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RESEARCH ARTICLE

# Older adults can rely on an auditory cue to generate anticipatory postural adjustments prior to an external perturbation

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## Abstract

To minimize the potential postural disturbance induced by predictable external perturbations, humans generate anticipatory postural adjustments (APAs) using visual information about a perturbation. However, it is unknown whether older adults can generate APAs relying on auditory information. Ten older adults received external perturbations (a) with visual information but no auditory information available, (b) without neither visual nor auditory information, (c) with both visual and auditory information available, and (d) participated in training with only auditory information available. In addition, they were tested again after 1 week of washout period. Electromyography activities of eight leg and trunk muscles and ground reaction forces were recorded and analyzed during the anticipatory and compensatory phases. Outcome measures included the latencies and integrals of muscle activities, and center-of-pressure displacements. After a short period of training, participants were able to rely on the auditory cue only to generate APAs close to that when the visual information was available. In addition, after 1 week of washout period, they were able to partially retain the skill to rely on auditory cues to generate APAs. The outcome provides a foundation for future studies focusing on utilizing auditory cues to optimize postural control in individuals who have balance or vision deficit.

**Keywords** Anticipatory postural adjustments · Auditory cue · Older adults · Balance control · External perturbation

## Introduction

People experience external perturbations (i.e., a hit or a bump) that challenge their postural balance on a daily basis. When they see an upcoming postural perturbation, their central nervous system (CNS) usually activates muscles using two mechanisms to maintain balance: a feedforward mechanism called anticipatory postural adjustment (APA), and a feedback mechanism called compensatory postural adjustment (CPA). APAs happen prior to the external perturbation and involve activation or inhibition of the postural muscles that would control the position of the center-of-mass (COM) by minimizing the expected balance disturbance (Aruin et al. 2001; Bouisset and Zattara 1987; Massion 1992). In contrast, CPAs serve as a corrective measure that involves activation of muscles to restore the COM position after the actual perturbation impact (Piscitelli et al. 2017; Santos et al. 2010a). Previous studies found that the magnitude of APAs and CPAs are interrelated: when larger APAs were generated for an external postural perturbation, less postural instability was observed, and as a result the demand for CPAs after the physical impact was smaller (Santos et al. 2010a, b).

Falls are the number one cause of unintentional injuries in older adults above the age of 65 years old (Bergen et al. 2016). One fourth of those falls happened because older adults could not respond appropriately to a postural perturbation from an external source such as a hit or a bump (Robinovitch et al. 2013). Previous studies reported that older adults, especially those with balance deficiencies, show inefficient generation or utilization of APAs, such as delayed anticipatory muscle recruitment and smaller magnitudes (Kanekar and Aruin 2014). Consequently, older

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adults exposed to an external perturbation would experience greater postural disturbance and they require larger magnitude of muscle activities to correct the postural disturbance.

People usually require visual information to see the upcoming perturbation and generate APAs accordingly. When visual information was unavailable (as when people were asked to close their eyes in a lab setting) and the external perturbation became unexpected, large EMG responses and large center-of-pressure (COP) displacements were observed during the compensatory phase (Piscitelli et al. 2017; Santos et al. 2010a). When the visual information became inaccurate using distorted lenses, APAs became less efficient with smaller muscle activities and delayed muscle latencies (Mohapatra et al. 2012). Since in real life situations, visual information is not always available or accurate, the unpredictable external perturbations would present substantial challenges to postural stability, especially in older adults, and increase their risk of falls.

To make prediction of the expected external perturbations and generate appropriate APAs, people mainly rely on past experiences (Bastian 2006). Even though such experiences are majorly gained based on visual information, there are studies that supported the benefits of using cues other than visual to facilitate the generation of APAs to prepare for an external postural perturbation. One previous study explored the generation of APAs in individual's postural forearm based on central timing signal during a seated load-release perturbation (Paulignan et al. 1989). The authors reported that people were only able to generate and optimize APAs when this load-release perturbation was triggered by a voluntary movement of their contralateral arm but no APAs were observed when it was unexpectedly triggered by the experimenter. Another study reported that people were able to optimize their APAs after several repetitions of a standing perturbation task, given that the same external perturbation (with the same magnitude and timing) was provided (Arghavani et al. 2020; Aruin et al. 2015a, b). It was also reported that auditory cues could be used as conditioning stimulus and trigger APAs in healthy young adults in the events of an external balance perturbation (in the form of a support-surface tilt) (Campbell et al. 2009, 2012; Kolb et al. 2002). Our previous study showed that young adults were able to build a connection between the timing of an auditory cue and an external perturbation after 25–35 times of repetitive exposure (Liang et al. 2020). Additionally, we found that when relying on this auditory cue only, the participants could generate efficient APAs similar to that when they could see the external perturbation. Older adults have diminished APAs when experiencing external postural perturbations (Kanekar and Aruin 2014), they learn new skills at a slower rate (Bennett et al. 2007), and they might only retain this new skill partially after a week (Lingo VanGilder et al. 2018). Therefore, the purpose of this study was to investigate if after a short period of training older adults can use an auditory cue to generate APAs in the event of an external postural perturbation. We also intended to investigate if this learned skill retains. Our first hypothesis was that after a short period of training, older adults would be able to generate APAs based on an auditory cue only. Furthermore, we hypothesized that to optimize APAs older adults would need to be exposed to the same external perturbation more than 35 times. Finally, we hypothesized that older adults would retain this learned skill partially after a week.

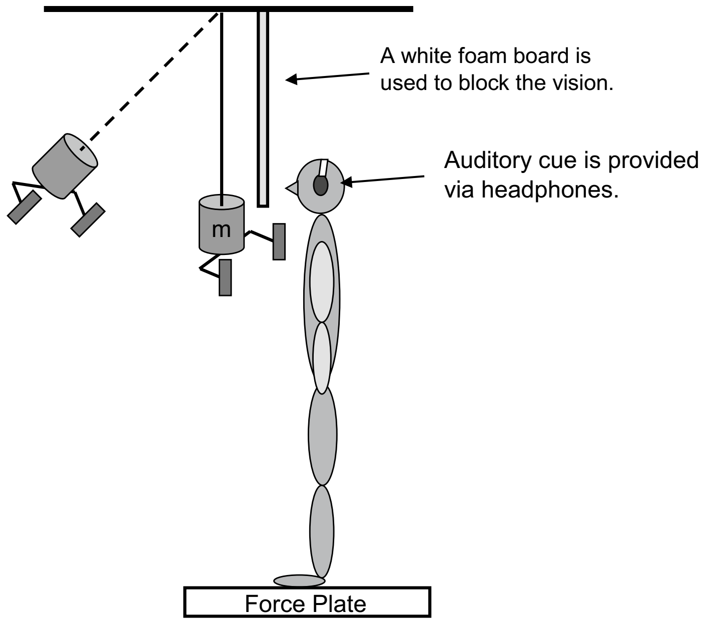
## Materials and methods

### Participants

Thirteen older adults (6M/7F) above the age of 65 years old were recruited for this study. The inclusion criteria were the ability to stand straight independently for at least 5 min, normal or corrected to normal vision, and ability to follow instructions. The exclusion criteria included any existing balance, neurological, or musculoskeletal disorders, any injuries or surgeries to the musculoskeletal system within the past 6 months, or inability to withstand the external perturbation provided by a swinging pendulum. Three participants dropped out of the study since they could not tolerate the pendulum impact. The mean (SD) of the age, height, and weight for the remaining ten participants (5M/5F) were 70 (5.2) years old, 166.9 (11.3) cm, and 75.9 (14.3) kg, respectively. This study was approved by the hosting university's institutional review board and all participants provided written informed consent before the data collection.

### Procedure

The participants were asked to stand barefoot with feet shoulder width apart in the middle of a force plate (AMTI, Watertown, MA, USA) and be prepared for an external perturbation created by a swinging pendulum. The aluminum pendulum was attached to the ceiling with its initial position at an angle of 30° to the vertical and at a distance of 0.6 m from the shoulders of the participants (Fig. 1). An additional load equaling to 3% of body mass was attached to the end of the pendulum and there were two wooden boards covered with foam pads extended from the end of the pendulum. The settings were adjusted for each participant's so that the two foam pads would hit front side of both shoulders simultaneously. An accelerometer (PCB Piezotronics, Inc., Depew, NY) was attached to the end of the pendulum to identify the moment of its impact with the participants' shoulders (T0). The participants had headphones on them throughout the data collection session to block environmental noise majorly caused by the release of the pendulum. A removable



| Condition | BL_V | BL_NV | Acclimation | Training | Catch | Retention |
|---|---|---|---|---|---|---|
| Number of trials | 5 * 1 | 5 * 1 | 5 * 2 | 5 * 10 | 1 | 5 * 2 |
| Visual information | Yes | No | Yes | No | No | No |
| Auditory cue | No | No | Yes | Yes | Yes | Yes |

**Fig. 1** A schematic representation of the experimental setup and a summary chart of all the conditions during two lab visits. The pendulum hits both shoulders at the same time with an additional mass (*m*) attached to it (3% of each individual's body mass). *BL_V* baseline with visual information available, *BL_NV* baseline with visual information blocked

screen (a 30 × 30 cm white foam board) was placed in front of the participants at the eye level to block the sighting of the upcoming pendulum but preserve the peripheral visual field. The participants were expected to stand straight with their upper extremities along the body and maintain their balance without moving their feet during the pendulum impact. A harness system loosely attached to the ceiling was used to ensure the safety of participants. Following a "ready" signal, the same research assistant released the pendulum with a 1–5 s delay so that the participants could not predict the exact timing of the pendulum impact based on previous experience. Participants were given 2–3 practice trials of receiving the pendulum perturbation with full vision. There were 5 conditions implemented in the following order: baseline while vision was available (*BL_V* condition) for 5 trials, baseline while vision was not available (*BL_NV* condition) for 5 trials, *Acclimation* condition for 10 trials, training (*Tr*) condition for 50 trials, and 1 *Catch* trial (Fig. 1).

During *BL_V* condition, participants received the pendulum perturbation with full vision information available. During *BL_NV* condition, participants received the pendulum perturbation while their vision was blocked by the screen. During *Acclimation*, participants received the pendulum perturbation with full vision and an auditory cue. The auditory cue (a beep sound) was delivered via headphones at the moment of pendulum release. A magnetic switch (Absolute Automation, Casco, MI, USA) was attached to the frame holding the pendulum and it sent the signal to initiate the beep (1 kHz, 0.25 s duration) triggered by the pendulum release. The timing between the auditory cue and the pendulum impact was 0.5 s for all the trials. Participants were encouraged to connect the timing of the auditory cue with the timing of the following pendulum impact. Then, during the *Tr* condition, the screen was used to block the vision and participants received the pendulum perturbation with the same auditory cue only. Finally, one *Catch* trial was performed that the participants still received the auditory cue, but the pendulum was stopped by a researcher just before it hit the participants. Pendulum perturbations were provided in blocks of five trials and a 10-second-rest was provided between blocks. Participants could also take longer rest when needed to avoid fatigue.

The participants were invited to come back to the lab for retention test (*Re* condition) after 1 week of washout period. During *Retention* condition, the same pendulum setup was used, and participants received the pendulum impact 10 times with the same auditory cue only, but with vision blocked by the screen. No practice trial was provided before the retention trials.

An electromyography (EMG) system (Myopac, RUN Technologies, USA) was used during both lab visits to record muscle activities bilaterally from leg and trunk muscles including tibialis anterior (TA), medial gastrocnemius (MG), rectus femoris (RF), biceps femoris (BF), gluteus medius

(GM), external obliques (EO), rectus abdominus (RA), and erector spinae (ES). The skin area was cleaned with alcohol wipes and the disposable surface electrodes (Red Dot, 3M, St. Paul, MN, USA) were attached in pairs with a center-to-center distance of 25 mm and the placements were based on the recommendations reported in the literature (Zipp 1982). The ground electrode was placed on the right lateral malleolus. A customized LabView 8.6.1 software (National Instruments, Austin, TX, USA) was used to collect the data from the magnetic switch, accelerometer, force plate, and the EMG system at a frequency of 1000 Hz, as well as sending a beeping sound at the time of pendulum release.

## Data analysis

Data processing was done using a custom-written MATLAB program (Mathworks, Natick, MA, USA). The accelerometer data were used to identify the time of pendulum impact (T0) as the first time point when the accelerometer signal exceeds 5% of its peak value (Aruin et al. 2015a, b). All other data from the force plate and EMG system were aligned with T0.

The EMG signals were filtered with a fourth-order 30 Hz high-pass Butterworth filter (Drake and Callaghan 2006). Then the EMG signals were full-wave rectified. A 20 Hz low-pass Butterworth filter was used to create linear envelopes. The baseline muscle activity was calculated using the mean value between − 1000 and − 850 ms. The muscle latency was defined as the first time point within a 50 ms sliding time window where the EMG amplitude was consistently larger (activation) or smaller (inhibition) than its baseline value ± 2SD. All the baseline muscle activity and latency detections were checked visually for its accuracy by an experienced researcher. To estimate the magnitude of muscle activity, EMG integrals (IntEMGi) were calculated during two 300 ms windows: (1) anticipatory postural adjustment (APA), from − 250 to + 49 ms; and (2) compensatory postural adjustment (CPA), from + 50 to + 349 ms (Santos et al. 2010a). Then, each integral was corrected by its corresponding baseline activity and normalized by the absolute maximum value across all conditions for each muscle and participant, respectively (Lee 2019):

$$\mathrm{NormEMG\_APAi} = \left( \int_{-250}^{+49} \mathrm{EMGi} - 2 \int_{-1000}^{-849} \mathrm{EMGi} \right) / \, \mathrm{IntEMGi} - \mathrm{max},$$

$$\mathrm{NormEMG\_CPAi} = \left( \int_{+50}^{+349} \mathrm{EMGi} - 2 \int_{-1000}^{-849} \mathrm{EMGi} \right) / \, \mathrm{IntEMGi} - \mathrm{max},$$

where *i* stands for each of the 16 muscles tested.

Force plate data were filtered with a fourth-order 40 Hz low-pass Butterworth filter (Kanekar and Aruin 2014). The center-of-pressure (COP) time series in the anterior–posterior (AP) direction were derived from the force plate data. The baseline of COP-AP was calculated using the mean value from − 1000 and − 850 ms and the baseline was subtracted from the COP-AP time series. The COP-AP displacement at T0 was identified to represent its movement during APA phase; and its peak value after T0 was identified to represent the movement during CPA phase.

Since the pendulum hit the participant's both shoulders simultaneously, the perturbation can be considered symmetrical, which was also confirmed by our preliminary analysis of the EMG data. To simplify our data analysis, only the EMG outcomes of the right side were used for further statistical analysis. For each participant, perturbation trials were organized into blocks of five and the outcomes from five trials were averaged for further analysis. Namely, there was one block for *BL_V* condition, one block for *BL_NV*, two blocks for *Acclimation* condition, and ten blocks for *Tr* condition. There was one single trial for the *Catch* condition. Additionally, there were two blocks for *Re* condition. On rare occasions when the latency of a muscle within a condition cannot be identified in certain participants, we replaced it with an estimate using the group average. The outcomes during the APA phase (muscle latencies, integrals during APA, and COP at T0) for the *Catch* trial and the outcomes during the APA and CPA phases for all other conditions were used for further analysis.

## Statistical analysis

A series of one-way repeated measures ANOVAs were conducted on the dependent variables (EMG latency, normalized EMG integrals during the APA and CPA for each muscle, COP at T0, and COP peak) for the *BL_V* and two blocks of *Acclimation* conditions. No differences were found in any of the variables. Therefore, we considered that our participants' response in *BL_V* condition was their optimal reaction, and we excluded the *Acclimation* condition from further analysis. A series of one-way repeated measures ANOVAs were conducted on the abovementioned dependent variables among *BL_V*, *BL_NV*, *Tr1* through *Tr10*, and *Catch* conditions to test the effectiveness of auditory cue training. A series of one-way repeated measures ANOVAs were conducted on the dependent variables among *BL_V*, *BL_NV*, *Tr10*, *Re1*, and *Re2* conditions to test retention. Post hoc pairwise comparisons with Bonferroni adjustments were conducted when necessary. Skewness and kurtosis were used to assess the normality of the data and a log transformation of the data was applied when necessary. Statistical significance was set at $\alpha = 0.05$.

## Results

All ten participants completed all the training trials during the first lab visit. Seven participants managed to come back to the lab for a second visit and complete the retention trials before the study was affected by COVID-19 pandemic.

### EMG and COP-AP displacement profiles

Ten older adults showed variable activation/inhibition patterns of the ventral/dorsal muscles utilized to maintain balance in the event of an external perturbation. Most participants displayed a combination of reciprocal and co-activation patterns at different joints: the activation of TA and the inhibition of MG were observed for the ankle joint; while the activation of both RF and BF were observed for the knee joint. Only one participant demonstrated an overall reciprocal pattern with the activation of all ventral muscles (TA, RF, and RA) and the inhibition of all dorsal muscles (MG, BF, and ES). For the BF, data from the majority of the participants that showed a clear pattern of muscle activation was used to plot the group average integrals in Fig. 3a but statistical analysis of BF integrals was not conducted due to inconsistency of activation patterns. For the ES, there were a couple of participants showing inhibition of the muscle and a couple of participants not showing a clear pattern. Therefore, data that showed a clear pattern of muscle activation was used to represent the group average muscle latency and integrals in Fig. 3a but were deemed insufficient for statistical analysis.

Figure 2 shows the EMG traces of TA muscle and COP-AP displacements of a representative participant during different conditions. It was observed in most participants that during the *BL_V* condition when vision information was available, there was an activation of TA and a slight posterior shift of COP-AP during the APA phase (before T0). During the *BL_NV* condition, when vision information was not available, no changes in the muscle activity or COP-AP displacements were observed before T0; however, large muscle activities and posterior shift of COP-AP were observed after T0. Throughout the training trials (*Tr1* through *Tr10*) when the auditory cue was provided, there was an increase of anticipatory muscle activity and a decrease of compensatory muscle activity. In addition, there was an increase of anticipatory COP-AP posterior shift and a reduction of compensatory COP-AP posterior shift. In the *Catch* trial, anticipatory activity similar to condition *Tr10* was observed. During the retention trials (*Re1* and *Re2*) when only the auditory cue was available, the anticipatory muscle activity and COP-AP posterior shift were larger than in *BL_NV* condition and compensatory muscle activity and COP-AP posterior shift were smaller. We also observed a larger anticipatory and a smaller compensatory muscle activity and COP-AP displacement in *Re2* compared to *Re1* condition.

### Training session

#### EMG latency

In the *BL_V* condition, muscle latencies were detected before the physical impact (T0); while in the *BL_NV* condition, muscle latencies were detected after T0. Throughout the training session (*Tr1* to *Tr10*), the latencies of the leg muscles became earlier and almost reached a similar level as *BL_V* towards the end of the training session (Table 1). The latency for RA was not detected for one-third of the trials, so statistical analysis was not conducted. The latency of ES+ or ES− was not detected for more than half of the trials so the statistical analysis was not conducted. Statistical analysis for the other muscles revealed a significant condition effect for the latencies of TA ($F(12,108) = 6.79$, $p < 0.001$), MG ($F(12,108) = 6.42$, $p < 0.001$), RF ($F(12,108) = 15.38$, $p < 0.001$), BF ($F(12,108) = 9.75$, $p < 0.001$), GM ($F(12,108) = 7.36$, $p < 0.001$), and EO ($F(12,108) = 3.81$, $p < 0.001$). Post-hoc analysis revealed that for TA and RF, the latencies observed in all the *Tr* trials were earlier than in *BL_NV* condition, but later than in *BL_V* condition (all $p < 0.05$). For MG, BF, GM, and EO muscles, the latencies observed in all the *Tr* trials were earlier than those in *BL_NV* condition (all $p < 0.05$); while latencies in some blocks towards the end of the training session showed no differences than those in *BL_V* condition (*Tr6* through *Tr10* for MG, *Tr8* and *Tr10* for BF, *Tr9* for GM, and *Tr9* and *Tr10* for EO).

#### Muscle integrals

Compared to *BL_V* condition, the participants showed smaller APA integrals and consequently larger CPA integrals when the vision was blocked (*BL_NV* condition). During the training session, the participants gradually showed an increase of APA integrals and a decrease of CPA integrals, which was more prominent for the lower leg and thigh muscles (Fig. 3a).

For the APA integrals, statistical analysis showed a significant condition effect for TA ($F(12,108) = 3.92$, $p < 0.001$), RF ($F(12,108) = 5.08$, $p < 0.001$), and EO ($F(12,108) = 2.64$, $p = 0.004$). Post hoc analysis revealed that for TA and RF, the APA integrals during all *Tr* blocks and *Catch* were significantly larger than *BL_NV*, and only the APA integrals during the first half of the *Tr* blocks were significantly smaller than *BL_V* condition (all $p < 0.05$). For EO, the APA integrals during all training blocks were smaller than that in *BL_V* condition (all $p < 0.05$) but were not different from *BL_NV* condition.

For the CPA integrals, statistical analysis showed significant condition effects for TA ($F(11,99) = 3.00$, $p = 0.002$),

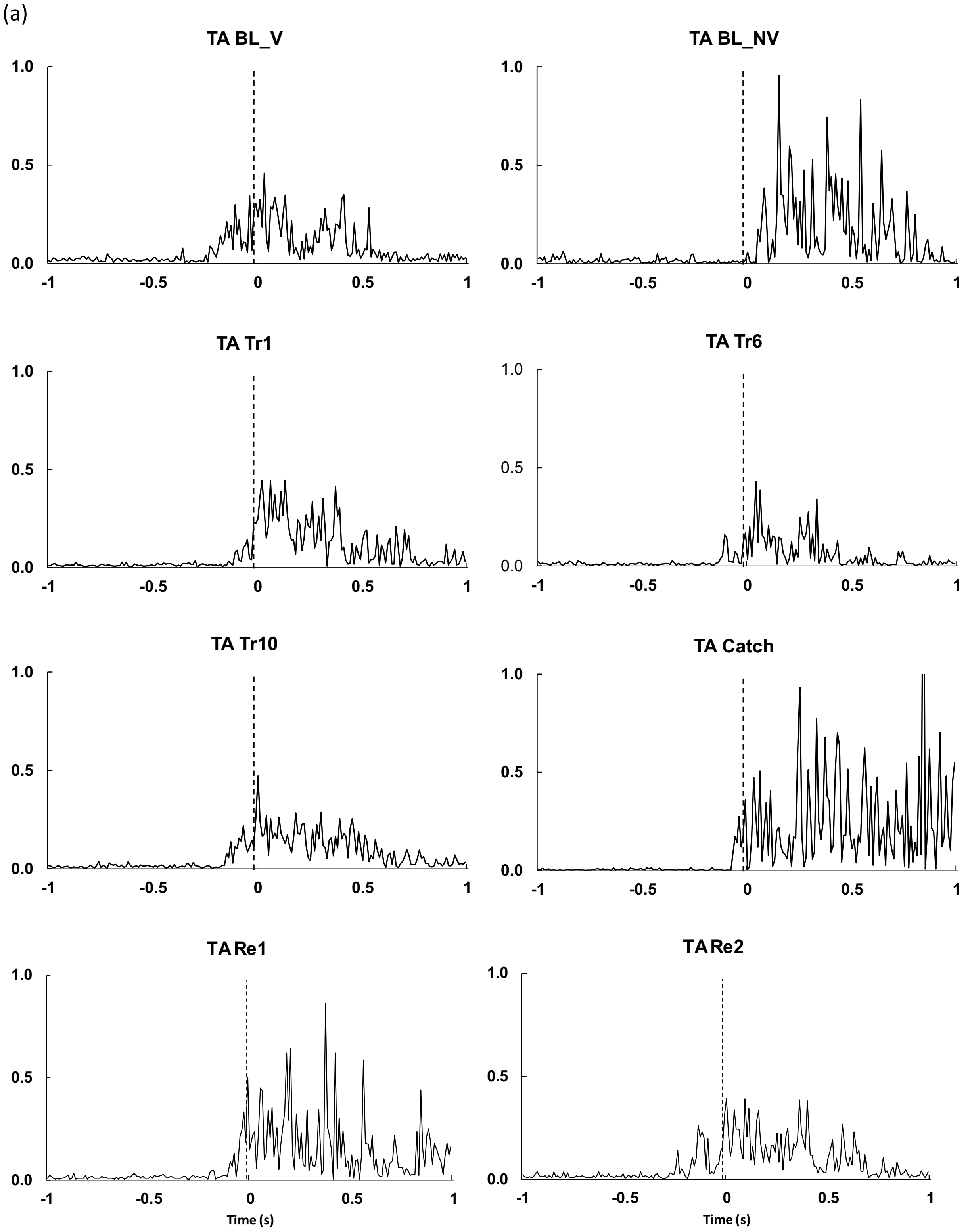


**Fig. 2** **a** EMG traces of the tibialis anterior (TA) and **b** COP-AP displacement of a representative participant recorded during different conditions. Data are aligned with the moment of perturbation impact (T0), shown as the vertical dotted reference line. Time scales are in seconds and EMG scales are in arbitrary units. In panel **b**, negative values indicate displacement in the anterior direction and positive values indicate displacements in the posterior direction. *BL_V* baseline with visual information available, *BL_NV* baseline with visual information blocked, *Tr* training conditions. *Tr1* represents the beginning of the training, *Tr6* represents the middle of the training, and *Tr10* represents end of the training. *Re* retention conditions. *Re1* represents the first block of retention condition and *Re2* represents the second block of retention condition

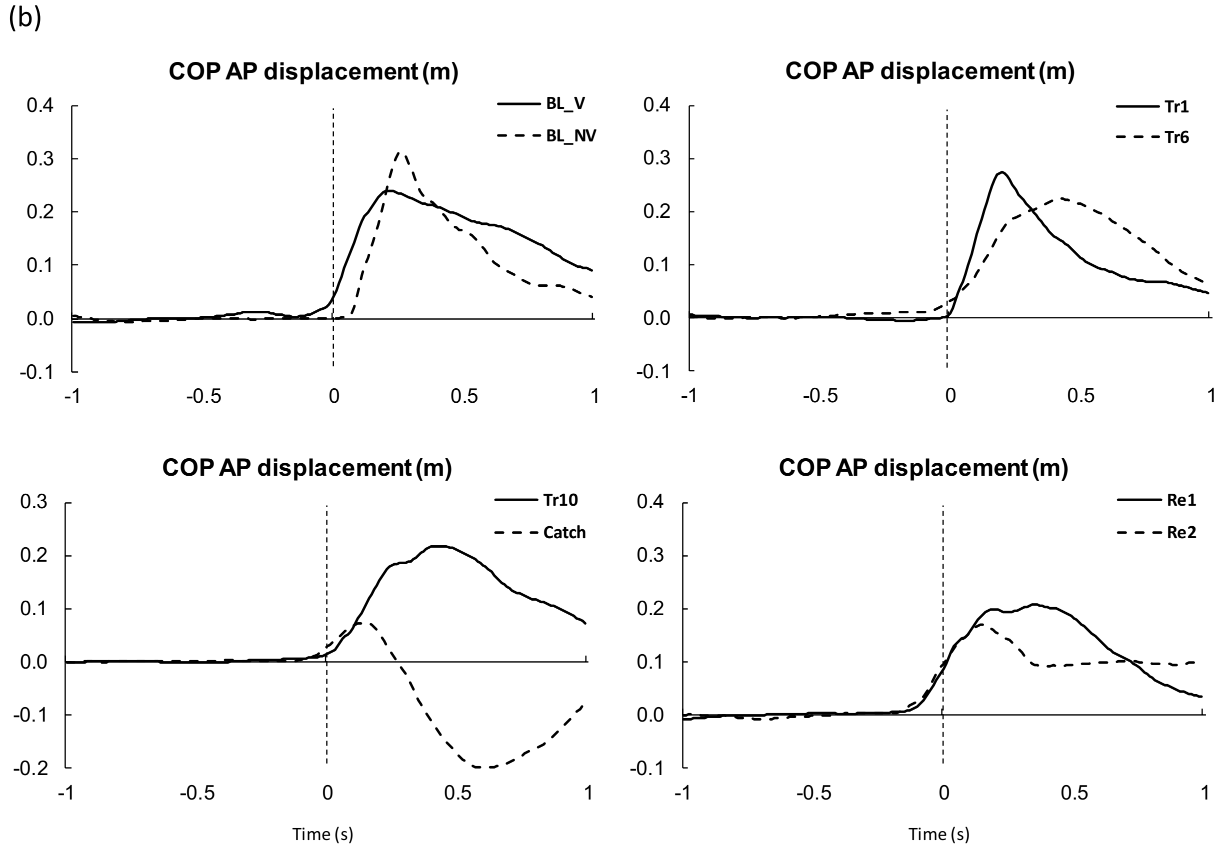


**Fig. 2** (continued)

**Table 1** Mean ± SD of EMG latencies (in ms) of the postural muscles in selected conditions during training

| Muscles | BL_V | BL_NV | Tr1 | Tr2 | Tr5 | Tr6 | Tr10 | Catch |
|---|---|---|---|---|---|---|---|---|
| RA | − 23.8 ± 60.4 | 59.2 ± 34.9 | 11.8 ± 69.6 | 24.1 ± 49.5 | − 11.7 ± 69.3 | − 2.9 ± 48.6 | − 3.67 ± 58.8 | − 45.3 ± 107.7 |
| ES (activation) | − 51.5 ± 47.8 | 68.9 ± 33.9 | − 11.1 ± 31.0 | 23.8 ± 40.2 | 27.3 ± 55.9 | − 16.2 ± 33.2 | − 28.2 ± 48.3 | 84.5 ± 74.5 |
| ES (inhibition) | − 111.1 ± 112.8 | 57.8 ± 25.6 | − 142.2 ± 65.3 | − 118.4 ± 61.8 | − 139.1 ± 73.2 | − 100.0 ± 62.5 | − 138.9 ± 71.8 | − 145.3 ± 71.8 |
| GM | − 7.6 ± 45.5 | 83.4 ± 23.6 | 52.3 ± 38.6 | 42.6 ± 42.1 | 36.4 ± 51.7 | 45.7 ± 24.2 | 40.2 ± 23.5 | − 14.5 ± 1.1 |
| EO | − 87.9 ± 71.7 | 49.8 ± 55.0 | − 25.8 ± 70.2 | − 27.3 ± 50.3 | − 34.9 ± 58.3 | − 32.3 ± 60.8 | − 54.4 ± 43.8 | − 10 ± 127.7 |
| RF | − 181.2 ± 31.9 | 22.1 ± 27.0 | − 71.8 ± 44.9 | − 90.5 ± 43.5 | − 95.2 ± 45.9 | − 90.8 ± 40.8 | − 97.6 ± 44.9 | − 107.3 ± 56.8 |
| BF | − 136.7 ± 37.6 | 44.6 ± 57.4 | − 38.9 ± 70.9 | − 91.4 ± 86.6 | − 80.0 ± 56.1 | − 74.4 ± 61.0 | − 104.6 ± 66.6 | − 80.3 ± 62.4 |
| TA | − 143.7 ± 62.3 | 23.9 ± 23.9 | − 78.4 ± 58.9 | − 85.8 ± 47.4 | − 95.7 ± 58.1 | − 90.6 ± 63.9 | − 104.9 ± 49.9 | − 89.0 ± 111.6 |
| MG | − 177.9 ± 106.7 | 37.1 ± 47.0 | − 122.2 ± 74.9 | − 100.6 ± 85.8 | − 123.8 ± 75.4 | − 138.8 ± 72.4 | − 134.9 ± 58.0 | − 67.7 ± 148.7 |

RF ($F(11,99) = 4.57$, $p < 0.001$), GM ($F(11,99) = 4.14$, $p < 0.001$), EO ($F(11,99) = 4.66$, $p < 0.001$), and RA ($F(11,99) = 2.41$, $p = 0.011$). Post-hoc analysis revealed that the CPA integrals during almost all the training blocks for TA, RF, GM, and EO were significantly smaller than that of *BL_NV* condition, except for RF at *Tr1*; additionally, during the second half of training, the CPA integrals for RA were smaller than *BL_NV* condition (all $p < 0.05$). The CPA integrals were only significantly larger than *BL_V* condition during the *Tr1* condition for TA and RF muscles.

### COP displacements

During data analysis, we found that the COP data from one participant was not available due to the malfunction of the device, and it was excluded from the analysis. Generally, participants shifted their COP posteriorly prior to the physical impact when they were able to see the upcoming pendulum (*BL_V*), and this shift was presented as a positive COP value at T0 (Fig. 4a). During the *BL_NV* condition, minimal COP movement was detected at T0, and a large

**Table 2** Mean ± SD of EMG latencies (in ms) of the postural muscles during retention

| Muscles | BL_V | BL_NV | Tr10 | Re1 | Re2 |
|---|---|---|---|---|---|
| RA | − 39.2 ± 57.8 | 53.6 ± 33.7 | − 17.2 ± 53.5 | − 16.2 ± 32.8 | − 37.1 ± 37.3 |
| ES[a] (activation) | − 84.8 | 68.2 | − 96.2 | 61.6 | − 11.2 |
| ES (inhibition) | − 111.1 ± 112.7 | 57.8 ± 25.6 | − 138.9 ± 71.7 | − 97.4 ± 53.8 | − 91.0 ± 29.8 |
| GM | 4.1 ± 48.9 | 77.3 ± 25.6 | 47.9 ± 22.9 | 44.3 ± 24.0 | 7.9 ± 80.6 |
| EO | − 98.6 ± 61.2 | 29.6 ± 19.8 | − 66.3 ± 42.8 | − 36.2 ± 29.7 | − 55.8 ± 33.7 |
| RF | − 172.8 ± 33.1 | 34.3 ± 12.1 | − 97.4 ± 49.9 | − 50.9 ± 59.4 | − 74.4 ± 28.0 |
| BF | − 111.3 ± 24.4 | 55.8 ± 18.2 | − 111.9 ± 73.4 | − 8.4 ± 75.2 | − 43.6 ± 89.6 |
| TA | − 123.7 ± 62.9 | 38.0 ± 12.1 | − 106.5 ± 58.1 | − 16.9 ± 66.3 | − 71.0 ± 59.1 |
| MG | − 147.2 ± 105.1 | 50.8 ± 43.9 | − 109.1 ± 59.6 | − 121.2 ± 94.2 | − 140.2 ± 62.7 |

*BL_V* baseline with visual information available, *BL_NV* baseline with visual information blocked, *Tr10* the last block of training condition, *Re1* first block of retention condition, *Re2* second block of retention condition. See text for statistical results

[a] Among all participants that completed the retention sessions, only one demonstrated activation pattern of the ES, and no SD was available

COP peak value was observed. Throughout the *Tr* blocks, participants showed a gradual increase of the posterior COP shift at T0, and a smaller COP peak value than *BL_NV*. Statistical analysis showed a condition effect for COP at T0 ($F(12,96) = 2.36$, $p = 0.011$). Post hoc analysis revealed that all Training blocks except *Tr1* showed larger COP shift than *BL_NV*, and only some of the early Training blocks (*Tr1*, *Tr3*, *Tr4*, and *Tr6*) showed smaller COP shift than *BL_V* condition (all $p < 0.05$).

## Retention session

During the retention test, the general trend was that in the first block of retention test (*Re1*), participants demonstrated APA muscle activities and COP movement that were superior to *BL_NV* condition, but were not similar to that in *BL_V* condition or the end of the Training session (i.e., *Tr10*). However, the APAs improved during *Re2* condition, and reached the similar level as *BL_V* or *Tr10* conditions for some variables (Table 2, Figs. 2, 3b, and 4b).

### Muscle latencies

Muscle latencies during the retention blocks are presented in Table 2. Statistical analysis showed a condition effect for latency of all muscles tested: TA ($F(4,24) = 9.31$, $p = 0.001$), MG ($F(4,24) = 10.93$, $p < 0.001$), RF ($F(4,24) = 20.15$, $p < 0.001$), BF ($F(4,24) = 16.35$, $p < 0.001$), GM ($F(4,24) = 3.4$, $p = 0.024$), and EO ($F(4,24) = 14.32$, $p < 0.001$). Post hoc analysis revealed that for MG, latencies detected during both *Re1* and *Re2* were earlier than *BL_NV* and similar to *BL_V*/*Tr10* conditions. For TA and GM, muscle latencies detected in *Re1* were later than *BL_V* and similar to *BL_NV* condition; however, latencies detected in *Re2* were earlier than *BL_NV* and similar to *BL_V* condition. For RF, BF, and EO, latencies detected in both *Re1* and *Re2* were earlier than *BL_NV*, but later than *BL_V* condition.

### Muscle integrals

Integrals of the leg muscles during the APA and CPA phases are presented in Fig. 3b. For the APA integrals, statistical analysis showed a condition effect for TA ($F(4,24) = 4.13$, $p = 0.011$) and RF ($F(4,24) = 11.19$, $p < 0.001$). Post hoc analysis revealed that APA integrals for TA during both *Re1* and *Re2* were smaller than *BL_V* and similar to *BL_NV* condition. APA integrals for RF during *Re2* were larger than *BL_NV* but smaller than *BL_V* condition.

For the CPA integrals, statistical analysis showed a condition effect for TA ($F(4,24) = 3.97$, $p = 0.013$). Post hoc analysis revealed that CPA integrals of TA during both *Re1* and *Re2* were smaller than *BL_NV* condition, and similar to *BL_V*/*Tr10* conditions.

### COP displacements

During data analysis, we found that the retention session COP data from two participants was not available due to the malfunction of the device, and it was excluded from the analysis. COP displacement at T0 and its peak displacement after the physical impact are presented in Fig. 4b. Statistical analysis showed a condition effect for COP peak value after physical impact ($F(4,16) = 8.67$, $p < 0.001$). Post hoc analysis revealed that COP peak value at *Re1* was smaller than *BL_NV* but larger than *BL_V* conditions, while COP peak value at *Re2* was smaller than *BL_NV* but no different than *BL_V* condition.

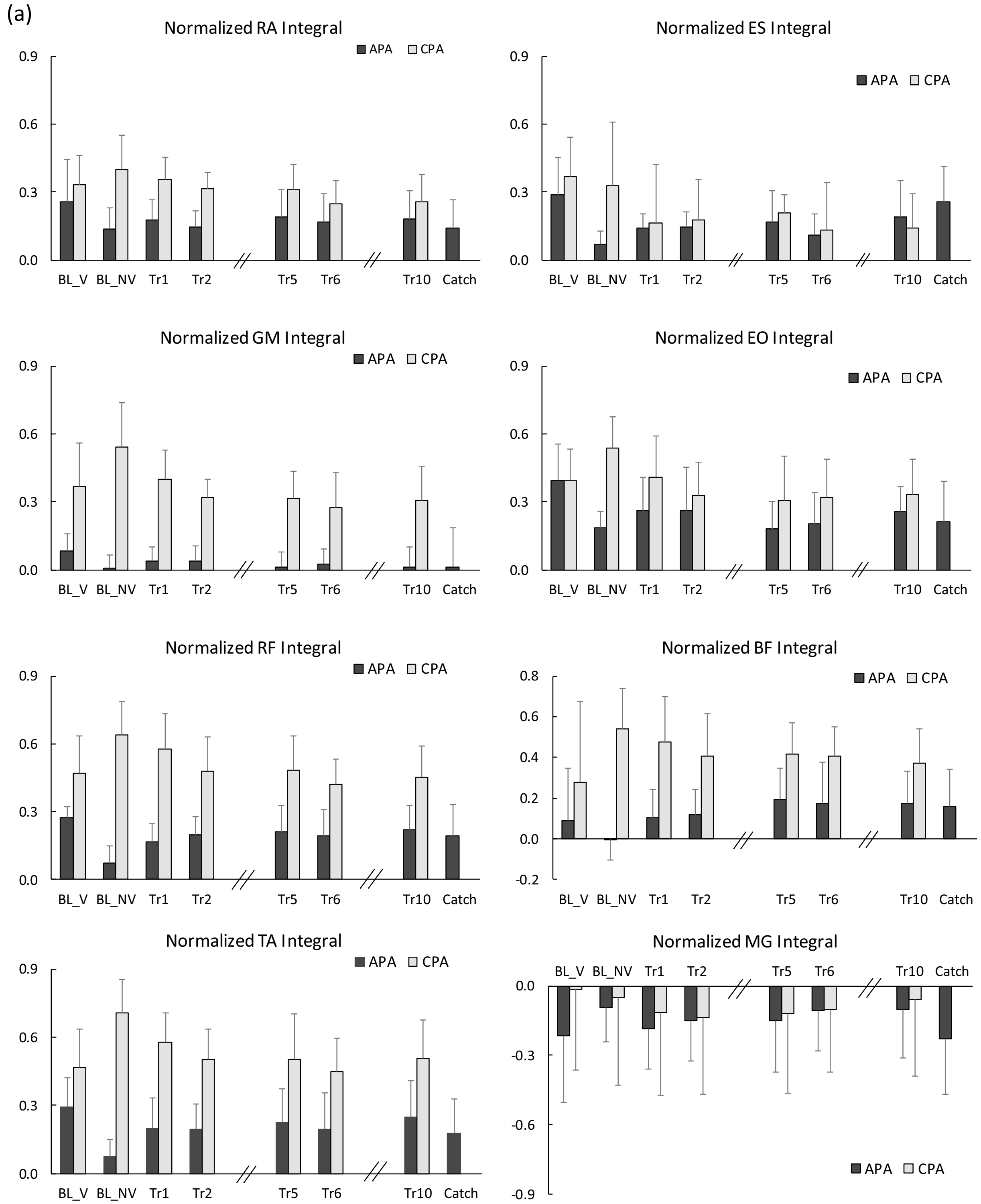


**Fig. 3** Mean (SD) of normalized EMG integrals of postural muscles during the anticipatory (APA) and compensatory (CPA) phases **a** when comparing training conditions with baseline conditions; and **b** when comparing retention conditions with baseline conditions. Muscles included rectus abdominus (RA), erector spinae (ES), gluteus medius (GM), external obliques (EO), rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), and medial gastrocnemius (MG). *BL_V* baseline with visual information available, *BL_NV* baseline with visual information blocked, *Tr* training conditions, where *Tr1* and *Tr2* represent the beginning of the training, *Tr5* and *Tr6* represent the middle of the training, and *Tr10* represents end of the training, *Re* retention conditions, where *Re1* is the first block and *Re2* is the second block of retention testing. Note that positive values indicate muscle activation and negative values indicate muscle inhibition relative to background activities

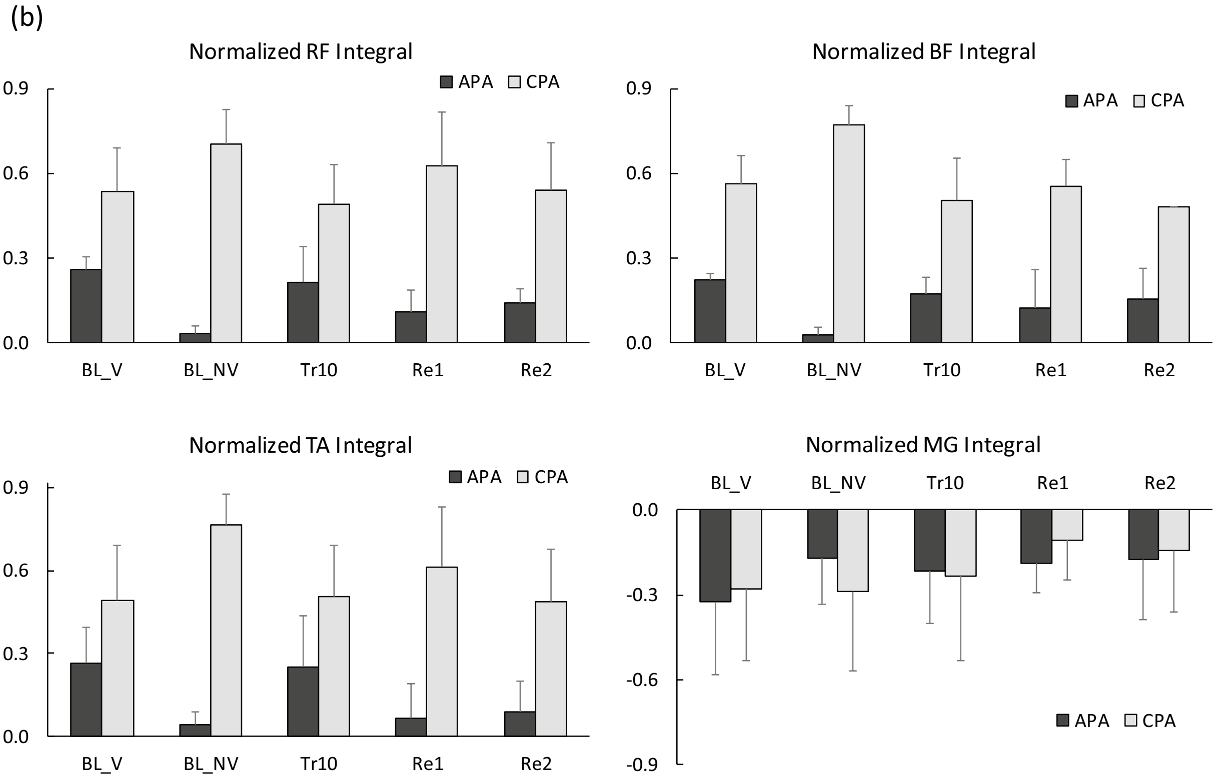


**Fig. 3** (continued)

## Discussion

This study examined whether an auditory cue could be used to generate APAs prior to an upcoming external perturbation. Our results supported the hypothesis that older adults were able to rely on auditory information only to generate adequate APAs that were comparable to that when visual information was used. Additionally, after 1 week of washout period, they were able to pick up this skill to some degree rather quickly.

### Role of sensory information in postural control

Visual information is usually critical to generate efficient APAs prior to postural disturbance, as it has been discussed extensively in the literature (Aruin et al. 2001; Mohapatra et al. 2012; Piscitelli et al. 2017; Santos et al. 2010b). Our results are in agreement with the previous literature, and we observed minimal anticipatory muscle activities or COP shift when older adults experienced a pendulum perturbation with their vision blocked (*BL_NV* condition). Previous studies also reported that healthy young adults could rely on an auditory cue to generate postural responses to external perturbation (Campbell et al. 2012; Kolb et al. 2002; Liang et al. 2020). Our results demonstrated that older adults could utilize an auditory cue similarly: when they were repetitively exposed to an auditory cue (signaling the moment of perturbation), they were able to use it effectively as a warning signal and demonstrated anticipatory muscle activities and anticipatory COP shift prior to the physical impact of the pendulum. When comparing the effectiveness of using different sensory information, older adults showed comparable APAs in the latency and integrals of leg muscles when relying on an auditory cue; however, the generation of APAs in the trunk muscles was insufficient or inconsistent (especially *Tr6* through *Tr10*) compared to their response when visual information was available (*BL_V* condition). Previous literature reported that the APA generation follows a distal to proximal pattern (Santos et al. 2010a), which could explain our results that older adults prioritized the generation of APAs in the distal segments to stabilize themselves relative to the ground to neutralize the destabilizing effect of external postural perturbations.

Previous literature reported a relationship between the magnitude of APAs and CPAs during challenging postural tasks such that the generation of large APAs would reduce the demands for CPAs to correct postural disturbance (Liang et al. 2020; Santos et al. 2010a). We observed a similar

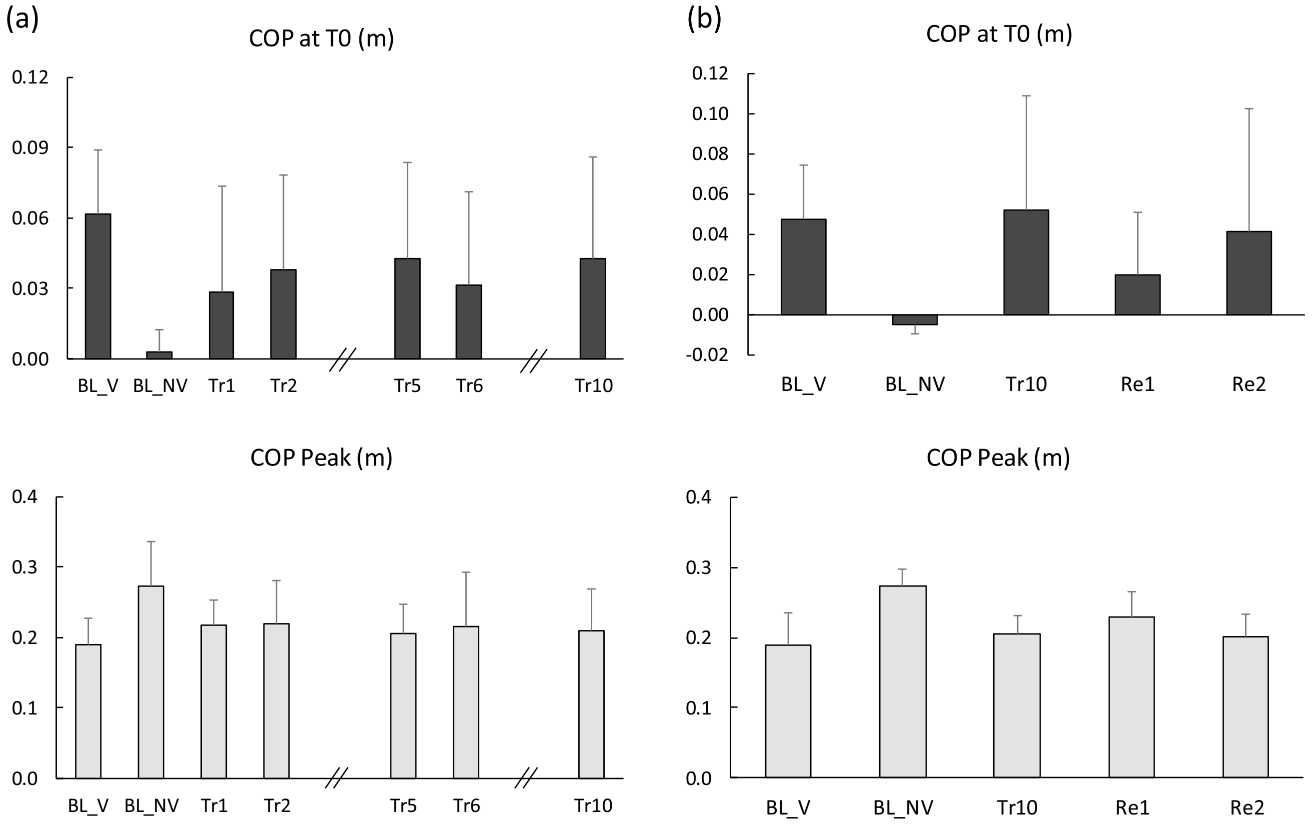


**Fig. 4** Mean (SD) of center-of-pressure (COP) displacements at T0 and COP peak displacements after T0 **a** when comparing training conditions with baseline conditions; and **b** when comparing retention conditions with baseline conditions. Values are presented in meters, and positive values represent posterior displacements. *BL_V* baseline with visual information available, *BL_NV* baseline with visual information blocked, *Tr* training conditions, where *Tr1* and *Tr2* represent the beginning of the training, *Tr5* and *Tr6* represent the middle of the training, and *Tr10* represents end of the training, *Re* retention conditions, where *Re1* is the first block and *Re2* is the second block of retention testing

phenomenon that older adults required larger muscle activities during the CPA phase when the muscle activities were smaller in the APA phase (*BL_NV* condition). Moreover, the participants showed smaller compensatory muscle activities in conditions when they were able to generate larger anticipatory muscle activities (*BL_V* and *Training* conditions).

Previous studies reported that when preparing for the frontal external perturbation with visual information available, the participants demonstrated a posterior displacement of COP in the APA phase, which produced momentum to cause the center-of-mass to move forward and downward to better prepare for the upcoming perturbation (Santos et al. 2010b; Stapley et al. 1998). Our results also exhibited this backward COP sway in the APA phase, when either sensory information was available. Additionally, during the *Catch* condition when the auditory cue was presented but the pendulum was stopped before it hit our participants, they still presented anticipatory muscle activities and an anticipatory COP shift, with similar timing and magnitude to those during the late training blocks. It is important to note that while our participants were in a lab environment exposed to the same pendulum perturbation, even though they might be in an "alert" mindset and were able to response almost instantaneously to the physical impact, they did not know the exact timing of the pendulum's physical impact. However, when the participants were provided with the auditory cue identifying the moment of the pendulum release, the generation of APAs was based on the timing of this auditory cue and they demonstrated sufficient APAs. These results suggest that older adults were able to generate APAs based on the auditory cue only.

## Training effects of using auditory information

It was reported that not only the availability, but also the accuracy of sensory information influences the generation of APAs. Thus, when the accuracy of visual information was affected using positive and negative glasses, young adults demonstrated delayed and diminished APAs (Mohapatra et al. 2012). Moreover, when a combination of auditory cues and visual obstruction was used to facilitate APA generation during a ball catching task while seated, participants displayed inconsistent APA patterns, because the auditory cue provided to participants was not relevant to the timing of the event (Lacquaniti and Maioli 1987). Quite the opposite, the timing of the auditory cue in our study was consistently related to the timing of the pendulum physical impact, so the participants were able to learn to rely on a new form of sensory information to predict the postural perturbation and generate sufficient APAs after a short period of training.

We also observed a training effect such that in the early training blocks, the generation of APAs were inferior to that in the *BL_V* condition. After repetitive exposure, the latencies became earlier and magnitude of APAs integrals got larger, which were more prominent in the leg muscles. Still, at the end of training session, the generation of APAs in the trunk muscles was not comparable to that when visual information was available. In our previous study, we used the same training protocol on young adults, and reported that young adults required 20–25 repetitions to learn to use this auditory cue to optimize their APAs in preparation for a pendulum perturbation (Liang et al. 2020). Older adults generally utilize diminished APAs for postural disturbance and they usually are slower to learn new skills (Bennett et al. 2007; Kanekar and Aruin 2014). Our results suggest that around 50 repetitions of a postural perturbation might be needed to train older adults to generate APAs at a similar level as that when visual information is available.

It is important to note that in our study protocol, we had an *Acclimation* condition (two blocks of five trials) when both the visual and auditory information were available. This condition expedited participants' ability to build a connection between the timing of a new auditory cue and the timing of pendulum hit with the assistance of a familiar visual cue. Without such connection, older adults might need even more repetitions to predict the timing of the postural perturbation accurately relying only on a novel auditory cue.

## Retention of the learned skill

After a washout period, our data on retention showed that APAs during the retention trials were superior to *BL_NV* condition but inferior to *BL_V* condition. The 2nd block of retention showed improvement with earlier onset and larger APA muscle activities than the 1st block. This indicates that after the initial training session, older adults would require enhancement sessions to reinforce their abilities to generate APAs to prepare for a postural perturbation relying on an auditory cue only. Our results are also promising and imply that the enhancement sessions might only need to include a few repetitions of external perturbations for older adults to be able to generate sufficient APAs relying on an auditory cue only.

## Muscle activation patterns

The CNS uses two patterns of muscle activation to maintain balance: co-contraction and reciprocal activation (Mochizuki et al. 2004). In our previous study on young adults, we reported that the majority of subjects used a reciprocal activation pattern during the APA phase to prepare for a pendulum perturbation, which included activation of the ventral muscles (TA and RF) and inhibition of the dorsal muscles (MG and BF) (Liang et al. 2020). Reciprocal activation of muscles is considered a more efficient strategy to maintain a standing posture (van der Fits et al. 1998). On the other hand, co-contraction involves concurrent activation of agonists and antagonists to increase the joint stiffness and stability. It is commonly used by older adults to maintain balance in the events of external perturbations (Lee et al. 2015) at a cost of increased energy expenditure. In this current study, we observed a variety of muscle activation patterns from different older participants ranging from co-contraction in all muscle pairs (TA–MG, RF–BF, and RA–ES), to co-contraction in some muscle pairs and reciprocal activation in other pairs, to reciprocal activation in all muscle pairs. Even for the same participant, we observed a variation of muscle activation patterns throughout training trials. We speculate that the inconsistency of muscle responses imply that throughout training blocks older adults might be still exploring the ideal strategy to generate APAs that provides joint stability and is energy efficient, and they displayed "inappropriate" response from time to time before the "appropriate" response was learned and remembered. This also suggests that older adults might need at least 50 repetitions to learn to generate optimal APAs relying only on an auditory cue.

## Limitations

The older adults included in this study displayed varies muscle activation patterns in their APAs. These variations of muscle activation patterns resulted in larger SDs, especially in the dorsal muscles. However, we deem that they generally showed similar patterns in the ventral muscles and large variation in movement patterns are common in older adults when performing challenging tasks. Future studies could categorize older adults into high/low function subgroups and allow for a longer training period to examine the learning effects within each subgroup. Future research could also look closely at the muscle activation on both sides of the body and compare different stages of training to identify "inappropriate" or possible "lateralized" responses. In this study, we included older adults who were generally healthy and did not have balance issues. We did not have enhancement sessions or a control group, and only tested the retention after one week of washout period. Future studies could examine clinical populations such as older adults with poorer balance and higher risks of fall, include a control group, allow a longer familiarization period before training with auditory cue to let the participants develop a more consistent APA pattern, implement weekly training sessions with small numbers of repetitions (i.e. ten repetitions), include a *Catch* trial in the test of retention, and test retention over a longer period of time.

## Conclusion

After one session of training, older adults could learn to generate APAs for an otherwise unpredictable postural perturbation relying only on an auditory cue. They might need at least 50 repetitions to learn to generate APAs close to that when visual information is available. Furthermore, after 1 week of washout period, they could partially regain this learned skill quickly after 5–10 repetitions.

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**Data availability** All data generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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