DYNAMIC CONTRIBUTION ANALYSIS ON THE PROPULSION MECHANISM OF SPRINTER DURING INITIAL ACCELERATION PHASE

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The purpose of this study was to propose a method that quantifies the functional roles of the support leg joint torques during sprinting acceleration phase. The acceleration of whole-body centre of gravity caused by the joint torques at 1*st*, 3*rd*, 5*th* and 7*th* steps from the crouch start were calculated based on the equation of motion for the whole body modeled as a linked system of fifteen rigid segments. The generation mechanism of eccentric ankle joint torque was quantified as the contributions of joints torques to the generations of joint angular velocities. The results indicate that 1) the eccentric plantarflexion torque is the largest contributor to the whole-body propulsion, 2) the eccentric plantarflexion torque is generated by the torques of hip and knee joints, and 3) the step number influences the propulsion mechanism.

KEY WORDS: functional roles of joints, support leg, sprint motion, step number, eccentric joint torque

INTRODUCTION: A correlation between the record of athletics 100m race and the maximal velocity has been reported from statistical analyses (Krzysztof M., 2007; B. Gajer et al., 1999). Since the maximal velocity depends on historical motions during start and acceleration phases (Ian N. Bezodis et al., 2008), the acceleration phase is one of the crucial phase on the record. Although previous studies on the acceleration phase have mainly reported kinematic variables e.g. step length, step frequency, and sprinting time (Krzysztof M., 2007; B. Gajer et al., 1999; F. Kugler et al., 2010) and/or kinetic variables e.g. torque, power, and work (Ian N. Bezodis et al., 2008; Simonsen E. B. et al., 1985; Jeseph P. Hunter et al., 2003), these variables do not make clear the roles of joint torque directly to the generation of whole-body acceleration. Koike et al. (2007) quantified the functional roles of joint torques during jumping motion via dynamic contribution analysis. However, the quantification of the functional roles of the joint torques to the whole-body propulsion during acceleration phase has not been reported.

Joint torques can be divided into two types of components such as eccentric and concentric torques that show negative and positive arithmetic signs of torque power, respectively. Since directions of exerting joint torque and angular velocity are opposite in the case of exerting eccentric joint torque, the eccentric torque is caused by external factors such as other joint torques. The generating mechanism of the eccentric joint torques has not been studied.

The purposes of this study were to propose a method that is 1) to quantify the functional roles of the support leg joint torques to the whole-body propulsion during sprint acceleration, 2) to clarify the generation mechanism of the eccentric plantarflexion torque, and 3) to investigate characteristics of plantarflexion/dorsiflexion angular displacements during individual steps.

METHODS: Two male short-distance sprinters, members of a university athletics team, performed 20m maximal sprints. The participants were instructed to start with crouch start from the starting block. The motions of the 1*st*, 3*rd*, 5*th*, and 7*th* steps from the start were analyzed. Ground reaction force and three dimensional trajectories of markers, which were attached to characteristic points of human body, were measured with a force plate (Kistler, 9287B, 1000Hz) and a motion capture system (Vicon Motion Systems, VICON-MX, 13-camera, 250Hz).

The whole body was modeled as a rigid linked fifteen-segment model consisting of the right and left upper limbs, the right and left lower limbs, the upper and lower trunks, and head. The functional roles of support leg joints at 1*st*, 3*rd*, 5*th* and 7*th* steps from the crouch start were analyzed by quantifying dynamic contribution of the joint torques using the equation of whole-body motion. This equation was derived from the combination of 1) the equations of motion for the individual segments, 2) the equations for constraint condition in which adjacent segments are connected by joint, and 3) the equations for anatomical constraint axes of joints such as adduction/abduction axis of the knee (S. Koike et al., 2014). Then, the quation of whole-body motion can be expressed as follows:

$$\dot{\boldsymbol{V}} = \boldsymbol{A}_{T\mathrm{a}}\boldsymbol{T}_{\mathrm{act}} + \boldsymbol{A}_{V} + \boldsymbol{A}_{G}\boldsymbol{G} \tag{1}$$

where $\boldsymbol{V}$ is the generalized velocity vector containing the translational and rotational velocity vectors of the individual segment centre of gravity (cg), $\boldsymbol{A}_{T\mathrm{a}}$ and $\boldsymbol{A}_{G}$ are the coefficient matrices of the active joint torques vector $\boldsymbol{T}_{\mathrm{act}}$ and of the gravitational acceleration vector $\boldsymbol{G}$, and $\boldsymbol{A}_{V}$ is the motion-dependent term which consisted of the nonlinear force terms such as centrifugal force, Coriolis' force and gyro moment.

The contributions to the generation of whole-body cg's acceleration were derived from eq. (1) using the selective matrix $\boldsymbol{S}$ which transforms the generalized acceleration vector into the whole-body cg's acceleration with use of mass properties of the individual segments as follows:

$$\ddot{\boldsymbol{x}}_{\mathrm{cg,Body}} = \boldsymbol{S}\dot{\boldsymbol{V}} = \boldsymbol{S}\boldsymbol{A}_{T\mathrm{a}}\boldsymbol{T}_{\mathrm{act}} + \boldsymbol{S}\boldsymbol{A}_{V} + \boldsymbol{S}\boldsymbol{A}_{G}\boldsymbol{G} \tag{2}$$

where $\boldsymbol{S}\boldsymbol{A}_{T\mathrm{a}}\boldsymbol{T}_{\mathrm{act}}$ is the active joint torques term, $\boldsymbol{S}\boldsymbol{A}_{V}$ is the motion-dependent term, and $\boldsymbol{S}\boldsymbol{A}_{G}\boldsymbol{G}$ is the gravitational acceleration term. The active joint torques term $\boldsymbol{S}\boldsymbol{A}_{T\mathrm{a}}\boldsymbol{T}_{\mathrm{act}}$ can be divided into contributions of the individual active joint torques as follows:

$$\boldsymbol{S}\boldsymbol{A}_{T\mathrm{a}}\boldsymbol{T}_{\mathrm{act}} = \sum_{\boldsymbol{j}=1}^{\boldsymbol{n_j}} \boldsymbol{C}_{T\mathrm{a},\boldsymbol{j}} \tag{3}$$

$$\boldsymbol{C}_{T\mathrm{a},\boldsymbol{j}} = \boldsymbol{S}\boldsymbol{A}_{T\mathrm{a},\boldsymbol{j}}\boldsymbol{T}_{\mathrm{act},\boldsymbol{j}} \tag{4}$$

where $\boldsymbol{C}_{Ta,j}$ represents the contribution of the individual joint torque to the generation of the horizontal whole-body cg's acceleration.

The torque power at the ankle joint was observed as negative values in the first half of support phase in sprinting (Ian N. Bezodis et al., 2008). When a joint torque power indicates negative values, the generating mode of the joint torque is eccentric which caused by external factors such as other joint torques. In order to find the external factors, the contributions to the generation of the ankle angular velocity were quantified by using the equation of whole-body motion. This equation was obtained by the time integration of eq. (1), described as follows:

$$\dot{\boldsymbol{\theta}}_{\boldsymbol{j}} = \boldsymbol{S}_{\boldsymbol{j}}\left(\int \boldsymbol{A}_{T\mathrm{a}}\boldsymbol{T}_{\mathrm{act}}dt + \int \boldsymbol{A}_{V}\,dt + \int \boldsymbol{A}_{G}\boldsymbol{G}dt + \boldsymbol{V}_{0}\right) \tag{5}$$

$$\boldsymbol{S}_{\boldsymbol{j}} = \left[\boldsymbol{O}\ \cdots\ \boldsymbol{O}\ \cdots -\boldsymbol{E}\ \ \boldsymbol{O}\ \ \boldsymbol{E}\ \ \boldsymbol{O} \cdots\ \boldsymbol{O}\right] \tag{6}$$

where $\boldsymbol{S}_{j}$ is the transformation matrix from the generalized velocity vector to the ankle angular velocity, and eq. (5) can be described as the sum of the individual joint axis components. For example, the contribution to the x-axial angular velocity about *j-th* joint can be expressed as follows:

$$\boldsymbol{C}_{\boldsymbol{j}} = \sum_{\boldsymbol{k}}^{\boldsymbol{n_k}} \left[1\ \ 0\ \ 0\right] \boldsymbol{S}_{\boldsymbol{j}} \int \boldsymbol{A}_{T\mathrm{a},\boldsymbol{k}}\boldsymbol{T}_{\mathrm{act},\boldsymbol{k}}\ dt \tag{7}$$

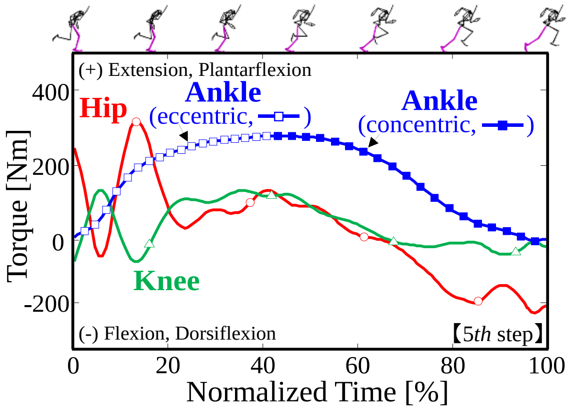

Figure 1: Time-history curves of the support leg joint torques during the support phase of the 5*th* step.

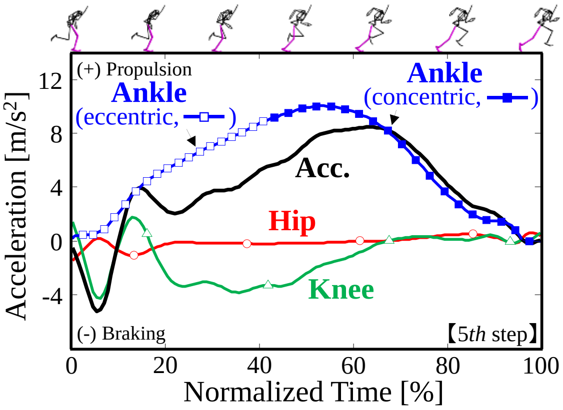

Figure 2: Time-history curves of the contributions of joint torques to the generation of whole-body cg's acceleration at 5*th* step.

RESULTS AND DISCUSSION: Figure 1 shows the time-history curves of the support leg joint torques at 5*th* step of the participant A. The ankle joint exerted plantarflexion torque throughout the majority of the support phase. The ankle joint torque generating mode, which is judged from arithmetic sign of ankle joint torque power, switched from eccentric to concentric around the half time of the phase. The knee joint exerted extension torque during 0-70% time and then exerted small flexion torque until toe-off. The hip joint exerted extension torque during 10-60% time and then exerted flexion torque increasing toward toe-off. These kinetic variables of the support leg joint torques were consistent with the previous study (Ian N. Bezodis et al., 2008).

Figure 2 shows the time-history curves of the contributions of the joint torques to the generation of whole-body cg's anterior/posterior acceleration, which is expressed by black solid line, at the 5th step of the participant A. The eccentric and concentric ankle joint torques showed the largest contributions to the whole-body propulsion throughout the majority of the support phase. The knee joint torque prevented the propulsion during 0-10% and 20-70% times. The hip joint torque contributed slightly to the propulsion of the support phase.

Figure 3 shows the time-history curves of contributions of the joint torques to the generation of the ankle joint angular velocity, which is expressed by black solid line, at 5*th* step. The ankle torque contributed to the large plantarflexion angular velocity, while the hip and knee torques contributed to the dorsiflexion angular velocity. That is, the hip and knee torques caused the eccentric ankle torque. This result indicates that the hip and knee torques are indirect contributors to the whole-body propulsion in the first half of support phase.

In order to investigate the influence of the step number from the start on the functional roles of the support leg joint torques in the generation of the eccentric ankle joint torque, dynamic contributions of all active joint torques of the support leg to the generation of the ankle angular displacement were calculated from the time integration of eq. (7) in the duration while the generating mode of ankle torque shows eccentric. Figure 4 shows the contributions of support leg joint torques to the generation of ankle angular displacements at individual steps. The contribution of the hip extension torque to the generation of dorsiflexion angular displacements was significantly large at the 1*st* step compared to those at the 3*rd*, 5*th* and 7*th* steps. The contributions of knee flexion/extension torques to the generation of ankle angular displacement decrease as the number of steps from the start increases. Naturally, the ankle plantarflexion torque contributed to the generation of plantarflexion angular displacements at the individual steps. The ankle inversion rotation torque also contributed to the plantarflexion angular displacement especially at the first step. From these results, the step number from the start influences on the functional roles of the hip and knee joint torques.

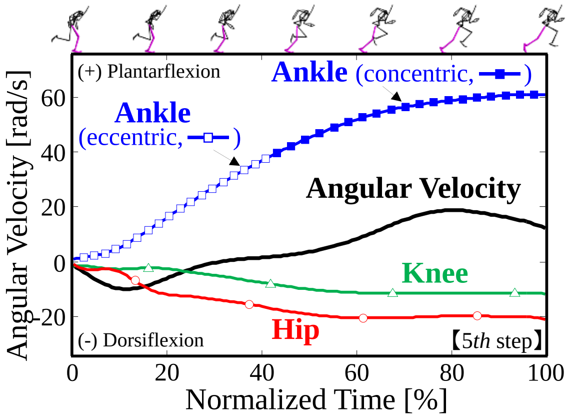

Figure 3: Time-history curves of the contributions of joint torques to the generation of the ankle joint angular velocity at 5*th* step.

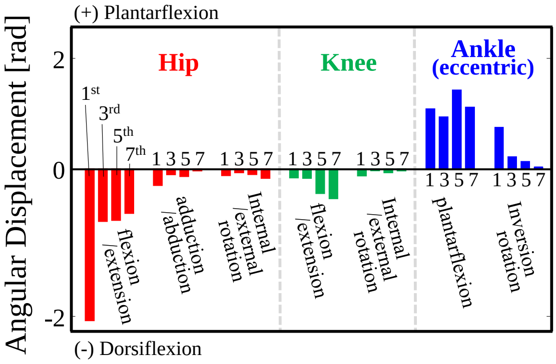

Figure 4: Contributions of joint torques to the generation of the ankle angular displacement at individual steps.

CONCLUSION: This study has successfully proposed a method that quantifies the propulsion mechanism of the support leg joint torques during sprint initial acceleration phase such as the 1*st*, 3*rd*, 5*th* and 7*th* steps from the crouch start. The results are summarized as follows:

(1) The ankle dorsiflexion torque was the largest contributors to the generations of the whole-body propulsion.

(2) The eccentric dorsiflexion torque was generated by the hip and knee torques in the first half of support phase.

(3) The hip and knee torques were indirect contributors to the generations to the whole-body propulsion.

(4) As the number of the step increases, the functional role of hip joint torques was gradually decreasing while the role of knee joint torques was gradually increasing.

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