RESEARCH ARTICLE

Anticipatory and compensatory postural adjustments in response to loading perturbation of unknown magnitude

Lin Xie[1,2] · Jian Wang[3,4]

Abstract

In response to sudden postural perturbations, the posture control system uses anticipatory and compensatory postural adjustments (APAs and CPAs) to maintain balance and equilibrium. APAs strengthen as the perturbation magnitude increases, while CPAs remain constant because APAs make the necessary adjustments. However, the magnitude of a postural perturbation cannot always be fully known. This research focused on postural adjustments in response to perturbations with unknown magnitude. Participants caught falling sandbags of three weights on a tray held in their hands. Participants were told about the weight used for the upcoming trial in the KNOWN condition and not told in the UNKNOWN condition. Surface electromyography (sEMG) of the lumbar muscles and displacement of the center of pressure (COP) were recorded synchronously. The results showed that APAs and CPAs were stronger in the UNKNOWN condition than in the KNOWN condition. Meanwhile, in the UNKNOWN condition, the activity of the lumbar muscles and displacements of the COP showed no difference between weight levels. The lumbar erector spinae (LES) and lumbar multifidus (LMF) activated earlier in the UNKNOWN condition than for the heaviest weight in the KNOWN condition. The outcome of this study indicates that APAs and CPAs of lumbar muscles and displacements of the COP are affected by the knowledge of postural perturbations. The central nervous system (CNS) coped with load perturbations of unknown magnitude with redundancy response strategy, based on the maximum assumption of perturbation magnitude.

Keywords Posture control · Sudden postural perturbation · Anticipatory postural adjustments · Compensatory postural adjustments · Redundancy response strategy

Introduction

Postural perturbation disturbs the body posture from equilibrium and destabilizes the body by accelerating its center of mass (COM) (Horak et al. 1997). The central nervous system (CNS) detects and predicts stability-disturbing forces and generates appropriate muscular contractions to counteract postural perturbations. This ongoing process keeps the COM well controlled and maintains balance. Researchers have found that postural muscles activate in advance of the muscles related to the perturbations when perturbations are triggered by self-movement (Shumway-Cook and Woollacott 2007). Furthermore, other researchers found that postural muscles were pre-activated when predictable perturbations were triggered by others (Wilder et al. 1996; Hwang et al. 2008; Santos et al. 2010; Krishnan et al. 2012c). These advance activities of postural muscles are referred to as anticipatory postural adjustments (APAs) and are based on the knowledge of disturbance or movement intention (Shumway-Cook and Woollacott 2007; Eriksson Crommert and Thorstensson 2009). Meanwhile, the reflexive adjustments made by muscles in response to perturbations are referred to as compensatory postural adjustments (CPAs) (Horak 2006; Magill 2006).

The organization of APAs and CPAs can be affected by many factors, including the magnitude, velocity and orientation of perturbation (Horak et al. 1984; Aruin and Latash

✉ Jian Wang
  pclabeeg@zju.edu.cn

1 Department of Psychology and Behavioral Sciences, Zhejiang University, Hangzhou 310028, China

2 Institute of Health and Sports Science and Medicine, Juntendo University, Inzai 270-1695, Japan

3 Institute of Sports Science and Technology, Zhejiang University, Hangzhou 310028, China

4 Center for Psychological Sciences, Zhejiang University, Hangzhou 310028, China

1995, 1996); the stability and area of the support surface and the mental state of the individual (Gantchev and Dimitrova 1996; Aruin et al. 1998; Adkin et al. 2002); age (Riach and Hayes 1990; Hay and Redon 1999; Harwood 2001; Hwang et al. 2008); and some pathological factors (Latash et al. 1995; Aruin et al. 1996; Radebold et al. 2000). The effect of perturbation magnitude is commonly used to study in APAs and CPAs. Previous studies showed that in the ball-catching test, the APAs of muscles intensified as the increased height or weight of the falling ball magnified the impulse level of the perturbation (Lacquaniti and Maioli 1989a, b; Shiratori and Latash 2001). In our previous study, we also found that postural muscles activated earlier and more strongly when the expected magnitude of perturbation was greater, whether the perturbation was triggered internally or externally (Xie et al. 2014).

Accurate estimate of the magnitude of perturbation is important for adequate preparation of postural control. In daily life, however, the magnitude of a postural perturbation cannot always be fully predicted. Former study demonstrated that overestimating the magnitude of loading in a lifting task lead to increased balance loss and mechanical load on the lumbar muscles (Aruin and Rao 2018; Chen et al. 2018). While underestimating the magnitude of loading appeared not lead to these risks (Reschke et al. 2017; Curuk et al. 2018). It seems that the optimal postural control strategies are organized based on the assumption of the minimum magnitude of perturbation, for safety purpose. But the sudden, unpredictable loading still appears to be a major risk factor for low-back pain (Paloski et al. 2008). Some studies had investigate the posture control strategies in conditions of unstable loads (Lee et al. 2018b), loads with unexpected lateral mass (Lee et al. 2018a), and unknown perturbation magnitude. There were some disputes in the studies in condition of unknown perturbation magnitude. A finger-grip test showed that the muscle response under unknown perturbation magnitude conditions appeared to depend on the magnitude of the strongest expected interference to ensure the completion of the catching task (Kazennikov and Lipshits 2010). By contrast, the unilateral ball-catching test showed that the response of the arm muscles under unknown magnitude conditions was organized on the assumption of moderate perturbation magnitude (Eckerle et al. 2012; Aruin et al. 2017). These two studies also explored the response of erector spinae during the ball-catching task, and Berg and Hughes' (2017) study showed that participants organized greater activation of this muscle when the ball weight was unknown than when it was known. While the superficial back muscle, erector spinae, are important for producing movement and counterbalancing to postural perturbations, the intersegmental spinal muscle, multifidus, also plays a crucial role in maintaining stability of this region (Panjabi et al. 1989). To further study on the effect of a

sudden postural perturbation on the spinal stability, the present study investigated the lumbar multifidus, besides the erector spinae. Meanwhile, the present study also intended to examine the stability of the whole body during postural perturbation of unknown magnitude.

To explore the postural control strategy organized by the CNS in the condition of incomplete information, the present study investigated the APAs and CPAs of lumbar muscles and displacements of the COP in response to unknown perturbation magnitude, using the paradigm of catching a falling sandbag bilaterally. Based on the previous studies of arms and fingers, we hypothesized that the CNS would not respond to uncertain perturbations using speculative strategies. In addition, we hypothesized that the CNS, to ensure the completion of the posture task, would respond to the uncertain perturbations based on the maximum assumption of perturbation magnitude.

Method

Participants

Twenty-two participants (20 males, two females) were included in this study after giving informed consent. The subjects had a mean age of 20.59 (± 6.18) years, a mean height of 172.45 (± 7.86) cm, and a mean body mass of 65.27 (± 8.01) kg. All participants were right-handers. They were in good health, with no neurological diseases or musculoskeletal disorders, and they were fully familiarized with the procedure before the test and signed an informed consent approved by the university's Institutional Review Board.

Procedure

A sandbag-catching task was studied. The participants were instructed to maintain an upright stance while standing on the force platform with their feet shoulder width apart. They were instructed to keep their elbows bent 90° and their forearms horizontal while holding a metal tray in their hands. One sandbag was held by the experimenter above the tray at the subjects' eye level, aligning to the center mark in the tray. After a sound signal, the sandbag was released and freely fell into the tray. During this process, participants were asked to gaze at the sandbag and to maintain the stability of their body and the tray. A vibration sensor was positioned on the bottom of the tray to detect the time point when the sandbag landed.

Based on pilot experiments in which participants were surveyed about their tolerance to the weight of falling sandbags, three sandbag weights were selected: 1, 1.5 and 2 kg. The sandbags were the same size and visually indistinguishable. Two conditions were used during the sandbag-catching

test: (1) KNOWN—participants were told the weight of the sandbag before each trial; (2) UNKNOWN—participants were not told the weight of the sandbag for any of the trials. Before the formal test, the participants repeatedly practiced until they were fully familiar with the testing process and the weights of the sandbags. Then, in the formal test, three trials were performed for each weight and condition. The order of experimental conditions was randomized for each participant. Thus, 18 trials were performed with each participant. For safety purposes, the participants wore a harness and had sufficient rest between trials.

Instrumentation

The electromyographic activity of the lumbar erector spinae (LES) (L4~L5) and the lumbar multifidus (LMF) (L5~S1) on the right side was recorded with an ME6000 electromyograph (Mega Electronics Ltd., Finland). After the skin of the target area was prepared with fine sandpaper and a cotton ball soaked with 75% alcohol to reduce the impedance, silver chloride electrodes were attached over the bellies of the lumbar muscles. The electrodes were aligned with the long axis of the muscle being measured. The electrodes were 0.5 cm in diameter, with a separation distance of 2 cm, and the reference electrode was placed 3 cm away from the probe electrode. The sampling frequency of the surface electromyography (sEMG) signal is 1000 Hz, with input impedance of less than 10 GΩ, a 10–500 Hz bandpass filter, and a noise level of less than 3.5 μV.

Displacements of the COP (center of pressure) were collected by a self-designed force platform. This 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 axis was calculated from the amplified values, by an open-source electronic prototyping platform (Arduino micro). The sampling frequency was 500 Hz. The calculation formula is as follows:

$$d(y) = \left(\frac{f1 + f2}{f1 + f2 + f3 + f4} \right) \times l.$$

In the formula, $d(y)$ refers to the displacement of COP in anterior–posterior axis, while $f1$ (the upper left corner), $f2$ (the upper right corner), $f3$ (the lower left corner), $f4$ (the lower right corner) referring to the force value and l referring to the distance between force sensors.

Data processing

The data were analyzed off-line using C++ programs (Visual Studio 2008, Microsoft Corporation, USA). The initial time of perturbation was determined by the initial signal of the tray vibration sensor and was referred to as time zero (T0). Trials within each condition were averaged for each subject. The average value and standard deviation of the EMG signals from − 500 to − 450 ms were calculated as a baseline. Then, the activation time was detected in a time window from − 250 to 250 ms in relation to T0 by a combination of a computer algorithm and visual inspection of the averaged trials. In the computer algorithm, the activation time for a specific muscle was defined as the first instant when its EMG amplitude has been greater (activation) or smaller (inhibition) than the mean of its baseline value by 2 SD for at least 50 ms continuously (Santos et al. 2010). If the activation time was earlier than 50 ms in relation to T0, then it was defined as a pre-activation time.

Integrals of the EMG activity (IEMGs) during tasks were calculated for two epochs: the APA period and the CPA period. The APA period lasts from − 100 to 50 ms in relation to T0, and the CPA period lasts from 50 to 200 ms (Shiratori and Latash 2001; Santos et al. 2010). The IEMGs were normalized to the baseline activity from − 500 to − 450 ms in relation to T0. The formula for calculation is as follows:

$$\text{IEMG(ratio)} = \frac{a - 3b}{3b}.$$

In the formula, "a" refers to the IEMG from − 100 to 50 ms for the APAs or the IEMG from 50 to 200 ms for the CPAs. "b" refers the IEMG from − 500 to − 450 ms. The LMF data of 3 participants contained anomalies or were too weak to be detected; therefore, in the LMF analysis, only 19 participants were included.

Displacements of the COP along the anterior–posterior axis were calculated. The initial time of perturbation (T0) was also confirmed by the initial signal of the tray vibration sensor. The average value and standard deviation of the COP displacements from − 500 to − 450 ms were calculated as a baseline. The COP displacement at T0 was defined as the COP for APAs (A-COP), and the peak displacement as the COP for CPAs (C-COP) (Latash et al. 1995; Mohapatra et al. 2012). The time from T0 to C-COP (peak time, PT) was also recorded. All the COP displacements were normalized to the baseline, and a negative value indicates leaning back, while a positive value indicates leaning forward if the COP was displaced outside the boundary of the force table, the data were deemed abnormal and eliminated. Therefore, in the COP displacement analysis, only 18 participants were included.

Statistics

Each quantity is reported as the mean and standard deviation, and the statistical analysis was performed in SPSS 18.0 (SPSS Inc., USA). Repeated-measures multiple ANOVA with two within-subjects factors (two conditions – KNOWN/

UNKNOWN; three weight levels—1 kg/1.5 kg/2 kg) were used to compare the pre-activation time, $IEMG_{APAs}$ and $IEMG_{CPAs}$ for each muscle, as well as the displacements of the COP during APAs and CPAs. A simple effect analysis was performed for further comparisons between the weight levels to analyze any significant main effects of load weight levels. When there was a significant main effect of KNOWN/UNKNOWN condition, to further investigate on which assumption did the CNS organize the postural control in the known condition, the pairwise t test was used to compare between muscle reaction between known/unknown condition. Statistical significance was set at $p < 0.05$, and only those results that were significant were reported here.

Results

sEMG of lumbar muscles

Activation time

The means and SDs for the activation time of the LES and LMF are presented in Fig. 1a, b. There was a significant main effect of KNOWN/UNKNOWN condition for both LES ($F_{(1,21)} = 62.65$, p < 0.001) and LMF ($F_{(1,18)} = 54.85$, $p < 0.001$), as well as a significant effect of weight levels for both the LES ($F_{(2,42)} = 9.83$, $p < 0.001$) and the LMF ($F_{(2,36)} = 11.40$, $p < 0.001$). An interaction between KNOWN/UNKNOWN condition and weight levels was also found in both the LES ($F_{(2,42)} = 13.10$, $p < 0.001$) and the LMF ($F_{(2,36)} = 18.25$, $p < 0.001$). Simple effect analysis revealed that under the KNOWN condition, the activation time of postural muscles advanced as the load weight increased (LES: $F_{(2,42)} = 16.72$, $p < 0.001$; LMF: $F_{(2,36)} = 12.44$, $p < 0.001$), while under the UNKNOWN condition, the activation time of postural muscles showed no significant difference between load levels. The lumbar muscles elicited earlier under the UNKNOWN condition of the LES and LMF than that of the heaviest load level under the KNOWN condition (LES: 1 kg-unknown vs. 2 kg-known: $t = -3.282$, sig = 0.004; 1.5 kg-unknown vs. 2 kg-known: $t = -3.913$, sig = 0.001; 2 kg-known vs. 2 kg-known: $t = -4.782$, sig < 0.001; LMF: 1 kg-unknown vs. 2 kg-known: $t = -3.264$, sig = 0.004; 1.5 kg-unknown vs. 2 kg-known: $t = -3.014$, sig = 0.007; 2 kg-unknown vs. 2 kg-known: $t = -4.259$, sig < 0.001).

IEMG of APAs

The means and SDs of the IEMGs (APAs) of the LES and LMF are presented in Fig. 1c, d. There was a significant effect of KNOWN/UNKNOWN condition in both the LES ($F_{(1,21)} = 26.78$, $p < 0.001$) and the LMF ($F_{(1,18)} = 13.18$,

$p = 0.002$). There was also a significant effect on weight levels in LMF ($F_{(2,36)} = 9.73$, $p < 0.001$). An interaction between KNOWN/UNKNOWN condition and weight levels was found only in LMF ($F_{(2, 36)} = 7.95$, $p = 0.001$). Simple effect analysis showed that the IEMGs (APAs) of LMF strengthened as the load weight increased under the KNOWN condition ($F_{(2,36)} = 16.14$, $p < 0.001$), while the IEMGs (APAs) of the LMF remained consistent under the UNKNOWN condition. No significant difference in IEMG (APAs) in LMF was found between any weight level under the UNKNOWN condition and the heaviest load weight under the KNOWN condition.

IEMG of CPAs

The means and SDs of the IEMGs (CPAs) of the LES and LMF are presented in Fig. 1e, f. There was a significant effect of KNOWN/UNKNOWN condition in both the LES ($F_{(2,42)} = 35.04$, $p < 0.001$) and the LMF ($F_{(2,36)} = 19.79$, $p < 0.001$). More concretely, the IEMG (CPAs) under the UNKNOWN condition was significantly stronger than that under the KNOWN condition, while no significant effect of weight level was found in either LES or LMF. There was no interaction between KNOWN/UNKNOWN condition and weight level.

COP displacements

The means and SDs of A-COP are presented in Fig. 2a. There was a significant effect of KNOWN/UNKNOWN condition on A-COP ($F_{(1,17)} = 25.71$, $p < 0.001$), as well as a significant effect of weight level ($F_{(2,34)} = 8.04$, $p = 0.001$). An interaction was found between KNOWN/UNKNOWN condition and weight level ($F_{(2,34)} = 5.16$, $p = 0.011$). Simple effect analysis showed that A-COP increased with load level under the KNOWN condition ($F_{(2,34)} = 8.11$, $p = 0.004$) but showed no significant difference under the UNKNOWN condition. No significant difference in A-COP was found between any weight level under the UNKNOWN condition and the heaviest load weight under the KNOWN condition.

The means and SDs of C-COP and PT are presented in Fig. 2b, c. There was no significant effect of KNOWN/UNKNOWN condition or load weight level on either C-COP or PT. In addition, there was no interaction effect of KNOWN/UNKNOWN condition and load weight level on C-COP or PT.

Discussion

The present study was focused on examining the rapid response of the lumbar muscles to an unknown magnitude of perturbation to investigate the posture control strategies
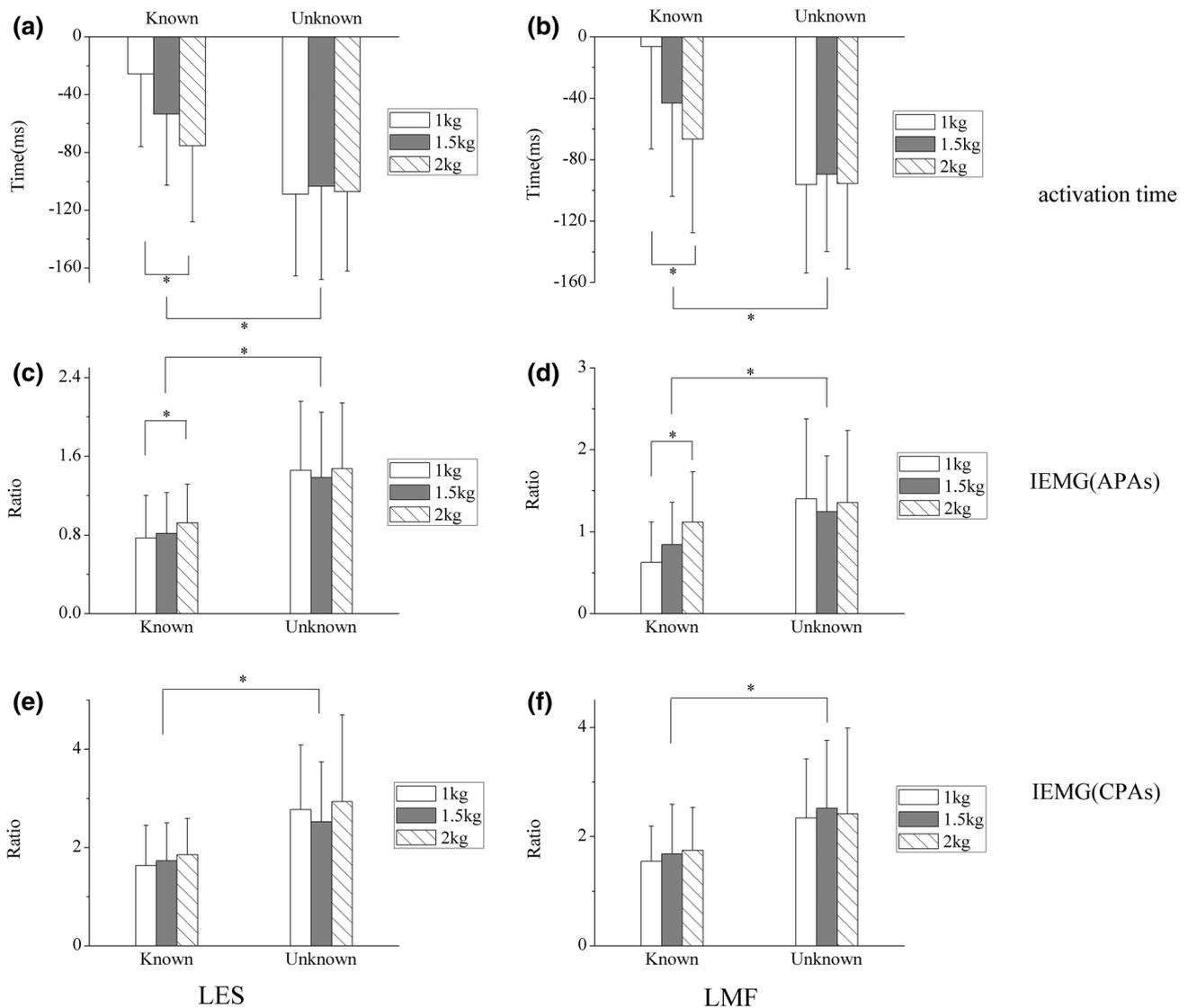
Fig. 1 sEMG of the LES and LMF. **a, b** Activation time of the LES and LMF. These two muscles activated prior to the perturbation. In the KNOWN condition, they activated earlier when the sandbag weight was greater, while in the UNKNOWN condition, the activation time of the LES and LMF showed no significant difference between weight levels. The LES and LMF activated earlier in the UNKNOWN condition than in the KNOWN condition. **c, d** Normalized IEMGs of APAs. In the KNOWN condition, LES and LMF acti-vated more strongly when the weight was heavier; in the UNKNOWN condition, however, they showed no significant difference between weight levels. The LES and LMF activated more strongly in the UNKNOWN condition than in the KNOWN condition. **e, f** Normalized IEMGs of CPAs. In both the KNOWN and UNKNOWN conditions, these muscles showed no significant difference between weight levels. The LES and LMF showed stronger CPAs in the UNKNOWN condition than in the KNOWN condition. $*p < 0.05$

of governing APAs and CPAs. The findings of the study demonstrated that if the magnitude of the perturbation was known in advance, postural muscles showed stronger APAs and the body swayed more strongly for greater per-turbation magnitudes. These results are consistent with previous studies (Lacquaniti and Maioli 1989a, b; Har-wood 2001; Shiratori and Latash 2001; Xie et al. 2014). However, if the perturbation magnitude was not known in advance, the APAs and CPAs of postural muscles and displacements of the COP showed no significant change between weight levels but were larger than those in the KNOWN condition.

The multifidus and erector spinae, the postural muscles located in the trunk and lumbar segments, make major con-tributions to the stability of the lumbar segment. In particu-lar, the multifidus, the core postural muscle of the lumbar spine, contributes up to 80% of the stability of the L4~S1 segments (Wilke et al. 1995; Mok et al. 2011). In the face of sudden postural perturbation, the proper and accurate activ-ity of these postural muscles maintains lumbar stability. In
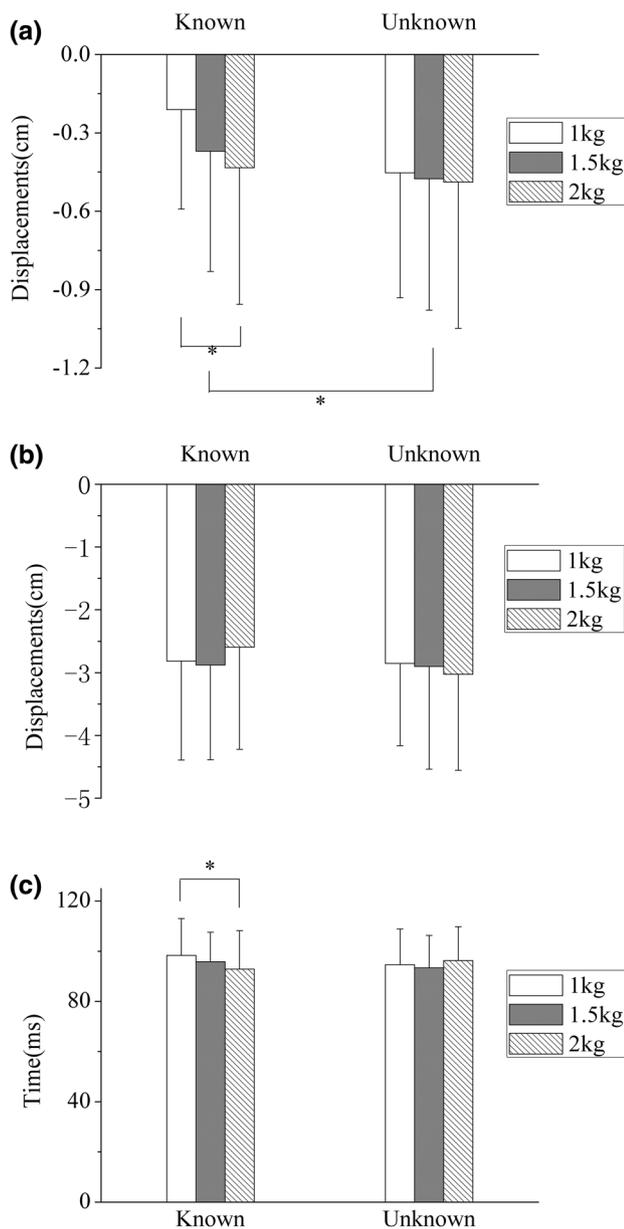
Fig. 2 Displacements of the COP. **a** A-COP. In the KNOWN condition, the COP displacement increased with the perturbation magnitude, while no difference was found in the UNKNOWN condition. COP displacements were larger in the UNKNOWN condition than in the KNOWN condition. **b** C-COP. No significant difference was found among weight levels or between the KNOWN and UNKNOWN conditions. **c** The time when displacements of COP get to its peak. In the KNOWN condition, the peak time shortened as the weight of the load increased, while no significant change was found in the UNKNOWN condition. *$p < 0.05$

the sandbag-catching test, the proper responses of lumbar postural muscles are an important guarantee of balance and postural stability of posture, which is organized by CNS based on the accurate knowledge of sudden perturbation (Cholewicki et al. 2000). Therefore, in the condition

of known magnitude of perturbation, the CNS will orchestrate an optimal response by the postural muscles through adjustments of both the latency and the intensity of APAs. However, in the condition of unknown magnitude, the CNS cannot direct an optimal response by the postural muscles, as it lacks the necessary information to form an accurate knowledge of the perturbation. The results of this study revealed that the CNS organizes postural control based on the maximum assumption of perturbation magnitude—in other words, "the worst case". This "redundancy response strategy" is employed by the CNS to organize the rapid reaction of the postural muscles. It should be noted that the CNS did not organize postural control based on an speculation of the object weight for the current trial; similar results were found in previous studies (Kazennikov and Lipshits 2010; Eckerle et al. 2012). The oral reports of the participants after the test indicated that they did not try to guess because of the lack of information. In this study, all three weight levels occurred with the same frequency. It would be meaningful to study the relationship between the occurrence rate of weight levels and the strategies organized by the CNS for a deeper understanding of the strategies of posture control. This topic will be one of the directions of our further research.

The present study showed that the CNS organized APAs and CPAs based on the maximum assumption of perturbation magnitude in the unknown condition. In the load-catching test used in this study, participants were requested to maintain a stable standing posture with a tray in their hands. If the magnitude of the perturbation was underestimated, the postural muscles would activate too weakly to resist the disturbance caused by the falling sandbag. During the training period, some participants dropped the tray when the falling sandbag hit it because they thought the sandbags would be lighter than they actually were. In a test that required subjects to catch objects in a bowl held in their fingers, Kazennikov and Lipshits observed similar occurrences in the first few trials (Kazennikov and Lipshits 2010). It can be inferred that one of the reasons why the CNS employs the maximum-redundancy response strategy is to ensure that the posture control task can be completed. Additionally, when APAs are too weak, the CNS needs to organize a stronger compensatory muscle reaction to cope with the perturbation. This sudden adjustment would damage the stability of the body and raise the risk of injury. Patients with low-back pain, Parkinson's disease and multiple sclerosis, who have a poor ability to organize APAs, show a tendency toward falling and muscle injuries (Latash et al. 1995; Krishnan et al. 2012a, b). Therefore, besides completion of the postural task, maintaining balance and preventing injuries are also among the likely reasons why the CNS employs the maximum-redundancy response strategy in response to sudden postural perturbations.

However, it is also counterproductive to organize excessively strong APAs, which would consume unnecessary energy and cause a new disturbance in postural stability (Aruin et al. 1998). A series of studies reveal that APAs would decrease or even disappear on an unstable support or in an unstable postural task environment (Aruin et al. 1998; Nouillot et al. 2000). This situational adaptation is a defensive strategy used by the CNS to avoid postural perturbation caused by improper APAs (Aruin 2002). In this study, the displacements of the COP in the APA period showed no difference between the KNOWN and UNKNOWN conditions, which reveals that the overall stability during the APA period has not changed despite improper muscle reactions. Although LES and LMF increased stronger CPAs in response to the component of postural perturbation caused by APAs, the increase in COP displacement was not significant, and the latency to reach peak displacement was not prolonged. These findings indicate that this posture control strategy helps the body to maintain balance and equilibrium, in spite of additional interference caused by improper APAs, in the present sandbag-catching task.

Finally it is important to mention that the results of this study were similar to those of a study by Kazennikov and Lipshits (2010) but differed in some respects from the results found by the unilataral load-catching task. The results of Eckerle et al.'s study revealed that with load uncertainty in catching, APAs of the upper limb muscles were relatively consistent at a level similar to that for a known intermediate weight, while the LES showed no significant change between known and unknown loads. And Berg and Hughes' study replicated Eckerle et al's work. The unilateral/bilateral paradigm may be one of the reasons for the discrepancy in the findings of these two studies, as well as the measurement of APAs. In Eckerle et al.'s study, sEMG recordings from the pre-drop period (the 1 s period prior to the release of the sandbag) and the drop period (the period between when the sandbag is released and when it is caught) were analyzed. In this study, however, we defined the APA period as – 100–50 ms in relation to when the weight hits the tray. Furthermore, there were some differences in the physical data of the participants in these two studies, which may affect their tolerance for catching loads.

Conclusion

The APAs and CPAs of lumbar muscles and displacements of COP are affected by the certainty of postural perturbations. The central nervous system coped with load perturbations of unknown magnitude with redundancy response strategy in a bilateral sandbag-catching task, based on the maximum assumption of perturbation magnitude.

References

Adkin AL, Frank JS, Carpenter MG, Peysar GW (2002) Fear of falling modifies anticipatory postural control. Exp Brain Res 143:160–170. https://doi.org/10.1007/s00221-001-0974-8

Aruin AS (2002) The organization of anticipatory postural adjustments. J Autom Control 12:31–37

Aruin AS, Latash ML (1995) Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. Exp Brain Res 103:323–332. https://doi.org/10.1007/BF00231718

Aruin AS, Latash ML (1996) Anticipatory postural adjustments during self-initiated perturbations of different magnitude triggered by a standard motor action. Electroencephalogr Clin Neurophysiol 101:497–503. https://doi.org/10.1016/S0013-4694(96)95219-4

Aruin AS, Rao N (2018) The effect of a single textured insole in gait rehabilitation of individuals with stroke. Int J Rehabil Res 41:218–223. https://doi.org/10.1097/MRR.0000000000000287

Aruin AS, Neyman I, Nicholas JJ, Latash ML (1996) Are there deficits in anticipatory postural adjustments in Parkinson's disease? Neuroreport 7:1794–1796

Aruin AS, Forrest WR, Latash ML (1998) Anticipatory postural adjustments in conditions of postural instability. Electroencephalogr Clin Neurophysiol 109:350–359

Aruin AS, Ganesan M, Lee Y (2017) Improvement of postural control in individuals with multiple sclerosis after a single-session of ball throwing exercise. Mult Scler Relat Disord 17:224–229. https://doi.org/10.1016/j.msard.2017.08.013

Berg WP, Hughes MR (2017) The effect of load uncertainty and foreperiod regularity on anticipatory and compensatory neuromotor control in catching. Motor Control 21(1):1–25

Chen B, Lee YJ, Aruin AS (2018) Standing on a sliding board affects generation of anticipatory and compensatory postural adjustments. J Electromyogr Kinesiol 38:168–174. https://doi.org/10.1016/j.jelekin.2017.12.008

Cholewicki J, Simons AP, Radebold A (2000) Effects of external trunk loads on lumbar spine stability. J Biomech 33:1377–1385

Curuk E, Lee Y, Aruin AS (2018) The effect of a textured insole on symmetry of turning. Rehabil Res Pract 2018:6134529. https://doi.org/10.1155/2018/6134529

Eckerle JJ, Berg WP, Ward RM (2012) The effect of load uncertainty on anticipatory muscle activity in catching. Exp Brain Res 220:311–318. https://doi.org/10.1007/s00221-012-3139-z

Eriksson Crommert AE, Thorstensson A (2009) Trunk muscle reactions to sudden unexpected and expected perturbations in the absence of upright postural demand. Exp Brain Res 196:385–392. https://doi.org/10.1007/s00221-009-1860-z

Gantchev GN, Dimitrova DM (1996) Anticipatory postural adjustments associated with arm movements during balancing on unstable support surface. Int J Psychophysiol 22:117–122

Harwood RH (2001) Visual problems and falls. Age Ageing 4(30 Suppl):13–18

Hay L, Redon C (1999) Feedforward versus feedback control in children and adults subjected to a postural disturbance. Exp Brain Res 125:153–162. https://doi.org/10.1007/s002210050670

Horak FB (2006) Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? Age Ageing 35(Suppl 2):ii7–ii11. https://doi.org/10.1093/ageing/afl077

Horak FB, Esselman P, Anderson ME, Lynch MK (1984) The effects of movement velocity, mass displaced, and task certainty on associated postural adjustments made by normal and hemiplegic individuals. J Neurol Neurosurg Psychiatry 47:1020–1028. https://doi.org/10.1136/jnnp.47.9.1020

Horak FB, Henry SM, Shumway-Cook A (1997) Postural perturbations: new insights for treatment of balance disorders. Phys Ther 77:517–533. https://doi.org/10.1093/ptj/77.5.517

Hwang JH, Lee YT, Park DS, Kwon TK (2008) Age affects the latency of the erector spinae response to sudden loading. Clin Biomech (Bristol Avon) 23:23–29. https://doi.org/10.1016/j.clinbiomech.2007.09.002

Kazennikov OV, Lipshits MI (2010) Influence of preliminary information about the mass on anticipatory muscle activity during the catching of a falling object. Hum Physiol 36:198–202%@ 0362–1197

Krishnan V, Kanekar N, Aruin AS (2012a) Anticipatory postural adjustments in individuals with multiple sclerosis. Neurosci Lett 506:256–260. https://doi.org/10.1016/j.neulet.2011.11.018

Krishnan V, Kanekar N, Aruin AS (2012b) Feedforward postural control in individuals with multiple sclerosis during load release. Gait Posture 36:225–230. https://doi.org/10.1016/j.gaitpost.2012.02.022

Krishnan V, Latash ML, Aruin AS (2012c) Early and late components of feed-forward postural adjustments to predictable perturbations. Clin Neurophysiol 123:1016–1026. https://doi.org/10.1016/j.clinph.2011.09.014

Lacquaniti F, Maioli C (1989a) Adaptation to suppression of visual information during catching. J Neurosci 9:149–159

Lacquaniti F, Maioli C (1989b) The role of preparation in tuning anticipatory and reflex responses during catching. J Neurosci 9:134–148. https://doi.org/10.1523/JNEUROSCI.09-01-00134.1989

Latash ML, Aruin AS, Neyman I, Nicholas JJ (1995) Anticipatory postural adjustments during self inflicted and predictable perturbations in Parkinson's disease. J Neurol Neurosurg Psychiatry 58:326–334

Lee Y, Goyal N, Aruin AS (2018a) Effect of a cognitive task and light finger touch on standing balance in healthy adults. Exp Brain Res 236:399–407. https://doi.org/10.1007/s00221-017-5135-9

Lee YJ, Chen B, Liang JN, Aruin AS (2018b) Control of vertical posture while standing on a sliding board and pushing an object. Exp Brain Res 236:721–731. https://doi.org/10.1007/s00221-017-5166-2

Magill RA (2006) Motor Learning And Control [Chinese edition]. Chinese Light Industry Press, Beijing

Mohapatra S, Krishnan V, Aruin AS (2012) Postural control in response to an external perturbation: effect of altered proprioceptive information. Exp Brain Res 217:197–208. https://doi.org/10.1007/s00221-011-2986-3

Mok NW, Brauer SG, Hodges PW (2011) Changes in lumbar movement in people with low back pain are related to compromised balance. Spine (Phila Pa 1976) 36:E45–E52. https://doi.org/10.1097/BRS.0b013e3181dfce83

Nouillot P, Do MC, Bouisset S (2000) Are there anticipatory segmental adjustments associated with lower limb flexions when balance is poor in humans? Neurosci Lett 279:77–80 (%@ 0304–3940)

Paloski WH, Oman CM, Bloomberg JJ et al (2008) Risk of sensory-motor performance failures affecting vehicle control during space missions: a review of the evidence. J Gravitational Physiol 15(2):1–29

Panjabi M, Abumi K, Duranceau J, Oxland T (1989) Spinal stability and intersegmental muscle forces. A biomechanical model. Spine (Phila Pa 1976) 14:194–200

Radebold A, Cholewicki J, Panjabi MM, Patel TC (2000) Muscle response pattern to sudden trunk loading in healthy individuals and in patients with chronic low back pain. Spine (Phila Pa 1976) 25:947–954

Reschke MF, Good EF, Clément GR (2017) Neurovestibular symptoms in astronauts immediately after space shuttle and international space station missions. OTO Open. https://doi.org/10.1177/2473974X17738767

Riach CL, Hayes KC (1990) Anticipatory postural control in children. J Mot Behav 22:250–266

Santos MJ, Kanekar N, Aruin AS (2010) The role of anticipatory postural adjustments in compensatory control of posture: 1. Electromyographic analysis. J Electromyogr Kinesiol 20:388–397. https://doi.org/10.1016/j.jelekin.2009.06.006

Shiratori T, Latash ML (2001) Anticipatory postural adjustments during load catching by standing subjects. Clin Neurophysiol 112:1250–1265. https://doi.org/10.1016/S1388-2457(01)00553-3

Shumway-Cook A, Woollacott MH (2007) Motor control: translating research into clinical practice. People's Medical Publishing House, Beijing (Chinese Edition)

Wilder DG, Aleksiev AR, Magnusson ML, Pope MH, Spratt KF, Goel VK (1996) Muscular response to sudden load. A tool to evaluate fatigue and rehabilitation. Spine (Phila Pa 1976) 21:2628–2639

Wilke HJ, Wolf S, Claes LE, Arand M, Wiesend A (1995) Stability increase of the lumbar spine with different muscle groups. A biomechanical in vitro study. Spine (Phila Pa 1976) 20:192–198

Xie L, Wang J, Zhang Z, Yuan L, Wang C(2014) Psychological predictive effects of sudden posture perturbation. Acta Psychol Sin 46:951–959