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Keeping your balance while balancing a cylinder: interaction of postural and voluntary goals

Selma Papegaaij¹, Andrea C. de Lima-Pardini², Beth A. Smith³, Egbert Otten¹, Rajal G. Cohen^{3,4}, and Fay B. Horak³

¹Center for Human Movement Sciences, Faculty of Medical Sciences, University of Groningen, Antonius Deusinglaan 1, 9713AV, Groningen, the Netherlands ²Human Motor System Laboratory, School of Physical Education and Sport, University of São Paulo, Av. Prof. Mello de Moraes, 65, Cidade Universitária, CEP: 05508–030, São Paulo, SP, Brazil ³Department of Neurology, Oregon Health & Science University, 3181 SW Sam Jackson Park Road, Portland, Oregon 97239–3098, United States ⁴Department of Psychology & Communication Studies, University of Idaho, P.O. box 443043, Moscow, Idaho 83844–3043

Abstract

The present study investigated whether postural responses are influenced by the stability constraint of a voluntary, manual task. We also examined how task constraint and first experience (the condition with which the participants started the experiment) influence the kinematic strategies used to simultaneously accomplish a postural response and a voluntary task. Twelve healthy older adults were perturbed during standing, while holding a tray with a cylinder placed with the flat side down (low constraint; LC) or with the rolling, round side down (high constraint; HC). Central set changed according to the task constraint, as shown by a higher magnitude of both the gastrocnemius (GAS) and tibialis anterior (TA) muscle activation bursts in the HC than the LC condition. This increase in muscle activation was not reflected, however, in changes in the center of pressure or center of mass displacement. Task constraint influenced the peak shoulder flexion for the voluntary tray task but not the peak hip flexion for the postural task. In contrast, first experience influenced the peak hip flexion but not the peak shoulder flexion. These results suggest an interaction between two separate control mechanisms for automatic postural responses and voluntary stabilization tasks.

Keywords

posture; postural responses; central set; voluntary task; dual-task

1. Introduction

Because people engage in voluntary activities while standing, such as talking, reading, or manually controlling objects, postural control needs to adapt based on the stability constraints of the other task. For example, when the voluntary task requires postural stabilization, postural sway in standing decreases (Haddad et al. 2010; Balasubramaniam et al. 2000; Morioka et al. 2005; Stoffregen et al. 2000; Krishnamoorthy et al. 2002). However, when the voluntary task decreases attention to postural stabilization, sway increases (Woollacott and Shumway-Cook 2002). Although the influence of stability constraint of a voluntary task on postural control is apparent in quiet stance, the influence of stability

constraint of a voluntary task on postural responses to external perturbations is unknown. Unlike quiet stance, in which the stability constraint of a voluntary task influences body sway via closed loop feedback (Peterka 2002), the effect of stability constraint on initial postural responses must be via feed-forward control, called central set (Horak et al. 1989; Prochazka et al. 2000). Central set is defined as a modified neuromotor state due to changes in initial context (Prochazka 1989).

Although postural responses are proprioceptively triggered at only 100 ms after the perturbation with stereotyped synergies (Ting and Macpherson 2005; Horak and Nashner 1986; Diener et al. 1988), studies suggest that the cortex can influence central set for postural responses (Jacobs and Horak 2007). This influence on central set is via two main loops, one including the cerebellum and one including the basal ganglia. Studies suggest that the cerebellar-cortical loop is responsible for adapting postural responses based on prior experience (Horak and Diener 1994; Timmann and Horak 1997), and that the basal ganglia is responsible for pre-selecting postural responses based on current context (Beckley et al. 1993; Bloem et al. 1995; Chong et al. 2000; Horak et al. 1992; Horak et al. 2005). Prior experience has also been shown to influence the kinematic postural strategy (Horak and Nashner 1986). In this Horak and Nashner study (1986) participants stood on support surfaces of various lengths while they were perturbed. Participants needed 5 to 15 trials to change strategy when switching from a long surface, where the ankle strategy is used, to a short surface, where the hip strategy is used. Taken together, control of postural responses is not only reactive, but also has a predictive component. We are interested in how postural control of perturbed stance interacts with voluntary control of a manual stabilization task.

The aim of the current study was therefore to determine whether people change their postural responses based on the intention to perform a voluntary task that required more or less stabilization of a tray held in their hands. We looked at changes in muscle activity and kinematic strategies through both pre-selection and experience. Two studies have been published on postural responses during performance of a voluntary task (Trivedi et al. 2010; de Lima et al. 2010). Trivedi et al. (2010) reported modifications in amplitude of the late postural response (100–200 ms after muscle activation onset), but not of the initial postural response (0–100 ms after muscle activity onset), when participants were perturbed during reaching. However, the participants did not know the direction of the perturbation. Therefore, they could only use feedback, not central set, to change the postural responses to aid the reaching.

The importance of certainty of direction was confirmed by de Lima et al. (2010), who let subjects hold a tray under low and high stability constraint conditions, while the surface was translated forward or backward. The authors found decreased postural muscle onset latencies and a modification of the contribution of the different joints in the high constraint condition, only when the direction of translation was known, i.e.; when changes in central set were possible. While these results suggest that the constraints imposed by a manual task can modify central set for postural responses to an external perturbation, a direct measure of postural response magnitude, such as muscle burst magnitude, displacement of center of pressure (CoP), or displacement or center of mass (CoM) sway, is missing. Moreover, in the de Lima et al. study only the effect of current task constraint was investigated, and not the effect of experience.

In the present study, we translated the support surface backward while participants were standing and holding a tray with a cylinder on it. The stability constraint of the task was modified by placing the same cylinder either with the flat side down (low constraint; LC) or with the rolling, round side down (high constraint; HC). Differences in postural responses between conditions were assigned to the influence of current context; differences between

people who started with one or the other condition were assigned to the influence of first experience. We hypothesized that the postural responses would be influenced by both the current context and the first experience. We expected a decreased CoM sway in the HC condition, in order to accomplish the voluntary task goal of minimizing cylinder rotation. This decreased CoM displacement was expected to be achieved by a higher magnitude and shorter onset time of the postural muscle responses, resulting in a faster change in CoP displacement.

2. Methods

2.1. Participants

Five male and seven female participants, aged between 61 and 79 years (mean $\pm$ SD = 68 $\pm$ 5), were recruited to participate in this study. The data from these participants was also used for another study, where they were compared with Parkinson patients (de Lima-Pardini et al. 2012). The participants were age-matched to these Parkinson patients. All participants had neurological and musculoskeletal function within normal limits, were free of any condition that prevented standing independently for at least 30 minutes, and had normal or corrected-to-normal vision. In addition, participants using medication known to affect balance or attention, or suffering from cognitive impairments (score < 26 on the Montreal Cognitive Assessment Scale (Nasreddine et al. 2005)), were excluded. Participants signed an informed consent form that was approved by the Oregon Health & Science University Institutional Review Board.

2.2. Experimental procedures

Fig 1a shows the experimental setup. Participants stood upright on a movable platform with each foot on a separate force plate, while holding a wooden tray (30 cm $\times$ 40 cm, weight 432 g). A cylinder (roll of tape with a diameter of 9.5 cm, height of 5.0 cm, and weight of 124 g) was situated in the middle of the tray. In the *low constraint condition (LC)*, the cylinder was lying on its flat side, so that it did not move in relation to the tray. In the *high constraint condition (HC)*, the same cylinder was placed on its round side, so that it was free to roll in the anterior-posterior direction. However, rolling was limited to ± 90 degrees by a weight of 20 g glued in the bottom of the cylinder. All participants were screened before the experiment to make sure they were able to hold the cylinder stable three times for ten seconds while standing on a steady floor.

All participants wore a harness that was attached to the ceiling, and an assistant stood at their left side to assist in case of falls into the harness support. The following instructions were given to the participants in both low and high constraint conditions: “Stand straight with your upper arms parallel to your body and your elbows at 90 degrees, and look at the cylinder. The platform will move backward. We will not tell you to get ready, so you won’t know when exactly the perturbation will start. Please keep looking at the cylinder and try to avoid any movement of the cylinder. Also, try not to step during the perturbation.” The participants were asked to place their feet in a comfortable position (stance width 14 $\pm$ 3 cm). To make sure the same position was maintained during the experiment, the foot position was marked with tape and the initial CoP position before each trial was checked with an oscilloscope. The movable platform translated backward by means of a servomechanism over 11 cm with a mean velocity of 16 cm/s and peak acceleration of 12 cm/s². These parameters were chosen so that balance could be recovered with either an ankle or a hip strategy (Runge et al. 1999; Hwang et al. 2009).

The experimental protocol consisted of 3 blocks of 7 trials in each condition (LC or HC) for a total of 42 trials. In each trial, data was recorded for 7 seconds, including 2 seconds before the perturbation. To avoid anticipatory control, participants did not know the start time of

the trials. LC and HC blocks alternated, with the initial condition pseudo-randomized between subjects. Between blocks, one-minute rest breaks were given. After three blocks, a longer rest was allowed, in which subjects sat down for 15 minutes.

2.3. Data collection and analysis

A custom built system recorded electromyographic (EMG) activity from the agonist, i.e.; medial head of the right gastrocnemius (GAS) and antagonist, i.e.; tibialis anterior (TA) muscles, using bipolar Ag-AgCl surface electrodes spaced 2–4 cm apart. The EMG signals were amplified at a gain of 2000–10,000, band-pass filtered from 15–2000 Hz, sampled at 480 Hz, and then low pass filtered at 10 Hz. The signals were normalized for background EMG by subtracting average EMG activity measured in the 1.5 seconds before perturbation. The onset latency of the muscle burst was identified as the first sustained activity (lasting at least 25 ms) greater than two standard deviations above the baseline after onset of perturbation, using an identification algorithm programmed in MATLAB. All latencies were verified and occasionally modified manually (<10% of trials). The magnitude of the initial postural response was defined as the integrated EMG (iEMG) 0–75 ms after muscle activity onset.

Custom built force plates were used to measure the CoP displacement, with a sample frequency of 480 Hz. The initial rate-of-change of CoP displacement was determined from individual trials, between 50 and 150 ms after onset of GAS activity. This time period was chosen to represent the initial response before long-loop feedback correction could take place, with the electromechanical delay of about 50 ms taken into account (Horak et al. 1996).

A Motion Analysis system with eight Falcon video cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) provided 3-dimensional spatial coordinates of the reflective markers on body, tray, cylinder and movable surface, at a sample frequency of 60 Hz. Body markers were placed bilaterally on the fifth metatarsophalangeal joints, heels, lateral malleoli, lateral knee joint centers, greater trochanters, acromions, lateral epicondyles, wrist joint centers, and on the head at the jaw joint centers. Twenty-six anthropometric measures of head, limb, and trunk segments (length, width, and perimeter) were collected from each participant (adapted from Chandler et al. 1975). These anthropometric measures, together with the motion analysis data, were used to estimate the sagittal plane body CoM position. Peak flexion angles were calculated for the hip and shoulder joints, representing respectively the postural and voluntary kinematic strategies.

The total path of the cylinder marker, which represents the actual performance of the voluntary task, could only be calculated in the HC condition since it did not move on the tray in the LC condition. Therefore, the peak horizontal tray velocity was used to compare performance of the voluntary task between the LC and HC conditions. Peak tray velocity was positively correlated with the cylinder path in HC trials ($r=0.68$).

2.4. Statistical analysis

All outcome measures were averaged for each subject across trials within each condition. To test the influence of first experience, subjects were split into two groups; one group started with the LC condition and the other group started with the HC condition. Three outcome measures were logarithmically transformed before statistical testing because of skewed distributions: peak hip and shoulder flexion and response magnitude of TA. A two-way repeated measures ANOVA was used to assess the influences of task constraint (within subjects factor) and first experience (between subjects factor) on the following dependent variables: peak tray velocity, muscle onset latency of TA and GAS, initial rate-of-change of

CoP, amplitude of CoM sway, and peak hip and shoulder flexion. Interaction effects are reported when significant. The magnitude of TA and GAS responses could only be tested for within subject differences, because maximum voluntary contraction (MVC) measurements are needed to normalize the data for between subject comparisons. Therefore, paired t-tests were conducted to test the differences between LC and HC conditions for the response magnitude of TA and GAS. The alpha level was set at 0.05 for all comparisons. Results are presented as mean $\pm$ SD.

3. Results

3.1 Performance of voluntary task

The grand subject means for tray displacement and velocity show that subjects stabilized the tray more in the HC condition than in the LC condition (Fig 1). Task constraint showed a main effect on peak tray velocity, $F(1,10)=13$, $P<0.01$, in which peak tray velocity was slower in the HC condition ($12.3\pm 4.3\text{cm/s}$), than in the LC condition ($15.5\pm 2.5\text{cm/s}$). There was no effect of first condition on peak tray velocity.

3.2 Influence of task constraint on postural response

EMG—Subjects responded to surface translations with a burst of activation in the stretched GAS, followed by activation of the shortened TA. Fig. 2a illustrates EMG responses of one LC trial and one HC trial from a representative subject.

The magnitude of initial muscle bursts was larger in HC than in LC trials (Fig. 2b). Specifically, GAS iEMG was 14 (SD=16) percent larger ($t(9)=-2.8$, $P<0.05$), and TA iEMG was 30 (SD=46) percent larger ($t(11)=-2.3$, $P<0.05$), in the HC condition than in the LC condition.

The influence of task constraint on muscle onset latencies is illustrated in Fig. 2c. There was a significant main effect of task constraint on TA onset latency: TA was activated later in the HC condition ($134\pm 41\text{ms}$) than in the LC condition ($116\pm 39\text{ms}$; $F(1,10)=5.2$, $P=0.046$). There was no difference in GAS onset latency between the LC and HC conditions.

CoP & CoM—The increase in magnitude of muscle bursts was not reflected in alteration of the CoP rate-of-change or CoM displacement, which were similar across conditions (Fig. 3a and 3b).

Kinematic strategies—Peak hip flexion was variable across subjects and was not significantly affected by task constraint (Fig. 3c). However, there was a significant main effect of task constraint on peak shoulder flexion (Fig. 3d; $F(1,10)=103$, $p<0.001$). Shoulder flexion was greater during the HC condition (7.7 ± 3.4 degrees) than the LC condition (5.3 ± 3.1 degrees).

3.3 Influence of first experience on postural response

EMG—There was no significant main effect of first experience on either the GAS or the TA onset latency.

CoP & CoM—Fig. 4 illustrates the influence of first experience for CoP rate-of-change, peak hip and shoulder flexion, and peak tray velocity. There was no significant main effect of first experience on the CoP rate-of-change or CoM displacement.

Kinematic strategies—There was a significant main effect of first experience on peak hip flexion ($F(1,10)=21$, $P<0.01$): participants who started with LC used more hip flexion

(8.6 ± 1.8 degrees), than those who started with HC (2.7 ± 1.6 degrees). In contrast, there was no main effect of first experience on peak shoulder flexion. Both participants who start with LC and those who started with HC showed a higher peak hip and shoulder flexion in the first trial compared to the rest of the trials. This exaggeration of responses in the first trial is often called the first trial effect (Allum et al. 2011). This effect was not different between the groups.

The interaction between first experience and task constraint was significant for both hip and shoulder flexion (hip: $F(1,100)=9.6$, $P<0.05$; shoulder: $F(1,100)=23$, $P<0.01$). Participants who started with LC had less difference between the LC and HC conditions in hip and shoulder flexion than participants who started with HC.

4. Discussion

The aim of the study was to investigate whether and how postural responses were influenced by the stability constraint of a voluntary manual task. As expected, central set for postural responses was affected by the voluntary task constraint, shown by a higher magnitude of both the GAS and TA muscle activation bursts in the HC condition. This increase in muscle activation was not reflected, however, in the CoP rate-of-change or CoM displacement, which were similar across conditions. Postural responses were also influenced by the first experience with the task. Participants who started with LC used more hip flexion than those who started with HC. Both the influence of task constraint and that of first experience on postural responses show the interaction between postural and voluntary goals.

4.1. Influence of task constraint

Participants in the current study were able to adapt their voluntary behavior to the stability constraints of the conditions. This adaptation was shown by a reduction in peak tray velocity in the HC condition compared to the LC condition. Feed-forward control of central set was also used to adapt postural responses in order to prevent postural disequilibrium and to reduce tray velocity (to prevent cylinder movement). This was shown by an increase of both the GAS and TA postural muscle response magnitude in the HC condition.

However, this increase in muscle responses was not reflected in initial rate-of-change in CoP or in CoM displacement. A possible explanation is that the increase in muscle activity had no postural purpose, but instead served to limit tray movement. However, in such a situation differences in the CoP and CoM between conditions would still be expected. Therefore, we think it is more likely that the increase in magnitude of the TA muscle burst did serve a postural purpose and was caused by anticipatory postural adjustments for the shoulder flexion present in the HC condition (Aruin and Latash 1995; Bouisset and Zattara 1981). Because the CoP displacement is dependent on both the agonist and antagonist, the increase in TA activity could have counteracted the increase in GAS activity, resulting in similar rates-of-change of CoP in the HC and LC conditions. Altogether, the results suggest that the increase in muscle activation was not aimed at reducing body sway, but was necessary to incorporate the voluntary movement into the postural response without increasing disequilibrium. This cooperation of the voluntary and postural responses might seem contradictory to previous work on dual tasking that reported disruption in the performance of both the voluntary and postural task when performed together (Norrie et al. 2002). However, the voluntary task used in that study is not comparable with ours. Their participants had to track a moving target on a computer screen, controlling the cursor movement by rotating a potentiometer. In this task destabilization of the body is not directly linked with performance of the voluntary task. In our task, destabilization of the body would directly affect movement of the cylinder; therefore a cooperation of postural and voluntary responses was established.

Besides being larger, we expected the postural muscle responses to have shorter onset latencies (de Lima et al. 2010). Instead, there was no difference for the agonist (GAS) onset latency, and the antagonist (TA) onset latency was even later in the HC condition. Our hypothesis was based on the study of de Lima et al. (2010), who found a shorter onset latency for the TA muscle in the HC condition. There are at least two possible explanations for this discrepancy in results. First, their data was obtained from a younger group; age could have affected the flexibility in muscle onset latency in the older adults. The discrepancy could also be explained by the fact that they only analyzed trials with a forward perturbation, whereas the current study used a backward perturbation. The TA would be the agonist for the forward perturbation, and it has been shown that the TA has more influence from corticospinal pathways than the GAS (Brouwer and Qiao 1995; Bawa et al. 2002). The suggestion that the TA muscle was used for anticipatory postural control for shoulder flexion in the HC condition could explain why the onset latency of TA activity was later in this condition, since latencies to voluntary postural activities are longer than latencies to automatic postural responses (Cordo and Nashner 1982).

Voluntary control of tray velocity was accomplished by shoulder flexion. In the HC condition, participants tried to keep the tray still in space while their bodies were moved backward with the support surface. Therefore, they moved the tray forward to counteract the backward platform translations by flexing their shoulders while extending their elbows. The increase in shoulder flexion seen in the HC condition is unlikely to be part of the postural response because hip flexion did not increase similarly with task constraint. In fact, it seems to be a voluntary movement, since the onset latency of upper arm movement in the HC trials (428 ± 32 ms) was longer than the average voluntary reaction time (277 ± 12 ms for 4 participants who were asked to move the tray (without cylinder) forward as fast as possible after detecting the perturbation).

4.2. Influence of first experience

The postural strategy was highly influenced by the first experience with the task. Participants who started with LC used more hip flexion than participants who started with HC, and they continued doing this during the whole experiment. The initial rate-of-change in CoP showed the same trends as the peak hip angle, although this was not statistically significant. This finding strengthens our notion that the peak hip angle represents the postural component of the task. Apparently, first experience is an important factor in selection of postural strategy. As said in the introduction, the influence of experience has been shown before when switching from a long surface, where the ankle strategy is used, to a short surface, where the hip strategy is used (Horak and Nashner 1986). Difference between this study and ours is that the appropriate strategy was defined by the condition, whereas in our study both a hip and ankle strategy could be used in both conditions. Therefore, we could look at the influence of the first condition, while Horak and Nashner (1986) looked at the prior condition. The voluntary task goal could be achieved with either a hip or ankle strategy, so there was no need to change it. It appears that preference goes to recalling previous motor plans, because this may require less attention than generating a new plan. This finding is consistent with the computational model of motor planning developed by Rosenbaum et al. (2001), which proposes that goal postures are planned by a two-stage process of recall and generation (Rosenbaum et al. 2001). This hypothesis has been supported by experiments investigating grasp planning and other arm movement tasks (Cohen and Rosenbaum 2004; Cohen and Rosenbaum 2010; Jax and Rosenbaum 2009), but this study is the first to demonstrate the same principle in the context of postural responses.

Participants who started with LC had less difference between the LC and HC conditions in hip and shoulder flexion, than participants who started with HC. This interaction effect can be explained by the fast adaptation that is seen in the first block of the participants who start

with HC. This adaptation is slower or absent in the participants who start with LC. Interestingly, the participants who start with LC also do not show this behavior when they have their first HC block.

4.3. Postural and voluntary control mechanisms

If the postural responses and the voluntary task in the present study were controlled by a common underlying mechanism, one would suspect that the postural and voluntary kinematic strategies would be influenced in the same way by task constraint and first experience. This was not the case, since shoulder flexion was only affected by task constraint, and hip flexion was only affected by first experience. These results suggest separate control mechanisms, although not independent, shown by the higher magnitude of both the GAS and TA muscle activation bursts in the HC condition.

Although it seems logical to assume that postural and voluntary control mechanisms operate separately, the literature shows that it is not that straightforward. In fact, some researchers argue that “spinal reflexes” and “voluntary movement” cannot be separated from each other, since sensory information is continuously integrated with descending motor commands at the level of spinal interneurons (Nielsen 2004). Other evidence for a common underlying neural mechanism for control of postural responses and voluntary movements comes from clinical studies. Cerebellar patients, for example, show hypermetria in both voluntary tasks (Hore et al. 1991) and postural responses (Horak and Diener 1994). And Parkinson patients show anticipatory control deficits in both voluntary step initiation (Burleigh-Jacobs et al. 1997) and compensatory stepping as a response to a perturbation (King et al. 2010). The present study adds evidence to this debate, advocating for separate, but not independent, postural and voluntary control mechanisms.

4.4. Limitations and recommendations

This is the first study of the effect of a voluntary task on postural responses in older adults; the results may not apply directly to young adults. Older adults tend to have smaller and delayed postural responses, to be more reliant on hip strategy, and to have a limited ability to adapt their postural responses to various perturbation parameters compared to younger adults (Lin and Woollacott 2002; Tokuno et al. 2010). Also, the decrease in performance as a result of a cognitive task during a postural task appears to be more pronounced in older, compared to younger, adults (Woollacott and Shumway-Cook 2002; Redfern et al. 2002). Comparison with the study of de Lima et al. (2010), who studied young adults, is difficult because they used a different perturbation direction and let participants hold the tray with their arms locked in extension. Therefore, future studies with both young and older adults are needed to see the effect of aging on how voluntary task constraint influences postural responses.

Moreover, the effects of retention of postural strategies should be investigated further. Understanding the influence of the order in which a patient is given certain exercises could be of great importance for rehabilitation. For example, one can speculate that it is better to start balance training with more challenging tasks, instead of easy tasks, to encourage the development of appropriate strategies.

4.5. Conclusions

When the arms perform a stabilizing voluntary task simultaneous with a whole body postural task in response to perturbations, voluntary and postural mechanisms interact, and central set for postural responses adapts to the stability constraint of the voluntary task. Also, initial experience with a concurrent voluntary task is an important factor in selection of postural strategy, even when the constraint of the voluntary task is later removed. Postural

responses are thus influenced by both the stability constraint and the first experience of a voluntary task.

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a. Experimental setup **b. Tray displacement (cm)** **c. Tray velocity (cm/s)** **Fig. 1.**

Schematic representation of the experimental setup in the low constraint (LC) and high constraint (HC) conditions and the definitions of hip and shoulder angles. In the right picture (a) the subject is flexing the shoulders and hips forward to balance the tray. Small circles represent the kinematic markers. Horizontal arrows indicate the direction of the surface translation. Grand mean and standard error (shaded area) for LC and HC conditions of (b) tray displacement and (c) tray velocity in the sagittal plane. Dashed line represents the platform displacement and velocity, respectively. Arrows indicate forward direction.

Fig. 2.

(a) Muscle activity in the tibialis anterior (TA) and gastrocnemius (GAS) for subject 9, trials 11 (LC) and 4 (HC). Vertical dashed line represents onset of perturbation (0 s). (b) Mean (± 1 SE) percentage difference in TA and GAS iEMG (0–75 ms) between LC and HC conditions. (c) Mean (± 1 SE) of TA and GAS muscle onset latency in the LC and HC conditions. * denotes significant difference between conditions ($p < 0.05$).

Fig. 3. Grand mean and standard error (shaded area) for LC and HC conditions of **(a)** CoP and **(b)** CoM displacement in sagittal plane, **(c)** hip and **(d)** shoulder angle, and **(e)** platform movement.

Fig. 4.

Group average for all trials of **(a)** initial rate-of-change CoP, **(b)** peak hip flexion, **(c)** peak shoulder flexion, and **(d)** peak tray velocity. Groups are defined by their initial condition (LC or HC). Vertical dashed lines represent the start of a new block. Note the difference in hip flexion between groups and the difference in shoulder flexion and tray velocity between conditions..