Relationship between Leg Stiffness and Kinematic Variables According to the Load while Running

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Objective: This study aimed to investigate the relationship between leg stiffness and kinematic variables according to load while running.

Method: Participants included eight healthy men (mean age, 22.75 ± 1.16 years; mean height: 1.73 ± 0.01 m; mean body weight, 71.37 ± 5.50 kg) who ran with no load or a backpack loaded with 14.08% or 28.17% of their body weight. The analyzed variables included leg stiffness, ground contact time, center of gravity (COG) displacement and Y-axis velocity, lower-extremity joint angle (hip, knee, ankle), peak vertical force (PVF), and change in stance phase leg length.

Results: Dimensionless leg stiffness increased significantly with increasing load during running, which was the result of increased PVF and contact time due to decreased leg lengths and COG displacement and velocity. Leg length and leg stiffness showed a negative correlation (r = -.902, R² = 0.814). COG velocity showed a similar correlation with COG displacement (r = .408, R² = .166) and contact time (r = -.455, R² = .207).

Conclusion: Dimensionless leg stiffness increased during running with a load. In this investigation, leg stiffness due to load increased was most closely related to the PVF, knee joint angle, and change in stance phase leg length. However, leg stiffness was unaffected by change in contact time, COG velocity, and COG displacement.

Keywords: Leg stiffness, Load, Running, Relationship, Kinematic variables

INTRODUCTION

Humans change their walking and running patterns to conserve energy and increase speed during locomotion (Cappellini, Ivenenko, Poppele, & Lacquaniti, 2006). Running, a popular activity worldwide, is a major component of various sports (Cheung & Rainbow, 2014) and has a known positive effect on cardiovascular and mental health (Williams, 2009a, 2009b).

However, as numerous people participate in running, some issues are being reported, with 39~85% of runners reporting that they have experienced injuries in the past year (Bovens et al., 1989; van Gent et al., 2007; Watson, 1987). In addition, Taunton et al. (2002) showed that, regardless of sex, those injured due to running show a strongly positive relationship between tibial stress syndrome and the occurrence of injury; this is related to the risk of patellofemoral pain, iliotibial band friction syndrome, and plantar fasciitis. It is also known that the risk of spinal damage for women with a body mass index (BMI) < 21 kg/m² is very high.

To improve running efficiency and prevent injury, studies have investigated the complexity of legs; it is now generally assumed that most of the energy that is consumed by muscles during running is used to convert chemical energy to mechanical energy (Alexander, 1980). Taylor, Heglund, & Maloys (1982) explained that the greater the hopping speed of a kangaroo, the more economical it is; it was also reported that input mechanical energy is temporarily stored in the elastic material of the active muscle for use in subsequent muscle actions (Asmussen & Bonde-Petersen, 1974).

From this perspective, although the motion of human running is performed by a complex musculoskeletal system composed of muscles, tendons, and ligaments, it functions very similarly to a single linear spring (Farley & Gonzalez, 1996). Therefore, the dynamics of human running can use the spring-mass model to very accurately explain the complex movements of the legs (Arampatsiz, Brüggemann, & Metzler, 1999; Blum, Lipfert, & Seyfarth, 2009; Donelan & Kram, 2000; Farley & Gonzalez, 1996; Lipfert, Günther, Renjewski, Glimmer, & Seyfarth, 2012; McMahon & Cheng, 1990). In the spring-mass model, the legs are seen as linear springs with no mass, while the stiffness of the leg spring was closely related to the peak vertical force (PVF) and change in leg length during ground contact (Farley, Glasheen, & McMahon, 1993). In addition, leg stiffness differed among terrains and was inversely proportional to the stiffness of the surface to which the locomotion is applied (Alexander, 1989, 1992; Feehery, 1986). Ferris, Louie, & Farley...
Seung Hyun Hyun, et al. (1998) reported that the leg stiffness of animals is not related to speed or gravity but is determined by musculoskeletal characteristics; however, they reported that if stiffness is unchanged on different surfaces, similar running motions can be sustained by changing the characteristics of running (PVF, contact time).

There are reports that humans also can regulate leg stiffness while running (Farley, Blickhan, Saito, & Taylor, 1991; Farley & Gonzalez, 1996); for optimal locomotion, a certain level of stiffness must be maintained (Arampatzis et al., 1999; Dutto & Smith, 2002; Kerdock, Biewener, McMahon, Weyand, & Herr, 2002; Kuitunen, Komi, & Kyrolainen, 2002; McMahon & Cheng, 1990; Seyfarth, Geyer, Gunther, & Blickhan, 2002; Stefanyshyn & Nigg, 1998). However, during the motions of running in the early stages of ground contact, the distance between the center of gravity (COG) and parts of the feet that reach the minimal level in the mid-stance phase beginning with the curve of the angle of the hip, knee, and ankle (McMahon & Cheng, 1990) and in each instance the foot contacts the ground, a repeated left-right, front-back, vertical direction impact occurs (Ryu, 2013, 2014, 2015). In addition, the average ground contact time is 0.24 sec, the change in leg length is 7.3%, and the PVF is a mean 2.3 times the individual’s body weight (Silder, Besier, & Delp, 2015).

However, despite the availability of this information, many people are often forced into situations in which they must move objects during everyday life. In addition, we often observe elite athletes or ordinary people who want to gain quick effects of exercise by running with the addition of vests, lead, or sandbags. Thus, leg stiffness, which is affected by mass on solid ground, must be appropriately regulated, but information on the regulation of leg stiffness following changes in mass are very limited, and leg stiffness using the spring-mass model is only explained as an increase proportional to the increase in mass in various animals (Farley et al., 1993).

Although many studies have analyzed and interpreted the correlation between changes in leg stiffness and related variables to investigate the characteristics of motion while running, they are merely explained by the differences in the increase or decrease of specific variables. That is, in addition to PVF, leg joint angle (hip, knee, ankle) and changes in leg length, ground contact time, and movement speed are all important factors in leg stiffness analysis, but there is a need to more clearly understand their relationship. In addition, as PVF is an important factor in stiffness level and load changes vary based on an individual’s goals in everyday life, new research on the efficiency of locomotion and the provision of improved efficiency that applies more varied changes in loads is needed.

Therefore, the purpose of this study is to quantitatively analyze the relationship between leg stiffness and kinematic variables by load during running. We especially aimed to provide useful information to decrease injuries that can occur due to changes in loads during running, increase efficiency, and accumulate basic material related to leg stiffness focusing on various changes in loads.

**METHODS**

**1. Subject**

Eight adult men (mean age, 22.75 ± 1.16 years; mean height, 1.73 ± 0.01 m; mean body weight, 71.37 ± 5.50 kg) who were able to run normally were selected as subjects. Before the experiment, all subjects were informed of its purpose and contents, and those who voluntarily wished to participate provided written informed consent.

**2. Experimental procedure**

The personal trial times for all subjects were recorded, and each performed a sufficient warmup to avoid musculoskeletal system strain. The runs were mostly 15-m long, and a force plate (AMTI-OR-7, USA) was installed at the 8-m mark. The Kwon 3D XP (2007) program (Visol, Korea) was used to analyze the visual data, and four cameras (HDR-HC7/HDV 1080i, SONY) and lights were installed. After the camera speed was set at 60 frames/sec, exposure time at 1/500 sec, and force plate sampling rate at 600 Hz, a control object (2 m × 2 m × 1 m) was recorded to set three-dimensional (3D) spatial coordinates. At this time, the margin of error for the 3D spatial coordinates was 4.16 mm. After these spatial coordinates were set, to quantify the video material of subjects performing the motions, 19 reflective markers were attached as shown in (Figure 1) (right and left toe, right and left heel, right and left lateral and medial malleolus, right and left shank, right and left lateral and medial epicondyles, right and left thigh, right and left anterior superior iliac spine, and sacrum).

Running was first performed with no load (0 kg), followed by the carrying of backpacks weighing 10 kg (14.08 ± 1.10% of the body weight) or 20 kg (28.17 ± 2.20% of the body weight) in a random

![Figure 1. Marker attachment points (ASIS: anterior superior iliac spine)](image-url)