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Comparison of segmental analysis and sacral marker methods for determining the center of mass during level and slope walking

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ABSTRACT

Background: A human's center of mass (COM) is a widely used parameter in both clinical and practical applications. The segmental analysis method for determining the COM is considered the gold standard but is difficult to apply in a real environment.

Research question: The purpose of this study was to confirm the efficacy of an alternative COM determination method—the sacral marker method—by comparing segmental analysis and sacral marker method results in three dimensions during level or slope walking.

Methods: Ten healthy young subjects (age = 24.0 ± 4.5 yr, height = 174.5 ± 5.9 cm, and weight = 66.9 ± 9.4 kg) participated in the study. Each participant was monitored using a Helen Hayes full-body marker set and asked to walk on level and sloped (7°) terrain. The markers' trajectories were subsequently recorded. Each participant's COM was determined using segmental analysis and sacral marker methods via calculation and direct measurement, respectively.

Results: Comparative results indicated no significant differences ($p > 0.05$) between the segmental analysis and sacral marker method results for the COM displacement, velocity, or acceleration in the fore-aft and vertical directions. Conversely, significant differences ($p < 0.05$) between the two methods were observed for the COM displacement and acceleration in the medial-lateral direction, suggesting kinematic differences.

Significance: Based on this latter finding, caution should be exercised when determining COM kinematics using the sacral marker method.

1. Introduction

A human's center of mass (COM) is a widely used parameter in both clinical and practical applications. The COM provides useful information about a gait's energy requirements and is one of the most important descriptors of pathological gaits [1]. The COM has frequently been used as an indicator of gait deficiencies or as a complement to standard gait analysis [2]. It has also been used to compare the left and right side gait asymmetry between a patient and able-bodied subjects [3]. In addition to describing gait features, the dynamic stability of the COM has been correlated with slip-related falls [4,5].

The segmental analysis method has been widely used to determine a human's COM during walking. This method uses lower-body kinematic measurements obtained from multiple markers and lower- and upper-body anthropometric measurements [6]. The upper body is assumed to be a rigid body, and the COM during walking is subsequently calculated [3,7]. This method is considered the gold standard for determining a human's COM because of its accuracy [8]. However, this method requires a sophisticated motion capture system to record the trajectory of the each segment's markers, making it difficult to apply in a real environment [4].

To overcome the application challenges of the segmental analysis method, the sacral marker method, which uses a human's sacrum bone to represent the COM, has been applied [4,9]. Unlike the segmental analysis method that relies upon multiple marker trajectories, the sacral marker method estimates the COM using the trajectory of a single marker attached to the sacrum. Given its simplicity, the feasibility of the sacral marker method remains controversial. Select studies have shown that the sacral marker method effectively determines the COM in the vertical direction [3,4,9], while other studies have suggested that the sacral maker method is inaccurate [10,11]. These latter findings may be attributable to differences in the sacrum and true COM locations in a human body.

Most prior comparisons of COM determination methods have been conducted during walking on level terrain. In real environments, sloped terrain is common. During slope walking, the motion of the trunk and pelvis [12], as well as the lower-extremity kinematics [13], are changed. These changes may affect the COM determined by the

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segmental analysis method. In addition, most prior comparisons of COM determination methods have considered only the vertical direction COM [3,7,9]. Determination of the fore-aft and medial-lateral COM is also important for estimating metabolic energy consumption, dynamic stability during walking, and the prediction of slip-related falls [14–16]. No prior studies were uncovered that considered method-related differences in the COM velocity and acceleration, which are important parameters when estimating energy consumption [17–19] and balance [20,21] during walking.

In response to these noted investigative shortcomings, the purpose of this study was to compare the segmental analysis and sacral marker methods for determining a human's COM in three dimensions during level and slope walking. During our assessments, we considered method-related differences in the COM velocity and acceleration, as well as the COM displacement.

2. Methods

2.1. Experiments

Ten healthy young subjects (age = 24.0 ± 4.5 yr, height = 174.5 ± 5.9 cm, and weight = 66.9 ± 9.4 kg) with no musculoskeletal disease participated in this study. Prior to the experiments, all participants provided informed consent, and the methods were approved by the Korea Orthopedics and Rehabilitation Engineering Center's Institutional Review Board.

Each participant was monitored using a Helen Hayes full-body marker set. Static trials were performed using 29 markers; 4 medial markers were subsequently removed for the dynamic trials. In particular, the sacral marker was placed on mid-point of posterior superior iliac spine. Each participant, wearing the same running shoes (Nike Downshifter 6 Mesh/Synthetic Leather), was asked to walk at a self-selected velocity on level and uphill and downhill-sloped (7°) terrain. During walking, a three-dimensional motion capture system (Eagle4, Motion Analysis, USA) with 11 infrared cameras was used to record marker trajectories at a sampling rate of 120 Hz. The data of markers were filtered by using a Butterworth filter at 6 Hz.

2.2. Data analysis

Data collected during each of the experiments was used to determine each participant's COM in three dimensions using the segmental analysis and sacral marker methods during level, upslope, and downslope walking. Based on the markers, 15 segments (pelvis, right thigh, left thigh, right shank, left shank, right foot, left foot, trunk, head/neck, right upper arm, left upper arm, right forearm, left forearm, right hand and left hand) were generated and neighboring segments were articulated by a link. The position of COM was calculated as a weighted sum of the each segment's COM. The anthropometric data of Zatsiorsky-Seluyanov including the mass and inertial properties of each segment was used. The trajectory of the COM was computed by using Cortex 6.0 software (Motion Analysis, USA).

The COM displacement values were calculated as the difference in peak-to-valley magnitudes. Fig. 1 identifies these observed COM displacement peaks and valleys (denoted as P1–P*n*) in the fore-aft, medial-lateral, and vertical directions during level, upslope, and downslope walking.

In the segmental analysis method, all 25 markers were used to determine the COM displacement. Specifically, the COM was determined using lower-body kinematic measurements and lower- and upper-body anthropometric measurements. The upper body was assumed to be a rigid body. In the sacral marker method, a single marker placed on the skin of the sacrum was used to represent COM displacement during walking.

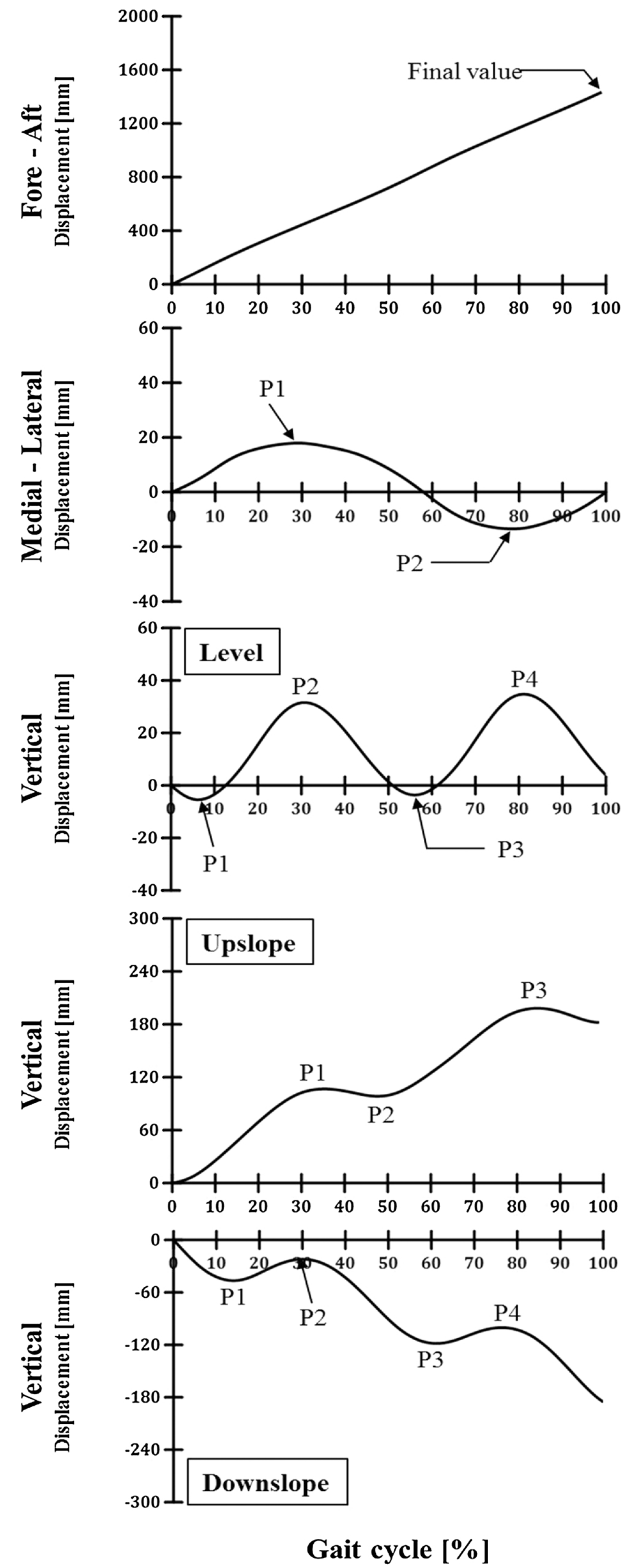

Fig. 1. Observed COM displacement peaks and valleys (denoted as P1–P*n*) in three dimensions during walking.