Human Movement Science 64 (2019) 398–408

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Effects of vision and cognitive load on anticipatory and compensatory postural control

Zhi Zhang[a], Ying Gao[b], Jian Wang[b,c,*]

[a] Department of Investigation, Zhejiang Police College, China
[b] Education College, Zhejiang University, China
[c] Center for Psychological Sciences at Zhejiang University, Zhejiang University, China

ARTICLE INFO

Keywords:
Anticipatory postural adjustments
Compensatory postural adjustments
Sudden postural perturbation
Electromyography
Centre of pressure

ABSTRACT

This study assessed the effects of vision and cognitive load on anticipatory postural adjustments (APAs) and compensatory postural adjustments (CPAs) in response to an externally triggered postural perturbation. A ball-hitting test was repeated under different visual conditions (eyes open, EO; eyes closed, EC) and cognitive loads (no load, 3-subtraction task, time-limited 3-subtraction task). Data were collected separately for I) surface electromyography from the right side of the biceps brachii (BIC) and erector spinae (ES) to detect the latency and response intensity (RI); and II) displacement of the centre of pressure (ΔCOP) to detect the standard deviation (ΔCOP_{SD}) and maximum value (ΔCOP_{max}) in the anterior-posterior direction. Compared with the results under the EC condition, the ES latency was shorter and the RI of the BIC was lower under the EO condition. Accordingly, the ΔCOP_{SD} and ΔCOP_{max} were increased in the APAs phase and decreased in the CPAs phase. Cognitive load had no effect on APAs and CPAs or on ΔCOP in the APAs phase. However, ΔCOP_{max} was decreased in the CPAs phase during the EC condition. In conclusion, vision played an important role in APAs and CPAs for muscle activation and ΔCOP. Cognitive load had no effect on neuromuscular APAs or CPAs except when the postural perturbation occurred when visually unexpected.

1. Introduction

Sudden postural perturbations are a common issue during daily life. Delayed responses to these perturbations may disturb the body's postural stability, especially for elderly people and people with motor dysfunction, such as Parkinson's disease and stroke, increasing the risk of falling down (Hyodo et al., 2012; Hwang et al., 2008; Tagliabue et al., 2009). In such conditions, the central nervous system maintains the stability of the body's centre of gravity via two different neuromuscular control mechanisms: feed-forward mechanism and feedback mechanism (Shumway-Cook and Woollacott, 2009). Feed-forward is a top-down neuromuscular control pattern represented by anticipatory postural adjustments (APAs), in which the central nervous system pre-triggers muscle

Abbreviations: APAs, anticipatory postural adjustments; CPAs, compensatory postural adjustments; EMG, electromyography; COP, centre of pressure; EO, eyes open; EC, eyes closed; BIC, biceps brachii; ES, erector spinae; RI, response intensity; RI_{APAs}, response intensity during the anticipatory postural adjustments phase; RI_{CPAs}, response intensity during the compensatory postural adjustments phase; ΔCOP, displacement of the centre of pressure; ΔCOP_{SD}, standard deviation of displacement of the centre of pressure; ΔCOP_{max}, maximum value of displacement of the centre of pressure; ANOVA, analysis of variance

* Corresponding author at: Center for Psychological Sciences at Zhejiang University, Department of Physical Education of Education College, Zhejiang University, China, Xixi Campus, Zhejiang University, Tianmushan Road No. 148, Hangzhou, China.
E-mail address: pclabeeg@zju.edu.cn (J. Wang).

https://doi.org/10.1016/j.humov.2019.02.011
Received 16 August 2018; Received in revised form 1 February 2019; Accepted 19 February 2019
Available online 12 March 2019
0167-9457/

activity based on perceptive and cognitive information such as vision, hearing, proprioception, and motion intention to optimize the control of muscle activity (Latash, 2008). In contrast, feedback is a bottom-up reflex motor control pattern represented by compensatory postural adjustments (CPAs), which are produced by lower motor centres of the nervous system and are based on afferent impulses from proprioceptors on the muscles, fascia, and joints (Shumway-Cook and Woollacott, 2009). Both APAs and CPAs are strategies used by the central nervous system in response to a body perturbation. As a result, exploring posture stability and the APAs and CPAs of related muscles in response to sudden postural perturbations is the main paradigm of feed-forward and feedback studies, and these studies help to quantitatively evaluate postural control performance.

Many parameters affect the generation of APAs and CPAs, including the magnitude and direction of the postural perturbation (Eckerle, 2010; Allison et al., 2008), body posture (Aruin et al., 1998), expectation (Brown et al., 2003), age (Hwang et al., 2008), muscle fatigue (Mawston et al., 2007), and pathema (Pereira et al., 2014). However, more studies are needed on the effect of cognitive tasks on anticipatory and compensatory phases of postural control. The dual-task paradigm of cognition and postural control is the classical paradigm used to study the interaction between cognitive load and postural control performance (Zhang et al., 2013). Postural control consumes cognitive resources. There are multiple models that attempt to explain dual task interference, and numerous factors or research participants specific to the selected tasks (Saxena, Majnemer, Li, Beauchamp, & Gagnon, 2019). For example, Zhang et al. (2013) reported that when the information presented during a dual task exceeds the processing capability of the brain, the performance of the tasks can deteriorate (Zhang et al., 2013); this finding has been supported by additional studies (Jones et al., 2014; Rosso et al., 2017; Fortaleza et al., 2017; Mujdeci et al., 2016). Previous studies have examined the differences in postural sway and stability between conditions with and without cognitive tasks. The postural control tasks in these studies were mainly performed under conditions of a quiet stance rather than conditions of sudden postural perturbations (Deschamps et al., 2014; Shiravi et al., 2017; Richer et al., 2017; Polskaia et al., 2015; Memari et al., 2014). A few studies have reported surface electromyography (EMG) data from subjects with a fear of falling (Uemura et al., 2012) and multiple sclerosis (Jacobs and Kasser, 2012) while performing postural control and cognitive tasks simultaneously. The former study found that cognitive tasks significantly prolonged the APAs phase, and the latter study found that cognitive tasks significantly delayed the onset of APAs during gait initiation. The reason may be based on cognitive resource consumption due to the cognitive tasks and the greater degree of co-contraction of agonistic and antagonistic muscles. However, the perturbations in the dual-tasking studies mentioned above were mainly applied to the lower body instead of the upper body. The effects of cognitive tasks on neuromuscular APAs and CPAs under conditions of sudden arm loading are not clear.

Centre of pressure (COP) is another index that can be used to measure postural control in addition to EMG. It represents postural stability by measuring the shift of the centre of body pressure. Some studies have reported that cognitive load and visual expectation significantly affect COP during the stance phase (Albertsen et al., 2017; Bonnet and Baudry, 2016; Bustillo-Casero et al., 2017). Laessoe and Voigt (2008) investigated the postural control of elderly and young subjects on a moveable force plate. They found that both groups used APAs strategies to reduce the effects of the perturbation and had increased anticipatory COP displacement under dual-task conditions. However, they did not consider the function of visual expectation on performance under the dual-task condition. It is expected that vision plays an important role in the APAs and CPAs phases in response to sudden postural perturbations. Several studies with different paradigms found that when the perturbations were visually predictable, strong anticipatory activation was seen and the latencies were shortened in tested muscles (Hwang et al., 2008; Santos et al., 2010a, 2010b; Zhang and Wang, 2014). As a result, there is a need to study the role of vision in the interaction between cognitive and postural control tasks under a sudden arm-loading paradigm. In addition, understanding how the body manipulates responses to sudden postural perturbations and remains stable by adjusting the COP in the APAs and CPAs phases is of interest.

In this research, the paradigm of a ball-hitting test was used to examine the effects of vision and cognitive load on APAs and CPAs through muscle activation (Study I) and kinetic (Study II). The aim was to compare the effects of vision and different cognitive loads on neuromuscular feed-forward and feedback control in response to externally triggered postural perturbations. We hypothesized the following: the muscle latency would be shorter and the reaction time would be lower with vision; that COP would be increased in the APAs phase and decreased in the CPAs phase; and different levels of cognitive load would have different influences on APAs and CPAs.

2. Methods

2.1. Subjects

A total of 16 subjects (7 men and 9 women, age 25.9 ± 2.3 years, height 168.1 ± 6.2 cm, weight 57.4 ± 7.2 kg) participated in Study I. Of those subjects, 14 (6 men and 8 women, age 25.9 ± 2.3 years, height 167.9 ± 6.1 cm, weight 57.0 ± 7.0 kg) were also involved in Study II, and another two subjects of Study I dropped out for personal reasons. All the subjects were right-handed. They were free of mental and neuromuscular disorders, and their visual acuity was normal or corrected to normal. All participants provided informed consent before participating in any measurements. The research protocol was approved for human subjects.

2.2. Procedure

The experiment was conducted considering two factors: vision and cognitive load. There were two levels of the vision factor: eyes open (EO) and eyes closed (EC). There were three levels of the cognitive load factor: without load, load with a 3-subtraction task and load with a time-limited 3-subtraction task. In total, there were 6 experimental conditions. The order of conditions was random, and

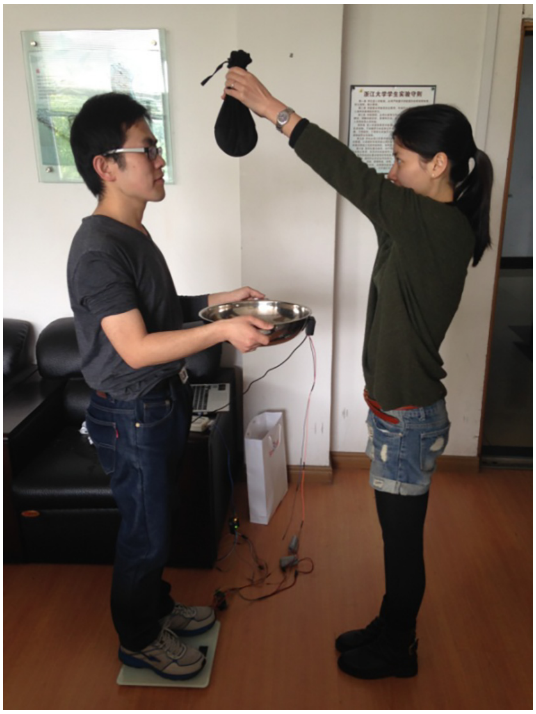

Fig. 1. The ball-hitting test.

each condition was repeated for three trials.

During the ball-hitting test, subjects were asked to wear their own shoes to maintain a stance with their feet placed at shoulder width and with both hands holding the handles of a pot with the upper arms vertical to the ground and the elbows flexed at 90°. The experimenter stood facing the subject and held a sandbag with two hands so that the bottom of the sandbag was at the same height as the subject's eyes; the experimenter then released the bag so that it dropped in the centre of the pot (Fig. 1). Subjects were asked to maintain the stability of their bodies and arms throughout the experiment.

Under the EO condition, the subjects could watch the sandbag fall into the pot, while under the EC condition, they wore earmuffs and closed their eyes. Under each condition, the subjects were asked to perform the ball-hitting test without performing cognitive tasks and while performing a 3-subtraction task as well as a time-limited 3-subtraction task in succession. For the 3-subtraction task, the subjects performed a 100-minus-3 operation consecutively and reported the results at their own pace. For the time-limited 3-subtraction task, the subjects did a 98-minus-3 operation consecutively and reported the results according to a given rate (40 beats/min) based on a metronome.

Prior to the start of data collection, the subjects were provided with two practice trials to familiarize themselves with the task of catching the sand bag released by the experimenter. During the measurements, the time interval between two trials in the EO condition was 15 s, while in the EC condition it was 20 to 30 s in order to prevent predicting the release time. In Study I, the subjects were asked to fill out a questionnaire after the experiment about the level of cognitive load.

When the data collection for study I was finished, the subjects rested for 2 h before participating in Study II. Similar experimental procedures were implemented in both studies, except that in Study II participants were asked to stand on the platform with their heels together and their toes 30° apart so that they could best maintain stability in response to the postural perturbation.

2.3. Apparatus and analysis

The ball-hitting test. The subjects were asked to hold a pot with two handles. The upper diameter of the pot was 32 cm, and the lower was 21 cm. The weight of the pot was 0.9 kg. A custom-made accelerometer (Zhejiang University, China) was attached to the bottom of the pot; its signal was used to record when the body was perturbed by the object being dropped into the pot. The sensor consisted of a buzzer and contact springs. Its response range was 0–105 dB, and the response latency was approximately 1 ms, which allowed for an accurate and timely report of the vibration of the pot. The dropped object was a sandbag weighing 1.5 kg.

In Study II, the subjects were asked to hold the pot and stand in the middle of a custom-made platform (Zhejiang University, China). The platform was repurposed from a weight scale; the length of each side was 18.5 cm, and the thickness was 2 cm. The platform was designed with four pressure sensors, one at each corner, which were connected to the pot as well as a computer (Fig. 1).

Surface electromyography (EMG). An ME6000 system (Mega Electronics Ltd., Finland) was used to record the EMG activity of the right side of the biceps brachii (BIC), which was the focal muscle, and lumbar erector spinae (ES), which was the postural muscle of the perturbation in Study I. The disposable ECG electrodes (Zhejiang Yiyang Medical Technology Co. Ltd.) were placed over the muscle bellies 1) midway between the axillary fold and the midpoint of the fossa cubit for the BIC and 2) appropriately 3 cm lateral from the L1 spinous process for the ES. The diameter of each electrode was 0.5 cm. The distance between the two electrodes of a pair was approximately 2 cm. EMG signals were bandpass filtered (10–500 Hz) prior to sampling at 1000 Hz. All EMG signals were rectified, viewed on a computer screen and aligned according to the first visible onset of a rise in the vibration signal. The alignment time was referred to as time zero ($T_0 = 0$). Then, the data were cut off 500 ms before T_0. Muscle latency was detected in a time window from −200 ms to + 200 ms in relation to T_0 by a combination of a computer algorithm and visual inspection of the averaged trials. The latency for a specific muscle was defined as the period of at least 15 ms when the EMG amplitude was greater (activation) or smaller (inhibition) than the mean of its baseline value, measured from −500 to −350 ms, plus 3 standard deviations (SDs). The time window from −200 to 50 ms was defined as the APAs phase, and the window from 50 to 200 ms was defined as the CPAs phase (Santos et al., 2010a). The response intensity of the EMG activity during the APAs phase (RI_{APA}) was defined as the ratio of the absolute intensity to the baseline value, the former of which was the averaged EMG amplitude of the tested muscles in the time window from the onset time to +50 ms. The response intensity of the EMG activity during the CPAs phase (RI_{CPAs}) was defined as the ratio of the absolute intensity to the baseline value, the former of which was the averaged EMG amplitude of the tested muscles in the time window from the onset time to +200 ms if the muscles were activated after 50 ms or from 50 to 200 ms if the muscles were activated before 50 ms. There was sufficient test–retest reliability for the three trials (intraclass correlation coefficient: 0.691, 95% confidence interval: 0.555–0.790) under the EO condition without load.

Displacement of the centre of pressure (ΔCOP). The custom-made pressure platform (Zhejiang University, China) was designed to record ΔCOP in Study II. The platform was square, with pressure sensors (YZC-161B, Guangce, China) placed at the four corners of the bottom. The collected value of pressure sensors was amplified by the amplifiers (INA-128, Texas Instruments, USA). The displacement of the COP in the anterior-posterior direction was calculated from the amplified values, by an open-source electronic prototyping platform (Arduino micro). The sampling frequency of the pressure sensors in the platform was 500 Hz. Taking the rear-left corner of the platform as the origin, the relative position of the COP in the anterior-posterior direction was defined as the ratio of the sum of the signals from the front two sensors relative to the signals from all four sensors, with values between 0 and 1. ΔCOP was the ratio multiplied by the distance between the anterior and posterior sensors, which referred to the position of the COP. The starting point of the postural perturbation ($T_0 = 0$) was defined as the time that the vibration sensor started to produce a signal and transmitted it to the platform. The time window from −150 to 100 ms was defined as the APAs phase, and the time window from 100 to 250 ms was defined as the CPAs phase (Santos et al., 2010b; Seidler et al., 2004; Gurfinkel et al, 2006). The baseline value of COP displacement was the mean value measured from −500 to −450 ms. The baseline value of the relevant trial was subtracted from the standard deviation of the position over time (ΔCOP_{SD}) and the peak anterior (or posterior) value of the ΔCOP (ΔCOP_{max}) in the APAs and CPAs phases of every trial in the experiment for standardization. Since the perturbation was induced in the sagittal plane and applied to both arms, it did not produce lateral or rotational postural perturbations. As a result, only the ΔCOP in the anterior-posterior direction was discussed. Sufficient test–retest reliability of three trials was found (intraclass correlation coefficient: 0.829, 95% confidence interval: 0.734–0.894) under the EO condition without load. Thus, the repeatability of our measures was considered acceptable. Xie and Wang used the same force platform to examine anticipatory and compensatory postural adjustments in response to perturbations with unknown magnitude and found that APAs and CPAs of lumbar muscles and displacements of the COP are affected by the knowledge of postural perturbations (Xie and Wang, 2018).

Questionnaire. The questionnaire consisted of three items about relative cognitive load associated with time, mental effort and stress (Zhang and Zhu, 1995). The question regarding load related to time was asked as “How did you feel about the cognitive load related to timing in the first/second tasks?” The question regarding load related to mental effort was asked as “How did you feel about the cognitive load related to mental effort in the first/second tasks?” The question regarding load related to stress was asked as “How did you feel about the cognitive load related to stress in the first/second tasks?” Each item was rated on a 0 to 4 scale, with higher scores indicating greater cognitive load. The sum of the scores for the three items was used to indicate the cognitive load of each task.

2.4. Statistical analysis

All three trials were recorded in each experimental condition. All results were analysed using SPSS 19.0 (IBM, USA). Data are presented as the mean ± SD. Data were averaged from the repeated trials for each condition. One-way analysis of variance (ANOVA) was used for the comparison among the scores from the questionnaire about different levels of cognitive load. Two-way ANOVA with two within-subjects factors (two conditions: EO, EC; three levels of cognitive load) were used to compare the muscular latencies and RI for each muscle, as well as to compare ΔCOP_{SD} and ΔCOP_{max} in the anterior-posterior direction in the APAs and CPAs phases. A post hoc analysis using the least significant difference was further used for the multiple comparisons within the three levels of cognitive load. In all tests, statistical significance was set at a two-tailed $p < 0.05$.

3. Results

3.1. The validity discriminating cognitive load levels

Table 1 shows the questionnaire scores regarding the cognitive load levels. The score was highest for the time-limited 3-subtraction condition and the lowest for the condition without a cognitive task ($F_{(2,45)} = 65.727$, $p < 0.001$). The difference between

Table 1
The scores from the questionnaire on the levels of cognitive load. * indicates a significant difference between the scores for without cognitive load vs. 3-subtraction (p < 0.001), without cognitive load vs. time-limited 3-subtraction (p < 0.001), and 3-subtraction vs. time-limited 3-subtraction (p < 0.001).

Cognitive load	Scores
Without cognitive load	0
3-Subtraction	3.38 ± 1.93*
Time-limited 3-subtraction	7.06 ± 2.32*

the two scores was statistically significant (p < 0.001).

3.2. The effects of vision and cognitive load on the latency of postural and focal muscles (Study I)

Fig. 2 shows the latency of the ES (a) and BIC (b) under the different conditions. For both muscles, the activation time was significantly earlier in the EO condition than in the EC condition (ES: $F_{(1,91)} = 16.430$, $p < 0.001$, $\eta^2 = 0.073$; BIC: $F_{(1,91)} = 77.562$, $p < 0.001$, $\eta^2 = 0.220$), while cognitive load had no significant influence on the latency (ES: $F_{(2,91)} = 1.186$, $p = 0.308$, $\eta^2 = 0.011$; BIC: $F_{(2,91)} = 1.476$, $p = 0.230$, $\eta^2 = 0.011$), and there was no significant interaction between the effects of vision and cognitive load (ES: $F_{(2,91)} = 0.346$, $p = 0.708$, $\eta^2 = 0.003$; BIC: $F_{(2,91)} = 1.021$, $p = 0.362$, $\eta^2 = 0.007$).

3.3. The effects of vision and cognitive load on the RI_{APAs} of postural and focal muscles (Study I)

Fig. 3 shows the RI_{APAs} of the ES (a) and BIC (b) under the different conditions. For the ES, there was no significant effect of vision ($F_{(1,91)} = 0.238$, $p = 0.626$, $\eta^2 = 0.001$) or cognitive load ($F_{(2,91)} = 1.675$, $p = 0.190$, $\eta^2 = 0.016$), and there was no interaction ($F_{(2,91)} = 0.317$, $p = 0.729$, $\eta^2 = 0.003$). For the BIC, the RI_{APAs} was significantly lower under the EO condition than under the EC

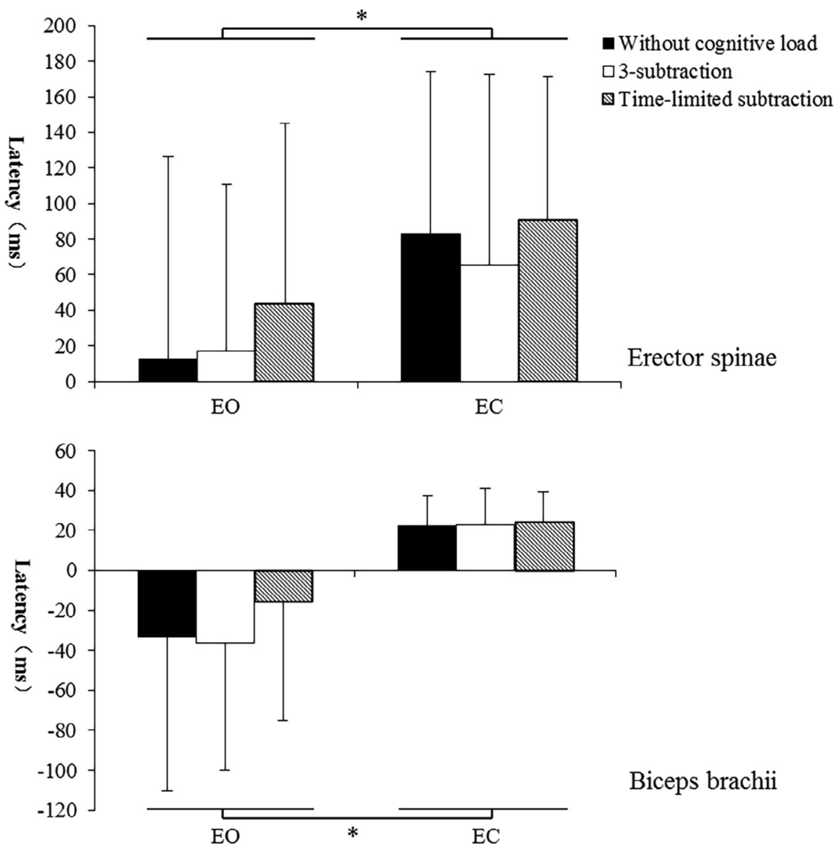

Fig. 2. Comparison of the latency of erector spinae and biceps brachii muscles under the different conditions. * indicates a significant difference between the latency in the EO and EC conditions for the ES and BIC. EO: eyes open, EC: eyes closed.

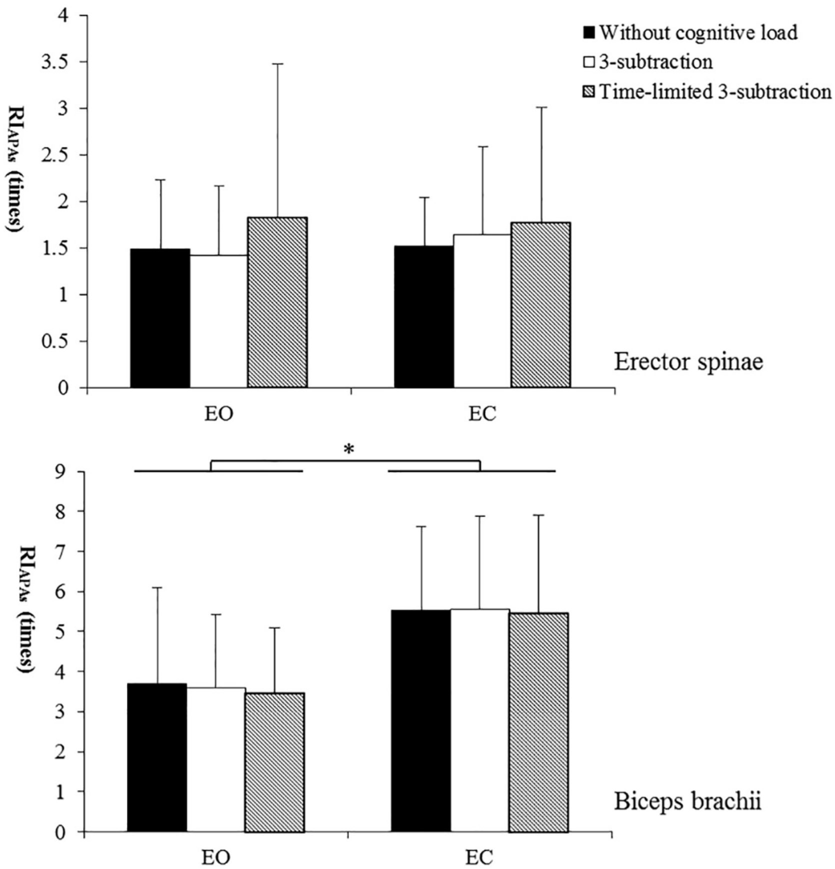

Fig. 3. Comparison of the RI_{APAs} of erector spinae and biceps brachii muscles under the different conditions. * indicates a significant difference between the RI_{APAs} in the EO and EC conditions for the ES and BIC. EO: eyes open, EC: eyes closed.

condition ($F_{(1,91)} = 56.627, p < 0.001, \eta^2 = 0.171$), while cognitive load had no significant influence on the RI_{APAs} ($F_{(2,91)} = 0.129$, $p = 0.879$, $\eta^2 = 0.001$), and there was no significant interaction between the effects of vision and cognitive load ($F_{(2,91)} = 0.037$, $p = 0.963$, $\eta^2 = 0.000$).

3.4. The effects of vision and cognitive load on the RI_{CPAs} of postural and focal muscles (Study I)

Fig. 4 shows the RI_{CPAs} of the ES (a) and BIC (b) under the different conditions. For the ES, there was no significant effect of vision ($F_{(1,91)} = 0.238$, $p = 0.626$, $\eta^2 = 0.001$) or cognitive load ($F_{(2,91)} = 1.675$, $p = 0.190$, $\eta^2 = 0.016$), and the interaction was not significant ($F_{(2,91)} = 0.317$, $p = 0.729$, $\eta^2 = 0.003$). For the BIC, RI_{CPAs} was significantly lower under the EO condition than under the EC condition ($F_{(1,91)} = 43.679$, $p < 0.001$, $\eta^2 = 0.137$), while cognitive load had no significant influence on the RI_{CPAs} ($F_{(2,91)} = 2.668$, $p = 0.071$, $\eta^2 = 0.019$). There was no significant interaction between the effects of vision and cognitive load ($F_{(2,91)} = 0.006$, $p = 0.994$, $\eta^2 = 0.000$).

3.5. The effects of vision and cognitive load on COP displacement in the APAs phase (Study II)

Fig. 5 shows the ΔCOP_{SD} (a) and ΔCOP_{max} (b) in the APAs phase under the different conditions. The ΔCOP_{SD} was significantly larger in the EO condition than in the EC condition ($F_{(1,79)} = 24.563, p < 0.001, \eta^2 = 0.091$), while cognitive load had no significant influence on the ΔCOP_{SD} ($F_{(2,79)} = 2.591$, $p = 0.077$, $\eta^2 = 0.021$), and there was no significant interaction between the effects of vision and cognitive load ($F_{(2,79)} = 1.798, p = 0.168, \eta^2 = 0.014$). The ΔCOP_{max} was significantly larger in the EO condition than in the EC condition ($F_{(1,79)} = 22.949$, $p < 0.001$, $\eta^2 = 0.085$), while cognitive load had no significant influence on the ΔCOP_{SD} ($F_{(2,79)} = 1.411$, $p = 0.246$, $\eta^2 = 0.011$), and there was no significant interaction between the effects of vision and cognitive load ($F_{(2,79)} = 0.156$, $p = 0.856$, $\eta^2 = 0.001$).

3.6. The effects of vision and cognitive load on COP displacement in the CPAs phase (Study II)

Fig. 6 shows the ΔCOP_{SD} (a) and ΔCOP_{max} (b) in the CPAs phase under the different experimental conditions. The ΔCOP_{SD} was

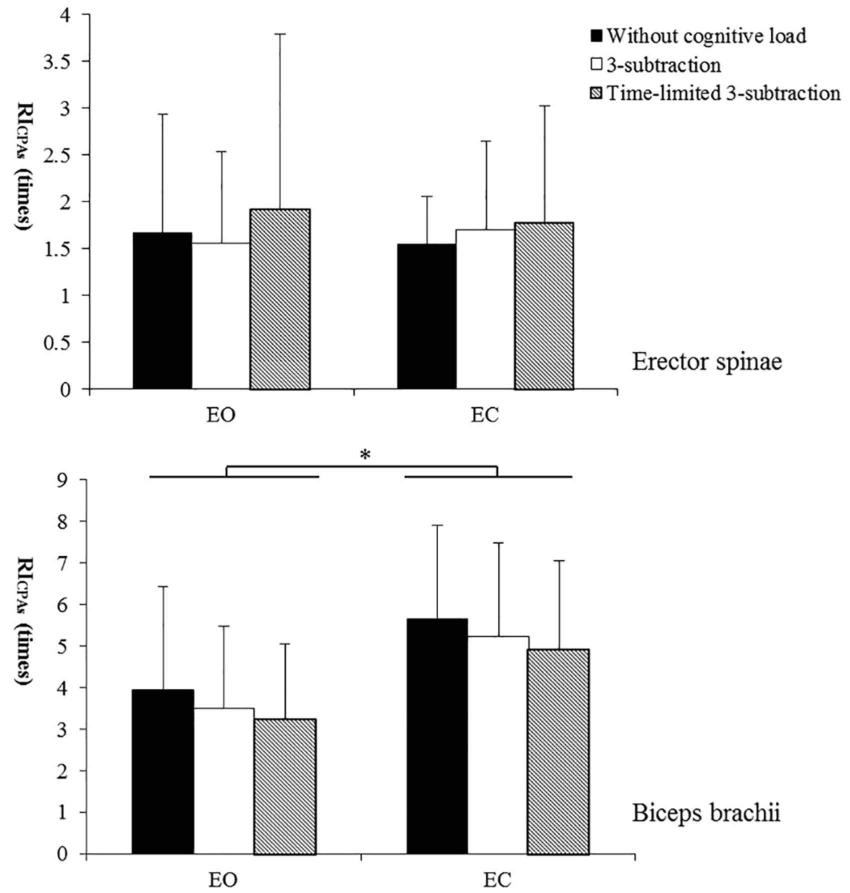

Fig. 4. Comparison of the RI_{CPAs} of erector spinae and biceps brachii muscles under the different conditions. * indicates a significant difference between the RI_{CPAs} in the EO and EC conditions for the ES and BIC. EO: eyes open, EC: eyes closed.

significantly larger in the EC condition than in EO condition ($F_{(1,79)} = 56.495$, $p < 0.001$, $\eta^2 = 0.187$), while cognitive load had no significant influence on the ΔCOP_{SD} ($F_{(2,79)} = 1.494$, $p = 0.227$, $\eta^2 = 0.012$), and there was no significant interaction between the effects of vision and cognitive load ($F_{(2,79)} = 2.097$, $p = 0.125$, $\eta^2 = 0.017$). The ΔCOP_{max} was significantly larger in the EC condition than in the EO condition ($F_{(1,79)} = 29.747$, $p < 0.000$, $\eta^2 = 0.108$), while the main effect of cognitive load was not significant ($F_{(2,79)} = 0.701$, $p = 0.497$, $\eta^2 = 0.006$). However, there was a significant interaction between the effects of vision and cognitive load ($F_{(2,79)} = 3.749$, $p = 0.025$, $\eta^2 = 0.030$), as shown by the fact that cognitive load had no significant influence on the ΔCOP_{SD} in the EO condition ($F_{(2,39)} = 0.848$, $p = 0.431$) but had a marginally significant main effect in the EC condition ($F_{(2,39)} = 3.001$, $p = 0.053$).

4. Discussion

Our research assessed the effects of vision and cognitive load on APAs and CPAs in response to an externally triggered perturbation. It seems that vision played an important part in APAs and CPAs for both muscle activation and COP displacement. Furthermore, we found that the latency and RI of postural and focal muscles in the APAs and CPAs phases were not significantly different under different levels of cognitive load. However, the cognitive load decreased the ΔCOPmax when subjects could not see, indicating that when the postural perturbation was not visually predictable, cognitive load promoted the recovery of body stability after the perturbation. Although these results did not totally support our hypothesis, they were consistent with the findings of Bohm's study, which reported that additional cognitive demand did not compromise predictive motor control during disturbed walking (Bohm et al., 2012).

As an open-loop system, anticipatory postural control involves an adaptive motor pattern that is primarily based on experience instead of real-time processing of sensory information input (Bastian, 2006). Taylor and Thoroughman (2007,2008) suggested that cognitive capacity affects the form of predictive motor control and real-time processing of sensory information input, but has no effect on the execution of predictive motor control. In our experiment, the subjects were aware that the perturbation would occur before the trials. As a result, the execution of anticipatory postural control was primarily involved. Cognitive load had no effect on the anticipatory postural control of postural and focal muscles, suggesting that the execution of anticipatory postural control may not

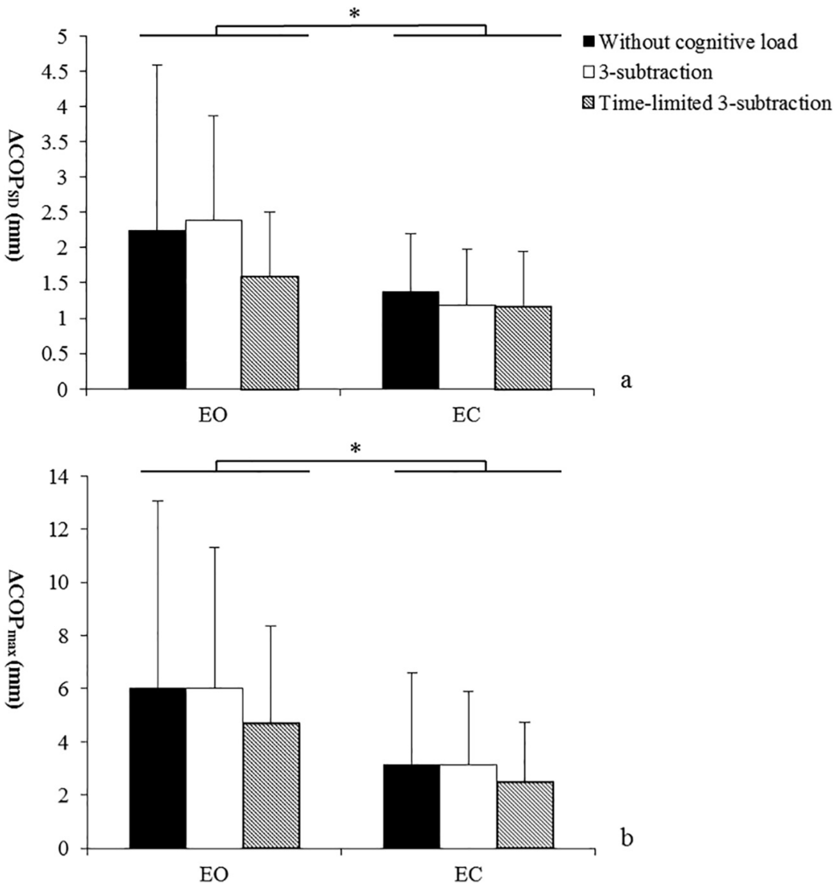

Fig. 5. Comparison of the ΔCOP_{SD} and ΔCOP_{max} in the APAs phase under the different conditions. * indicates a significant difference between the ΔCOP_{SD} and ΔCOP_{max} in the APAs phase in the EO and EC conditions. EO: eyes open, EC: eyes closed.

require cognitive resources or that the cognitive resources needed did not exceed subjects' cognitive capacity. In this study, participants were healthy young adults performing relatively simple cognitive and postural tasks. However, people can simultaneously perform cognitive tasks and cope with postural perturbations to maintain stability in daily life, which should be investigated to further confirm if cognitive load affects anticipatory and compensatory postural control.

Our results show that being able to see during the perturbation resulted in an earlier latency for both the ES and BIC but reduced the RI_{APAs} and RI_{CPAs} for only the BIC, which is partially consistent with the findings of previous studies (Hwang et al., 2008; Santos et al., 2010a, 2010b)). But Santos et al. did not mention the effect of vision on RI_{APAs}, which might be caused by the difference in postural perturbation. A lack of interaction between vision and cognitive load suggests that cognitive load does not affect APAs and CPAs regardless of whether the subject could see. This also suggests that the role of vision in APAs and CPAs did not diminish because of the decrease in available attentional resources caused by cognitive tasks. Given the findings of Zhang's study, which reported that the role of temporal cues in muscle latency is diminished without optical clues (Zhang and Wang, 2014), it seems that vision not only provides information to the brain about the characteristics of the target triggering the postural perturbation and the time of the perturbation but also enables a predictive response to the perturbation through unconscious neuromuscular pre-activation and appropriate activation. These inferences are consistent with the dual-path theory of vision. The ventral stream provides information on the features of objects such as the size and shape to produce a conscious, perceptual experience, while the dorsal stream provides spatial information and guides unconscious goal-directed actions (Magill, 2006).

Previous studies reported COP indices within APAs and CPAs phases during body perturbation, but they did not further explore the effects on vision and cognitive load (Shiravi et al., 2017; Polskaia et al., 2015). In this experiment, we examined the effects of vision and cognitive load on COP displacement in the APAs and CPAs phases and found that vision expectation significantly increased the ΔCOP_{SD} and ΔCOP_{max} in the APAs phase and decreased these values in the CPAs phase. Cognitive load had no significant effect on COP displacement in the APAs phase, while it decreased the ΔCOP_{max} to a certain extent in the CPAs phase, and this effect only occurred when the subjects were visually unprepared.

When experiencing a sudden postural perturbation, the central nervous system uses APAs when possible to keep balance, so that CPAs can be reduced after the perturbation (Santos et al., 2010a). Our experiment found that when the postural perturbation was visually expected, the ΔCOP_{SD} and ΔCOP_{max} increased before the perturbation and decreased after it. These results suggest that when

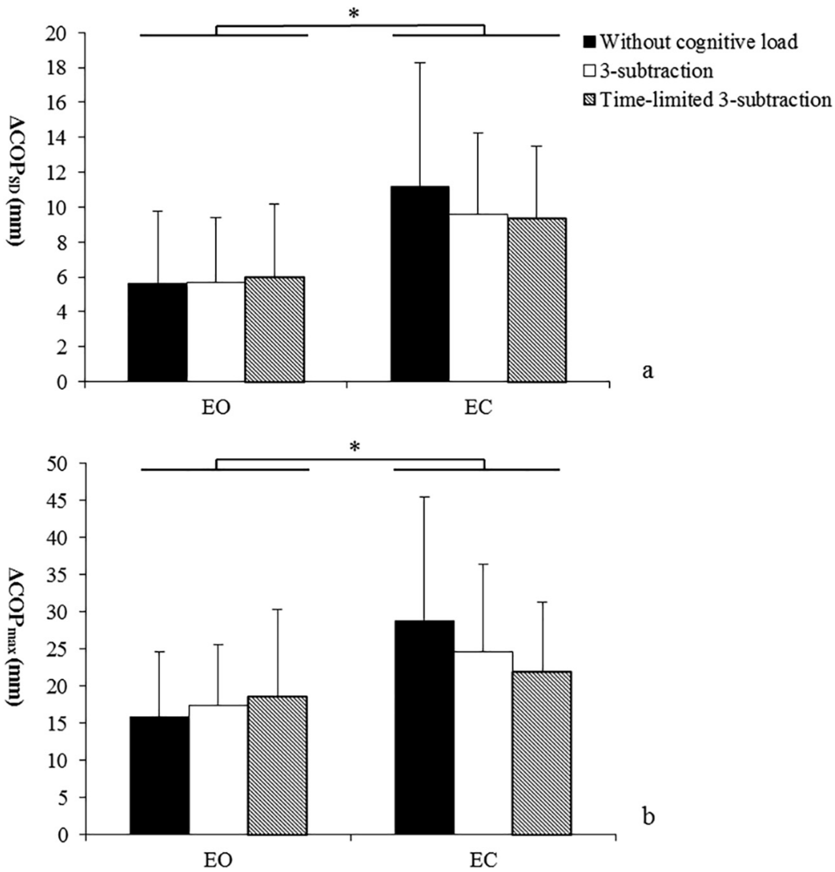

Fig. 6. Comparison of the ΔCOP_{SD} and ΔCOP_{max} in the CPAs phase under the different conditions. * indicates a significant difference between the ΔCOP_{SD} and ΔCOP_{max} in the CPAs phase in the EO and EC conditions. EO: eyes open, EC: eyes closed.

key information about a postural perturbation is known, people can reduce its detrimental effect on postural stability through increased body sway in advance; otherwise, the change in COP displacement would be smaller in the APAs phase and larger in the CPAs phase. These findings are in line with the studies of Santos et al. (2010a, 2010b). They investigated COP displacement in the APAs and CPAs phases in a pendulum paradigm that induced external perturbations and found that when the postural perturbation was visually predictable, COP displacement changed in advance of the perturbation. However, when the perturbation was unpredictable, COP displacement was not significantly changed in the APAs phase but showed a larger change in the CPAs phase (Santos et al., 2010a; Santos et al., 2010b). Laessoe et al. (2008) also found advanced COP displacement reduced postural perturbations.

Cognitive tasks are thought to affect postural control through the effects of attentional resource sharing. Our experiment found that when the postural perturbation was visually predictable, cognitive load had no significant effect on COP displacement in either the APAs or CPAs phase. This result is not in agreement with the results of Laessoe's study (2008), which found increased COP displacement in the APAs phase under dual-task conditions, but the results of this previous study are consistent with the findings of experiment 1 in our study. It is noteworthy that there was a significant interaction between the effects of vision and cognitive load on ΔCOP_{max} in the CPAs phase. It seems that in the CPA phase, although cognitive load had no significant effect on COP displacement when visual prediction was possible, cognitive load could decrease the ΔCOP_{max} in the absence of vision. The results suggest that when the postural perturbation was not visually predictable, more attentional resources were involved in processing the cognitive load so that postural control was more automatic. As a result, subjects could maintain body stability through the use of smaller CPAs when experiencing a sudden postural perturbation.

It should be noted that there were several limitations in current study. Due to the limited space of the custom-made apparatus, the EMG and COP data were not able to measure simultaneously. As a result, the current study was separated into two studies. Study I assessed the effects of cognitive load and vision on the APAs and CPAs of postural and focal muscles, while Study II assessed the effects of these same factors on COP displacement in the APAs and CPAs phases. Secondly, it was limited for the data records and analysis. In lines with previous studies for the definitions of the APAs and CPAs phases (Santos et al., 2010a; Santos et al., 2010b), we used different time windows in Study I and Study II. Thus, it may not be able to provide comparable results within subjects between studies. Future studies should improve the apparatus to measure the EMG and COP simultaneously and consider to use the same time window. Elderly people and people with motor dysfunction such as Parkinson's disease and stroke constantly have to cope with dual-task problems. Our study found that vision and cognitive load facilitated anticipatory and compensatory postural control to some extent, but how these results fit with the findings of the previous studies mentioned above is not yet clear. Further studies should focus on the effects of vision and cognitive load on APAs and CPAs in elderly people and in people with motor dysfunction to provide a theoretical basis for individualized prevention of and protection from accidents related to postural control.

5. Conclusion

This research assessed the effects of vision and cognitive load on APAs and CPAs in response to an externally triggered postural perturbation, and the conclusions were as follows:

(1). Vision played an important part in APAs and CPAs for both muscle activation and COP displacement.
(2). Cognitive load had no effects on neuromuscular anticipatory or compensatory postural control and did not affect COP displacement in the APAs or CPAs phase when the postural perturbation was visually predictable.
(3). Cognitive load decreased the ΔCOP_{max} when subjects were visually unexpected. This finding indicated that when the postural perturbation was unexpected, cognitive load promoted the recovery of body stability after the perturbation.

The authors declare that they have no conflict of interest.

Authors' contributions

ZZ, YG and JW: conception and design of the study; ZZ: acquisition of the data; ZZ and JW: analysis and interpretation of the data; ZZ and YG: drafting the article; ZZ, YG and JW: critically revising the article for important intellectual content. All authors gave final approval of the version to be submitted.

Acknowledgements

The work was supported by the National Natural Science Foundation of China (Grant No. 31671239) and the National Key Research and Development Program of China (No. 2018YFF0300502).

Conflicts of interest

The authors have no conflicts of interest to report.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.02.011.

References

Albertsen, I. M., Ghédira, M., Gracies, J. M., & Hutin, É. (2017). Postural stability in young healthy subjects – Impact of reduced base of support, visual deprivation, dual tasking. *Journal of Electromyography and Kinesiology, 33*, 27–33.
Allison, G. T., Morris, S. L., & Lay, B. (2008). Feedforward responses of transversus abdominis are directionally specific and act asymmetrically: implications for core stability theories. *Journal of Orthopaedic and Sports Physical Therapy, 38*(5), 228–237.
Aruin, A. S., Forrest, W. R., & Latash, M. L. (1998). Anticipatory postural adjustments in conditions of postural instability. *Electroencephalography and Clinical Neurophysiology/Electromyography and MotorControl, 109*(4), 350–359.
Bastian, A. J. (2006). Learning to predict the future: the cerebellum adapts feedforward movement control. *Current Opinion in Neurobiology, 16*(6), 645–649.
Bohm, S., Mersmann, F., Bierbaum, S., Dietrich, R., & Arampatzis, A. (2012). Cognitive demand and predictive adaptational responses in dynamic stability control. *Journal of Biomechanics, 45*(14), 2330–2336.
Bonnet, C. T., & Baudry, S. (2016). Active vision task and postural control in healthy, young adults: Synergy and probably not duality. *Gait & Posture, 48*, 57–63.
Brown, S. H. M., Haumann, M. L., & Potvin, J. R. (2003). The responses of leg and trunk muscles to sudden unloading of the hands: implications for balance and spine stability. *Clinical Biomechanics, 18*(9), 812–820.
Bustillo-Casero, P., Villarrasa-Sapiña, I., & García-Massó, X. (2017). Effects of dual task difficulty in motor and cognitive performance: Differences between adults and adolescents. *Human Movement Science, 55*, 8–17.
Deschamps, T., Beauchet, O., Annweiler, C., Cornu, C., & Mignardot, J. (2014). Postural control and cognitive decline in older adults: Position versus velocity implicit motor strategy. *Gait & Posture, 39*(1), 628–630.
Eckerle, J. J. (2010). *The effect of uncertainty about ball weight on anticipatory muscle activity in a one-handed catching task.* The United States of America: Miami University.
Fortaleza, A. C., Mancini, M., Carlson-Kuhta, P., King, L. A., Nutt, J. G., Chagas, E. F., ... Horak, F. B. (2017). Dual task interference on postural sway, postural transitions and gait in people with Parkinson's disease and freezing of gait. *Gait & Posture, 56*, 76–81.
Gurfinkel, V., Cacciatore, T. W., Cordo, P., Horak, F., Nutt, J., & Skoss, R. (2006). Postural muscle tone in the body axis of healthy humans. *Journal of Neurophysiology, 96*(5), 2678–2687.
Hwang, J. H., Lee, Y., Park, D. S., & Kwon, T. (2008). Age affects the latency of the erector spinae response to sudden loading. *Clinical Biomechanics, 23*, 23–29.
Hyodo, M., Saito, M., Ushiba, J., Tomita, Y., Minami, M., & Masakado, Y. (2012). Anticipatory postural adjustments contribute to age-related changes in compensatory steps associated with unilateral perturbations. *Gait & Posture, 36*, 625–630.
Jacobs, J. V., & Kasser, S. L. (2012). Effects of dual tasking on the postural performance of people with and without multiple sclerosis: a pilot study. *Journal of Neurology, 259*(6), 1166–1176.
Jones, P., Sorinola, I., & Strutton, P. H. (2014). Effect of dual tasking on postural responses to rapid lower limb movement while seated on an exercise ball. *Gait & Posture, 40*(2), 297–304.

Laessoe, U., & Voigt, M. (2008). Anticipatory postural control strategies related to predictive perturbations. *Gait & Posture, 28*, 62–68.

Latash, M. L. (2008). *Neurophysiological Basis of Movement* (2nd ed.). Champaign: Human Kinetics.

Magill, R. A. (2006). *Motor Learning and Control* (7th ed.). Beijing: China Light Industry Press.

Mawston, G. A., McNair, P. J., & Boocock, M. G. (2007). The effects of prior warning and lifting-induced fatigue on trunk muscle and postural responses to sudden loading during manual handling. *Ergonomics, 50*(12), 2157–2170.

Memari, A. H., Ghanouni, P., Shayestehfar, M., Ziaee, V., & Moshayedi, P. (2014). Effects of visual search vs. auditory tasks on postural control in children with autism spectrum disorder. *Gait & Posture, 39*(1), 229–234.

Mujdeci, B., Turkyilmaz, D., Yagcioglu, S., & Aksoy, S. (2016). The effects of concurrent cognitive tasks on postural sway in healthy subjects. *Brazilian Journal of Otorhinolaryngology, 82*(1), 3–10.

Pereira, S., Silva, C. C., Ferreira, S., Silvaa, C., Oliveiraa, N., Santosa, R., ... Correiad, M. V. (2014). Anticipatory postural adjustments during sitting reach movement in post-stroke subjects. *Journal of Electromyography and Kinesiology, 24*(1), 165–171.

Polskaia, N., Richer, N., Dionne, E., & Lajoie, Y. (2015). Continuous cognitive task promotes greater postural stability than an internal or external focus of attention. *Gait & Posture, 41*(2), 454–458.

Richer, N., Saunders, D., Polskaia, N., & Lajoie, Y. (2017). The effects of attentional focus and cognitive tasks on postural sway may be the result of automaticity. *Gait & Posture, 54*, 45–49.

Rosso, A. L., Cenciarini, M., Sparto, P. J., Loughlin, P. J., Furman, J. M., & Huppert, T. J. (2017). Neuroimaging of an attention demanding dual-task during dynamic postural control. *Gait & Posture, 57*, 193–198.

Santos, M. J., Kanekar, N., & Aruin, A. S. (2010a). The role of anticipatory postural adjustments in compensatory control of posture: 1.Electromyographic analysis. *Journal of Electromyography and Kinesiology, 20*(3), 388–397.

Santos, M. J., Kanekar, N., & Aruin, A. S. (2010b). The role of anticipatory postural adjustments in compensatory control of posture: 2. Biomechanical analysis. *Journal of Electromyography and Kinesiology, 20*(3), 398–405.

Saxena, S., Majnemer, A., Li, K., Beauchamp, M., & Gagnon, I. (2019). A cross-sectional analysis on the effects of age on dual tasking in typically developing children. *Psychological Research, 83*(1), 104–115.

Seidler, R. D., Noll, D. C., & Thiers, G. (2004). Feedforward and feedback processes in motor control. *Neuroimage, 22*(4), 1775–1783.

Shiravi, Z., Moghadam, S. T., Hadian, M. R., & Olyaei, G. (2017). Effect of cognitive task on postural control of the patients with chronic ankle instability during single and double leg standing. *Journal of Bodywork and Movement Therapies, 21*(1), 58–62.

Shumway-Cook, A., & Woollacott, M. (2009). *Motor control: Translating research into clinical practice* (3rd ed.). Beijing: People' Medical Publishing House.

Tagliabue, M., Ferrigno, G., & Horak, F. (2009). Effects of parkinson's disease on proprioceptive control of posture and reaching while standing. *Neuroscience, 158*, 1206–1214.

Taylor, J. A., & Thoroughman, K. A. (2007). Divided attention impairs human motor adaptation but not feedback control. *Journal of Neurophysiology, 98*(1), 317–326.

Taylor, J. A., & Thoroughman, K. A. (2008). Motor adaptation scaled by the difficulty of a secondary cognitive task. *PLoS One, 3*(6) e2485.

Uemura, K., Yamada, M., Nagai, K., Tanakac, B., Morib, S., & Ichihashi, N. (2012). Fear of falling is associated with prolonged anticipatory postural adjustment during gait initiation under dual-task conditions in older adults. *Gait & Posture, 35*(2), 282–286.

Xie, L., & Wang, J. (2018). Anticipatory and compensatory postural adjustments in response to loading perturbation of unknown magnitude. *Experimental Brain Research*.

Zhang, Z., & Wang, J. (2014). Effects of perceptual clues on the subconscious neuromuscular feed-forward and feedback control. *Acta Psychologica Sinica, 46*(1), 50–57.

Zhang, Z., Wang, J., & Feng, J. S. (2013). A Neuropsychology review of cognition and postural control. *Space Medicine & Medical Engineering, 26*(4), 333–337.

Zhang, Z. J., & Zhu, Z. X. (1995). Experimental research on multidimensional subjective assessment of psychological load. *Chinese Journal of Ergonomics, 1*(2), 4–7.