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Short Communication

Behavioral effect of knee joint motion on body's center of mass during human quiet standing

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ABSTRACT

The balance control mechanism during upright standing has often been investigated using single- or double-link inverted pendulum models, involving the ankle joint only or both the ankle and hip joints, respectively. Several studies, however, have reported that knee joint motion during quiet standing cannot be ignored. This study aimed to investigate the degree to which knee joint motion contributes to the center of mass (COM) kinematics during quiet standing. Eight healthy adults were asked to stand quietly for 30 s on a force platform. Angular displacements and accelerations of the ankle, knee, and hip joints were calculated from kinematic data obtained by a motion capture system. We found that the amplitude of the angular acceleration was smallest in the ankle joint and largest in the hip joint (ankle < knee < hip). These angular accelerations were then substituted into three biomechanical models with or without the knee joint to estimate COM acceleration in the anterior–posterior direction. Although the "without-knee" models greatly overestimated the COM acceleration, the COM acceleration estimated by the "with-knee" model was similar to the actual acceleration obtained from force platform measurement. These results indicate substantial effects of knee joint motion on the COM kinematics during quiet standing. We suggest that investigations based on the multi-joint model, including the knee joint, are required to reveal the physiologically plausible balance control mechanism implemented by the central nervous system.

1. Introduction

Human upright stance has often been modeled as a single- (SIP) or double-link inverted pendulum (DIP), involving the ankle joint only or both the ankle and hip joints, respectively [1,2]. Several recent studies, however, have suggested that the knee joint also contributes to the control of the center of mass (COM). For example, the angular displacement of the knee joint during quiet standing is as large as that of the ankle joint [3,4] and there is a high spatiotemporal correlation between knee joint torque and COM kinematics in the anterior–posterior (A–P) direction [5]. Although the potential contribution of the knee joint has been suggested, to our knowledge, there is no study investigating the degree of this contribution. In this study, we quantified the behavioral contribution of knee joint motion to COM kinematics during quiet standing.

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2. Methods

2.1. Participants

Eight healthy young males (height = 174.0 ± 7.3 cm; weight = 67.2 ± 8.9 kg, age = 26.6 ± 2.4 years; means ± SD) voluntarily participated in this study. No participants had any history of neurological or musculoskeletal disorders. Participants gave their informed consent before entering the study. The study was in accordance with the Declaration of Helsinki and was approved by the local ethics committee.

2.2. Experimental procedures and measurements

Participants were asked to maintain quiet standing barefoot on a force platform (Type 9281B, Kistler, Winterhur, Switzerland) with their eyes open (EO) or closed (EC). The participants had their arms hanging along the sides of their body with their feet 20 cm apart. Five 30-s trials in each visual condition were conducted with a rest period between the trials. Five spherical markers, 11 mm in

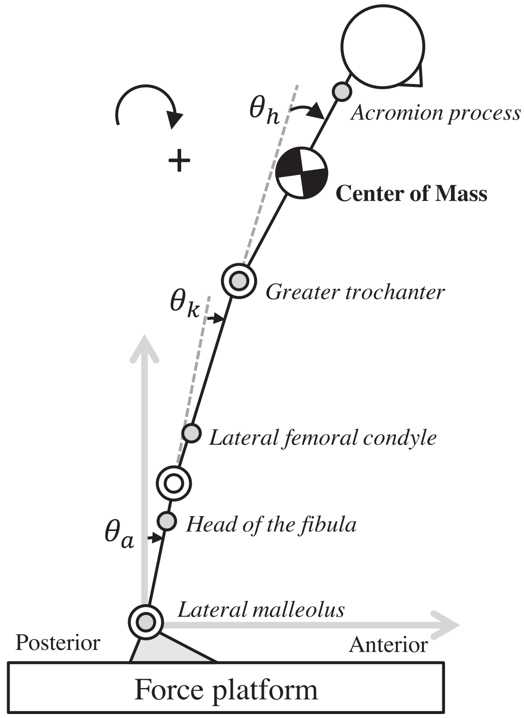

Fig. 1. Stick diagram of the triple-link inverted pendulum (TIP) model of upright standing in the sagittal plane. Joint angles (θ_a, θ_k, θ_h) are defined as positive in the clockwise direction. Gray circles represent the spherical markers placed on the anatomical landmarks. Inclination of the body is depicted exaggerated for the reader's convenience.

diameter, were placed on anatomical landmarks of the left side of the body (Fig. 1). The three-dimensional Cartesian coordinates of the markers were obtained with an optical motion capture system (OptiTrack: V100R2, NaturalPoint, OR, USA) composed of six infrared cameras in a semi-circular arrangement. The kinetic and kinematic signals were both sampled at 100 Hz.

2.3. Data analysis

The kinetic and kinematic signals were digitally smoothed with a bi-directional second-order low-pass Butterworth filter with cut-off frequencies of 3.0 and 1.5 Hz for the kinetic and kinematic signals, respectively [6]. From the marker coordinates, the joint angles at the ankle (θ_a), knee (θ_k), and hip (θ_h) (Fig. 1) and their angular accelerations ($\ddot{\theta}_a, \ddot{\theta}_k, \ddot{\theta}_h$) were calculated.

The A–P COM acceleration ($\ddot{X}_{\mathrm{COM}}$) can be expressed as a linear summation of the joint angular accelerations [7]

$$\ddot{X}_{\mathrm{COM}} = k_1\ddot{\theta}_a + k_2\ddot{\theta}_k + k_3\ddot{\theta}_h \quad (1)$$

where k_i ($i \in \{1, 2, 3\}$) are constant values calculated from the participants' anthropometric measurements and standard anthropometric data [8].

If only ankle joint motion has a primary contribution to COM kinematics, the COM acceleration can be estimated by the following equation (SIP model):

$$\ddot{X}_{\mathrm{COM}}^{\mathrm{SIP}} = k_1\ddot{\theta}_a \quad (2)$$

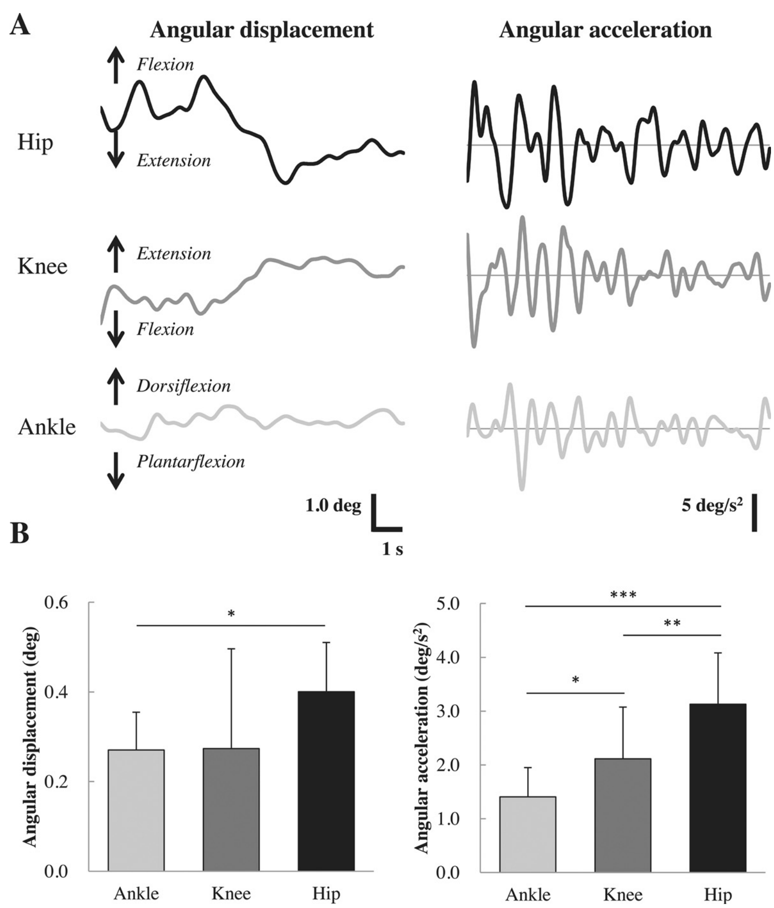

Fig. 2. (A) Typical time series of the angular displacement (left column) and angular acceleration (right column) of the hip (black), knee (dark gray), and ankle (light gray) joints for an eyes-open trial. Horizontal lines in the right column represent $\ddot{\theta} = 0$. Note that only 10 s of data from the whole 30-s trial are presented to isolate the signal features. (B) Bar chart showing the RMS values of the angular displacements (left column) and angular accelerations (right column) of the ankle (light gray), knee (dark gray), and hip (black) joints. The error bars represent 1 SD. $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$ between joints.