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Short communication

Knee stiffness is a major determinant of leg stiffness during maximal hopping

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ABSTRACT

Understanding stiffness of the lower extremities during human movement may provide important information for developing more effective training methods during sports activities. It has been reported that leg stiffness during submaximal hopping depends primarily on ankle stiffness, but the way stiffness is regulated in maximal hopping is unknown. The goal of this study was to examine the hypothesis that knee stiffness is a major determinant of leg stiffness during the maximal hopping. Ten well-trained male athletes performed two-legged hopping in place with a maximal effort. We determined leg and joint stiffness of the hip, knee, and ankle from kinetic and kinematic data. Knee stiffness was significantly higher than ankle and hip stiffness. Further, the regression model revealed that only knee stiffness was significantly correlated with leg stiffness. The results of the present study suggest that the knee stiffness, rather than those of the ankle or hip, is the major determinant of leg stiffness during maximal hopping.

1. Introduction

Jumping and running typically involve spring-like leg behavior and their maximal performance is crucial for various sports activities. In these movements, the musculoskeletal structure of the legs is often modelled with a spring-mass model which consists of a body mass and a linear leg spring supporting the body mass (Blickhan, 1989; Butler et al., 2003; Farley and Ferris, 1998). Increase in the stiffness of the leg spring (leg stiffness), which is defined as the ratio of maximal ground reaction force to maximum leg compression at the middle of the stance phase, has been shown to increase with hopping height (Farley et al., 1991; Farley and Morgenroth, 1999). Overall leg stiffness depends on the stiffness of the torsional joint spring (joint stiffness, which is defined as the ratio of the maximal joint moment to the maximum joint flexion at the middle of the stance phase).

It has been reported that leg stiffness during submaximal hopping depends primarily on ankle stiffness (Farley and Morgenroth, 1999), but exactly how stiffness is regulated remains unclear. Arampatzis et al. (2001a) found that during jumping on a sprung surface the knee stiffness shows a higher contribution to the leg stiffness than the ankle stiffness. Thus, the goal of this study was to examine the hypothesis that knee stiffness is a major determinant of leg stiffness during the maximal hopping.

2. Methods

2.1. Participants

Ten well-trained male athletes with no neuromuscular disorders or functional limitations in their legs participated in the study. Their physical characteristics were: age 20.3 ± 1.4 years, body weight 66.3 ± 7.2 kg, and height 1.76 ± 0.05 m (mean ± S.D.). Informed consent, approved by the Human Ethics Committee, Waseda University, was obtained from all subjects before the experiment.

2.2. Task and procedure

Subjects were instructed to jump barefoot on a force plate (60 cm × 120 cm, Power Max-1500, Bertec Inc., Japan) with arms akimbo; the vertical ground contact force was recorded at 1000 Hz. In the present study, we defined "maximal effort" as the effort of trying to achieve maximal height. Thus, the subjects were instructed to hop as high as possible. Before data collection, each subject took as much time to practice as was needed.

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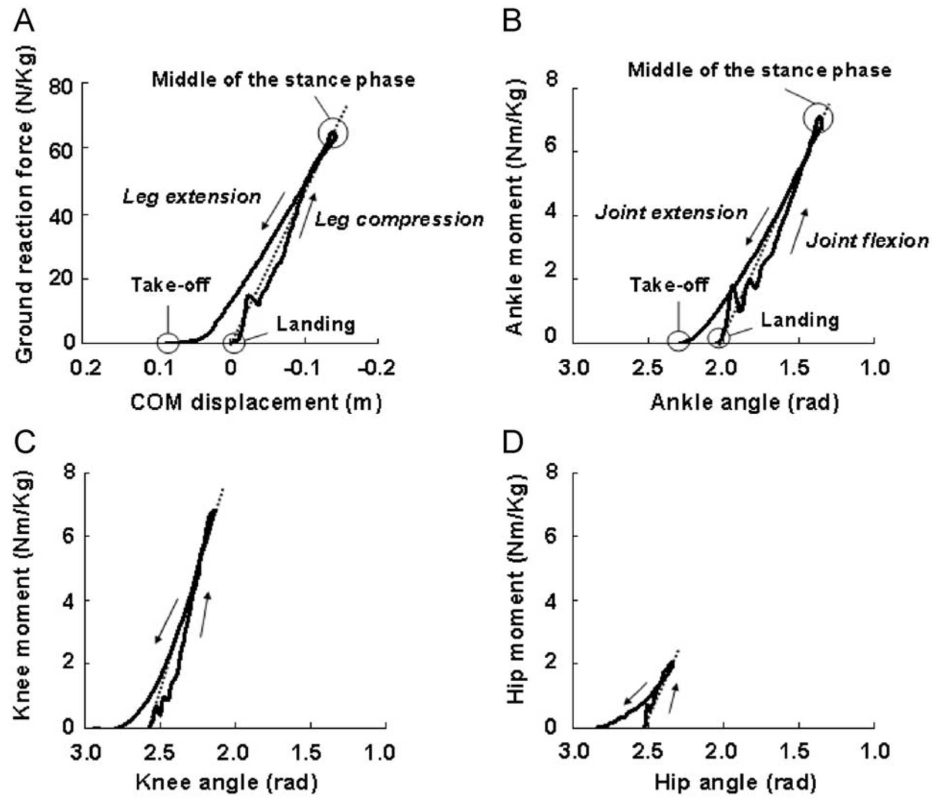

Fig. 1. Typical examples of force–COM displacement (A) and moment–angular displacement curves of the ankle (B), knee (C), and hip (D). The leg (or joints) was compressed (flexed) from the instant of touchdown, and ground reaction force (joint moment) increased. Ground reaction force (joint moments) peaked at midstance, and subsequently, the force (joint moment) decreased with extension of the leg (joints) until take-off. Leg (joint) stiffness is represented by the slope (dotted lines) of the force–displacement (moment–angular displacement) curve in the leg compression phase.

2.3. Data collection and analysis

Hopping was repeated 15 times and five consecutive hops from the sixth to the tenth were used in the analysis. From the measurement of ground reaction force, hopping frequency (f), ground contact time (t_c), and flight time (t_f) were determined.

Six 25-mm reflective markers were placed on 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. Each subject was videotaped in the sagittal plane at 250 fields per second using a high-speed video camera (HSV-500C3, NAC Inc., Japan). Two-dimensional positional data of the reflective makers were obtained using 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.

Leg stiffness was calculated utilizing the spring–mass model. During hopping, the peaks of vertical ground reaction force (F_{max}) and leg compression coincide in the middle of the ground contact phase (Fig. 1-A). At this point, leg stiffness can be calculated as the ratio of peak vertical ground reaction force to peak leg compression (Farley and Morgenroth, 1999). Leg compression is equal to the maximum vertical displacement of the center of mass (COM) during ground contact, which was calculated by integrating the vertical acceleration twice with respect to time (Farley and Morgenroth, 1999). Similarly, joint stiffness (K_{joint}) was calculated as the ratio of peak joint moment to joint angular displacement at the middle of the ground contact phase (Farley and Morgenroth, 1999; Fig. 1-B–D). Joint moment was computed using inverse dynamics analysis in conjunction with anthropomorphic data (Dempster, 1955). 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. Before data analyses, we confirmed that in all of trials the maximal vertical ground reaction force (and joint moments) and the maximal leg compression (joint flexions) occurred at the same time (middle of the stance phase).

2.4. Statistics

One-way repeated measure ANOVA was performed for each parameter to determine whether there were significant differences among the joints. A Scheffe, post-hoc multiple comparison test was performed if a significant main effect was observed. Multiple regression analyses were performed using K_{leg} as a dependent variable and joint stiffness (K_{ankle}, K_{knee} or K_{hip}) as an independent variable. Within the multiple regression analysis, a standardized partial regression coefficient was used to determine the relative importance of joint stiffness to K_{leg}. Statistical significance was set at $P<0.05$. All data are presented as mean values ± a standard deviation (S.D.).

3. Results

3.1. Temporal parameters

The data for each subject's temporal parameters are summarized in Table 1. Average values of hopping frequency, contact time, and flight time were 1.272 ± 0.185 Hz, 0.185 ± 0.020 s, and 0.497 ± 0.056 s, respectively.

3.2. Leg and joint stiffness

Fig. 1-A shows a typical example of the relationship between force and COM displacement in single cycles of hopping, recorded from one subject. The leg was compressed from the moment of landing, and the ground reaction force increased with COM displacement. The ground reaction force peaked at the moment of maximum leg compression, and subsequently, the force decreased with extension of the leg until take-off. Leg stiffness is represented by the slope of the force–displacement curve in the leg compression phase. Average values of K_{leg}, F_{max} and ΔCOM were shown in Table 1.

Fig. 1-B–D depicts typical examples of the relationship between joint moment and angular displacement in the ankle, knee and hip, respectively. These data were obtained from the same subject and the same hopping cycle as in Fig. 1-A. From the