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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:

$$K_{leg} = F_{peak}/\Delta COM \tag{1}$$

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:

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

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):

$$v_0 = -0.5gt_a \tag{3}$$

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

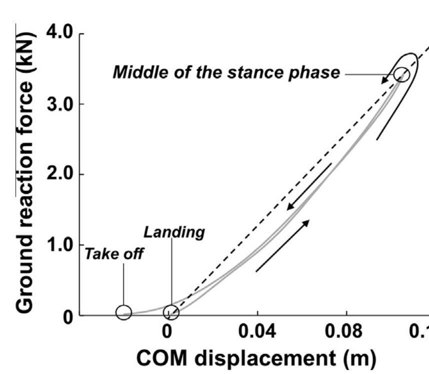

Fig. 1. Typical examples of vertical ground reaction force (vGRF)-maximum center of mass (COM) displacement curve of a single young subject while hopping. The leg was compressed from the instant of touchdown, and the vGRF increased. The vGRF peaked at mid-stance and subsequently decreased with leg extension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

Bonferroni post hoc multiple comparison was performed if a significant main effect was observed. Furthermore, we calculated effect sizes (ES; 0.20, 0.50, and 0.80 for small, medium and large effects, respectively) using partial eta squared for each ANOVA (Cohen, 1988). Based on analysis of the data using a Kolmogorov–Smirnov Z test for normality, all outcome variables were found to be normally distributed. Statistical significance was set at $p < 0.05$. Each statistical analysis was executed using Statistical Package for the Social Sciences software, version 19 (IBM SPSS Statistics; SPSS Inc., Chicago, IL, USA).

3. Results

Fig. 2 shows a typical example of the relationship between vGRF and COM displacement in single hopping cycles recorded from one subject in each group. In both groups, the leg was compressed from the touchdown, and vGRF increased with COM displacement. The vGRF value peaked at the moment of maximum leg compression (middle of the stance phase) and subsequently decreased with extension of the leg until take-off. In both groups, the correlation between vGRF and COM displacement was >0.80 at all hopping frequencies.

Hopping frequency had a significant main effect ($F_{(1.16,\ 11.62)} = 87.68$, $p < 0.01$, ES = 0.90) on the contact time. In both groups, contact time was shortest at a frequency of 3.0 Hz, followed by 2.6 Hz and 2.2 Hz, respectively (Table 1; $p < 0.01$ for all frequencies). Although there were no main effects of group ($F_{(1,\ 10)} = 0.79$, $p = 0.39$, ES = 0.07), we found a significant interaction effect between hopping frequency and group on the contact time ($F_{(2,\ 20)} = 4.18$, $p < 0.05$, ES = 0.30).

There was a significant main effect of hopping frequency on the aerial time ($F_{(2,\ 20)} = 58.35$, $p < 0.01$, ES = 0.85), where the aerial time was shortest at a frequency of 3.0 Hz, followed by 2.6 Hz and 2.2 Hz (Table 1) in both groups, respectively. On the other hand, there was no significant main effect of group ($F_{(1,\ 10)} = 1.35$, $p = 0.27$, ES = 0.12) on aerial time. A significant interaction between hopping frequency and group was identified for aerial time ($F_{(2,\ 20)} = 5.90$, $p < 0.05$, ES = 0.37).

There was a significant main effect of hopping frequency on K_{leg} ($F_{(2,\ 20)} = 103.83$, $p < 0.01$, ES = 0.91), where K_{leg} increased with hopping frequency (Table 1; $p < 0.01$ at all frequencies). However, there was no significant main effects of group on K_{leg} ($F_{(1,\ 10)} = 0.73$, $p = 0.41$, ES = 0.07). Statistical analysis revealed the existence of a significant interaction between hopping frequency and group on K_{leg} ($F_{(1.31,\ 13.12)} = 4.50$, $p < 0.05$, ES = 0.31).

There was a significant main effect of hopping frequency on F_{peak} ($F_{(2,\ 20)} = 4.12$, $p < 0.05$, ES = 0.29; Table 1), where F_{peak} tended to increase with increasing hopping frequency (Table 1). However, there was no significant main effects of group on F_{peak} ($F_{(1,\ 10)} = 3.54$, $p = 0.10$, ES = 0.26). Statistical analysis also revealed the existence of a significant interaction between hopping frequency and group on F_{peak} ($F_{(2,\ 20)} = 8.53$, $p < 0.01$, ES = 0.46).

As shown in Table 1, there was a significant main effect of hopping frequency ($F_{(2,\ 20)} = 94.14$, $p < 0.01$, ES = 0.90), where the ΔCOM value decreased with an increase in hopping frequency in both elderly and young subjects ($p < 0.01$). However, there was no significant main effects of group ($F_{(1,\ 10)} = 2.35$, $p = 0.16$, ES = 0.19) and interaction ($F_{(2,\ 20)} = 1.61$, $p = 0.23$, ES = 0.14) on ΔCOM.

4. Discussion

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 earlier studies (Granata et al., 2002; Korff et al., 2009; Padua et al., 2005 and Padua et al., 2006), if the correlation between vGRF and COM displacement is >0.8, the human body can be assumed to act as a spring-mass model. In the present study, the correlations between vGRF and COM displacement in both groups were >0.8 at all hopping frequencies. These results do not support our initial hypothesis, which stated that the lower extremities of elderly individuals would not behave like a simple spring-mass system during hopping. It has been shown that the lower extremities of humans 12–27 years old behaved like a simple spring-mass system during hopping (Korff et al., 2009; Padua et al., 2005 and Padua et al., 2006). Therefore, the current results suggest that spring-like leg behavior during hopping is sustained in all age groups.

We found significant interactions between hopping frequency and group on spring-mass parameters with small to medium effect size (0.30–0.46), except for ΔCOM (Table 1). Further, as shown in Table 1, there were no significant differences in K_{leg} between the two groups at any of the three hopping frequencies. This is in contrast with our second hypothesis that elderly individuals would have lower K_{leg} values than young subjects. Therefore, the current results suggest that the sensitivity of K_{leg} to accommodate for variations in hopping frequency is likely to be different between the two age groups.

The current results do not correspond with those of earlier studies demonstrating that elderly individuals have lower K_{leg} values than young subjects during counter-movement jump (Liu et al., 2006), drop jump (Hoffrén et al., 2007), and repetitive hopping motion (Hoffrén et al., 2011, 2012). This discrepancy may be due to methodological differences. First, the subjects in the previous study were asked to perform maximal counter-movements, drop jumps (Hoffrén et al., 2007; Liu et al., 2006), and hopping with maximal effort as well as at intensities of 50%, 65%, 75%, and 90% (Hoffrén et al., 2011, 2012). In other words, despite the fact that the K_{leg} value is influenced by temporal constraints such as hopping frequency (Farley et al., 1991; Granata et al., 2002; Padua et al., 2005) and contact time (Arampatzis et al., 2001; Farley et al., 1991; Hobara et al., 2007), these variables were not controlled. Interestingly, there were no significant differences in the current study in either hopping frequency or contact time between the two age groups at any of the hopping frequencies (Table 1). Thus, it seems likely that the discrepancies between the previous studies and current results may be due to the contact time. Second, Hoffrén et al. (2011, 2012) investigated tendon stiffness using ultrasonography and joint stiffness in their kinetic–kinematic analyses rather than vertical stiffness. This suggests that vertical stiffness may not be a suitable variable to detect age-related differences in the musculoskeletal system compared with tendon and joint stiffness.

A previous study (Korff et al., 2009) compared K_{leg} during hopping between pre-adolescents (11–13 years old) and adolescents (16–18 years old). The authors found that both groups behaved like a simple mass-spring system, and that there were no significant differences in K_{leg} between the age groups when normalized to body mass. Further, Lloyd et al. (2012) investigated the age-related differences in K_{leg} among three ages (9, 12, and 15 years old) at submaximal hopping (~2.4 Hz). They showed that normalized K_{leg} values in 15 year olds are significantly greater than those in 9 year olds. Furthermore, Oliver and Smith (2010) compared K_{leg} between boys (11–12 years old) and men (19–30 years old) at 1.5 Hz, 3.0 Hz, and their preferred frequency. They found that adults have greater normalized K_{leg} than boys during hopping at the preferred frequency and at 3.0 Hz. Hence, the present study and past findings suggest that K_{leg} during hopping increases with age in adolescence, but may plateau thereafter and remain stable into old age. Additionally, given that physical training enhances K_{leg} (Girard et al., 2010; Harrison et al., 2004; Hobara et al., 2008 and Hobara et al.,

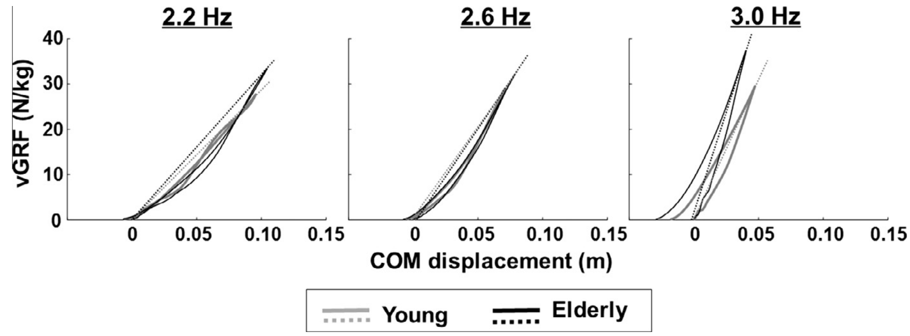

Fig. 2. Vertical ground reaction force-COM displacement curves of elderly and young subjects at 2.2, 2.6, and 3.0 Hz of one subject in each group. Gray thick and black thin lines represent young and elderly subjects, respectively. The slopes (dotted lines) of these curves represent leg stiffness.

Table 1
Comparisons of spring-mass parameters between elderly and young subjects at three hopping frequencies.

	2.2 Hz		2.6 Hz		3.0 Hz	
	Elderly	Young	Elderly	Young	Elderly	Young
Contact time, s $^{\#}$	0.260 ± 0.036	0.236 ± 0.032	0.218 ± 0.026	0.210 ± 0.024††	0.191 ± 0.022**,††	0.191 ± 0.019**,††
Aerial time, s $^{\#}$	0.148 ± 0.038	0.186 ± 0.039	0.135 ± 0.022	0.142 ± 0.039††	0.115 ± 0.030**	0.119 ± 0.023**,†
Leg stiffness, kN/m/kg $^{\#}$	0.408 ± 0.102	0.409 ± 0.074	0.555 ± 0.094††	0.566 ± 0.091††	0.806 ± 0.102**,††	0.703 ± 0.098**,††
Peak GRF, N/kg $^{\#}$	30.081 ± 4.281	35.807 ± 4.900	32.219 ± 2.80	34.025 ± 3.552	31.533 ± 3.464	31.857 ± 2.447*,†
ΔCOM, m	0.079 ± 0.020	0.089 ± 0.010	0.060 ± 0.009††	0.060 ± 0.011††	0.040 ± 0.007**,††	0.046 ± 0.006**,††

$^{\#}$ Significant interaction between hopping frequency and groups, $p < 0.05$).
† Significant differences between adjacent frequencies at $p < 0.05$ respectively.
†† Significant differences between adjacent frequencies at $p < 0.01$ respectively.
* Significant differences between 2.2 and 3.0 Hz at $p < 0.05$ respectively.
** Significant differences between 2.2 and 3.0 Hz at $p < 0.01$ respectively.

2010a; Hobara et al., 2010b; Laffaye et al., 2005; Rabita et al., 2008), age-related changes in K_{leg} may be modifiable by training level in each individual.

There are several concerns about interpreting these findings. First, we used the spring-mass model, but this model might be too simplistic to adequately reflect the intrinsic properties of the human body in both elderly and young subjects. As reviewed previously (Lamontagne and Kennedy, 2013), caution is needed to prevent drawing inappropriate conclusions about hop performance due to oversimplification. Second, although we calculated K_{leg} as the ratio of maximum GRF to ΔCOM at the middle of the stance phase, the stiffness measures depend on the computational method (Hébert-Losier and Eriksson, 2014; Hobara et al., 2014). Therefore, computational methods may explain in part some of the invariant K_{leg} between the two age groups in this study. Third, in a multi-jointed system, K_{leg} further depends on a combination of torsional joint stiffness, touchdown joint angles, muscular activity, and muscle coordination (Farley et al., 1998; Hobara et al., 2010a; Hobara et al., 2010b). Although the overall K_{leg} was similar between the older and young adults, there might be differences in joint stiffness or touchdown joint angle. Additionally in such a multi-joint system, ground reaction force and COM displacement will partly result from a complex combination of activation and inactivation of the various muscle groups involved in hopping. Indeed, a previous study demonstrated that aging apparently alters the preparatory scaling of muscle activity during downward stepping task, creating an overscaling bias that is a precursor to increased limb stiffness (Hortobágyi and DeVita, 2000). Further research is recommended to follow the evolution of K_{leg} to investigate whether values change or remain stable over time in a given population; such studies would provide insight on neuromuscular control and whole-body stiffness regulation with aging. Finally, our results were based on cross-sectional, rather than longitudinal, observations.

5. Conclusion

The present results suggest that, as evaluated using a two-legged hopping task, elderly individuals have similar spring-mass behaviors and K_{leg} to those of young subjects during hopping over a range of hopping frequencies. However, the magnitude of the difference between the two groups is likely to vary with variations in hopping frequency. Clearly, additional work is necessary to determine the mechanisms responsible for the invariant spring-mass behavior and K_{leg} regulation that develops with age.

Conflict of interest

The authors report no conflicts of interest associated with this study.

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