DYNAMIC CONTRIBUTIONS OF SUPPORT LEG JOINT TORQUES TO THE GENERATION OF THE IPSILATERAL KNEE JOINT MOTION AND GROUND REACTION FORCE IN SPRINTING

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This study aimed 1) to quantify the contributions of the support leg joint torques to the generation of the anteroposterior forces, and 2) to clarify major contributors to the support leg knee joint angular velocity in terms of generating factors of the motion-dependent term (MDT) in sprinting. Dynamic contributions of the support leg joint torques in the maximal speed sprinting for elite and sub-elite sprinters were calculated, and the generating factors of the MDT were quantified The results showed that 1) ankle plantar flexion torque was the largest contributor to the generation of propulsive force regardless of performance level, and 2) the major contributors to the support knee flexion for sub-elite sprinter were ankle plantar flexion and hip flexion torques.

KEY WORDS: dynamic contribution, equation of whole-body motion, induced ground reaction force analysis(IGRFA), motion-dependent term(MDT), 3-D joint kinetics, support leg

INTRODUCTION: The main role of the support leg during sprinting is to produce the propulsive and braking forces as well as lift force from the ground to maintain running speed and support body against the gravitational force. Although joint kinetics of the support leg during sprinting have been reported (Bezodis et al., 2008), functional roles of the support leg joints are still unclear. An Induced ground reaction force analysis (IGRFA, Koike et al.,2019b) could be a useful tool to understand how high maximal speed sprinting is accomplished in terms of joint kinetics. But the IGRFA on the three-dimensional sprinting motion has not been demonstrated. In addition, Ito et al. (2008) indicated knee extension movement during the support phase would reduce maximal speed and they suggested suppressing knee extension would improve 100-m race performance. Thus, to clarify the major contributor to knee extension would be interesting for sprinters and coaches. This study aimed 1) to quantify the contributions of the support leg joint torques to the generation of the braking and propulsive forces, and 2) to clarify major contributors to the support leg knee joint angular velocity in terms of generating factors of the motion-dependent term in sprinting using a three-dimensional whole-body multi-segment model.

METHODS: Two male sprinters (elite, ES and sub-elite, sub-ES [age, 38 and 20 yrs; stature, 1.74 and 1.74 m; body mass, 78.0 and 67.1 kg; 100 m personal best time, 10.17 and 10.83 s]) performed maximal-effort sprints from crouched start position using starting blocks. Three-dimensional coordinate data of the sprint motion (body: 47 markers) were measured with a motion capture system consisted of 16 (ES) or 39 (sub-ES) cameras (Motion Analysis Corporation, Santa Rosa, CA, 250Hz). Ground reaction force of the support leg was obtained using a long force platform system (TF-90100, TF-3055, TF-32120, Tec Gihan, Uji, Japan, 1000Hz). Each participant provided written informed consent, and this study was approved by the ethics committee of the National Institute of Fitness and Sports in Kanoya. Whole body kinematic and kinetic data were calculated using the marker coordinates and ground reaction forces measured around the 45 m mark. The time history data was normalized by the period of support phase as 0-100%.

Two types of equations, such as 1) a dynamic equation for the generalized joint force vector $\boldsymbol{F}$ consisting of force vectors exerted at all joints including the virtual joint set at COP, and 2) the equation of the whole-body motion, were respectively derived from the combinations of three equations, such as 1) the equations of motion for the individual segments, 2) the equations for constraint conditions arising from the connection of adjacent segments at joints, and 3) the equations for anatomical constraint axes at certain joints. The equations of joint force vector $\boldsymbol{F}$ and the whole-body motion can be expressed in matrix forms with respect to all segments as follows (Koike et al., 2019a, 2019b):

$$\boldsymbol{F} = \boldsymbol{A}_{F,Ta}\boldsymbol{T}_a + \boldsymbol{A}_{F,\mathrm{MDT}} + \boldsymbol{A}_{F,G}\boldsymbol{G} + \boldsymbol{A}_{F,err}, \quad (1)$$

$$\dot{\boldsymbol{V}} = \boldsymbol{A}_{V,Ta}\boldsymbol{T}_a + \boldsymbol{A}_{V,\mathrm{MDT}} + \boldsymbol{A}_{V,G}\boldsymbol{G} + \boldsymbol{A}_{V,err}, \quad (2)$$

where the matrices $\boldsymbol{A}_{F,Ta,}$and $\boldsymbol{A}_{V,Ta}$are the coefficient matrices of active joint torque vector $\boldsymbol{T}_a$; the vectors $\boldsymbol{A}_{F,\mathrm{MDT},}$and $\boldsymbol{A}_{V,\mathrm{MDT}}$ show the vectors of the motion-dependent term (MDT) which are nonlinear terms consisting of centrifugal forces, Coriolis forces and gyroscopic effect(Koike et al.,2019a) moments.; $\boldsymbol{A}_{F,G,}$and $\boldsymbol{A}_{V,G}$ are the coefficient matrices regarding the gravitational acceleration vector $\boldsymbol{G}$. $\boldsymbol{A}_{F,err}$ and $\boldsymbol{A}_{V,err}$ are modeling error vectors (Koike et al., 2019b).

The contributions of the joint torque term can be decomposed into the contributions of individual axial active joint torque $\boldsymbol{C}_{\mathrm{GRF},a-p,\boldsymbol{T}_{a,j\mathrm{axis}}}$ to the generation of the anterior-posterior component of the ground reaction force vector (propulsive/ braking force). (Koike et al., 2019b).

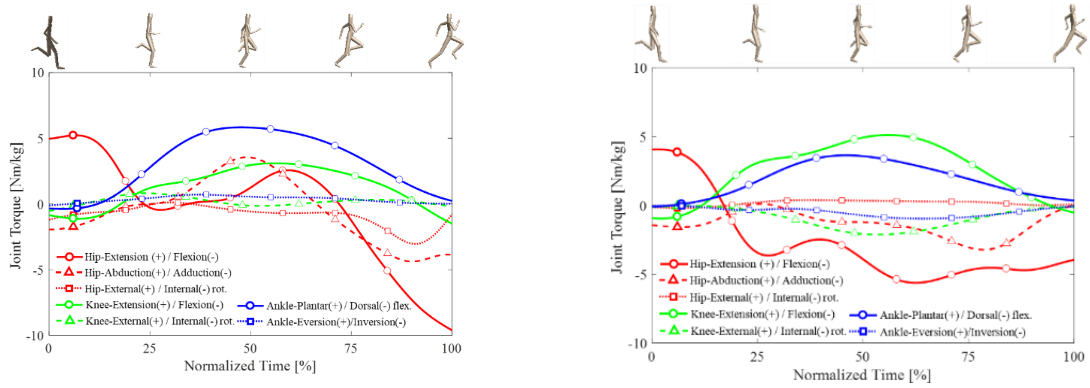
The contributions of the individual axial joint torque terms to the generation of the support leg's knee joint angular velocity (flexion/extension angular velocity) can be expressed by the following form after considering the relationship between time derivative of the knee joint FE angle using Cardan angle expression and angular velocity vectors of adjacent segments (e.g. thigh and shank segments) with use of time integration of Eq.2:

$$\dot{\boldsymbol{\theta}}_{\mathrm{knee,FE}} = \boldsymbol{C}_{knee,FE,Ta} + \boldsymbol{C}_{\mathrm{knee,FE},V} + \boldsymbol{C}_{\mathrm{knee,FE},G} + \boldsymbol{C}_{\mathrm{knee,FE},err} + \boldsymbol{C}_{\mathrm{knee,FE},V0} \quad (3)$$

where the vectors $\boldsymbol{C}_{\mathrm{knee,FE},Ta}$, $\boldsymbol{C}_{\mathrm{knee,FE},V}$, $\boldsymbol{C}_{\mathrm{knee,FE},G}$, $\boldsymbol{C}_{\mathrm{knee,FE},err}$ and $\boldsymbol{C}_{\mathrm{knee,FE},V0}$ 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 knee angular velocity, respectively.

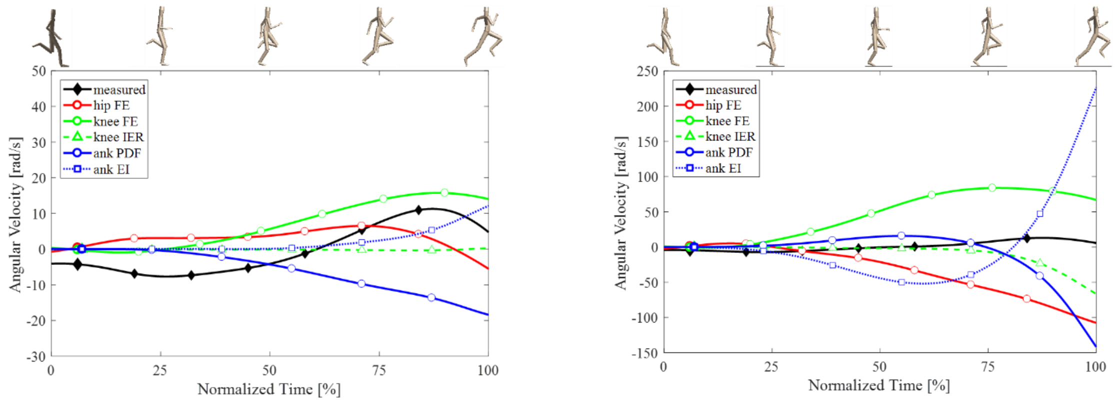
Furthermore, when the MDT showed large contribution to the knee angular velocity, the generating factors of the MDT was quantified according to the method in the previous study (Koike, et al., 2019a).

RESULTS AND DISCUSSION: Figure 1 shows the support leg joint torques of the ES and sub-ES. The ES had greater the plantar flexion torque of the ankle joint than the sub-ES throughout the support phase. From 25% to 75% of the support phase, the sub-ES showed greater internal rotation torque of the knee joint than the ES. Figure 2 shows the contributions of the individual joint torques to the generation of knee flexion/extension velocity for two sprinters taking into account the sources of the MDT. The positive contributions of the knee flexion/extension torque and the ankle eversion/inversion torque to the generation of the knee extension velocity was greater in the sub-ES compared to the ES from 80% to 100% of the support phase. In addition, the positive contributions of the hip flexion/extension torque, the knee external/internal rotation torque and the ankle plantar/dorsal flexion torque to the generation of knee flexion velocity were greater in sub-ES than ES from 80% to 100% of the support phase. Figure 3 shows the contributions of the individual joint torques to the generation of ground reaction force. The contribution of knee external/internal rotation torque on the generation of the braking force was greater in sub-ES than ES from 25% to 80% of the support phase. The ankle plantar flexion torque showed the greatest contribution to the generation of propulsive force as with the case in the IGRFA of the accelerating phase in sprinting (Koike and Nagai,2015).



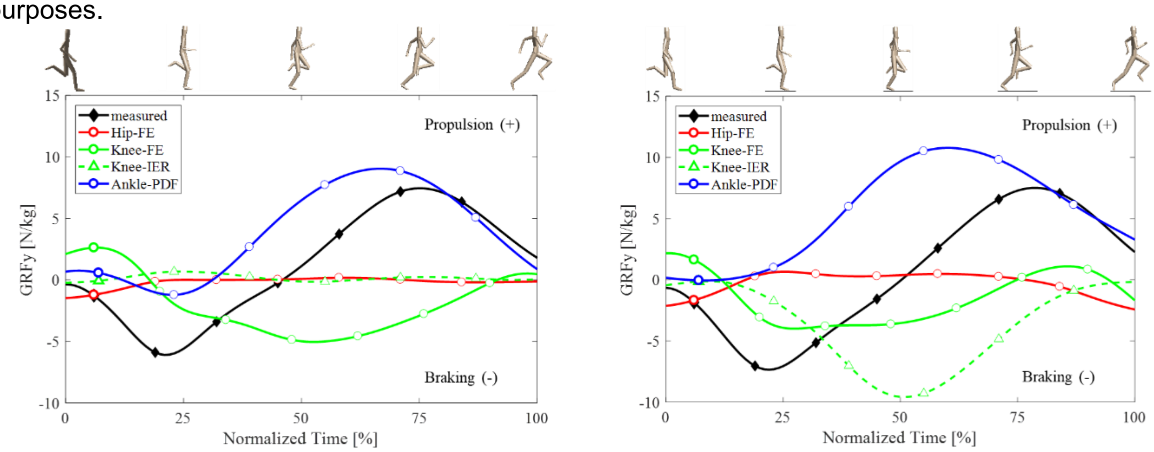
(a). Elite sprinter (b). Sub-elite sprinter

Figure 1: Joint torques of the support leg.



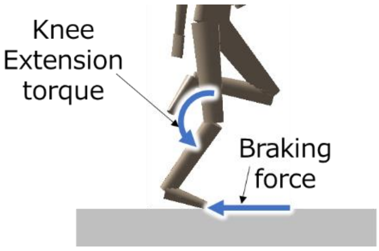
(a). Elite sprinter (b). Sub-elite sprinter

Figure 2: Contributions of individual joint torques to the knee joint angular velocity with consideration of the generating factors of the MDT. Note: the scale in Figures differs from the one for visual purposes.

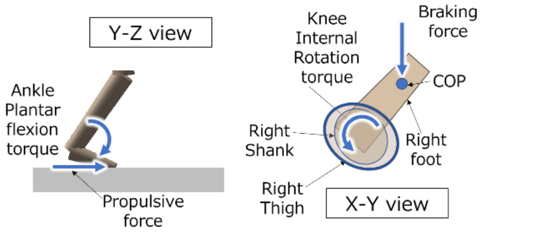


(a). Elite sprinter (b). Sub-elite sprinter

Figure 3: Contributions of individual joint torques to the ground reaction force in the direction of travel.



(a). effect of knee extension torque at 53% normalized time(ES)



(b). effects of ankle dorsiflexion and knee internal rotation torques

Figure 4: A schematic representation of the static relationship between joint torques and the anterior-posterior components of the GRF at knee and ankle joints.

Figure 4 shows a schematic representation of the relationship between joint torques and the anterior-posterior components of the GRF at knee and ankle joints. Although the relationship could be understood from the view of static relationship between knee joint torque and anterior-posterior component of the GRF (propulsive/braking force, Fig.4a), it is impossible to determine the static relationship between the torque and propulsive force due to the singularity of the Jacobian matrix (Koike et al., 2019b). The knee internal rotation torque would induce the braking force when the toe of the foot directs outside (Fig.4b). That said, further investigation based on the multi-body dynamics via the equation of whole-body motion is necessary for clarifying these relationships.

CONCLUSION: This study has clarified the generating mechanism of the ground reaction force and knee joint angular motion based on the equation of whole-body motion in sprinting. The results are summarized as follows:

(1) The ankle plantar flexion torque is the largest contributor to the generation of propulsive force even in maximal speed phase regardless of performance level.
(2) The knee joint internal rotation torque was a large contributor to the braking force for sub-ES mainly due to static characteristics between the torque and the force vector.
(3) The knee extension was generated predominantly from the contribution of the MDT except for the knee extension torque.
(4) The major contributors to the support knee flexion for sub-ES were ankle plantar flexion and hip flexion torques when considering the generating factor of the MDT.

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