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Short communication

Uncontrolled manifold analysis of gait variability: Effects of load carriage and fatigue

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ABSTRACT

The uncontrolled manifold (UCM) analysis has been demonstrated to be a powerful tool for understanding motor variability. The purpose of this study was to use the UCM analysis to investigate the effects of load carriage and fatigue on gait variability. Whole-body kinematic data during treadmill walking were collected from 12 healthy male participants when fatigue and load carriage were applied. The task-level variable for the UCM analysis was selected to be the whole-body COM. We chose to analyze the whole-body COM data at two important gait events: right heel contact and right toe off, and the UCM analysis was carried out in the sagittal and frontal planes, separately. The dependent measures were UCM variability measures and UCM ratio. Three-way ANOVA was performed to determine the main and interaction effects of back-carrying load, fatigue, and gait events on the dependent measures. The results showed that frontal UCM ratio significantly changed with the application of back-carrying load and fatigue, indicating that both factors had effects on motor performance in stabilizing the whole-body COM in the frontal plane. These findings can facilitate a better understanding of the nature of motor variability due to load carriage and fatigue.

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1. Introduction

Human motions are variable due to motor abundance [1]. The uncontrolled manifold (UCM) theory has been proposed to facilitate understanding motor variability [2,3]. According to the UCM theory, the space defined by all segmental configurations that contribute to a particular motor task can be divided into two orthogonal subspaces: UCM and its orthogonal subspace. The segmental configurations in the UCM lead to the same values of task-level variables. Motions orthogonal to the UCM destabilize task-level variables. The ratio between the variabilities within and perpendicular to the UCM has been calculated to assess motor performance [2,4,5]. If this ratio is larger than one, the motor performance is stable in terms of controlling task-level variables. Otherwise, any error will lead to unstable motor performance [5].

Gait is one of the most common motor tasks in daily life. Gait variability is associated with fall risks [6]. Falls are a major health problem and are often multi-factorial. It was suggested that knowledge about how fall-related risk factors affect gait can aid in developing effective fall prevention interventions [7]. Load carriage and fatigue have been identified as two major fall-related risk factors [7]. In a previous paper, we used kinematic descriptors to study the effects of load carriage and fatigue on gait variability [8]. In the present study, we aimed to further investigate the effects of load carriage and fatigue on gait variability using the UCM analysis. Unlike traditional measures, UCM measures can be used to explain the origin of gait variability, and help understand the functional purposes that gait variability plays in various task conditions [3]. The UCM measures used in the present study included the variabilities per degree of freedom within the UCM (||UCM) and perpendicular to the UCM (⊥UCM), and the UCM ratio. We hypothesized that both load carriage and fatigue would lead to decreased ||UCM, increased ⊥UCM, and decreased UCM ratio.

2. Methods

2.1. Experiment

The details of the experiment have been presented elsewhere [8]. Briefly, twelve young male participants were recruited (age = 26.6 ± 2.9 years; height = 1.77 ± 0.07 m; body mass = 65.4 ± 8.0 kg). Fatiguing protocol involved a running exercise, and fatigue was considered to be induced when the participants first gave a RPE rating at or above 17. Body kinematic data were collected using an eight-camera motion capture system (Motion Analysis Eagle System, Santa Rosa, CA, USA) when the participants walked on a treadmill at their self-selected comfortable speed. Different back-carrying loads (i.e. 0 kg, 7.5 kg, and 15 kg) were applied separately to the participants during

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the walking trials. Each participant was instructed to perform three walking trials under the three back-carrying loading conditions, respectively, both before and immediately after the fatiguing exercise. Each walking trial lasted two minutes. In order to minimize order effects, the order in which the different loading conditions were presented was randomized across the pre-fatigue or post-fatigue trials.

2.2. Dependent measures

Black et al. [5] suggested that the whole-body center of mass (COM) be the preferential controlled variable to achieve stability (e.g. without losing balance) during walking. Thus, the task-level variable for the UCM analysis was selected to be the whole-body COM. We chose to analyze the whole-body COM data at two important gait events: right heel contact and right toe off. Fifteen successive strides immediately following the determination of a steady-state gait pattern were selected from each walking trial for analysis.

The human body was modeled as a 12-segment rigid body including the head, trunk, upper arms, lower arms, thighs, shanks, and feet. The UCM analysis was carried out in the sagittal plane and frontal plane, separately. The geometric models of the whole-body COM in the sagittal plane and frontal plane were thus described by Eqs. (1) and (2), respectively.

$$\begin{cases} x = x_0 + C_1M_1L_1\cos(\theta_1) + C_2M_2L_2\cos(\theta_2) + \cdots + C_{12}M_{12}L_{12}\cos(\theta_{12}) \\ z = z_0 + C_1M_1L_1\sin(\theta_1) + C_2M_2L_2\sin(\theta_2) + \cdots + C_{12}M_{12}L_{12}\sin(\theta_{12}) \end{cases} \tag{1}$$

$$\begin{cases} y = y_0 + C_1M_1L_1\cos(\varphi_1) + C_2M_2L_2\cos(\varphi_2) + \cdots + C_{12}M_{12}L_{12}\cos(\varphi_{12}) \\ z = z_0 + C_1M_1L_1\sin(\varphi_1) + C_2M_2L_2\sin(\varphi_2) + \cdots + C_{12}M_{12}L_{12}\sin(\varphi_{12}) \end{cases} \tag{2}$$

where x, y, and z are the whole-body COM positions in the anterior–posterior, medial-lateral and superior–inferior directions, respectively; x_0, y_0, and z_0 are determined by the joint locations at the discrete points of interest; L_i and M_i stand for the segmental length and normalized segmental mass by the body mass, respectively; C_i is the parameter for estimating the segmental COM; θ_i and φ_1 are the segmental angles relative to the horizontal in the sagittal plane and frontal plane, respectively. The anthropometric parameters used in the geometric model (i.e. M_i and C_i) were from de Leva [9].

A linearization approximation of the geometric model of the whole-body COM in each plane (sagittal or frontal) was then obtained at the mean segmental configuration at each gait event (heel contact or toe off) across all repetitions (i.e. gait cycles) using the Jacobian, which is the matrix of the partial derivatives of the whole-body COM with respect to the segmental angles [2]. The null space of the Jacobian defined the linearized UCM. The null space has n-d vectors (e_1, e_2, ..., e_{n-d}), where $n = 12$ is the number of dimensions in the segmental configuration space and $d = 2$ is the number of dimensions of the task-level variable. ||UCM, ⊥UCM, and UCM ratio were calculated as follows [5].

$$\|\Theta = \sum_{i=1}^{n-d} (e_i^T(\theta - \bar{\theta}))e_i \tag{3}$$

$$\perp\Theta = (\theta - \bar{\theta}) - \|\Theta \tag{4}$$

$$\|\mathrm{UCM} = \sqrt{(n-d)^{-1}N^{-1}\sum(\|\Theta)^2} \tag{5}$$

$$\perp\mathrm{UCM} = \sqrt{d^{-1}N^{-1}\sum(\perp\Theta)^2} \tag{6}$$

$$\mathrm{UCM\ ratio} = \frac{\|\mathrm{UCM}}{\perp\mathrm{UCM}} \tag{7}$$

where $\theta - \bar{\theta}$ is the deviation of segmental angles from the mean segmental configuration at each repetition; $N = 15$ is the number of repetitions. Since the UCM analysis was carried out using the whole-body COM in the sagittal and frontal planes, separately, the dependent measures were sagittal ||UCM, sagittal ⊥UCM, sagittal UCM ratio, frontal ||UCM, frontal ⊥UCM, and frontal UCM ratio.

2.3. Analysis

The independent variables were back-carrying load, fatigue, and gait event. Three-way ANOVA was performed to determine the main and interaction effects of the independent variables on the dependent measures. Tukey's honestly significant difference criterion was used in post hoc comparisons to determine differences in the effects of different levels of 'back-carrying load'. The level of significance $\alpha = 0.05$.

3. Results

The results from ANOVA showed that load carriage significantly affected sagittal ⊥UCM ($F(2, 132) = 3.093$, p-value = 0.049), frontal ||UCM ($F(2, 132) = 3.965$, p-value = 0.021), and frontal UCM ratio ($F(2, 132) = 11.814$, p-value < 0.001). Post hoc comparisons indicated that sagittal ⊥UCM became significantly larger in the high load condition versus no load condition (Fig. 1b), frontal ||UCM was significantly larger in both loaded conditions versus no load condition (Fig. 2a), and frontal UCM ratio was significantly larger in the high load condition than those in the low load and no load conditions (Fig. 2c).

Fatigue only significantly affected frontal UCM ratio ($F(1, 132) = 5.285$, p-value = 0.023). Specifically, the fatigued condition was associated with a smaller frontal UCM ratio (Fig. 2c). ||UCM and ⊥UCM in both planes were significantly different between heel contact and toe off events (sagittal ||UCM: $F(1, 132) = 10.018$, p-value = 0.002; sagittal ⊥UCM: $F(1, 132) = 11.730$, p-value = 0.001; frontal ||UCM: $F(1, 132) = 11.304$, p-value = 0.001; frontal ⊥UCM: $F(1, 132) = 5.453$, p-value = 0.021). In addition, there was not any interaction among the independent variables.

4. Discussion

Sagittal ⊥UCM was found to increase with the application of high back-carrying load. Such changes may account for our earlier findings that load carriage led to increased lower-extremity joint range-of-motion in the sagittal plane [8]. However, load carriage did not destabilize the task-level variable (i.e. whole-body COM) in the sagittal plane, as there was no change in the sagittal UCM ratio across loading levels.

We found that load carriage led to more frontal ||UCM and more frontal UCM ratio. This finding was somewhat surprising since higher ||UCM and higher UCM ratio are often associated with good motor performance [5], while existing literatures generally reported that load carriage had adverse effects on motor performance [8,10]. A possible explanation for this finding might be that load carriage could affect the movement of the whole-body COM and people would adopt an adaptive postural control strategy that uses more segmental configurations to stabilize the whole-body COM in the frontal plane during load carriage.

Fatigue affected motor performance in the frontal plane only, since frontal UCM ratio decreased with fatigue and no dependent UCM measures in the sagittal plane changed with fatigue. This might be because the fatiguing exercise (i.e. running) mainly affects muscles controlling medial-lateral movements. This finding also suggests that people become less capable of controlling the whole-body COM in the frontal plane after being fatigued.

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