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Leg stiffness of older and younger individuals over a range of hopping frequencies

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ABSTRACT

The purpose of this study was to compare spring-mass behavior between older and younger individuals at a range of hopping frequencies. A total of 14 elderly and 14 young subjects performed in-place hopping in time with a metronome at frequencies of 2.2, 2.6, and 3.0 Hz. Using a spring-mass model, leg stiffness was calculated as the ratio of maximum ground reaction force to maximum center of mass displacement at the middle of the stance phase during ground contact. The lower extremities of both groups behaved like a simple spring-mass system at all three hopping frequencies. Further, statistical analysis revealed the existence of a significant interaction between hopping frequency and age group on leg stiffness. These results suggest that the sensitivity of leg stiffness to accommodate for variations in hopping frequency is likely to differ between elderly and young individuals.

1. Introduction

During hopping, jumping, and running, human legs exhibit characteristics similar to those of a spring. Thus, lower extremity movements are often modeled as a spring-mass model, consisting of a body mass supported by a linear leg spring (Blickhan, 1989). In the model, leg spring stiffness (leg stiffness; K_{leg}) is defined as the ratio of maximum vertical ground reaction force (vGRF) to the maximum center of mass displacement (COM) during the stance phase.

In this model, stiffness of the leg spring (leg stiffness; K_{leg}), defined as the ratio of maximal ground reaction force (vGRF) to maximum center of mass displacement (COM) at the middle of the stance phase, has been shown to change depending on the demand.

It has been demonstrated that K_{leg} increases with an increase in hopping frequency (Farley et al., 1991; Granata et al., 2002; Padua et al., 2005) and a decrease in contact time (Arampatzis et al., 2001; Farley et al., 1991; Hobara et al., 2007). According to a previous study (Farley and Gonzalez, 1996), these adaptations indicate that as the stiffness of the spring-mass system increases, the vertical displacement of COM during ground contact phase decreases. Consequently, the system makes it possible to bounce off the ground in less time at higher frequencies.

Despite the fact that aging influences neuromuscular control, tendon and muscle properties, and the musculoskeletal system (Narici et al., 2008; Baudry et al., 2010), little is known about the regulation of K_{leg} in elderly individuals. The relationship between K_{leg} and hopping frequency has been observed in younger individuals (Farley et al., 1991; Hobara et al., 2010a; Hobara et al., 2010b). Although several studies have demonstrated that elderly individuals display lower K_{leg} than young subjects during counter-movement jump (Liu et al., 2006), drop jump (Hoffrén et al., 2007), and repetitive hopping (Hoffrén et al., 2011, 2012), these studies did not consider the temporal constraint related to lower-extremity stiffness. Further, several studies have demonstrated that the lower extremities of 12- to 27-year-old individuals behaved like a simple spring-mass system during hopping (Padua et al., 2005, 2006; Korff et al., 2009). However, recent studies have demonstrated that elderly individuals have declined neuromechanical properties of the triceps surae during dynamic contraction (Barber et al., 2013; Mademli and Arampatzis, 2008). Therefore, it remains unclear whether older individuals respond similarly to younger individuals with respect to changes in hopping frequency and ground contact times.

The purpose of the present study was to compare spring-mass behavior between elderly and young subjects over a range of hopping frequencies. According to a previous study (Farley et al., 1991), human legs do not consistently behave according to a

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simple spring-mass model. For example, when individuals hop at frequencies below their preferred frequency, vGRF increases as the COM moves downwards (i.e., the muscle–tendon springs are being stretched, in line with the model), but the COM continues to move downwards as the vGRF peaks and begins to decrease. This is a clear deviation from the behavior of a simple spring-mass system: in a simple mechanical spring, the force can only increase as the spring is further stretched. Another clear deviation from spring-like behavior was that in some subjects, the force increased as the COM began to move upward and the muscle–tendon springs recoiled. In a simple mechanical spring, the force would never increase as it recoiled (Farley et al., 1991). Thus, we hypothesized that the lower extremities of elderly individuals would not behave like a simple spring-mass system during hopping motion. Further, several studies demonstrated that elderly individuals have less musculotendinous stiffness than young subjects in the lower extremities (Karamanidis and Arampatzis, 2005; Stenroth et al., 2012). In addition, neuromuscular coordination between the activated muscle groups also affects lower limb stiffness and this parameter could be predominant in elderly subjects (Hortobágyi and DeVita, 2000). Therefore, we also hypothesized that elderly individuals would also have lower K_{leg} values.

2. Methods

2.1. Participants

Twenty-two subjects participated in this study. Eleven young subjects (5 men, 6 women; mean age, 29.82 ± 5.81 years; body mass, 57.48 ± 7.81 kg; height, 1.64 ± 0.09 m) were recruited. Eleven elderly subjects (5 men, 6 women; mean age, 67.45 ± 4.30 years; mean body mass, 52.23 ± 10.45 kg; height, 1.55 ± 0.08 m) were also recruited. All elderly participants were able to walk independently, had normal or corrected-to-normal vision, and had no history of neuromuscular disease. Both groups were sedentary and had not participated in regular exercise or physical training over the previous year. The experimental protocol was approved by the local ethical committee, and all participants provided written informed consent prior to participating.

2.2. Task and procedure

Participants were asked to hop in place 15 times with their hands on their hips. The hopping was performed on a force plate (40 cm × 60 cm, BP400600-10000PT, AMTI) while barefoot. A hopping frequency of 2.2, 2.6, or 3.0 Hz was maintained by using a digital metronome, and the vGRF was recorded at 1000 Hz. The frequency range employed was selected based on a pilot investigation showing that elderly subjects were able to maintain adequate hopping performance within this range. Since contact time instructions can affect K_{leg} regulation during hopping at a given hopping frequency (Arampatzis et al., 2001), the participants were asked to hop using as short a contact time as possible. Before data collection, all participants were instructed to complete the task while maintaining pace with the metronome for as long as needed until they felt comfortable with performing the task. All individuals practiced for 2–3 min and reported that the practice session had sufficiently prepared them for data collection. No subjects reported feeling fatigue. The order of the three frequencies was randomly assigned for each individual in both groups.

2.3. Data collection and analysis

Five consecutive hops (the sixth to the tenth of the 15 hops) were used for the analysis (Hobara et al., 2008, 2009, 2010, and Hobara et al., 2012). Actual hopping frequency, ground contact time, and aerial time were determined from vGRF measurements.

K_{leg} was calculated using the spring-mass model (Blickhan, 1989). During hopping, the peaks of vGRF and maximum COM displacement (ΔCOM) coincide in the middle of the ground-contact phase (Fig. 1). Therefore, the K_{leg} can be calculated as:

$$K_{leg} = F_{peak}/\Delta COM \quad (1)$$

where F_{peak} is the vGRF peak and ΔCOM is the maximum COM displacement (Blickhan, 1989; Hobara et al., 2008, 2009, 2010, and Hobara et al., 2012). Time-course COM movement measurements were obtained by integrating the vGRF-time curve twice as:

$$COM(t) = \int\int \frac{F(t) - mg}{m}\,dt\,dt \quad (2)$$

where F is the vGRF, m is the body mass, and g is the gravitational acceleration. The initial value of the first integration (v_0) was obtained by using the following formula (Hobara et al., 2013):

$$v_0 = -0.5gt_a \quad (3)$$

where t_a is the aerial time. The initial value of the second integration is an unknown constant that disappears in the displacement calculation (Ranavolo et al., 2008). If the peaks of GRF and leg compression did not coincide with the middle of the ground contact phase, we calculated K_{leg} as the ratio of peak GRF and leg compression between ground contact and the instant of peak GRF (Hobara et al., 2010a; Hobara et al., 2010b). Since body size influences the K_{leg} value (Farley et al., 1993), K_{leg} was divided by body mass and expressed as kN/m/kg.

2.4. Statistics

Assuming that the lower extremities behave according to a simple spring-mass model, the correlation between vGRF and COM displacement during the ground contact phase should be greater than $r = 0.80$ (Granata et al., 2002; Korff et al., 2009; Padua et al., 2005, 2006). Therefore, we determined whether the correlation coefficient between the latter two variables was >0.80 for each subject. We also conducted a two-way repeated measures analysis of variance (ANOVA) with two factors (frequency [three levels] × group [two levels]) to compare spring-mass parameters between elderly and young groups. To assess assumptions of variance, Mauchly's test of sphericity was performed for all ANOVAs. Greenhouse–Geisser correction was performed to adjust the degree of freedom if an assumption was violated, while a

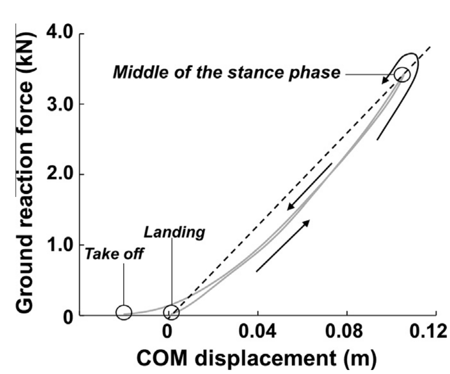

Fig. 1. Typical examples of vertical ground reaction force (vGRF)-maximum center of mass (COM) displacement curve of a single young subject while hopping. The leg was compressed from the instant of touchdown, and the vGRF increased. The vGRF peaked at mid-stance and subsequently decreased with leg extension until take-off. Leg stiffness (K_{leg}) is represented by the slopes (broken line) of these curves in the leg compression phase.