan
[b]Graduate school of comprehensive human sciences,Master's program in health and sport sciences, University of Tsukuba, Japan

Abstract

The purpose of this study was to develop a methodology that quantifies the contributions of the racket-side upper limb joint torques and shaft restoring torque to the generation of racket head speed during the badminton smash motion. The racket-side upper limb was modelled as successive rigid segments, such as upper arm, forearm and hand segments. The racket shaft was divided into a set of rigid segments connecting to its adjacent segments via virtual joints with rotational spring. The contributions of the joint torque term, motion-dependent term, gravitational term, and shaft restoring torque term to the generation of racket head speed were calculated from the equation of motion for the system consisting of racket-side upper limb and racket. A new algorithm which converts motion dependent term into other terms was proposed to investigate the main factor of the motion dependent term. The results showed that 1) the motion dependent term was the largest contributor to the generation of head speed prior to the impact, and 2) the shaft restoring torque term was positive contributor to the generation of motion dependent term over the forward swing period in the badminton smash motion.

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Keywords: Badminton Smash; Shaft Deformation; Dynamics Analysis; Dynamic Contribution

* Corresponding author. Tel.:+81-29853-2677;
E-mail address:koike@taiiku.tsukuba.ac.jp

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1. Introduction

The badminton smash is one of the highest tip-speed motions among various sports hitting motions. In the baseball pitching motion, which is considered as high speed swing motion, previous studies indicate that the motion dependent term, e.g. sum of centrifugal force, Coriolis force, and gyro moment terms (hereafter referred to as MDT), plays a significant role for the generation of end-point speed of linked segment systems (Naito et al., 2008; Hirashima et al., 2008). Although the badminton smash is a high-speed swing motion, the speed generation mechanism has not been examined. Additionally, racket shaft has elasticity due to its material property. However, the effect of the elastic characteristics on the tip-speed generation mechanisms of the swing motion has not been clarified. The purpose of this study was to develop a methodology that quantifies the contributions of the racket-side upper joint torques and shaft restoring torque to the generation of racket head speed during the badminton smash motion.

Nomenclature

$\boldsymbol{V}$	generalized velocity vector consisted of translational and rotational velocity vectors of all segments
$\boldsymbol{F}$	force vector composed of joint force vectors
$\boldsymbol{F}_{\mathrm{ext}}$	external force vector exerting on racket-side shoulder joint
$\boldsymbol{N}$	moment vector composed of each joint moment
$\boldsymbol{T}_{\mathrm{act}}$	active joint torque vector composed of individual joint axial torques

2. Methods

2.1. Modelling of racket-side upper limb and racket system

The racket-side upper limb was modelled as linked 3 rigid segments (upper arm, forearm and hand) that have 7 DOFs (3 for shoulder, 2 for elbow and 2 for wrist) considering anatomical constraint degrees of freedom at joint axes, e.g. inversion/eversion axis of the elbow joint, and internal/external rotation of the wrist joint (Fig.1). The racket model consisted of grip handle, racket shaft and face. The racket shaft was divided into a set of rigid segments connecting to its adjacent segments via virtual joints (Fig.1). The grip handle segment was connected to the hand segment via a virtual joint with 0 DOF.

2.2. Equation of motion for the system

The translational and rotational equations of motion for each segment of system can be summed up in a matrix form as follows:

$$\boldsymbol{M}\dot{\boldsymbol{V}} = \boldsymbol{P}\boldsymbol{F} + \boldsymbol{P}_{\mathrm{ext}}\boldsymbol{F}_{\mathrm{ext}} + \boldsymbol{Q}\boldsymbol{N} + \boldsymbol{H} + \boldsymbol{G} \tag{1}$$

where $\boldsymbol{M}$ is the inertia matrix and $\boldsymbol{V}$ is the vector containing the translational and rotational velocity vectors of each segment's CG, $\boldsymbol{P}$ and $\boldsymbol{P}_{\mathrm{ext}}$ are the coefficient matrices of vector $\boldsymbol{F}$ which contains all joint force vectors and of external force vector $\boldsymbol{F}_{\mathrm{ext}}$, $\boldsymbol{Q}$ is the coefficient matrix of vector $\boldsymbol{N}$ which contains moment vectors at all joints, $\boldsymbol{H}$ is the vector containing gyro moment vectors of all segments, and $\boldsymbol{G}$ is the vector of the gravitational component.

The equation for constraint condition in which adjacent segments are connected by joint is expressed as follows:

$$\boldsymbol{C}\boldsymbol{V} = \boldsymbol{0} \tag{2}$$

where $\boldsymbol{C}$ is the geometric constraint coefficient matrix of the generalized velocity vector.

The geometric equations for constraint axes of joints, such as, inversion/eversion axis of the elbow and internal/external rotation of the wrist joint can be expressed in matrix form as follows:

$$\boldsymbol{A}\boldsymbol{V} = \boldsymbol{0} \tag{3}$$