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Short communication

Protective balance and startle responses to sudden freefall in standing humans

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HIGHLIGHTS

- First trial posture responses (FTR) to external (EXT) and self (SLF) set freefall.
- Greater incidence of rapid EXT FTR neck muscle activation than SLF condition.
- Incidence and amplitude of EXT neck and arm FTRs habituated with repeated trials.
- EXT FTR freefall includes a startle incorporated with postural responses.

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ABSTRACT

The aim of the present study was to investigate whether or not startle reactions contribute to the whole body postural responses following sudden freefall in standing humans. Nine healthy participants stood atop a moveable platform and received externally-triggered (EXT) and selftriggered (SLF) drop perturbations of the support surface. Electromyographic (EMG) activity was recorded bilaterally over the sternocleidomastoid (SCM), deltoid (DLT), biceps brachii (BIC), medial gastrocnemius (GAS), and tibialis anterior (TA) muscles. Whole-body kinematics were also recorded with motion analysis. Rapid phasic activation of SCM during the first trial response (FTR) was seen for all participants for EXT and for 56% of subjects for SLF. Reductions in EMG amplitude between the EXT FTR and later trial responses for SCM, DLT, and BIC and reduced arm movement acceleration indicative of habituation occurred and exceeded adaptive reductions for SLF. These findings suggested that a startle reflex contributes to the exaggerated postural FTR observed during externally-triggered whole-body free falls.

1. Introduction

Sudden unforeseen disturbances to balance, such as slips or trips, may evoke startle responses representing reflexive reactions to intense tactile, vestibular, or acoustic stimuli [26]. Startle responses are characterized by rapid bilateral sternocleidomastoid muscle activation within ~80 ms of stimulus onset that propagates distally to limb muscles [9–11], marked reduction of neuromuscular and movement response amplitudes between first and subsequent repeated trials due to habituation [8,23], and large first trial electromyographic responses with co-contracting muscles throughout the body. Rapid and exaggerated postural responses during first trial reactions (FTRs) triggered by transient external perturbations resemble startle responses and are seen during sudden events which disturb posture while standing [5,21], walking [17,20], and sitting [6,8]. Studies of FTRs following standing balance perturbations have mainly focused on responses that stabilize the body in forward-backward or sideways directions, i.e., horizontally. However, common to all falls is the gravity-driven downward motion of the body. Limited data from studies of human freefall where participants are hoisted above the ground and suddenly dropped, showed rapid and exaggerated muscle activation in FTRs resembling generalized muscle activity evoked by strong sensory stimuli such as a loud sound that triggers a startle reaction [13,14]. The validity of this approach is questionable given the initial lack of ground support which is present prior to naturally occurring falls. If freefall FTR is characteristic of FTR to other threats to balance experienced during daily activities, then understanding whether FTRs aid or interfere with balance recovery is needed.

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Whether or not repeated standing freefall perturbations habituate is unknown. Moreover, modulating the exaggerated FTR component through participant awareness, and motor prediction (central set) may occur on voluntary self-activated freefall perturbations compared with externally imposed perturbations, indicating externally triggered FTRs include a startle reaction [12,19]. Thus, the aim of the present study was to determine whether whole-body postural responses following repeated standing freefall perturbations from stable ground support resembled startle-induced reactions.

2. Participants and methods

Nine healthy participants (five female) were enrolled (age 25.44 ± 2.3 years) and gave their informed consent to participate. The study was conducted in accordance with the standards of the Declaration of Helsinki and approved by the University of Maryland, Baltimore Institutional Review Board. Participants stood atop a moveable platform (45.6 cm wide, 50.5 cm long) secured to a fixed rigid frame using four electromagnets, (12 V DC, Magnetech Corp) allowing a 20 cm freefall onto a padded surface. The platform was soundlessly released via computer at randomized time intervals for externally-triggered (EXT) reactive trials at random time intervals, or by push-button remote during self-activated (SLF) predictive trials once a ready signal for trial start was given by the investigator. The time delay between trigger and release of electromagnets was approximately 100 ms.

Each session consisted of twelve trials of EXT and SLF condition freefalls with EXT trials preceding SLF. Participants were fitted with a safety harness with adequate slack to avoid interfering with postural responses. Participants were positioned consistently across both conditions and instructed to look straight ahead and react naturally. Thirty seconds were allotted between trials within each condition. Freefall onset occurred without warning in EXT trials, and was determined by participants who initiated it at a self-selected time once the signal for the trial was given during SLF trials. To minimize habituation participants received no practice trials, and 20 min were allotted between the end of EXT trials and the start of SLF trials [16]. To evaluate the effectiveness of the washout interval in minimizing possible order effects, a different cohort of five (one female) untested participants (age 23.6 ± 2.51 years) received sequential EXT trial blocks with a 20 min seated rest period between them.

Kinematic responses were recorded via a six camera motion capture system (VICON, Los Angeles, CA). Reflective markers were placed on the head, shoulders, elbows, wrists, and the drop platform to determine freefall onset. Data were sampled at 120 Hz for 5 s following perturbation onset. Coordinate data were smoothed with a 4th order low-pass Butterworth filter with a cutoff frequency of 7 Hz [25]. Pilot studies indicated the presence of robust arm flexion–abduction postural/startle responses to externally imposed freefalls. Thus, initial peak shoulder abduction acceleration defined as the maximum amplitude of acceleration elicited by initial shoulder abduction in response to platform release was used as a representative kinematic marker. Reflective markers placed on the acromia and lateral humeral epicondyles bilaterally formed a two segment model for determining the shoulder abduction angle relative to vertical and shoulder abduction angular acceleration was determined by double differentiation of the angular position data.

Electromyographic (EMG) activity was recorded (NORAXON, Scottsdale, AZ) bilaterally over the deltoid (DLT), biceps brachii (BIC), medial gastrocnemius (GAS), tibialis anterior (TA) muscles, as well as sternocleidomastoid (SCM) given the high probability of this muscle's activation following a startling stimuli [3,9,24]. Data were recorded at 1500 Hz from 2 s before to 3 s following trigger signal and filtered online with a 10–500 Hz band-pass filter before being high pass filtered (20 Hz), rectified, and smoothed using a digital 4th order Butterworth filter.

Customized graphical analysis programs (The MathWorks, Inc., Natick, MA) were used during EMG processing. EMG onset was defined relative to perturbation onset as the time when the rectified EMG value exceeded mean plus 3 standard deviations (SD) from baseline (100 ms before trigger signal) for 30 ms. Peak EMG activity was defined as the maximal EMG value recorded within the initial phasic response and was normalized as a percentage of the maximal root mean square (RMS) amplitude obtained during FTR. Prior to statistical analysis, peak EMG amplitude values were log-transformed to correct for skewed distributions and heteroscedasticity.

The overall incidence of SCM activation within 100 ms in FTR and subsequent trials between conditions was determined using Fisher's Exact Test. Wilcoxon Signed-Rank Test was used to assess significance of temporal organization in FTR for EXT condition. If significance was found, post-hoc analysis was performed using Friedman's test. To evaluate the effectiveness of a 20 min washout period in minimizing habituation carryover, the successive trial block EXT FTRs before washout ($Pre_{20\,min}$) and after washout ($Post_{20\,min}$) were compared using Wilcoxon signed-rank test. The effects of repeated freefall perturbations on response parameters (EMG onsets and peak amplitude, and peak shoulder acceleration) were compared between the FTR and trials 2–5 for each condition using a one-way repeated measures ANOVA with four levels (EXT_{FTR}, EXT_{2-5}, SLF_{FTR}, SLF_{2-5}) on the log transformed values with Bonferroni post-hoc analyses. Significance for all statistical tests was set at $p < 0.05$. Data are presented as mean ± SEM.

3. Results

3.1. Neuromuscular responses

Representative FTR bilateral SCM EMG activity during the EXT condition is shown in Fig. 1. Rapid phasic bilateral and synchronous SCM activity within 100 ms after stimulus onset is a hallmark

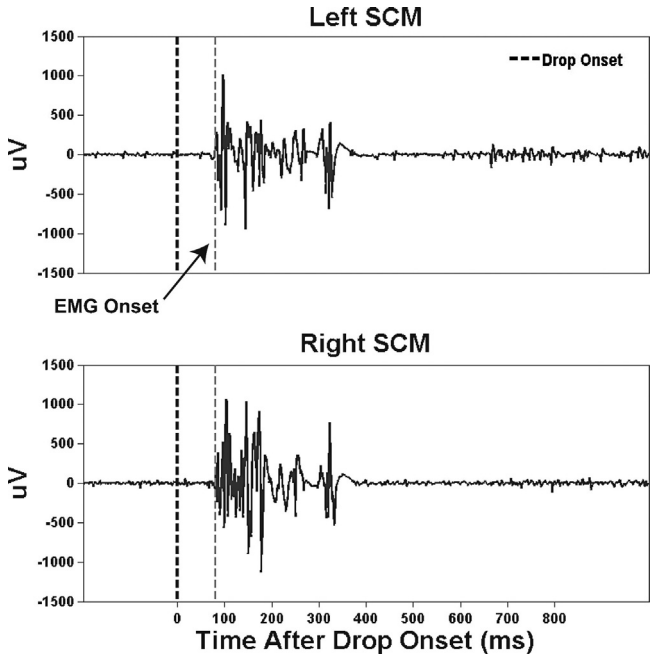

Fig. 1. Representative example trial of electromyographic (EMG) responses from bilateral sternocleidomastoid neck muscles following an externally triggered freefall perturbation of the standing support surface in one subject.