Relationship between Dimensionless Leg Stiffness and Kinetic Variables during Gait Performance, and its Modulation with Body Weight

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Received : 09 August 2016
Revised : 12 September 2016
Accepted : 12 September 2016

Objective: This purpose of this study was to analyze the relationship between dimensionless leg stiffness and kinetic variables during gait performance, and its modulation with body weight.

Method: The study sample consisted of 10 young women divided into 2 groups (Control, n=5 and Obese, n=5). Four camcorders (HDR-HC7/HDV 1080i, Sony Corp, Japan) and one force plate (AMTI., USA) were used to analyze the vertical ground reaction force (GRF) variables, center of pressure (COP), low limb joint angle, position of pelvis center and leg lengths during the stance phase of the gait cycle.

Results: Our results revealed that the center of mass (COM) displacement velocity along the y-axis was significantly higher in the obese group than that in control subjects. Displacement in the position of the center of the pelvis center (Z-axis) was also significantly higher in the obese group than that in control subjects. In addition, the peak vertical force (PVF) and dimensionless leg stiffness were also significantly higher in the obese group. However, when normalized to the body weight, the PVF did not show a significant between-group difference. When normalized to the leg length, the PVF and stiffness were both lower in the obese group than in control subjects.

Conclusion: In the context of performance, we concluded that increased dimensionless leg stiffness during the gait cycle is associated with increased velocity of COM, PVF, and the change in leg lengths (%).

Keywords: Dimensionless leg stiffness, Body weight, Gait, Peak vertical force, Obese

INTRODUCTION

Obesity is a strong risk factor for developing degenerative knee diseases including osteoarthritis, and is recognized worldwide as a chronic disability (Haslam & James, 2005). From the kinematic perspective, the gait of obese individuals is characterized by short strides, wide width between feet in the standing position and time delay (Spyropoulos, Piscotta, Pavlou, Cairns, & Simon, 1991; McGraw, McClennaghan, Williams, Dickerson, & Ward, 2000; Lai, Leung, Li, & Zhang, 2008; Browning & Kram, 2007). In addition, the range of motion of the hip and knee joints is reduced (Messier, 1994). Inappropriate gait and increased body weight cause an increase in the weight bearing of the joints in the lower limbs (Andriacchi & Mündermann, 2006), thereby causing injuries and arthritis (Hochberg et al., 1995; Stürmer, Günther, & Brenner, 2000).

Several studies have attempted to define the dynamic characteristics of the lower limb. The body is composed of very complex elements such as bones, cartilages and muscles. Therefore, extensive stiffness evaluations are conducted in biodynamics in order to understand the complexity in the dynamics of the lower limb (Butler, Crowell, & Davis, 2003).

Stiffness can be defined as the relationship between the application of external force on the body and the changes it effects (Butler et al., 2003). The dynamics of lower limb movements are usually described with spring-mass models (Arampatzis, Brüggemann, & Metzler, 1999; Blum, Lipfert, & Seyfarth, 2009; Donelan & Kram, 2000; Farley & Gonzalez, 1996; Lipfert, Günther, Renjewski, Grimmer, & Seyfarth, 2012; McMahon & Cheng, 1990). In the spring-mass model, the lower limbs are considered to be linear springs without mass and the peak vertical force (PVF) is closely related to the change in length of the lower (ΔL) during the support stage (Donelan & Kram, 2000; Farley & Gonzalez, 1996; McMahon & Cheng, 1990).

Stiffness is evaluated by two different methods based on changes in the lengths of the lower limb. Vertical stiffness is the most suitable for evaluating hopping and jumping, where changes in the length of the lower limb are large, while leg stiffness is the most suitable for evaluating the dynamic characteristics of the lower limb while walking or running (McMahon & Cheng, 1990; Cavagna, Franzetti, Heglund, & Willern, 1988; McMahon, Valiant, & Frederick, 1987). Leg stiffness is usually calculated by the formula proposed by McMahon & Cheng (1990), in which the PVF is divided by ΔL. The ΔL in this formula refers to the distance be-
between the center of the hip joint and the surface on contact with the lower limb in a standing position, the vector angle between the vertical axis and the line between the center of mass and the surface, the maximum value of COM, the vertical speed of COM and the time of contact with the floor surface. Weight standardization is not taken into account.

Weight standardization can be explained from two different perspectives. Although COM vertical speed, hop, support angle and the maximum COM vertical change were independent variables in the first leg stiffness evaluation in various types of animals (dog, goat, horse and kangaroo), they were only explained as a direct correlation between the mass and the leg stiffness (Farley, Glasheen, & McMahon, 1993). In comparison, human movement is very complex and diverse. Assuming that the changes in leg lengths are constant, PVF, weight bearing and leg stiffness are thought to increase with mass.

When the support time is delayed and the flexion angles of the joints of the lower limb increase during gait performance, the PVF decreases as a response (Silder, Delp, & Besier, 2013; Teunissen, Grabowski, & Kram, 2007). For example, a study on walking and running reported that PVF increases with increases in weight bearing and velocity (Slider et al., 2013; Teunissen et al., 2007). When 30% of body weight is applied during ambulation, the average PVF increases by 15% (Silder et al., 2013). However, when 30% of the body weight is applied during running, the average PVF only increases by 12% (Teunissen et al., 2007).

When a large weight is gradually applied during gait performance, the pelvic joint flexion angle (Silder et al., 2013), knee joint flexion angle (Birrell & Haslam, 2009; Silder et al., 2013) and the dorsiflexion angle of the ankle joint (Silder et al., 2013) are observed to increase. The concept of weight standardization (Silder, Besier, & Delp, 2015) suggests that when different loads are applied, the angles of the joints of the lower limb are altered and leg stiffness cannot be accurately determined.

Quantification of leg stiffness after controlling for movement-related variables was proposed as a method to overcome the above limitations (Hogan & Sternad, 2009; Lee, Ranganathan, & Newell, 2011). Since there are too many variables related to human exercise and movement, it is difficult to quantify the variables into a single value and analyze them. Slider et al. (2015) used a unit-less calculation method, in which the length between the center of pressure and center of pelvis is converted into a percentage and the PVF is standardized after being divided by N. This method was used to calculate what is referred to as dimensionless leg stiffness.

Although leg stiffness increases with an increase in PVF during gait, gait is produced by the repetitive interaction between the two legs (Hyun & Ryew, 2014) and the relationship between leg stiffness and the dynamic variables of the lower limb that are modulated by weight should be carefully analyzed. Therefore, the purpose of this study is to analyze how kinetic variable change according to the differences in body weight during gait performance. More specifically, we sought to analyze the relationship between dimensionless leg stiffness and kinetic variables, in order to provide quantifiable data related to effective gait.

### METHOD

#### 1. Subjects

In order to compare the leg stiffness measures between control and obese individuals, we enrolled 10 females into our study. The control group consisted of 5 participants with normal body weight (age: 25.40 ±2.30 years, height: 164.80±1.88 cm, weight: 53.95±4.00 kg, BMI: 19.86 ±1.32 kg/m²), while the obese group consisted of 5 participants with higher body weight than normal (age: 22.80±1.48 years, height: 167.24 ±1.34 cm, weight: 83.95±11.98 kg, BMI: 30.30±4.15 kg/m²). The subjects all had a rear-foot strike and had no vertebral injuries, knee injuries or foot diseases. The purpose and the procedure of the experiment were explained in detail to the participants prior to obtaining their informed consents.

#### 2. Procedure

In order to evaluate dimensionless leg stiffness, the changes in leg lengths during gait performance were analyzed using 3D image analysis. Four video cameras (HDR/HDV 1080i, Sony Corp, Japan) were used and a control object (2 m × 2 m × 1 m) along with the gait were used to calculate the coordinates. The recording speed was set to 60 fps and the exposure was set to 1/500 sec.

In order to induce natural gait, each participant went through a 5-minute long practice session prior to the experiment. Using the right foot as a reference, the ground reaction force produced after initial contact was measured using a ground reaction force measurer (AMTI-OR-7., USA) with a sampling rate of 600 Hz.

![Figure 1. Leg length was estimated by calculating the distance from the center-of-pressure to the center of the pelvis (Delp et al., 1990) and the lower limb angle.](image-url)