Journal of Biomechanics 43 (2010) 506–511

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

# Leg stiffness adjustment for a range of hopping frequencies in humans

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ARTICLE INFO

*Article history:*
Accepted 27 September 2009

*Keywords:*
Lower extremity
Leg spring
Joint stiffness
Ground reaction force

ABSTRACT

The purpose of the present study was to determine how humans adjust leg stiffness over a range of hopping frequencies. Ten male subjects performed in place hopping on two legs, at three frequencies (1.5, 2.2, and 3.0 Hz). Leg stiffness, joint stiffness and touchdown joint angles were calculated from kinetic and/or kinematics data. Electromyographic activity (EMG) was recorded from six leg muscles. Leg stiffness increased with an increase in hopping frequency. Hip and knee stiffnesses were significantly greater at 3.0 Hz than at 1.5 Hz. There was no significant difference in ankle stiffness among the three hopping frequencies. Although there were significant differences in EMG activity among the three hopping frequencies, the largest was the 1.5 Hz, followed by the 2.2 Hz and then 3.0 Hz. The subjects landed with a straighter leg (both hip and knee were extended more) with increased hopping frequency. These results suggest that over the range of hopping frequencies we evaluated, humans adjust leg stiffness by altering hip and knee stiffness. This is accomplished by extending the touchdown joint angles rather than by altering neural activity.



## 1. Introduction

The spring-like leg behavior of running, hopping, and jumping is a general feature of the mammalian gait. To describe this type of gait, the whole body is often modeled with a "spring-mass model" which consists of a body mass supported by a spring (Farley and Ferris, 1998; Farley et al., 1993; Blickhan, 1989; Butler et al., 2003). In this model, stiffness of the leg spring ("leg stiffness"), defined as the ratio of maximal ground reaction force to maximum leg compression at the middle of the stance phase, has been shown to change depending on the demand.

It has been demonstrated that leg stiffness becomes higher with an increase in hopping frequency (Dalleau et al., 2004; Farley et al., 1991; Ferris and Farley, 1997; Granata et al., 2002; Rapoport et al., 2003; Padua et al., 2005). Although these findings suggest that humans have a sophisticated system of leg stiffness control, detailed mechanisms of the frequency-dependent leg stiffness modulation are not well understood. The aim of the present study was to determine how humans adjust leg stiffness over a range of hopping frequencies.

Leg stiffness depends on the stiffness of the torsional joint spring (joint stiffness, defined as the ratio of maximal joint moment to maximum joint flexion at the middle of the stance phase). Previous studies suggest that leg stiffness during hopping largely depends on ankle stiffness (Farley and Morgenroth, 1999). Ankle stiffness is regulated by pre-activity (muscle activity before ground contact) and muscle activity including the short-latency stretch reflex response of the triceps surae at landing (Hobara et al., 2007). Moreover, several studies indicate that joint stiffness is influenced by antagonistic co-contraction (Hortobagyi and DeVita, 2000). In addition, joint stiffness is also influenced by changes in the touchdown joint angle (Farley et al., 1998). In the present study we hypothesized that increases in leg stiffness with increasing hopping frequency are due to changes in ankle stiffness, which is associated with the pre-activity and stretch-reflex responses of the triceps surae and/or co-contraction levels.

## 2. Methods

### 2.1. Participants

Ten healthy male subjects participated in the study. Their physical characteristics were: age 22.9 ± 2.9 years, height 174.0 ± 5.4 cm, and body mass 65.1 ± 6.1 kg (mean ± SD). Informed consent approved by the Human Ethics Committee, Faculty of Sport Sciences, Waseda University, was obtained from all subjects before the experiment.

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doi:10.1016/j.jbiomech.2009.09.040

### 2.2. Task and procedure

Barefoot subjects were asked to hop in place with their hands on their hips. Hopping was performed on a force plate ($60 \times 120$ cm, Power Max-1500, Bertec Inc., Japan); the vertical ground reaction force (GRF) was recorded at 1000 Hz. We set hopping frequency at 1.5, 2.1 and 3.0 Hz with a digital metronome. Since different contact time instructions can affect stiffness regulation during hopping at a given hopping frequency (Arampatzis et al., 2001), the subjects were asked to hop with as short a contact time as possible. Before data collection, each subject practiced at each frequency for as much time as was needed. Then, they performed hopping at the three frequencies in a random order, with a five-minute rest period in between each performance.

### 2.3. Data collection and analysis

Five consecutive hops from the sixth to the tenth of the 15 hops were used for the analysis. From the measurement of GRF, the actual hopping frequency, ground contact time and aerial time were determined.

Each subject was videotaped in the sagittal plane at 250 fields per second using a high speed video camera (HSV-500C3, NAC Inc., Japan). We placed six retroreflective markers on the subjects in the following locations: the tip of the first toe, the fifth metatarsophalangeal joint, the lateral malleolus, the lateral epicondyle of the femur, the greater trochanter, and the acromion scapulae. Two-dimensional positional data of the reflective makers was digitized by movement-analysis software (FrameDias II, DKH Inc., Japan). Based on a residual analysis (Winter, 1990), kinematic data were low-pass filtered by a fourth-order zero-lag Butterworth filter with a cut-off frequency of 8 Hz, from which joint angular displacements were determined. Further, for a single subject, we compared hip-joint kinematics based on the acromion scapulae marker with those of the iliac crest marker during three hopping conditions.

Leg stiffness was calculated utilizing the spring-mass model (Blickhan, 1989). During hopping, leg stiffness can be calculated as the ratio of peak vertical GRF to peak leg compression in the middle of the ground contact phase (Farley and Morgenroth, 1999). Leg compression is equal to the maximum vertical displacement of the center of mass (COM) during ground contact. The vertical total body center of mass displacement was calculated by integrating the vertical acceleration twice. Subtracting the gravitational acceleration from the GRF–time curve divided by the subject's body mass, we obtained the vertical acceleration of the COM. Then, vertical velocity of the subject's total body center of mass was calculated by integrating the vertical acceleration with respect to time (integration interval of 0.001 s). We determined an initial velocity from aerial time. Consequently, vertical displacement of COM during ground contact was calculated by integrating the vertical velocity–time curve. If the peaks of GRF and leg compression did not coincide in the middle of the ground contact phase, we calculated the leg stiffness as the ratio of peak GRF and leg compression between ground contact and the instant of peak GRF.

Joint stiffness was calculated with the torsional spring model (Farley et al., 1998; Farley and Morgenroth, 1999). We calculated joint stiffness by dividing peak joint moment by joint angular displacement (Farley and Morgenroth, 1999). Joint moments were determined by utilizing rigid-linked segment model, anthropomorphic data (Dempster, 1955), and an inverse dynamics analysis (Winter, 1990). As in the leg stiffness, joint stiffness calculation was based on the assumption that the peaks of joint moments and maximal joint flexions coincide in the middle of the ground contact phase. Since a subject's body size influences the stiffness value (Farley et al., 1993), both leg and joint stiffnesses were divided by the subject's body mass.

### 2.4. EMG collection and analysis

We measured electromyographic activity (EMG) from the biceps femoris (BF), rectus femoris (RF), vastus lateralis (VL), tibialis anteriors (TA), medial gastrocnemius (MG), and soleus (SOL) muscles of the right leg (FLA-128, Furusawa Lab Appliance Inc., Japan). Ag-AgCl bipolar surface electrodes (diameter 10 mm) with a 20 mm inter-electrode distance were placed on the belly of each muscle. We carefully checked electrode placement using the manual muscle testing procedure (Perotto et al., 1994) to minimize the EMG crosstalk between muscles. The reference electrode was attached to the medial malleolus. The skin at the electrode interface was shaved, and then cleaned using alcohol (skin impedance $< 10\text{k}\Omega$). To minimize movement artifact, leads were secured to the leg with adhesive tape. The EMG signals were amplified ($\times 1000$) with input impedance of 1000 M$\Omega$ and common mode rejection ratio (CMRR) of 95 dB. The EMG signals were further band-pass filtered (10–500 Hz), and stored in a personal computer via an A/D converter (sampling frequency at 1000 Hz).

The obtained EMG was full wave rectified, and then averaged, synchronizing the records to the instant of touchdown. We then created linear envelopes of EMG data using a fourth-order zero-lag Butterworth low-pass filter (cut-off frequency 10 Hz). We calculated mean EMG during the 100 ms before contact and termed it pre-activity (PRE). The first 30 ms after landing was calculated and termed background EMG activity (BGA: Voigt et al., 1998a; Voigt et al., 1998b). The mean EMG from 30 to 60 ms after landing was calculated and used to represent supraspinal voluntary command to activate muscle, and a short-latency stretch reflex component (M1: Hobara et al., 2007; Hobara et al., 2008; Taube et al., 2008; Voigt et al., 1998a; Voigt et al., 1998b). Finally, the mean EMG from 60 to 90 ms was calculated and used to represent voluntary muscle activity, and a long-latency stretch reflex component (M2: Horita et al., 1996; Golhofer et al., 1992; Taube et al., 2008). The mean EMGs were normalized relative to those that occurred during the maximum isometric voluntary contraction (MVC) of each muscle (%MVC). The MVC was determined after the hopping experiments.

In addition, co-activation index, which is the ratio of antagonistic muscle activity to agonistic muscle activity at each phase, were calculated (Hortobagyi and DeVita, 2000; Hsu et al., 2007). We considered that BF and RF activity as hip extensors and flexors, respectively. Further, VL and BF activity were considered as knee extensors and flexors, respectively. Similarly, co-activation index in ankle joint were determined by both the ratio of TA (dorsiflexors) to both MG and SOL (plantarflexors).

### 2.5. Statistics

One-way repeated measure ANOVA and Scheffe post-hoc multiple comparison test were performed to compare the biomechanical parameters among three frequencies. Statistical significance was set at $P < 0.05$. SPSS for Windows software (Version 13.0, SPSS Inc.) was used for all statistical analysis. All data are presented as the mean $\pm$ the standard deviation (SD).

## 3. Results

### 3.1. Hopping frequency, contact time and flight time

Ground contact time and aerial time under three hopping conditions are shown in Table 1. Ground contact time was the shortest in the 3.0 Hz, followed by the 2.2 Hz and then 1.5 Hz. Similarly, aerial time was the shortest in 3.0 Hz, followed by the 2.2 Hz and then 1.5 Hz.

### 3.2. Leg stiffness

Fig. 1 shows a typical example of the relationship between GRF and COM displacement in single cycles of hopping at 1.5, 2.1 and 3.0 Hz, recorded from one subject. The leg was compressed from the touchdown, and GRF increased with COM displacement. The GRF peaked at the moment of maximum leg compression (middle of the stance phase), and subsequently, the GRF decreased with extension of the leg until take-off. Leg stiffness (the slope of the force–displacement curve in the leg compression phase) was significantly greater in 3.0 Hz than in 1.5 Hz (Fig. 2).

**Table 1**
Comparison of temporal, kinetic and kinematic characteristics.

| | 1.5 Hz | 2.1 Hz | 3.0 Hz |
|---|---|---|---|
| Contact time, s | 0.26 (0.10) | 0.21 (0.06) | 0.18 (0.03)[a] |
| Aerial time, s | 0.41 (0.09) | 0.27 (0.06)[a] | 0.15 (0.03)[a,b] |
| Peak reaction force, N/kg | 50.3 (19.7) | 46.7 (11.5) | 36.2 (4.4) |
| COM displacement, m | 0.16 (0.04) | 0.10 (0.02)[a] | 0.05 (0.01)[a,b] |
| Peak hip moment, Nm/kg | 1.12 (0.60) | 1.50 (1.08) | 1.31 (0.69) |
| Peak knee moment, Nm/kg | 7.32 (2.26) | 4.59 (1.70)[a] | 2.43 (0.70)[a,b] |
| Peak ankle moment, Nm/kg | 4.15 (2.25) | 4.03 (1.59) | 3.23 (0.83) |
| Hip angular displacement, deg | 16.9 (10.4) | 6.0 (5.0)[a] | 2.1 (1.4)[a,b] |
| Knee angular displacement, deg | 30.8 (13.6) | 13.5 (8.2)[a] | 4.5 (2.7)[a,b] |
| Ankle angular displacement, deg | 36.1 (9.5) | 25.2 (9.5)[a] | 13.8 (5.1)[a,b] |
| Hip touchdown angle, deg | 164.8 (6.5) | 169.7 (5.4) | 172.2 (5.3)[a] |
| Knee touchdown angle, deg | 153.8 (9.0) | 154.1 (6.1) | 157.6 (6.2) |
| Ankle touchdown angle, deg | 126.1 (8.4) | 123.7 (9.7) | 119.5 (6.7) |

Each value is mean (SD).

[a] A significant difference ($P < 0.05$) from 1.5 Hz.
[b] A significant difference ($P < 0.05$) from 2.1 Hz.