RELATIONSHIPS BETWEEN LOWER LIMB JOINT KINEMATICS AND VERTICAL STIFFNESS DURING THE 400-M SPRINT

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We aimed to examine whether the lower limb joint kinematics related to the vertical stiffness differ between the early and the late phases of the 400-m sprint. An inertial measurement unit was used to collect the step-to-step whole-body kinematics during a 400-m sprint from twenty male collegiate track and field athletes. This study showed that larger knee flexion and ankle dorsiflexion angles were associated with larger vertical stiffness during the late phase, whereas there are no relationships between the vertical stiffness and lower limb joint kinematics during the early phase of the 400-m sprint. The magnitude of vertical stiffness during both the early and the late phases was negatively related to the 400-m sprint time. The current findings indicate that the 400-m sprint mechanics regulating the vertical stiffness differ between the early and the late phases.

KEYWORDS: inertial sensor, track and field, fatigue, mass-spring model, motion analysis

INTRODUCTION: In the 400-m sprint, running speed decreases from the peak sprint speed at 50-100 m to the end of the race (Hobara et al., 2010). Better performance in the 400-m sprint could be achieved by maintaining a higher sprint speed. Previous studies suggested that maintaining the vertical stiffness of the whole body, which is estimated by the spring-mass model, would maintain the sprint speed during the 400-m sprint (Hobara et al., 2010). Moreover, a larger vertical stiffness results in a higher sprint speed in 35-m sprinting (Paradisis et al., 2019). Thus, it may be hypothesized that a larger vertical stiffness could relate to a higher sprint performance in the 400-m sprint.

Some previous studies examined the relationships between vertical stiffness and lower limb joint kinematics during running and hopping. Farley et al. (1998) reported that a larger knee extension angle at the initial contact during hopping relates to larger vertical stiffness. Arampatzis et al. (1999) also found that the smaller knee flexion displacement during the ground contact phase could relate to the larger vertical stiffness. Thus, the characteristics of knee joint kinematics could be one of the factors to maintain the larger vertical stiffness during running. In addition to these findings in non-fatigue conditions, inter-individual differences in the lower limb joint kinematics during running were greater in a fatigue condition compared to a non-fatigue condition (Romero et al., 2022). Taken together, it may be hypothesized that the lower limb joint kinematics that affect the vertical stiffness during running could differ between fatigue and non-fatigue conditions. Because a larger vertical stiffness during a 400-m sprint could maintain the sprint speed, the differences in lower limb joint kinematics, regulating the vertical stiffness, between during the early and the late phases of the 400-m sprint would be vital information for coaches to achieve higher-level performance in fatigue conditions in 400-m sprint. However, there is no evidence that examining the differences in lower limb joint kinematics relates to the vertical stiffness, during a 400-m sprint.

Therefore, we aimed to examine whether the lower limb joint kinematics related to the vertical stiffness differ between the early and the late phases of the 400-m sprint. We hypothesized that knee extension/flexion angles could be related to vertical stiffness during the early phase, whereas none of the joint kinematic variables would exhibit relationship to stiffness during the late phase due to the larger inter-individual variations in sprint motion. To this end, we measured step-to-step whole-body kinematics during a 400-m sprint using an inertial measurement unit (IMU) because the lower limb joint angles on a sagittal plane, estimated by the IMU data during sprinting, were confirmed to have higher accuracy values compared to those estimated by an optical motion capture system (Schepers et al., 2018).

METHODS: Twenty healthy male collegiate track and field athletes (age: 20.2 ± 1.7 years; body mass: 64.3±7.7 kg; height: 1.74 ± 4.65 m) participated in this study. The group of participants included eight 400m sprinters, three 400m hurdlers, and nine 800m runners. The Research Ethics Committee at National Institute of Fitness and Sports in Kanoya approved this study (reference number: 23-1-32).

After an individual and adequate warm-up, more than 60 min, they sprinted 400 m at their maximal effort from starting blocks. The 400-m sprint trial was performed on an outdoor athletic track surface, using the sixth lane. The participants wore well-fitted suits and their own spiked shoes. To measure the whole-body kinematics during the 400-m sprint, the seventeen inertial sensors were attached to their trunk and limbs. The kinematic data during 400-m sprint trials were recorded using an IMU system (Xsens MVN Link system, Movella Inc., Netherlands), sampling at 240 Hz.

Data and statistical analyses were performed using MATLAB software (Matlab2023b, MathWorks Inc., USA). The foot strike and/or toe-off instants were detected using resultant acceleration data of foot-mounted sensors (Suzuki et al., 2022) to calculate flight and support times. The spring-mass model was used to estimate the vertical stiffness of the whole body in accordance with previous studies (Morin et al., 2005; Hobara et al., 2010) as follows:

$$K_{vert} = \frac{F_{max}}{\Delta y_c}$$

$$F_{max} = \frac{mg\pi(t_f/t_c + 1)}{2}$$

$$\Delta y_c = F_{max} \cdot \frac{t_c^2}{m\pi^2} + g\,\frac{t_c^2}{8}$$

where K_{vert}, F_{max}, and Δy_c represents the vertical stiffness, maximum vertical ground reaction force, and vertical displacement of the whole-body center of mass, respectively. F_{max} and Δy_c were estimated from body mass (m), flight time (t_f), and support time (t_c).

The early and the late phases were defined as from 100 m to 200 m and from 300 m to 400 m of the 400-m sprint, respectively. The mean values of the vertical stiffness, lower limb joint angles at initial contact, and lower limb joint angle displacement during both the early and the late phases were calculated. Pearson's correlation coefficient was used to examine the relationships between the vertical stiffness and the above-mentioned variables of lower limb joint angles. Additionally, because there is no evidence of the relationships between the vertical stiffness and running time of a 400-m sprint, Pearson's correlation coefficient was also used to examine these relationships. The significance level was set at $p < 0.05$.

RESULTS: The 400-m sprint time was 52.08 ± 1.92 s (min-max, 48.37-54.78). The vertical stiffness decreased after the timing of peak vertical stiffness (Figure 1a), which was observed from 25 m to 50 m. A significant negative correlation was observed between the 400-m sprint time and the mean vertical stiffness during overall, early, and late phases (Figure 1b&c).

Knee and ankle joint angles at initial contact were positively correlated with the mean vertical stiffness during the late phase, whereas there were no significant correlations between these variables during the early phase (Figure 2). Additionally, knee joint angle displacement was negatively correlated with the mean vertical stiffness during the late phase, whereas there were no significant correlations between these variables during the early phase (Figure 3).

DISCUSSION:

The present study examined the relationship between vertical stiffness and lower limb joint kinematics to determine the differences in this relationship during the early and the late phases of the 400 m sprint. We found that lower limb joint kinematics, which affects vertical stiffness, differs between the early and the late phases during the 400-m sprint. Additionally, we found that the vertical stiffness during the overall, the early, and the late phases of the 400-m sprint relates to higher performance in the 400-m sprint, as well as short sprints reported by a previous study (Paradisis et al., 2019).

The lower limb joint kinematics related to vertical stiffness were not identified during the early phase of the 400-m sprint. This finding did not support our hypothesis. Race pace strategies in the 400-m sprint exhibit larger inter-individual differences, especially in the sprint speed ratio to the maximal sprint speed during the early phase. These inter-individual differences in sprint speed could lead to larger variations in sprint motion. Thus, compared to during the late phase of the 400-m sprint, larger inter-individual differences in lower limb joint kinematics, which regulate vertical stiffness, might exist during the early phase.

We found that the larger knee flexion and ankle dorsiflexion angles at initial contact relate to larger vertical stiffness during the late phase of the 400-m sprint, though a previous study suggested the larger knee extension relates to the larger vertical stiffness in hopping (Farley et al., 1998). A simulation study revealed that an increase in the knee flexion and ankle dorsiflexion angles at initial contact could improve the absorption function during running (Gerritsen, 1995). Moreover, in our additional analyses, the greater knee flexion angle at initial contact during the late phase of the 400-m sprint relates to the lower displacement of knee flexion angle (r = -0.68, p < 0.01). Thus, to maintain the larger vertical stiffness during the late phase of the 400-m sprint, larger knee flexion angles at initial contact could contribute the effectively absorbing the ground reaction force with less knee flexion motion.

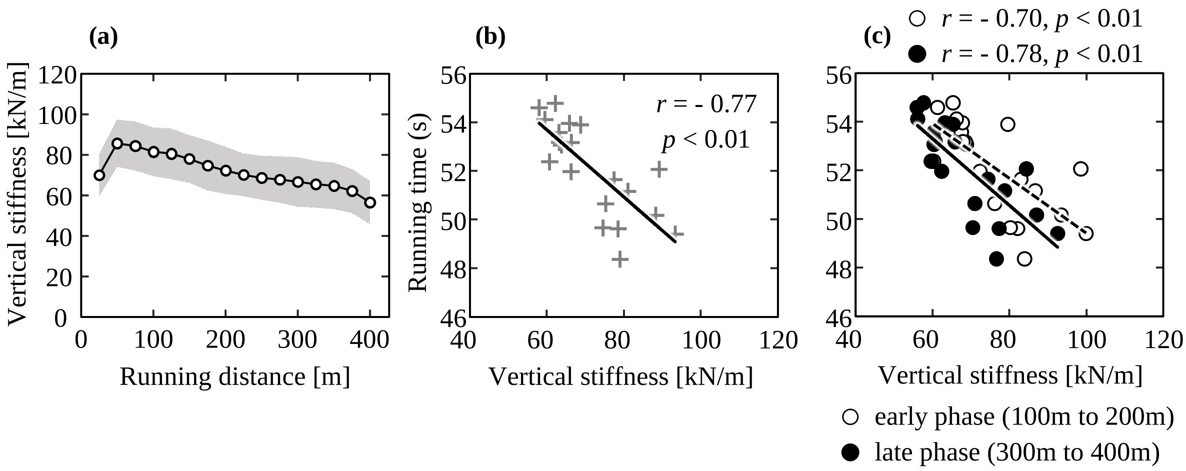

Figure 1: Vertical stiffness during 400-m sprint trial (a). Open circles and gray shadow area represent the mean and standard deviation, respectively. Relationship between the 400-m sprint time and mean vertical stiffness during 400 m (b), the early, and the late phases (c).

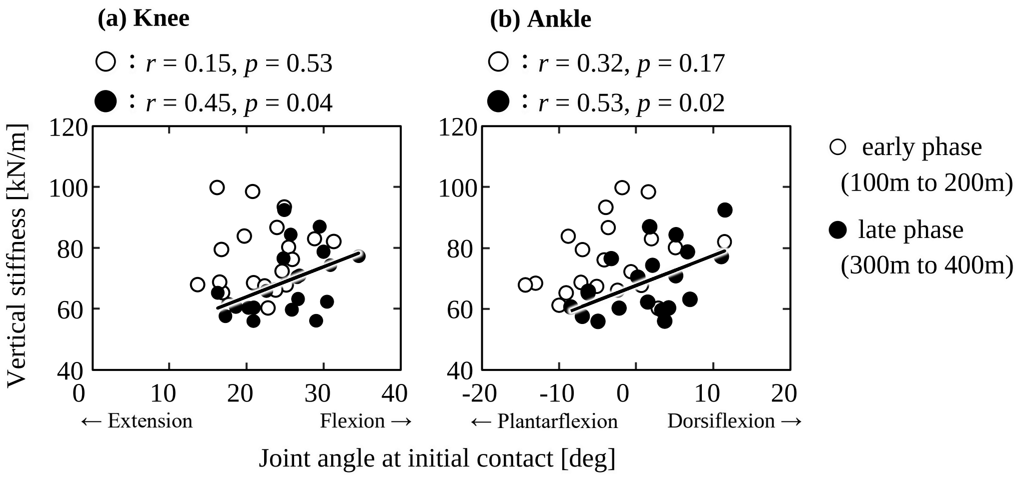

Figure 2: Relationship between the mean vertical stiffness and the mean knee (a) and ankle (b) joint angle at initial contact during the early and the late phases of 400-m sprint.

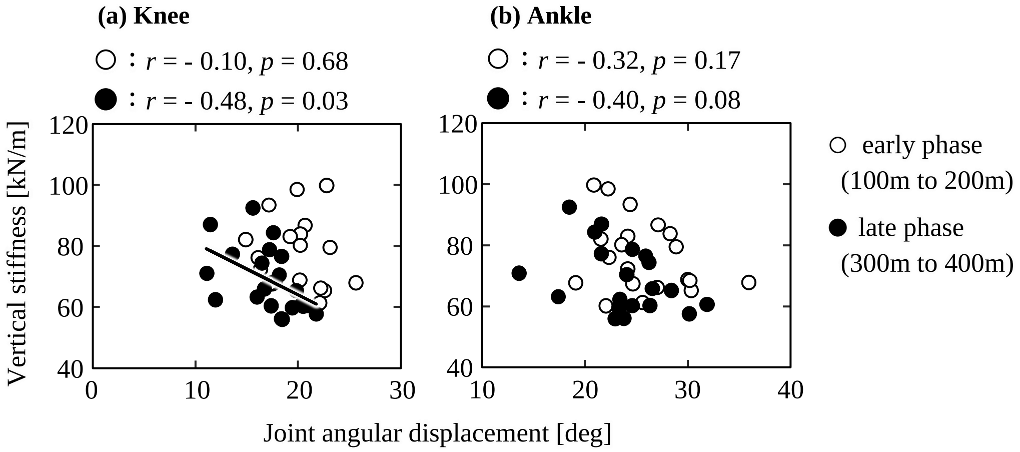

Figure 3: Relationship between the mean vertical stiffness and the mean knee (a) and ankle (b) joint angle displacements during the early and the late phases of 400-m sprint.

However, the participants of this study were heterogeneous (400m sprinters and huddlers, 800m runners), which may affect our results. Future studies should clarify the influence of participant characteristics on vertical stiffness and lower limb joint kinematics.

CONCLUSION: We examined whether the lower limb joint kinematics, which affect vertical stiffness, differ between during the early and the late phases in the 400-m sprint. We found that larger knee flexion and ankle dorsiflexion angles at initial contact relate to larger vertical stiffness during the late phase of the 400-m sprint, whereas there are no relationships between vertical stiffness and lower limb joint kinematics during the early phase.

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