The contribution of vestibular afference in walking stabilization

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Summary

Stabilization of walking relies on feedback control based on integrated sensory information. To investigate the use of vestibular afference in this process, we correlated deviations of the centre of mass (CoM) state to delayed horizontal ground reaction forces (GRF) during walking with and without vestibular perturbations. Our results suggest that vestibular afference is used to stabilize the CoM state in the mediolateral but not in the anteroposterior direction.

Introduction

To stabilize walking, the trajectory of the body's CoM needs to be controlled. Passive and active stabilization are likely to be used in parallel to this end [1] [2]. For example, in the anteroposterior direction (AP), forward falling of CoM can be passively controlled by the backward force due to ground contact [1]. In the mediolateral direction (ML), active control is required [2]. If corrective responses, reflected by the ground reaction force, are modulated based on the preceding CoM state, then this CoM state needs to be estimated from sensory afference. Earlier studies observed compensatory muscle activity or foot placement when perturbing the vestibular system with electrical vestibular stimulation (EVS) [3] [4]. During standing, sideward head orientation shifts the EVS induced perturbations from the ML into the AP direction [5]. Thus, this study aimed to investigate whether vestibular afference is used to estimate the CoM state to stabilize walking and if head orientation affects this process.

Methods

Thirteen participants walked on a treadmill with eyes open for 8 min at 78 steps/min and 2.8 km/h in four conditions, defined by the presence of EVS and by head orientations (HF: Head forward and HL: leftward). First, we calculated the coherence between the EVS stimulus and horizontal GRFs. Then, a linear regression between the CoM state, described as the extrapolated CoM, and the delayed ground reaction force (GRF) was fitted as:

$$GRF_i = a_i \cdot XCoM'_{(i-\delta)} + b_i + \epsilon_i$$

where $\boldsymbol{a_i}$ and $\boldsymbol{b_i}$ are the phase-dependent regression coefficients, $\boldsymbol{\epsilon_i}$ is the residual error, $\boldsymbol{i}$ is the phase (in % of the gait cycle) and $\boldsymbol{\delta}$ is the estimated delay in actuation (in % of the gait cycle).

We assessed the regression for every value of $\boldsymbol{i} \geq 50\%$ to predict the horizontal $\boldsymbol{GRF}$ from right to left heel strike, based on $\boldsymbol{XCoM'}$ at an earlier gait phase. For each participant, the correlation, gain and residual error were calculated from 78 consecutive gait cycles and averaged over 55% to 70% of the gait cycle for comparison.

A cluster-based permutation test, using t-statistics and 5000 permutations, was applied to the EVS-GRF coherence [6]. Repeated-measures ANOVAs were performed on averaged correlation, gain and residual error to investigate the effect of EVS, head orientation and their interaction.

Results and Discussion

Significant EVS-GRF coherence in both in AP and ML directions was found during walking with both head orientations. Leftward head orientation significantly decreased the EVS-GRF coherence in both the AP and ML direction. Negative correlations between the XCoM and delayed horizontal GRF were found in all conditions. The presence of EVS significantly increased the residual error of the linear regression between XCoM and delayed GRF in both the AP and ML direction. These results indicate that the GRF is modulated based on the estimated CoM state and that vestibular afference contributes to this process. When facing sideward, EVS induces illusions partly in the AP direction, which would be expected to increase the effect of EVS on AP feedback control. However, the effect of EVS on the residual error of the AP feedback model was larger when facing forward than facing leftward.

Conclusions

Our results indicate that vestibular afference is used to stabilize walking in the mediolateral but other than during standing, not in the anteroposterior direction.

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