MAIN CONTRIBUTORS TO HIP JOINT MOTION IN SWING LEG DURING MAXIMAL VELOCITY PHASE IN SPRINT

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The purposes of this study were 1) to quantify the dynamic contributions of the individual terms; such as, joint torque term, gravitational term, and motion-dependent term (MDT), to the generation of angular velocity of the swing leg hip joint, and 2) to investigate the main contributors to the hip angular velocity considering the generating factor of the MDT. Three male sprinters performed maximal-effort sprinting. Dynamic contributions of the individual terms were calculated, and then the generating factors of the MDT were quantified using a recurrence formula. The results showed that 1) the MDT is one of the great contributors to the hip joint angular velocity, and 2) main contributors of the swing leg hip angular velocity are not only instantaneous and cumulative effects of the swing leg hip joint torque but also instantaneous effect of the contralateral hip joint torque.

KEY WORDS: dynamic contribution, hip joint angular velocity, motion-dependent term (MDT), cumulative effect, instantaneous effect, generating factor of MDT

INTRODUCTION: Since the main role of the support leg is to obtain propulsive forces from the ground and the role of the swing leg may be to control step frequency and step length, the swing leg motion would be one of the determinative factors of the performance at the maximal speed in sprinting. In such a high-speed and high-acceleration swing motion, the joint angular accelerations of the swing leg would be caused by not only instantaneous effect of joint torque inputs, which also contains dynamic coupling effect due to the non-diagonal inertial matrix of the system, but also cumulative effect (Zajac et al., 2002; Hirashima et al., 2008) of time-history joint torque inputs. Therefore, kinetic variables of the lower limb joints in sprint were used mainly to show the instantaneous effect on the generation of the swing leg motion, and used indirectly to indicate the cumulative effect of joint torque inputs (Vardaxis and Hoshizaki, 1989; Novacheck, 1998; Schache et al., 2011).

As an example of the cumulative effect as well as the dynamic coupling effect on swing leg motion, Phillips et al. (1983) reported that the motion of proximal segment; such as thigh, induces the motion of distal segment; such as shank with foot. Huang et al. (2013) decomposed the swing leg joint torque into the components: the active muscle torque, the passive motion-dependent torque, the ground reaction torque, and the gravitational torque by using an intersegmental dynamic approach. Furthermore, the motion-dependent torque was decomposed into the torques produced by segment movements, e.g. angular velocity and angular acceleration of segments. Although this study deals with the motion-dependent torque expressing the dynamic characteristics of multi-joint structure, the time-history of causal factors to the generation of joint velocities were not quantified.

Koike and Sudo (2015) reported that the motion-dependent term (MDT) consisting of centrifugal force and Coriolis force shows large contribution to the generation of the knee joint angular velocity based on the analysis using the equation of motion for a planar three-rigid-segment model of the swing leg in sprint. This study also quantified the main contributors to the knee joint angular velocity in consideration of the generating factor of MDT with use of a recurrence formula, which is proposed to quantify the cumulative effect of time-history joint torque inputs in high-speed swing motion (Koike and Harada, 2014). Since the swing leg model was a three-segment model consisting of thigh, shank and foot segments, it is impossible to quantify the generating mechanism on hip joint angular velocity and the contributions of other major joint torques; such as torques of the contralateral leg joints and torso joint. The purposes of this study were 1) to quantify the contributions of the individual terms (e.g. joint torque term, motion-dependent term, gravitational term, and modeling error term) to the generation of the hip joint angular velocity of the swing leg, and 2) to obtain major contributors to the hip angular velocity considering the generating factors of the motion-dependent term in sprint using a whole-body multi-segment model.

METHODS: Three male sprinters (age: 23.5 ± 0.2 years, height: 173.5 ± 4.5 m, weight: 65.2 ±5.8 kg, 100m personal best: 11.25±0.19 sec) performed 60m maximal sprinting from crouch start using a starting block. Three-dimensional coordinate data of the sprint motion (body: 47 markers) were measured with a motion capture system (VICON-MX, Vicon Motion Systems, 12-camera, 250Hz). Ground reaction force of the support leg was measured using three force platforms (9281, 9281, 9287, Kistler Inc., 1000Hz). Kinematics and kinetics data were calculated using the motion and force data measured around 50m.The time history of data was normalized by the period of swing phase as 0-100%.

An analytical form of the equation of motion for the whole body consisting of 15-rigid segments can be expressed as follows:

$$\dot{\boldsymbol{V}} = \boldsymbol{A}_{Ta}\boldsymbol{T}_a + \boldsymbol{A}_V + \boldsymbol{A}_G\boldsymbol{G} + \boldsymbol{A}_{err} \tag{1}$$

where vector $\boldsymbol{V}$ is the generalized velocity vector consisting of the linear cg velocity and angular velocity vectors of all segments; $\boldsymbol{A}_{Ta}$is the coefficient matrix of joint torque; $\boldsymbol{A}_V$ is the vector of the MDT; $\boldsymbol{A}_G$is the coefficient matrix of the gravitational acceleration vector $\boldsymbol{G}$. $\boldsymbol{A}_{err}$ is the modeling error vector consisting of 1) fluctuations in segment's lengths and anatomical constraint joint axes, and 2) residual force and moment mainly due to the errors of the body segment parameters. After time integration of eq. (1), multiplying a selective matrix $\boldsymbol{S}_q$ that transforms the generalized velocity vector $\boldsymbol{V}$ into an evaluation value, q_{eval}, yields the following equations:

$$q_{eval} = \boldsymbol{S}_q\int \boldsymbol{A}_{Ta}\boldsymbol{T}_a\,dt + \boldsymbol{S}_q\int \boldsymbol{A}_V\,dt + \boldsymbol{S}_q\int \boldsymbol{A}_G\,\boldsymbol{G}dt + \boldsymbol{S}_q\int \boldsymbol{A}_{err}\,dt + \boldsymbol{S}_q\boldsymbol{V}_0 \tag{2a}$$

$$= \boldsymbol{C}_{Ta} + \boldsymbol{C}_V + \boldsymbol{C}_G + \boldsymbol{C}_{err} + \boldsymbol{C}_{V0} \tag{2b}$$

where $\boldsymbol{V}_0$ is the initial value of the generalized velocity vector, the vectors $\boldsymbol{C}_{Ta}$, $\boldsymbol{C}_V$, $\boldsymbol{C}_G$, $\boldsymbol{C}_{err}$ and $\boldsymbol{C}_{V0}$ are the contributions of the joint torque term, the MDT, the gravitational term, the modeling error term, and the initial velocity term, to the generation of the evaluation value, respectively. Furthermore, the contribution of the joint torque term can be divided into the contributions of individual joint toques, which show the instantaneous effect of the joint torques.

When the MDT $\boldsymbol{A}_V$ of eq. (1) is written as the product of coefficient matrix $\overline{\boldsymbol{A}}_V$ and the generalized velocity vector as

$$\boldsymbol{A}_V = \overline{\boldsymbol{A}}_V\boldsymbol{V}, \tag{3}$$

eq. (1) can be rewritten as the following form:

$$\dot{\boldsymbol{V}} = \boldsymbol{\Lambda}_V + \overline{\boldsymbol{A}}_V\boldsymbol{V},\ \boldsymbol{\Lambda}_V = \boldsymbol{A}_{Ta}\boldsymbol{T}_a + \boldsymbol{A}_G\boldsymbol{G} + \boldsymbol{A}_{err} \tag{4}$$

The equation of the whole-body motion, eq. (4), in a discrete time system was expressed as follows:

$$\dot{\boldsymbol{V}}(k) = \boldsymbol{\Lambda}_V(k) + \overline{\boldsymbol{A}}_V(k)\boldsymbol{V}(k),\ \ \boldsymbol{\Lambda}_V(k) = \boldsymbol{A}_{Ta}(k)\boldsymbol{T}_a(k) + \boldsymbol{A}_G(k)\boldsymbol{G}(k) + \boldsymbol{A}_{err}(k) \tag{5}$$

where k is the time of the discrete time system.

The generalized acceleration vector was expressed by a difference approximation shown as

$$\dot{\boldsymbol{V}}(k) = \frac{\boldsymbol{V}(k+1) - \boldsymbol{V}(k)}{\Delta t} \tag{6}$$

Combining eqs. (5) and (6) yields a recurrence formula for the generalized velocity vector $\boldsymbol{V}$:

$$\boldsymbol{V}(k+1) = \Delta t\boldsymbol{\Lambda}_V(k) + \{\boldsymbol{E} + \Delta t\overline{\boldsymbol{A}}_V(k)\}\boldsymbol{V}(k) \tag{7}$$

The contributions to the generation of evaluation values without use of the MDT can be realized using the selective matrix $\boldsymbol{S}_q(k)$ as follows:

$$q_{eval}(k) = \boldsymbol{S}_q(k)\boldsymbol{V}(k) = \widehat{\boldsymbol{C}}_{Ta} + \widehat{\boldsymbol{C}}_G + \widehat{\boldsymbol{C}}_{err} + \widehat{\boldsymbol{C}}_{V0} \quad (8)$$

where the vectors $\widehat{\boldsymbol{C}}_{Ta}$, $\widehat{\boldsymbol{C}}_G$, $\widehat{\boldsymbol{C}}_{err}$ and $\widehat{\boldsymbol{C}}_{V0}$ denote contributions considering the generating factors of the MDT of the joint torque term, the gravitational term, the modeling error term and the initial velocity terms respectively. Subtracting the contributions in eq. (2b) from those in eq. (8) yields the contributions of the cumulative effects of the individual joint torques that show the generating factors of the MDT.

RESULTS AND DISCUSSION: Figure 1 shows the contributions of the individual terms to the generation of flexion/extension hip joint angular velocity of the swing leg calculated by using eqs. (2a) and (2b). The contribution of the joint torque term to the hip joint flexion angular velocity increased from 10% to 60%, then decreased until 80%, and then increased toward 100%. Meanwhile, the MDT contributed to the generation of hip joint extension angular velocity. The gravitational term showed negligible small contribution, and the modeling error term showed small contribution to the hip joint angular velocity. The MDT is the greatest contributor to the hip joint extension angular velocity of the swing leg (Fig. 1). The MDT is cumulative effect of time-history joint torque inputs to the generation of the swing leg motion. Figure 2 shows the contributions of the individual terms to the generation of hip joint angular velocity with consideration of the generating factors of the MDT. The total joint torque term contributed positively to the generation of hip joint angular velocity over the swing phase. Figure 3(a) shows the contributions of instantaneous effects of the individual joint torques to the hip joint angular velocity. The instantaneous contribution of the flexion/extension hip joint torque of the swing leg to the hip joint flexion angular velocity increased from 0% to 50%, and then decreased toward 100%. Meanwhile, instantaneous contribution of the flexion/extension hip joint torque of the contralateral leg to the hip joint extension angular velocity increased from 0% to 50%, and then decreased toward 100%. These two great contributors cancelled with each other over the swing phase. The rotation torque of the torso joint contributed to the hip joint extension angular velocity over the swing phase. Figure 3(b) shows the contributions of cumulative effects of the individual joint torques to the hip joint angular velocity. The cumulative contribution of the flexion/extension hip joint torque of the swing leg to the hip joint flexion angular velocity showed a double-peak pattern and reached a large extension value around the second peak. The cumulative contributions of other terms showed small values over the swing leg phase.

The hip joint torque of the swing leg is the generating factor of the MDT to the hip joint motion (Fig. 3b) as well as to the knee joint motion (Koike & Sudo, 2015). The instantaneous effect of the joint torque showed large contribution to the hip joint angular velocity, meanwhile the cumulative effect of the hip joint in swing leg showed small contribution. The contralateral hip joint torque contributed largely to the generation of the hip joint motion, where the motion was in the opposite direction induced by the swing leg hip joint torque (Fig.3a).

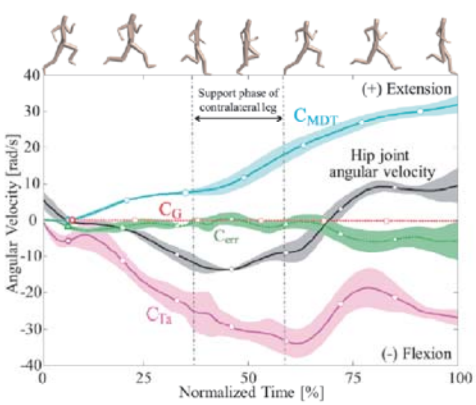


Figure 1: Contributions of the individual terms to the hip joint angular velocity.

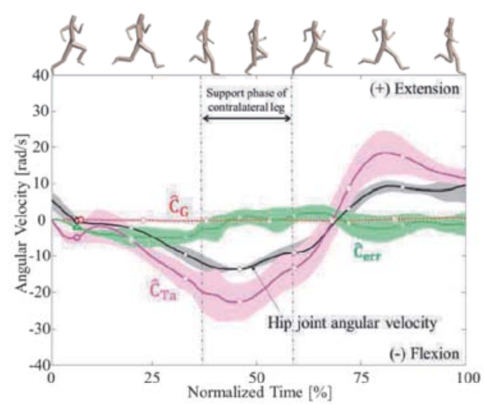
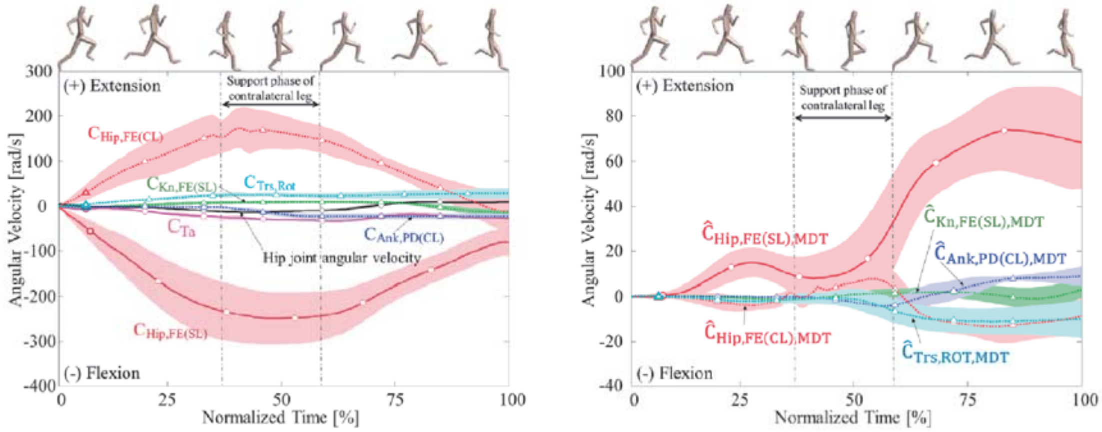


Figure 2: Contributions of individual joint torques to the hip joint angular velocity with consideration of the generating factors of the MDT.



(a). contributions of the instantaneous effects of the joint torques.

(b). contributions of the cumulative effects of joint torques (i.e., generating factors of the MDT).

Figure 3: Contributions of instantaneous and cumulative effects of the individual joint torques to the hip joint angular velocity. In the subscripts of C and $\hat{C}$, Hip, Kn, Ank and Trs denote hip, knee, ankle and torso joints; FE, PD and Rot denote flexion/extension, plantar/dorsal and right/left rotation axes; (SL) and (CL) denote swing leg and contralateral leg. In the subscripts of $\hat{C}$, MDT denotes generating factors of the MDT.

CONCLUSION: This study has clarified the generating mechanism of the hip joint motion of the swing leg in sprint. The results are summarized as follows:

(1) The contributions of the joint torque term and the motion-dependent term (MDT) to the hip joint angular velocity of the swing leg cancelled with each other, except for from 60% to 80%, over the swing phase.

(2) The total joint torque term contributed positively to the hip joint angular velocity over the swing phase with consideration of the generating factors of the MDT.

(3) The contributions of the instantaneous effects of hip joint torques of both hips to the hip joint angular velocity cancelled with each other.

(4) The main generating factor of the MDT, which shows the small contribution of the cumulative effect of joint torques to the hip angular velocity, was the hip joint torque of the swing leg. Thus, the swing leg hip motion can be generated intuitively in contrast to the swing leg knee motion induced by a large cumulative effect of the hip joint torque.

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