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Short communication

A robotic system for delivering novel real-time, movement dependent perturbations

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ABSTRACT

Perturbations are often used to study movement control and balance, especially in the context of falling. Most often, discrete perturbations defined prior to the experiment are used to mimic external disturbances to balance. However, the largest proportion of falls is due to self-generated errors in weight shifting. Inspired by self-generated weight shifting errors, we created a novel, continuous mediolateral perturbation proportional to subjects' mediolateral center of mass movement with minimal delays. This perturbation was delivered by a robotic platform controlled by a real time Matlab Simulink model using kinematic data from a marker positioned at subjects' L5 as input. Fifteen healthy young adults stood as still as possible atop the robotic platform with their eyes closed. We evaluated the performance of the perturbation in terms of accuracy and delay relative to the input signal by using cross-correlations. The perturbations were accurate ($r = -0.984$), with delays of 154 ms. Such systematic perturbation significantly affected mediolateral sway, increasing its range (from 5.56 ± 3.72 to 9.58 ± 4.83 mm, $p = 0.01$), SD (from 1.08 ± 0.74 to 1.72 ± 0.74 mm, $p = 0.02$), and mean power frequency (from 0.08 ± 0.05 to 0.25 ± 0.17 Hz, $p < 0.01$). These perturbation characteristics enable inducing systematic, movement-dependent perturbations and open the door for future studies investigating self-generated movement errors.

1. Introduction

Balance is often studied by investigating responses to perturbations and one of the most common experimental paradigms to elicit perturbations involves the participant standing on a moving platform [1–6]. Such experiments mostly use discrete perturbations consisting of simple platform translations [1–3,5,7], although some studies use more complex perturbations [4,6,8]. However, all of the abovementioned studies use perturbations defined prior to the experiment, which remain constant throughout. Such perturbations are representative of external disturbances to balance and the underlying research is often aimed at fall prevention. However, the largest proportion of falls is not due to an external disturbance. Namely, 41% of falls is attributed to incorrect weight shifting [9], probably reflecting self-generated movement errors. Indeed, a link between falling and errors in weight shifting is strengthened by studies showing that errors in weight-shifting during step initiation are especially likely in the elderly [10] and delay foot lift-off [11], which is a predictor of future falling [12]. Hence, it is important to study self-generated weight shifting errors; for which novel perturbation paradigms are needed. Our aim was to describe a system that can induce novel perturbations proportional to one's own center of mass (COM) movement with minimal delays. Such perturbations are inspired by self-generated weight shifting errors, since they add a systematic error to the whole movement, as opposed to a predefined error occurring at a specific time point. We present sophisticated, real-time, movement-dependent perturbations delivered by a closed-loop system consisting of a robotic platform moving in response to real-time COM displacements of the subject standing on top of it. The performance of this system is evaluated in terms of accuracy of the generated perturbation and its delay relative to the input signal (i.e., the COM kinematics). Additionally, we show that such perturbations induce increased postural sway in young adults (YA) during a simple task of quiet stance.

2. Methods

2.1. Technical implementation

A six degree of freedom Stewart platform [13] was controlled in real-time by a custom made Matlab Simulink 8.6 model (Mathworks, Natick, USA). The control model duplicated the participant's COM displacement online by moving the platform in the opposite direction,

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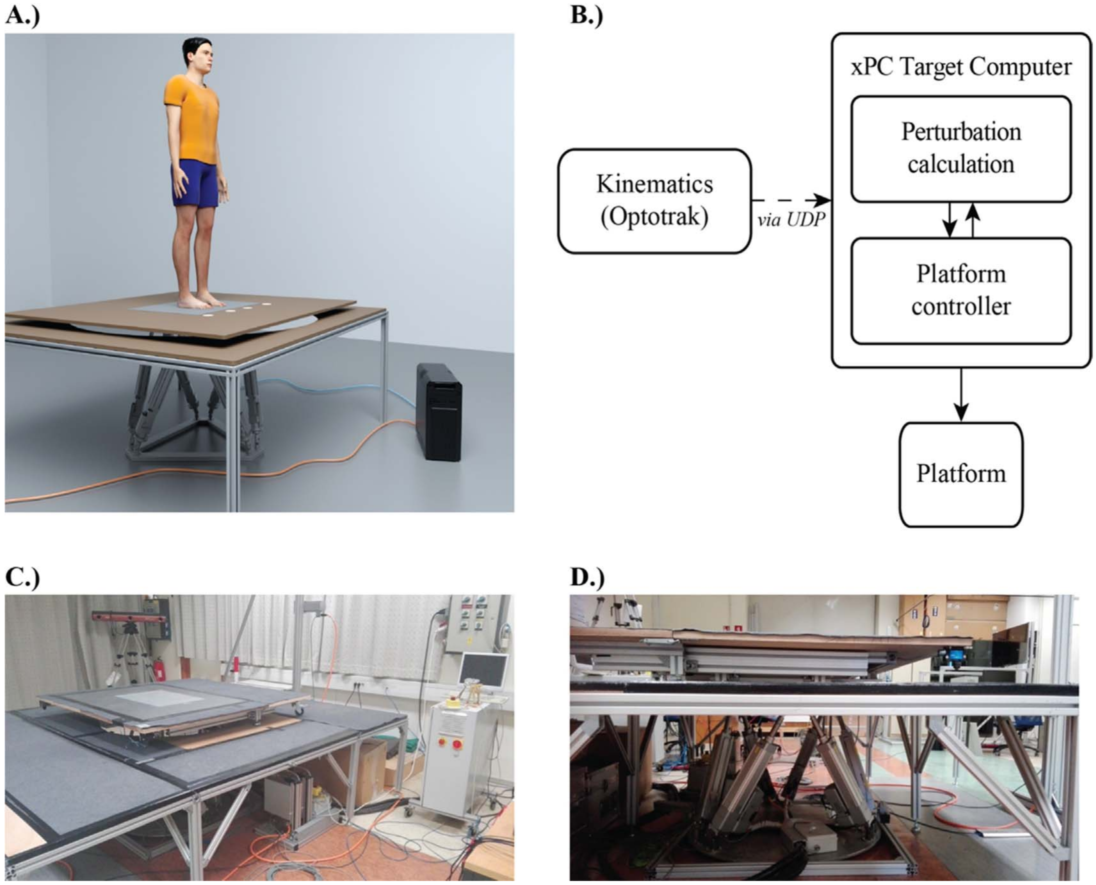

Fig. 1. Schematics of the hardware (A) and the software (B) of the perturbation setup and top (C), and side (D) views of the setup. On top of a six degree of freedom Stewart platform, we mounted two force plates (Kistler Instrumente AG, Winterthur, Switzerland), embedded within a larger wooden plate covered by a carpet. This created a moveable support surface of 1.5 × 1.5 m. For safety, we surrounded the support surface by a non-moveable wooden plateau (2.5 m x 3 m) and equipped it with safety switches that would arrest any movement in case it touched the wooden plateau. Hence, our participants stood on a moveable support surface 17 cm above a fixed and stable wooden plateau. The Stewart platform was controlled in real-time by a custom made Matlab Simulink 8.6 model (Mathworks, Natick, USA), which aimed to double the ML COM displacement by a corresponding ML platform translation in the opposite direction. For safety reasons, the platform displacement was defined for each time sample (1 ms) as the average of the COM displacement in the last four time samples (4 ms) and limited to max 7 mm/ms. We used a kinematic marker positioned at the L5 as input to the control model, which ran in real-time on an xPC Target (Mathworks, Natick, MA, USA). xPC Target is a solution that allows running the model on a dedicated "target" computer. This computer is booted with the xPC Target real-time kernel and its hardware is completely dedicated to xPC Target tasks, therefore achieving hard real-time performance. We sampled the kinematic data at 100 Hz, and ran the Simulink Model at 1000 Hz. Note that we limited platform movements to mediolateral translations in response to mediolateral COM displacement, but with a different Matlab Simulink model, the system would be able to produce support surface translations and tilts in all directions based on input from a marker placed at any anatomical landmark. Further details of the technical implementation can be found in the Supplementary material.

based on real-time input from a kinematic marker positioned at L5. The kinematic data were sampled at 100 Hz, and the Simulink Model ran at a 1000 Hz, resulting in millisecond control of the Stewart platform. Platform movements were limited to mediolateral (ML) translations in response to ML COM displacement. Technical details of the system are provided in Fig. 1 and Supplementary material.

2.2. Experimental procedures

We evaluated the performance of the perturbation in terms of delays and accuracy. Delivering a movement-dependent perturbation consists of two stages: processing, reflecting the input signal acquisition and calculation of the appropriate perturbation, and execution, reflecting platform movement once a perturbation has been calculated. We evaluated these separately. First, we used a predefined perturbation waveform as the input to platform movement and evaluated the execution phase, i.e., the mechanics of the system. Second, we used ML COM displacement of healthy YA as input to create ML movement dependent perturbations and evaluated the overall system performance, comprising both the processing and execution. In both cases, we calculated the cross-correlation between the input signal and platform movement and evaluated accuracy, defined by the maximal correlation coefficient and delay, defined by the corresponding lag. The execution phase was defined by the lag and correlation between measured platform movement and the predefined perturbation waveform. Overall performance was defined by lag and correlation between measured ML platform and COM movements of YA during quiet stance, averaged over participants.

Fifteen healthy YA (mean ± SD: age 24.1 ± 3.3 years, height 174.1 ± 7.6 cm, weight 70.2 ± 9.6 kg, 8 females) participated in this experiment after signing informed consent. Participants were instructed to stand as still as possible with their eyes closed, the feet hip-width apart and the arms relaxed by their body. The task was performed from the same starting position with the platform off and on for at least 175 s. We truncated the first 45 s of data, detrended the data and used the subsequent 30 s for our calculations. Kinematic data were recorded at 100 Hz, using a 1 × 3 Optotrak camera array (Northern Digital Inc., Waterloo, Ont., Canada) from markers positioned on the platform and the participant at the L5 level.

Finally, to asses the effect of the perturbation on postural sway, we calculated the range and SD of the COM movement relative to the platform and its mean power frequency (MPF) [14]. Data were compared between the platform on and off conditions using Wilcoxon signed rank test, with $\alpha = 0.05$.