CONTINUOUS CHANGES IN LEG STIFFNESS USING A MASS-SPRING-DAMPER MODEL WITH AN ACTUATOR DURING THE STEP PHASE OF THE TRIPLE JUMP

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The purpose of this study was to examine a calculation method of the leg stiffness using the simplified leg model for evaluating the continuous changes in leg stiffness during the step phase of the triple jump. The leg stiffness is the ratio of the ground reaction forces to a displacement of the simplified leg length. We compared the difference in the leg stiffness between the previous method and the proposed method in this study. There was a non-linear and exponential relationship between the displacement of the simplified leg length and the elastic force. The peak value of leg stiffness calculated by the previous method was larger than that by the mass-spring-damper model with an actuator of the proposed method in this study. The previous method could overestimate the leg stiffness during the triple jump. The leg stiffness of the proposed method has a potential for representing the muscle-tendon behaviors during the triple jump.

KEYWORDS: triple jump, leg stiffness, viscosity, elastic force.

INTRODUCTION: When humans run and jump, their lower limbs act as a spring-like element for bouncing the body. Athletes, who are jumpers and sprinters, are required larger leg stiffness to resist larger ground reaction forces during the ground-contact phase of jumping and sprinting. The ground reaction forces are larger in the triple jump than that of the long jump, and the step phase has larger ground reaction forces than the other phases of the triple jump (Ramey et al.,1985). Therefore, triple jumpers are required larger leg stiffness in the ground-contact phase to counter such larger forces during the step phase. Previous studies used a simplified leg model, which was configured with the line from the center of mass (CoM) to the point of foot contact, to evaluate spring functions (Ferris et al., 1997; Farley et al., 1999; Arampatzis et al., 1999). This model can represent the rotation around the point of foot contact and the leg extension during running and jumping (Jacobs et al., 1992; Zushi et al., 2003). The leg stiffness was calculated as the ratio of peak ground reaction force to a maximum displacement of the simplified leg length. This leg stiffness was useful to understand the behavior of running and jumping (Arampatzis et al., 1999; Mauroy et al., 2014). However, the previous model could not evaluate the continuous changes in leg stiffness during the ground-contact phase.

The purpose of this study was to examine a calculation method of the leg stiffness using the simplified leg model for evaluating the continuous changes in leg stiffness during the step phase of the triple jump. This model consists of three elements of a spring, damper, and actuator. The proposed method of this study could classify the ground reaction forces into the passive and active forces across the ground-contact phase.

METHODS: Four male collegiate triple jumpers participated in this study (Table 1). All the participants have written informed consent to participate in this study. They performed two or three triple jumps at the same conditions as the competition with their maximum effort after a suitable warm-up. The trials were recorded using four high-speed cameras (LUMIX FZ-300, Panasonic) sampling at 240 Hz. Ground reaction forces (GRF) data under the support leg of the step phase were recorded using a force platform (Kistler) sampling at 1000 Hz. The GRF data was synchronized with the kinematic data. 25 points of the human body model were digitized manually (Frame-DIASV, DKH, Japan). Three-dimensional coordinates of the body were calculated using a Direct Linear Transform method (Abdel-Aziz & Karara, 1971). The three-dimensional coordinates were low-pass filtered using a fourth-order zero-lag Butterworth digital filter with the optimal cut-frequency by residual analysis (14 – 38 Hz). The best record trial within two or three trials was used for the following analysis.

The leg stiffness reported by previous studies (Stiff$_{\text{prev}}$) (Ferris et al., 1997; Farley et al., 1999) was calculated using the values of peak GRF and the maximum displacement of the simplified leg length. The leg stiffness proposed by this study (Stiff$_{\text{new}}$) was calculated using a mass-spring-damper model with an actuator. The leg stiffness of both methods is normalized by the body mass of participant. The foot metatarsophalangeal (MTP) joint was adopted to the contact point to the ground, to avoid the error due to the move of the center of pressure. The leg length was defined as the distance between CoM of the whole-body and MTP joint. The CoM position was estimated using Japanese body segment inertia parameters (Ae et al., 1990). The displacement of the simplified leg length (Δx) was calculated. We also calculated the elastic coefficient and viscosity coefficient as follows described by Koike et al. (2005):

$$F_{GRF,i} = -k_i \Delta x_i - c_i \dot{x}_i \tag{1}$$

where F_{GRF} is the GRF projected onto the line of the simplified leg, k is the elastic coefficient defined by the spring, c is the viscosity coefficient defined by the damper, $\dot{x}$ is the changing rate of Δx at the time of t_i.

The elastic coefficient and viscosity coefficient are estimated at each time during the ground-contact phase minimizing the evaluation function η with respect to the force-spring-damper equation (Eq.1). The evaluation function η was determined as follows:

$$\eta_i = k_i^2 + \left(\frac{c_i}{T_c}\right)^2 \tag{2}$$

where T_c is the contact time of the step phase. The viscosity coefficient is divided by contact time to fix a dimension with the elastic coefficient.

The elastic force (F_E) is calculated as $-k\Delta x$, and the viscosity force (F_V) is calculated as $-c\dot{x}$. When elastic coefficient and viscosity coefficient are minuses, the elastic or viscosity force is replaced with the actuator force. Stiff$_{\text{new}}$ is calculated using F_E and Δx as follows:

$$\text{Stiff}_{\text{new},i} = -\frac{F_{E,i}}{\Delta x_i} \tag{3}$$

Stiff$_{\text{new}}$ is calculated for every data frame during the ground-contact phase, while Stiff$_{\text{prev}}$ is the fixed elastic value.

The mechanical power of the spring element (P_{Spring}) is calculated using F_E and $\dot{x}$ as follows:

$$P_{Spring,i} = F_{E,i}\dot{x}_i \tag{4}$$

Table 1: Participant characteristics.

Participant	Age [year]	Height [m]	Body mass [kg]	Personal best record [m]	IAAF score
A	21	1.74	63.3	14.55	906
B	20	1.78	68.5	15.23	977
C	19	1.85	70.9	14.15	864
D	19	1.73	63.3	15.65	1021

RESULTS: Stiff$_{\text{prev}}$ of all participants was larger than the peak value of Stiff$_{\text{new}}$ (Table 2). The participant who shows the larger Stiff$_{\text{prev}}$ also has the larger Stiff$_{\text{new}}$ (Table 2).

Table 2: The leg stiffness of all participants.
Stiff$_{\text{new}}$ was a peak value during the ground-contact phase.

Participant	Stiff$_{\text{prev}}$ [N/m/kg]	Stiff$_{\text{new}}$ [N/m/kg]
A	996.84	245.26
B	908.89	200.99
C	921.03	218.47
D	1010.67	260.64

Figure 1 showed the time-series data of Stiff$_{new}$ and the displacement of the simplified leg length during the step phase. The peak Stiff$_{new}$ occurred from 39 % to 45 % (mean ± SD: 41.5% ± 2.5%) of the step phase. The shortest displacement also occurred from 39 % to 45 % (mean±SD: 42.0% ± 2.4%). Figure 2 showed time-series data of the GRF projected onto the line of the simplified leg, the viscosity force (F_V), the elastic force (F_E), and the actuator force (F_A). The first peak of the GRF almost corresponds with the viscosity force. After the first peak, the elastic force and actuator force increased (Figure 2). There was a non-linear and exponential relationship between the displacement of the leg length and the elastic force (Figure 3). The mechanical power of the spring element changed from negative to positive at the time from 40% to 45% (mean±SD: 42.5% ± 2.5%) (Figure 4).

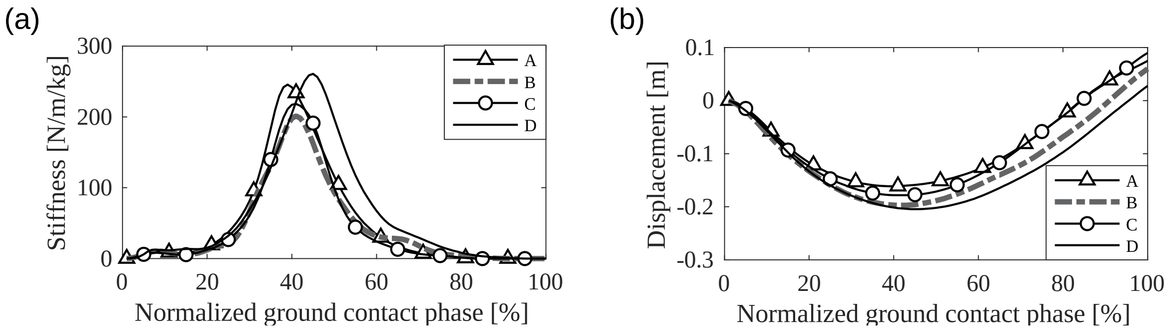

Figure 1: The Stiff$_{new}$ (a) and displacement of the simplified leg length (b) of all participants during the ground-contact phase.

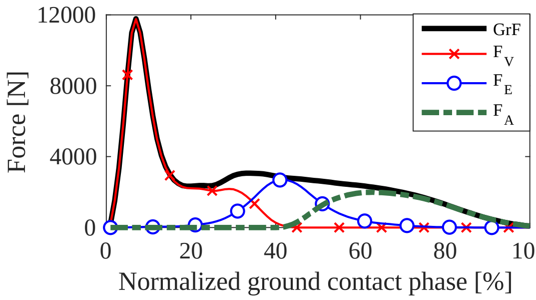

Figure 2: The mean GRF, viscosity force (F_V), elastic force (F_E), and actuator force (F_A) of all participants.

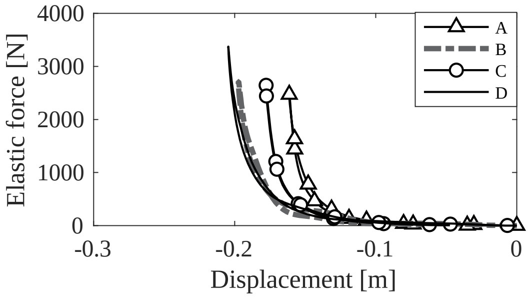

Figure 3: Relationship between the displacement of the simplified leg length and the elastic force of all participants.

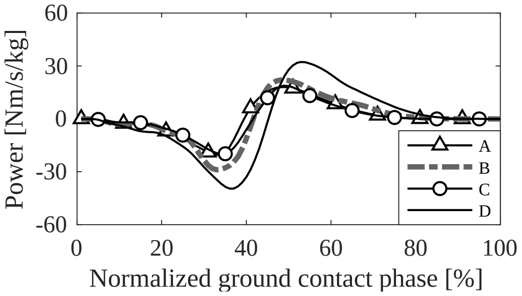

Figure 4: Mechanical power of the spring element of all participants.

DISCUSSION: This study examined the continuous changes in leg stiffness during the step phase of the triple jump. The main findings of this study were that 1) the peak value of Stiff$_{new}$, which was calculated using a mass-spring-damper model with an actuator, was smaller than Stiff$_{prev}$, 2) there was a non-linear and exponential relationship between the displacement of the simplified leg length and the elastic force. These results suggested that the mass-spring-damper model with an actuator could calculate the passive and active forces during a spring-like motion to evaluate leg stiffness.

$Stiff_{prev}$ was calculated using the values of peak GRF and the maximum displacement of the simplified leg length (Ferris et al., 1997; Farley et al., 1999). $Stiff_{prev}$ tended to be larger with increasing peak GRF due to the calculation method (Ferris et al., 1997; Farley et al., 1999). The previous method would overestimate the $Stiff_{prev}$ as an elastic element because the viscosity element was not considered. The proposed method of this study has the possibility to evaluate continuous changes of an elastic element and a viscosity element.

The relationships between the displacement of the leg length and the elastic force showed non-linear and exponential curves at all participants. Skeletal muscles in humans do not generate forces as a linear spring because the muscles have non-linear physiological functions such as muscle force-length-velocity properties (Thelen et al., 2003). Based on the functions, the $Stiff_{new}$ would represent the muscle-tendon behaviors and evaluate non-linear spring-like function during the ground-contact phase by classifying elastic and viscosity elements. In addition, the continuous changes of mechanical power showed that the two different phases for absorbing the impact load and generating the energy to forward and upward, respectively (Figure 4).

The relationships between the $Stiff_{new}$ and the triple jump performance were not clarified because there were only four participants in this study. In addition, the elastic and viscosity forces have the possibility to contain a part of the active force element. A future research on investigating the relationship between continuous changes in leg stiffness and the triple jump performances might extend the explanation of muscle-tendon behaviors in jumping motion.

CONCLUSION: This study compared two different methods for calculating leg stiffness. The previous method would overestimate leg stiffness because the viscosity element was not considered. The mass-spring-damper model with an actuator of this study could classify the passive and active forces during a spring-like motion. The model could also evaluate continuous changes in the leg stiffness during the ground-contact phase.

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