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# Effects of amplitude and predictability of perturbations to the arm on anticipatory and reactionary muscle responses to maintain balance

Ali Forghani [a,*], Richard Preuss [b], Theodore Edgar Milner [a]

[a] *Department of Kinesiology and Physical Education, McGill University, 475 Pine Avenue West, Montreal, Quebec H2S 1S4, Canada*
[b] *Department of Physical and Occupational Therapy, McGill University, 3654 Promenade Sir-William-Osler, Montreal, Quebec H3G 1Y5, Canada*

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ABSTRACT

Disturbances to balance arising from forces applied to the upper limb have received relatively little attention compared to disturbances arising from support surface perturbations. In this study we applied fast ramp perturbations to the hand in anterior, posterior, medial and lateral directions. The effects of perturbation predictability and amplitude on the postural response of upper limb, trunk and lower limb muscles were investigated. Perturbations were applied either in blocks of constant amplitude and direction (predictable) or with direction and amplitude varying randomly (random) from trial to trial. The spatial-temporal patterns of anticipatory muscle activation under the predictable condition and the reactionary responses following the perturbation under both conditions were similarly organized. The size of the response increased systematically with the perturbation magnitude for both anticipatory and reactionary changes in muscle activation. However, the slope of the relation between perturbation amplitude and the magnitude of the change in muscle activation was greater when perturbations were predictable than when they were randomly selected. The timing of both the anticipatory and reactionary increases in muscle activation was invariant across perturbation amplitudes. The characteristics of the reactionary responses have a similar organization to the long latency muscle responses to support surface perturbations.

## 1. Introduction

Interaction with the physical environment in tasks where the arms are used to apply forces results in equal and opposite forces being transferred to the body via the arm. Forces may also arise from the physical environment. The magnitude of the interaction force may be anticipated or unanticipated (e.g. trying to open a door that is unexpectedly jammed). Rapid changes in force not only perturb the arm but are also transferred to the other body segments and can destabilize balance if they are not effectively countered. However, the central nervous system (CNS) is capable of responding rapidly to preserve balance (Cordo and Nashner, 1982). We have recently shown that the CNS determines the direction of an unpredictable force applied to the hand so rapidly that it is able to activate ankle muscles tuned to the direction of the perturbation at latencies of 80–100 ms in advance of the perturbing effect that this force has on balance (Forghani et al., 2017a). When perturbation direction and onset were predictable feedforward control to stabilize balance in advance of the disturbance was evident in the activation of ankle muscles similar to what has been observed in advance of self-initiated actions such as reaching in different directions (Aruin and Latash, 1995; Leonard et al., 2009). Previous studies related to multi-directional support surface perturbations (Moore et al., 1998; Henry et al. 2001; Torres-Oviedo and Ting, 2007; Freyler et al., 2015) have focused primarily on the responses that follow the onset of the perturbation, known as automatic postural responses (APRs). Even studies which have examined the responses to predictable perturbations (Horak et al., 1989) have been concerned more with APRs than anticipatory postural adjustments (APAs). In our previous study (Forghani et al., 2017a), we showed that the patterns of activation are similarly organized in terms of directional responses whether or not perturbation direction and timing can be anticipated but we did not investigate whether they were similarly influenced by perturbation features such as force amplitude. We hypothesize that the timing and direction tuning of postural responses to arm perturbations will not change with the amplitude of the perturbation but will scale in magnitude. This hypothesis is not trivial since the sensory input which triggers the postural response arises from sensory

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* Corresponding author.
*E-mail addresses:* af5yr@virginia.edu (A. Forghani), richard.preuss@mcgill.ca (R. Preuss), theodore.milner@mcgill.ca (T.E. Milner).

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receptors in the upper limb which do not directly influence the excitability of lower limb and trunk muscles.

## 2. Methods

### 2.1. Participants

Twelve (six male, six female) subjects with a mean age of 23.4 ± 3.8 years, without any known neurological, visual, or orthopedic disorders, were recruited from the McGill University student population to participate in the present study. They were all right hand dominant. All subjects provided written, informed consent prior to participation. Ethics approval for this study was received from the research ethics board of McGill University.

### 2.2. Joystick-type robot

A custom-built, joystick-type robot was used for testing. The robot is a five-link, closed-chain mechanism, with two degrees of freedom (Fig. 1). The projection of the robot's handle position in the horizontal (*xy*) plane was displayed as a red square cursor (7 × 7 mm) on a 17″ LCD monitor, which was oriented in the vertical plane approximately 1 m from the subject, slightly below head level

### 2.3. Experimental task

The participants stood barefoot, at a stance width of 0.17 m, with a 7° toe out angle (McIlroy and Maki, 1997), holding the handle of the robot with their right hand (Fig. 1). In order to normalize the force amplitude based on the subject's strength, the peak force amplitude of each perturbation was set to a percentage of the maximum exertion force in the subject's weakest direction. To determine the maximum exertion force, subjects stood and grasped a handle which rigidly mounted at waist height. They exerted maximum force in each of the four directions used in the experiments (0°, 90°, 180° and 270° relative to the positive *x*-axis, i.e.in the medial, anterior, lateral and posterior directions, respectively). Each effort lasted approximately 3 s and was repeated three times for each direction. The handle was instrumented with a six-axis force transducer (ATI Mini 45). The maximum isometric force exerted in the subject's weakest direction (usually 0°) served as the reference force for normalizing the perturbation force for that subject. The average reference force across subjects was 121.5 ± 29.9 N. The perturbation force amplitude was 10%, 20%, or 30% of the subject's reference force, corresponding to force conditions F1, F2, or F3, respectively. During pilot testing we found that perturbation amplitudes greater than 30% of a subject's reference force frequently resulted in fatigue and recovery maneuvers to avoid falling (e.g. stepping).

During the experiment, the robot applied a perturbing force to the participant's hand in one of the four directions outlined in Fig. 1. Each perturbation consisted of a 150 ms ramp-up, 3000 ms hold at peak force amplitude, and 150 ms ramp-down. Participants were instructed to resist and return the cursor into the target square as rapidly as possible after initiation of each perturbation.

Each participant received 108 perturbation trials (4 directions, 3 force levels, 9 trials each) in an unpredictable, pseudo-randomized order (RND condition) followed by 108 perturbation trials in which the direction and the onset of the upcoming perturbation were visually cued, and therefore predictable (PRD condition). For the PRD condition, perturbations were delivered in 4 blocks of 9 perturbations at the same force level beginning with 9 trials in the 0° direction and proceeding in a counterclockwise fashion to the 270° direction. The order of the blocks was always the same, beginning with the lowest force level (F1) and ending with the highest force level (F3) for each force direction. Visual cuing consisted of a bar traveling at a constant speed from the edge of the screen to the central target, in the direction of the upcoming perturbation. The perturbation was initiated when the bar reached the center of the target.

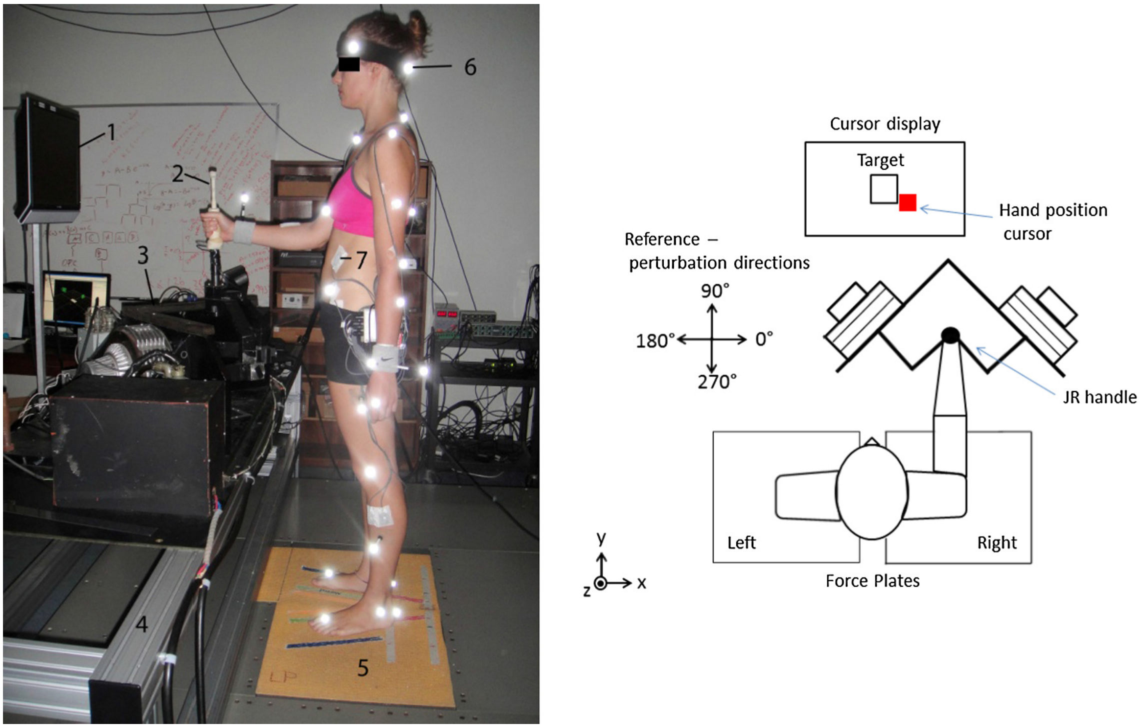

**Fig. 1.** Experimental setup: (1) LCD screen; (2) instrumented handle; (3) joystick robot; (4) mobile cart to facilitate the adjustment of robot position; (5) two force plates covered by stiff rubber mats; (6) Vicon markers; (7) EMG electrodes.