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Changes in muscle activity with increase in leg stiffness during hopping

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Abstract

While the spring-like leg behavior of legs in mammalian locomotion has been well documented, its neural basis remains ambiguous. The purpose of the present study was to examine leg stiffness control during hopping. Seven male subjects performed in place two-legged hopping at their preferred frequency with two different contact times of the stance phase, preferred and short ones (PCT and SCT, respectively). Based on a spring-mass model, leg stiffness was calculated from the subjects' body mass, ground contact and flight times. Surface electromyographic (EMG) activities of the medial gastrocnemius (MG), soleus (SOL) and tibialis anterior (TA) muscles were recorded. Leg stiffness was higher in the SCT condition than in the PCT condition. The SCT condition was characterized by high EMG activity of MG and SOL at both pre- and post-landing phases, which peaked at about 50 ms. On the other hand, the activity of TA was low throughout the contact phase as compared with those of MG and SOL, and its peak value around 50 ms after landing was significantly lower for the SCT condition than for the PCT condition. We conclude that (1) the leg stiffness is regulated by a change in centrally programmed muscle preactivation and probably also by a concomitant change in the short-latency stretch reflex response of the triceps surae muscles, and (2) the co-contraction of antagonistic TA does not play a major role in leg stiffness control.

Keywords: Spring-mass model; Stiffness regulation; Preactivation; Short-latency stretch reflex; Co-contraction

Spring-like behavior is a general feature of a "bouncing gait", such as running, hopping or jumping. 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 [3,6,9,12]. In this model, stiffness of the leg spring ("leg stiffness") changes depending on the demand. For instance, leg spring becomes higher with an increase in hopping height [8,10] or frequency [8,14,22]. These findings suggest that humans and animals have a system of leg stiffness control, but its neural basis remains ambiguous. The purpose of the present study is to examine control of leg stiffness utilizing "hopping", because it is the simplest type of bouncing gait.

It has been well-documented that the change in leg stiffness during hopping is primarily correlated with changes in ankle joint stiffness [1,10,11,18]. Previous studies have focused on activity of triceps surae muscles. Melvill-Jones and Watt [19] showed that during hopping activity in the medial gastrocnemius was initiated approximately 100 ms before landing. Thus, the modulation of triceps surae preactivation could be one of the strategies utilized to control ankle stiffness. Furthermore, Komi and Gollhofer [17] suggested that the short-latency stretch reflex evoked by ankle dorsiflexion at landing is a prerequisite for the maintenance of ankle stiffness. The stretch reflex, therefore, could also be a crucial factor in ankle stiffness control during hopping [23,24].

On the other hand, little is known about the role of the antagonistic muscle of the triceps surae, the tibialis anterior, in the control of ankle joint stiffness. Hortobagyi and DeVita [16] reported that the much of the variance in leg stiffness during downward stepping is associated with changes in co-contraction of ankle joint antagonists. Interestingly, the total joint stiffness produced by co-contraction of antagonistic muscles becomes larger than the summation of joint stiffness produced by the activation of each muscle, due to reflexes from one of the muscles onto the other [4]. From the observation of ballistic arm movements, Hasan [15] suggested that modulation of co-contraction level would be an economical strategy to change joint stiffness; co-contraction of antagonistic ankle muscles may also contribute to the leg stiffness control during hopping.

In the present study we hypothesize that leg stiffness modulation during hopping is mainly adjusted by a change in co-contraction of ankle joint antagonists. We compare elec-

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tromyographic (EMG) activity of the triceps surae and tibialis anterior muscles in two different conditions of ground contact time in which the leg stiffness should change without a change in hopping frequency [1].

Seven male subjects with no neuromuscular disorders or functional limitations in their legs participated in the study. Their physical characteristics were: age 23.7 ± 1.3 years, height 170.7 ± 4.7 cm, and body weight 67.0 ± 0.9 kg (mean ± S.D.). Informed consent approved by the Human Ethics Committee, Waseda University, was obtained from all subjects before the experiment.

The task consisted of 10 successive hops in place. The subjects kept their hands on their hips, and were told not to bend their knees with a maximal effort without external aid. Subjects were instructed to match the timing of landings with audible clicks generated by a metronome. Before each experiment, subjects practiced the task for about 10 min. According to the subjective impression of the subjects, this practice session was enough to get used to the task. While practicing, they determined their preferred hopping frequency by adjusting the metronome to the most comfortable frequency. Hopping was performed on a platform (500 mm × 350 mm). A strain sensitive load cell (50 mm × 50 mm, LP-200KB, Kyowa Dengyo) on the platform was used as a foot-switch, producing an on-off signal of landing and take-off. The duration of this signal allowed us to measure hopping frequency, ground contact time and aerial time.

According to Arampatzis et al. [1], leg stiffness during a jump movement can be altered by verbal instructions with respect to ground contact time. In this experiment two different ground contact times were utilized during the stance phase: preferred and short contact time (PCT and SCT, respectively). In the PCT condition, subjects were asked to choose their preferred ground contact time. In the SCT condition, subjects were asked to hop with as short a contact time as possible. They performed hopping in the PCT and SCT conditions in a random order with a minimum resting period of 2 min between hopping bouts.

Leg stiffness during the contact phase was calculated with a spring-mass model, which utilizes the body mass and a single leg spring supporting the body mass. Leg stiffness was defined

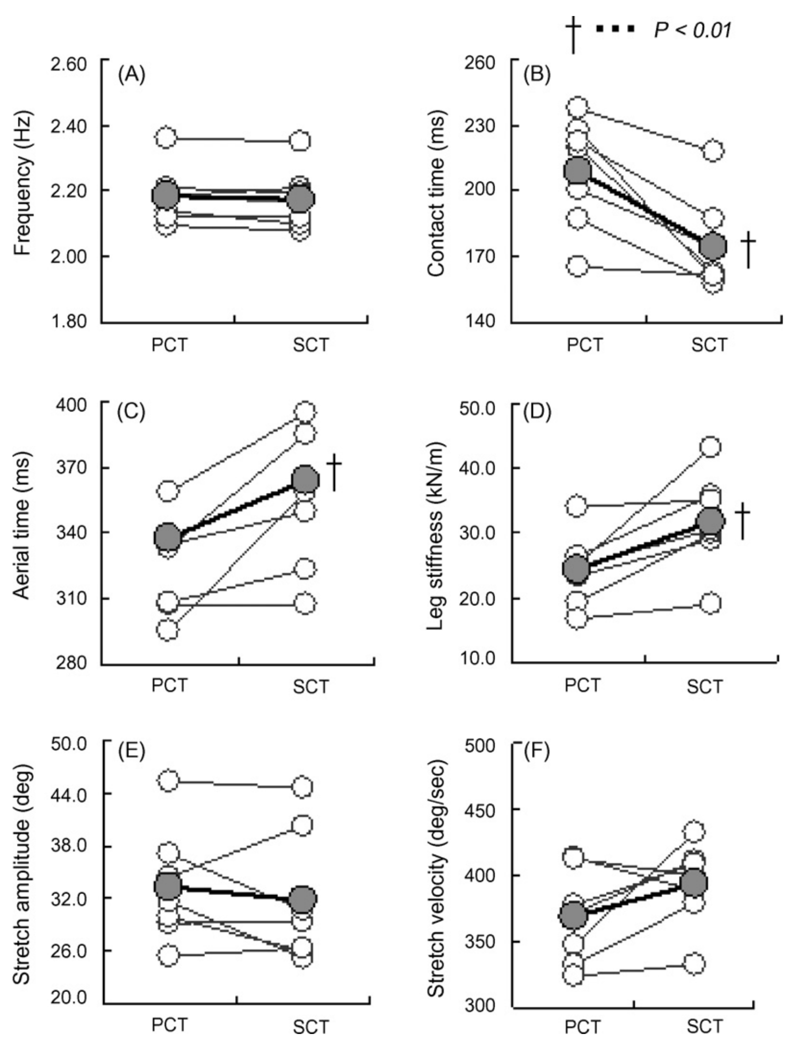

Fig. 1. Comparison of hopping frequency (A), contact time (B), aerial time (C), leg stiffness (D), dorsiflexion angle (E) and anglular velocity (F) for preferred contact (PCT) and short contact time (SCT) conditions. Unfilled circles represent an individual value for each subject. Filled circles represent the average value for the seven subjects. A dagger (†) indicates a significant difference between two conditions; $p < 0.01$.