Exp Brain Res (2016) 234:3193–3201
DOI 10.1007/s00221-016-4717-2

RESEARCH ARTICLE

# Control of grip force and vertical posture while holding an object and being perturbed

**Bing Chen**[1] · **Yun-Ju Lee**[2] · **Alexander S. Aruin**[2]

Received: 18 January 2016 / Accepted: 27 June 2016 / Published online: 15 July 2016

**Abstract** We investigated motor control perspectives of coordinating maintenance of posture and application of grip force when holding an object and being perturbed. Ten subjects stood on the force platform holding an instrumented object in their dominant hand and were exposed to an external perturbation applied to their shoulders. Task demands were manipulated by positioning a slippery cap on top of the instrumented object. Grip force applied to the object, the object acceleration and the center of pressure (COP) were recorded and analyzed during the time intervals typical for the anticipatory (APA) and compensatory (CPA) components of postural control. Onsets of grip force were seen before the onsets of the COP displacement and initiation of movements of the handheld object during the APA phase of postural control, while the onsets of maximum grip force preceded the maximum COP displacement during the CPA phase. When the task demands increased by holding a handheld object with the slippery cap, subjects tended to generate grip force earlier and of a smaller magnitude; also, the COP displacement in the APA phase was smaller as compared to holding a handheld object only. The outcome provides a foundation for future studies of maintenance of vertical posture in people with impairments of balance and grip force control when holding an object and being perturbed.

**Keywords** Dual task · Grip force · Postural control · Suprapostural task · Perturbation

## Introduction

Humans frequently perform daily activities that involve multitasking such as holding a cup of coffee or talking on the phone while standing or walking. Balance maintenance that involves interplay between internal factors (self) and external factors (environment) is based on the utilization of various feedback signals from the vestibular, somatosensory, and visual systems (Shumway-Cook et al. 1997).

Likewise, successful manipulation of a handheld object requires that the central nervous system (CNS) obtains the sensory information pertaining to postural control while taking into consideration the properties of the object to be lifted; this allows to exert appropriate grip force, thus preventing the object from slipping or crushing (Gordon et al. 1991; Chen and Aruin 2013). In addition, grip force increases to maintain the stability of the handheld object in anticipation of the potential destabilizing effects of the forthcoming perturbation affecting the stability of an object when, for example, moving the object to produce a collision with another object (Turrell et al. 1999; Nowak and Hermsdorfer 2006), or stability of posture, for example, during gait initiation with a handheld object (Diermayr et al. 2008). Thus, anticipatory coupling of grip force and inertial force of the transporting hand was observed during walking and carrying a handheld object, which suggested that the CNS uses continuous grip force adjustment as a generalized strategy to maximize efficiency during object transport (Gysin et al. 2003).

When an individual encounters a predictable imminent perturbation, the CNS uses two main types of adjustments

---

✉ Alexander S. Aruin
aaruin@uic.edu

[1] PhD Program in Rehabilitation Sciences, College of Applied Health Sciences, University of Illinois at Chicago, Chicago, IL, USA

[2] Department of Physical Therapy (MC 898), University of Illinois at Chicago, 1919 W. Taylor St., Chicago, IL 60612, USA

in the activity of postural muscles to maintain balance. Anticipatory postural adjustments (APAs) are generated to control the position of the center of mass (COM) prior to a forthcoming perturbation, minimizing the danger of losing equilibrium (Massion 1992). Compensatory postural adjustments (CPAs) are triggered by sensory feedback signals and serve as a mechanism to restore the COM position after the perturbation (Alexandrov et al. 2005). In most of the cases, APAs and CPAs coexist to regulate posture and spatial orientation; small CPA responses correspond to generation and utilization of strong APAs (Santos et al. 2010a, b).

Studies have shown that control of vertical posture is attentionally demanding; the attentional demands of balance control vary depending on the complexity of the task and the type of secondary task being performed (Woollacott and Shumway-Cook 2002). Thus, a contributing factor to postural constraints could be that the attentional requirements of balancing and performing a second task simultaneously cause diminished attention to balance control (Reilly et al. 2008); moreover, such a divided attention could affect the performance of a secondary task. Research in this new and expanding area involved studying performance of a motor task and a cognitive task at the same time (Shumway-Cook et al. 1997; Plummer et al. 2013), execution of two motor tasks simultaneously, for example, the performance of bimanual coordination task (Temprado et al. 2001), walking while holding a cup or buttoning a shirt (Horvat et al. 2013), or texting on the cell phone while keeping balance (Nurwulan et al. 2015). The later is also described in the literature as a suprapostural task (Stoffregen et al. 2000). It was reported that in such cases, concurrent demands for dual-task processes induce interference (Temprado et al. 2001; Muller et al. 2007). In most of the daily situations, when balance is threatened, the CNS primarily focuses on the maintenance of stability of posture (Shumway-Cook et al. 1997). On the other hand, when there is no immediate danger to balance, the CNS controls posture to be used as a foundation to facilitate the motor task (Stoffregen et al. 2000).

While postural control and grip force control were studied individually, it remains unclear how control of vertical posture interacts with grip force control, especially when balance is challenged or when the complexity of hand grip control is increased, such as when holding a mug full of water as compared to holding a solid object. Additionally, while previous studies mainly focused on the relation between the arm movement and control of grip force (Flanagan et al. 1993; Flanagan and Wing 1993; Diermayr et al. 2008; Kennedy et al. 2014), not enough attention has been given to the investigation of the relationship between control of vertical posture and grip force.

It is reported in the literature that performance of the suprapostural task could enhance postural control seen, for example, as a reduction in postural sway in standing while holding a fixed or mobile stick (Albertsen et al. 2010; Ustinova and Langenderfer 2013) or when subjects hold a glass full of water as compared to holding an empty glass (Morioka et al. 2005). On the other hand, performance of the suprapostural task could endanger postural control, since the movement that constitutes the suprapostural task itself may possibly induce an internal perturbation to balance (Riccio and Stoffregen 1988; Stoffregen et al. 2000). At the same time, it is not known how the CNS coordinates the performance of the postural and suprapostural tasks during the APA and CPA phases of postural control while dealing with external perturbations.

Thus, the purpose of this study was to investigate motor control strategies that the CNS uses coordinating control of posture and application of grip force. We were interested to explore whether the sequence of the events, the magnitude of grip force, and postural stability measured during both the APA and CPA phases are affected by the changes in the task demands. To do that, we varied the complexity of the task by asking subjects to hold an instrumented object (a cup) either with a slippery cap placed on the top of the cup or without it. We hypothesized that when holding an object and being perturbed, the onset of grip force will precede the onset of the object and COP movements and that these onsets will be observed during the APA phase of postural control. We also hypothesized that the sequence of the events related to the control of grip force and posture would be affected by the complexity of the task. Specifically, we expected to see an earlier exertion of grip force as well as a smaller magnitude of grip force and a smaller COP displacement in the higher demanding condition.

## Methods

Ten young right-handed volunteers (five males and five females, age 28.2 ± 3.55 years, body mass = 67.1 ± 20.27 kg, height = 1.66 ± 0.08 m) participated in the experiment. All subjects were free from any neuromuscular disorder that could affect control of posture or holding an object. The study was approved by the University of Illinois at Chicago Institutional Review Board, and all participants provided written informed consent before taking part in the experimental procedures.

The subjects were instructed to stand and hold an object made as a cylindrical plastic cup (height 16.5 cm, diameter 6 cm, total mass 435 g). The object was instrumented with a unidirectional strain gauge (Model 208CO3, Piezotronics) that was located at the center of the object (10.5 cm from its bottom) and extended out from both the sides of the object by flat aluminum projections of 9.5 cm × 2.5 cm each. The strain gauge provided measure of the grip force applied by the thumb and the four opposing fingers (Iyengar et al. 2009a). A three-axial accelerometer (Model356a16, Piezotronics) was attached to the instrumented object to measure the acceleration in three orthogonal directions ($X =$ up–down, $Y =$ medial–lateral, $Z =$ anterior–posterior). A flat plastic cap (height 1.5 cm, diameter 6 cm, total mass 5 g) was positioned on top of the instrumented object (cup). Holding a cup with the cap (that could slide off the top of the cup) simulated a common high demanding task of holding a mug full of water. Ground reaction forces and moments of forces were obtained from a force platform (Model OR-5, AMTI, USA). An accelerometer (Model333b42, Piezotronics) was attached to the left sternoclavicular joint to determine the moment of the body perturbation ($T_0$).

The participants stood barefoot on the force platform with their feet together and their right hand holding the instrumented object with the arm close to the body, elbow flexed to 90°, and wrist in mid pronation. The participants were instructed to maintain balance and stabilize the cup while being perturbed at the shoulder level by a pendulum. The aluminum pendulum was attached to the ceiling and consisted of a central rod with the distal end designed as two padded pieces positioned shoulder width apart and projected toward the participants (Fig. 1). The length of the central rod was adjusted to each individual's shoulder height, and the width of the padded surface was adjusted to match the subject's shoulder width. A load (5 % of the individual's body mass) was attached to the pendulum next to its distal end. The pendulum was positioned at an initial angle of 30° to the vertical (0.8 m between the body and the padded pieces) in front of the subjects and released by an experimenter. The interval between the pendulum release and the impact was about 800 ms. To minimize the effect of learning, the time of the pendulum release was varied in the interval from 1 to 1.5 s after the start of the data collection.

Perturbation consisted of unidirectional force applied by the pendulum on the shoulders of the subjects. The participants were instructed to look forward and maintain their posture. Two practice trials were given to the subjects in each experimental condition.

Two experimental conditions were used as follows: (1) holding an instrumented cup only [this condition will be referred as "cup-only (CO)"] or (2) holding the same cup with a plastic cover placed on top of it [this condition will be referred as "cup-cap (CC)"]. Five trials, each 5 s in duration, were collected in each experimental condition.

If the cup or its cap was dropped, the trial was discarded and repeated. The order of experimental conditions was randomized.

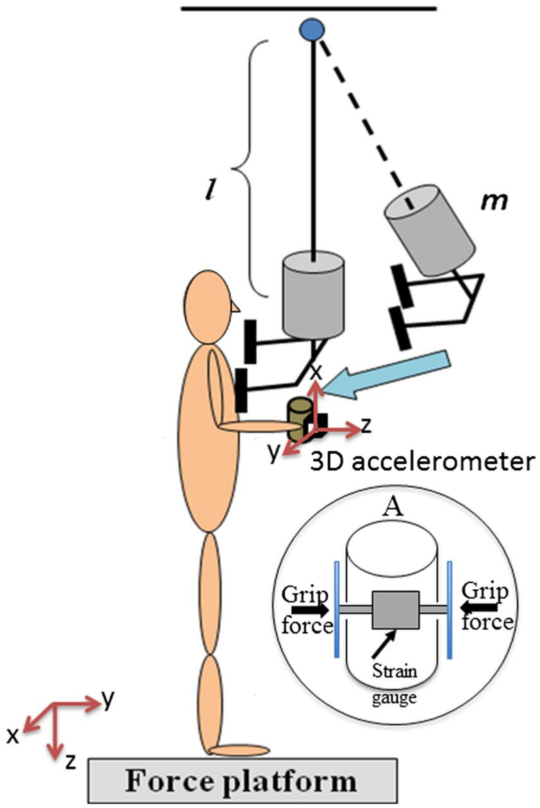

**Fig. 1** Schematic representation of the experimental setup. Subjects held an instrumented cup (schematically shown in the *circle A*) and received a perturbation at the shoulder level. The three-axis accelerometer attached to the cup was used to measure the acceleration of the object in three orthogonal planes. *X* vertical, *Y* medial–lateral, *Z* anterior–posterior

The forces, moments of forces, and accelerometer signals were digitized with a 16-bit A/D card at 1000 Hz using LabView 8.6.1 software (National Instruments, USA).

MATLAB (MathWorks, USA) was used for data processing. The moment of pendulum impact ($T_0$) and movement of the cup (in three directions) were derived from the acceleration signals using the Teager–Kaiser (TKE) onset time detection method (Li et al. 2007). The method that applies nonlinear Teager–Kaiser energy operator to surface EMG signal, and simultaneously consider both the amplitude and instantaneous frequency of the EMG data, increases the ability of detection of the onset of muscle activity (Li et al. 2007).

Baseline grip force applied to the strain gauge by the standing participant holding the cup was measured at the beginning of each trial (from 50 to 249 ms). Grip force onset time was measured at the moment when grip force was greater than the mean ± 2 SD of its baseline value. $\Delta$ (delta) grip force was calculated by subtracting the value of the baseline grip force from the peak value of grip force. Peak acceleration of the cup was measured as the maximum acceleration in each of the three directions during the task performance (m/s$^2$). Center of pressure (COP) displacement in the anterior–posterior direction was calculated using equations described in the literature (Winter et al. 1996) as

$$\text{COP} = \left[M_x - \left(F_y \times d_z\right)\right]/F_z$$

where $M_x$ is the moment in the sagittal plane, $F_z$ and $F_y$ are the vertical and the anterior–posterior components of the ground reaction force, and $d_z$ is the distance from the origin of the platform to the surface (0.038 m). The COP magnitude at $T_0$ which is anticipatory in nature and the peak displacement (maximum displacement after $T_0$) that is compensatory in nature were calculated.

First, repeated measures ANOVA was performed for the grip force, COP data, and acceleration data individually. Five trials collected in each experimental condition have been included in the analysis. CO and CC were used as within-subject factors. Then, in order to see the effect of changes in the task demands, one-way ANOVA was employed to evaluate the onset time mean difference of the cup acceleration, grip force, and COP displacement. To analyze the cup acceleration, both times of maximum and minimum acceleration were obtained, and then the type of the acceleration was used as a between-group factor in the repeated measures analysis to decide the direction of the movement. If the maximum acceleration happened before the minimum acceleration, then the maximum acceleration was used for further analysis, and vice versa. Post hoc analyses were done using the Dunn–Sidak correction for multiple comparison adjustments. Critical value was set at $\alpha = 0.05$. The data are presented as mean ± standard errors. Omega squared was provided as the effect size.

## Results

The baseline grip force in the CO condition was 11.19 ± 2.5 N, and it was 9.25 ± 0.93 N in the CC condition ($F(1,9) = 0.78$, $p = 0.4$). Grip force increased prior to the perturbation in both the experimental conditions; however, the moment of application of anticipatory grip force was different between the CO and CC conditions (Fig. 2). Thus, grip force onset time for the cup-only condition was −261.24 ± 24.93 ms, and for the cup-cap condition, it was −362.16 ± 42.13 ms. The difference in the onset time of grip force between the two conditions was statistically significant ($F(1,9) = 7.40$, $p = 0.024$, $\hat{w}^2 = 0.242$). After the perturbation impact, the delta grip force was 7.85 ± 2.43 N in the cup condition, and it was 6.16 ± 2.23 N in the cup-cap condition. The difference in the delta grip force between two conditions was statistically significant ($F(1,9) = 5.19$, $p = 0.049$, $\hat{w}^2 = 0.173$). The timing of the application of maximum grip force to the object was 138.40 ± 19.32 ms after the perturbation ($T_0$)

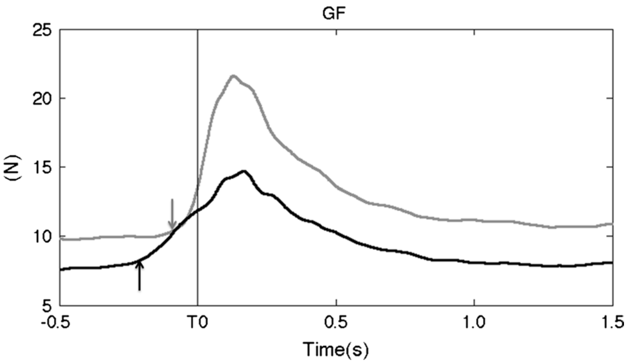

**Fig. 2** A typical example of grip force (GF) in the cup-only (CO) condition (*gray line*) and the cup-cap (CC) condition (*black line*). The *vertical line* at $T_0$ represents the moment of the pendulum impact. *Gray* and *black arrows* indicate the onset time in the CO and CC conditions, respectively

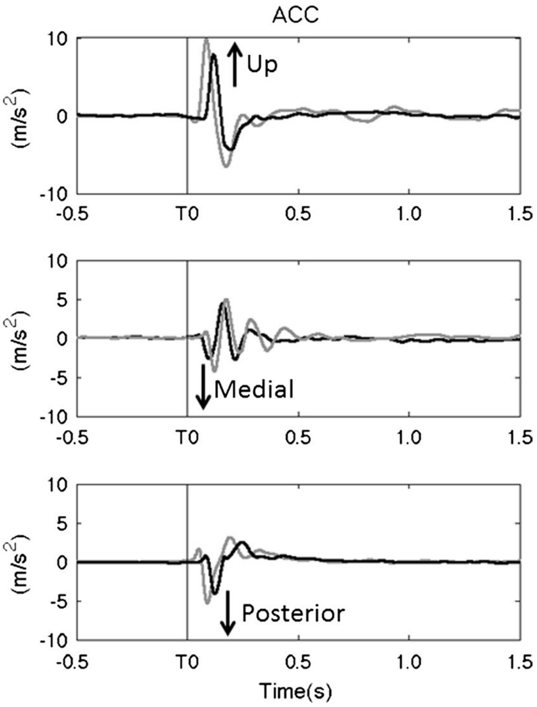

**Fig. 3** A typical example of the acceleration (ACC) in the up–down, medial–lateral, and anterior–posterior directions. *Gray lines* represent the cup-only (CO) condition, and *black lines* represent the cup-cap (CC) condition. The *vertical lines* at $T_0$ show the moment of the pendulum impact on the subject's shoulders. *Arrows* indicate the direction of the object movement

**Table 1** Grand mean of magnitude of the peaks of three-dimensional accelerations with corresponding time in the cup-only (CO) and cup-cap (CC) conditions

| Experimental condition | Acceleration plane | Magnitude | Negative | Positive |
|---|---|---|---|---|
| CO | Up–down | Peak timing | $-0.049 \pm 0.004$ m/s$^2$ (171.30 ± 6.38 ms) | $0.085 \pm 0.006$ m/s$^2$ (80.48 ± 6.38 ms) |
| CC | | Peak timing | $-0.047 \pm 0.006$ m/s$^2$ (163.24 ± 7.22 ms) | $0.084 \pm 0.006$ m/s$^2$ (79.90 ± 7.22 ms) |
| CO | Medial–lateral | Peak timing | $-0.035 \pm 0.003$ m/s$^2$ (102.10 ± 19.42 ms) | $0.033 \pm 0.005$ m/s$^2$ (185.46 ± 19.42 ms) |
| CC | | Peak timing | $-0.032 \pm 0.002$ m/s$^2$ (95.02 ± 12.74 ms) | $0.033 \pm 0.004$ m/s$^2$ (166.18 ± 12.74 ms) |
| CO | Anterior–posterior | Peak timing | $-0.055 \pm 0.005$ m/s$^2$ (88.56 ± 6.10 ms) | $0.029 \pm 0.003$ m/s$^2$ (200.00 ± 6.10 ms) |
| CC | | Peak timing | $-0.050 \pm 0.004$ m/s$^2$ (87.12 ± 6.23 ms) | $0.026 \pm 0.002$ m/s$^2$ (202.62 ± 6.23 ms) |

in the cup-only condition, and it was 111.28 ± 14.54 ms in the cup-cap condition. The difference in the time of maximal grip force between the two conditions was statistically significant ($F(1,9) = 5.93$, $p = 0.03$, $\hat{w}^2 = 0.198$).

The changes in the magnitude of the acceleration of the handheld object shown in Fig. 3 confirm that the object started moving only after the perturbation onset ($T_0$). Thus, the object started accelerating in the medial–lateral direction at 10.68 ± 5.16 ms after $T_0$ in the CO condition and at 22.02 ± 4.42 ms in the CC condition. The difference in the timing of the acceleration was significantly affected by the experimental condition (absence or presence of the plastic cover on the top of the cup) ($F(1,9) = 5.32$, $p = 0.04$, $\hat{w}^2 = 0.178$). In the anterior–posterior direction, the object started to move the object at 12.32 ± 4.32 and 14.96 ± 8.30 ms after $T_0$ in the CO and CC conditions, respectively. The movements of the cup in the up–down direction were recorded at 17.06 ± 5.68 and 19.36 ± 8.25 ms after $T_0$ in the CO and CC conditions, respectively. The differences in the maximal acceleration of the object in the anterior–posterior or up–down directions between the conditions, however, were not statistically significant (Table 1).

There were changes in the directions of the object movement in response to the perturbation impact. Thus, after the perturbation, the object started moving in the medial direction, which is confirmed by the observed negative peak of the acceleration signal. The negative peak of the ML acceleration was seen at 102.10 ± 19.42 ms for CC and at 95.02 ± 12.74 ms for CO conditions. In the anterior–posterior direction, the object started moving in the posterior direction as the negative peak was observed at 88.56 ± 6.10 ms for CO and at 87.12 ± 6.23 ms for CC. Furthermore, the positive peak value was observed at 80.48 ± 6.38 ms for the CO and at 79.90 ± 7.22 ms for CC in the up–down direction, suggesting that the object moved up.

The COP displacement was observed prior to the perturbation impact (Fig. 4). For the group, the onset of the COP displacement was seen at −127.38 ± 20.12 and −131.48 ± 15.30 ms for the CO and CC conditions, respectively. The COP displacement at $T_0$ was $-0.011 \pm 0.002$ and $-0.007 \pm 0.003$ m for the CO and CC conditions, respectively ($F(1,9) = 5.02$, $p = 0.05$, $\hat{w}^2 = 0.167$). However, there was no significant difference between the two conditions for the COP maximum displacement as the COP max was $-0.047 \pm 0.004$ and $-0.051 \pm 0.005$ m in the CO and CC conditions, respectively. The maximum COP displacement was recorded at 212.00 ± 34.40 and 232.62 ± 44.34 ms after the perturbation for the CO and CC conditions, respectively.

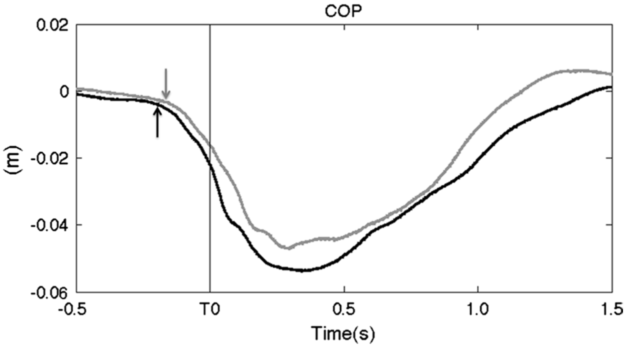

**Fig. 4** A typical example of the COP trajectory in the cup-only (CO) condition (*gray line*) and the cup-cap (CC) condition (*black line*). The *vertical line* at $T_0$ indicates the moment of the pendulum impact on the subject's shoulders. *Gray* and *black arrows* indicate the onset time of the COP displacement in the CO and CC conditions, respectively

Figure 5 shows the temporal sequence of the events related to the performance of the task in the cup-only (CO) and cup-cap (CC) conditions. The first event was the application of grip force to the object followed by the COP displacement; both events happened prior to the perturbation impact. Subsequently, after the perturbation, the handheld object started moving in the AP direction, then in the ML direction and in the up direction. After that, grip force reached its maximal value followed by the maximal COP displacement.

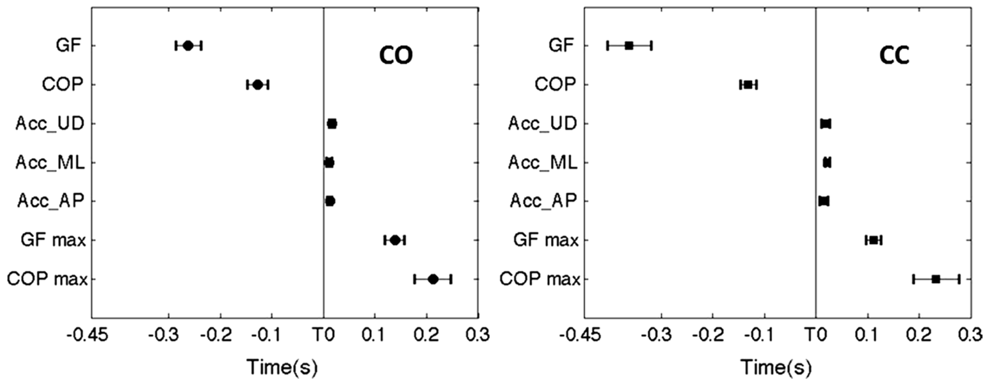

**Fig. 5** Onset times of grip force (GF), center of pressure (COP), three-dimensional accelerations in the up–down (Acc_UD), medial–lateral (Acc_ML), and anterior–posterior (Acc_AP) directions, maximum grip force (GF max), and maximum COP displacement (COP max) in the cup-only (CO) and cup-cap (CC) conditions. The *vertical line* at $T_0$ indicates the moment of the pendulum impact

## Discussion

Maintaining balance while being perturbed is a challenging task that requires the CNS to employ anticipatory and compensatory strategies. Keeping balance when holding an object and being perturbed is an even more challenging task that necessitates dealing with both balance maintenance and object stabilization. The current study clearly demonstrated that anticipatory control was used to control grip force and posture. Moreover, it demonstrated that when the CNS maintains balance in response to the external perturbation while the participant holds an object, its focus is first to stabilize the object in anticipation of the perturbation and then give attention to the body stabilization. Thus, the first hypothesis that when holding an object and being perturbed, the onset of grip force will precede the COP movements was supported. We also observed the subjects applying smaller magnitudes of grip force when holding the cup with a slippery cap. Thus, the second hypothesis that smaller magnitude of grip force will be observed in the higher demanding condition was also supported.

### Holding an object and postural control

It is known that postural balance is improved when standing and holding an object in the hand. Such an improvement of balance was shown in infants holding a visually attractive toy (Shumway-Cook et al. 1997) and young adults holding a stick (Ustinova and Langenderfer 2013). It was also demonstrated that balance is improved by applying a light touch to a stationary surface (Jeka and Lackner 1994). It was proposed that in such a condition, the CNS utilizes an extra sensory input provided through tactile and proprioceptive receptors to better control balance (Jeka and Lackner 1994). It was suggested in the literature that one possible explanation for the minimization of postural sway when holding an object could be associated with the effect of the suprapostural task (Stoffregen et al. 1999, 2000). As such, holding an object could be associated with improvement of overall balance control. Indeed, in the current study, we found a marginally significantly smaller COP displacement in the APA phase and larger COP displacements during the CPA phase when the participants performed a higher demanding task as compared to the less demanding task (CO). It is known that motor performance of the participants could be significantly affected by adding a cognitive task (Shumway-Cook et al. 1997). While no cognitive task per se was used in the current study, the observation of larger COP displacements during balance restoration phase while performing a higher demanding task suggests that, similarly to the cognitive task, performance of a high demanding motor task could serve as a constraint (Johannsen et al. 2007) affecting control of vertical posture when encountering an external perturbation. It is quite possible that in case of increased demands of the holding task, the CNS categorizes it as the primary task and thus focuses first on the stabilization of the object. Consequently, in such experimental conditions, a postural task might be considered as a secondary task; the likelihood of such a scenario is supported by the observation of smaller COP displacement at $T_0$ (that indicates diminished APA generation (Santos et al. 2010a, b) in conditions with holding CC. Another possible explanation of the observed changes in the magnitude of the COP displacements could be that holding an object is a suprapostural task (Stoffregen et al. 1999, 2000). Taken into consideration that increasing task demands could reduce body sway of subjects standing still (Mitra 2004), the observed smaller COP displacement in the APA phase could be an indication of the CNS first goal is to stabilize the cup-cap object, which is a high demanding task. As a consequence, the COP displacements in the CPA phase increase.

### Changes in grip force and external perturbation

Grip force in the current study was increased in anticipation of the forthcoming perturbation. This outcome is in line with the prior literature describing that grip force application is based on the prediction of the consequence of a perturbation [see, e.g., Bleyenheuft et al. (2009)]. Thus, changes in grip force during self-initiated movements typically are observed in anticipation to the load force (Flanagan and Wing 1993; Wing et al. 1997; Johansson and Westling 1984) or in response to predictable external load perturbations (Kwok and Wing 2006; Serrien et al. 1999; Turrell et al. 1999; Weeks et al. 2000). In the current study, in order to stabilize the cup, grip force was modulated based on the predictions of the magnitude of the external perturbation. In addition, change in grip force was found to be different between the two experimental conditions. Based on the facilitatory control theory (Stoffregen et al. 1999; Mitra 2004), one can suggest that when there is no imminent danger to postural stabilization, the CNS would most likely fine-tune the suprapostural task performance by exerting grip force earlier and using grip force needed for manipulation more optimally. Since no significant difference was found in the grip force baseline and mass of the object, the later explanation is more plausible. Similarly, one can expect that with an earlier onset and smaller change in grip force, the maximum grip force would be reached earlier in the CC condition compared to the CO condition.

### Sequence of events

A distinct order of the events was observed during the performance of the experimental tasks. Thus, both grip force onset and COP onset were observed within the APA phase. Although the movements of the cup started around 10–20 ms after the perturbation ($T_0$), they still could be considered as happening during the APA phase (Kanekar et al. 2008; Santos et al. 2010a; Krishnan et al. 2012; Chen et al. 2015). The onsets of the COP displacement and grip force that occurred prior or close to the onset of the perturbation reported in the current study are in line with the previous literature (Flanagan and Wing 1993; Aruin and Latash 1995; Wing et al. 1997; Lee and Aruin 2015).

Our results also showed that the moment of maximum grip force preceded the maximum COP displacement. This outcome suggests that as long as there was not an imminent danger of postural destabilization and the suprapostural task required a high precision demand (Mitra 2004), the CNS may prioritize the ongoing task of holding an object taking into consideration the complexity of the tasks. Such a strategy could allow balance to be restored while holding the handheld object without dropping it, even when the object itself has no stabilizing value (Bateni et al. 2004). Interestingly, the temporal order of the events started with grip force onset, COP onset, and followed with cup onset. It implies that in the presence of a predictable external perturbation, the CNS most likely increases grip force to stabilize the object in anticipation of the perturbation. It looks like the movement of the cup served as fine-tuning while reacting to both the external perturbation induced by a pendulum and the internal perturbation induced by the COP displacement observed in the APA phase. Moreover, the observed earlier movements of the cup in the CO condition provide an additional evidence to support a suggestion that movements of the cup most likely served as a fine-tuning strategy during the task performance because the onset of COP displacement in the CO condition was later than the CC condition. It looks like the CNS adjusted the spatial position of the cup earlier in the CO condition compared to the CC condition to stabilize the object and fulfill the requirements of the motor task performance. The temporary sequence revealed that the handheld object moved in the medial, posterior, and upward directions when the subjects encountered a predictable external perturbation.

The observed sequence of the events indicates that the CNS not only controls the posture component but also modulates the generation of grip force in order to maintain the position of the handheld object in the presence of an external perturbation and does it efficiently. The outcome of the current study provides a foundation for future studies of individuals with impaired grip and postural control such as stroke or multiple sclerosis (Slijper et al. 2002; Aruin 2005; Iyengar et al. 2009b; Aruin et al. 2015). At the same time, we would like to mention some limitations of the study. One is that the participants were a convenient sample of college students and as such could not represent the wider population. Another limitation is a relatively small sample size that most likely was a reason for observing a marginal significance of the changes in the anticipatory COP displacements.

## Conclusion

Grip force onset preceded the onset of the COP displacement and onset of the acceleration of the handheld object during the APA phase of postural control. The maximum grip force was observed before the maximum of the COP displacement during the CPA phase of postural control. Earlier grip force onset, smaller change in grip force, and lager maximum COP displacement were found when the subjects performed a more difficult task of holding a cup with a cap on top of it. The findings highlight the importance of investigating the strategy that the CNS uses while dealing with postural–suprapostural tasks. The study outcomes provide a foundation for future investigations of performance of the suprapostural and postural tasks by people with impairments of control of balance and grip force.

**Acknowledgments** We thank Charlie Ma for help in data collection. This work was supported in part by the NIH, Grant No. HD064838 and NIDRR Grant No. H133P110004.

**Compliance with ethical standards**

**Conflict of interest** The authors declare that there are no conflict of interest.

## References

Albertsen IM, Temprado JJ, Berton E (2010) Effect of haptic supplementation on postural stabilization: a comparison of fixed and mobile support conditions. Hum Mov Sci 29:999–1010

Alexandrov AV, Frolov AA, Horak FB, Carlson-Kuhta P, Park S (2005) Feedback equilibrium control during human standing. Biol Cybern 93:309–322

Aruin AS (2005) Support-specific modulation of grip force in individuals with hemiparesis. Arch Phys Med Rehabil 86:768–775

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

Aruin AS, Kanekar N, Lee YJ (2015) Anticipatory and compensatory postural adjustments in individuals with multiple sclerosis in response to external perturbations. Neurosci Lett 591:182–186

Bateni H, Zecevic A, McIlroy WE, Maki BE (2004) Resolving conflicts in task demands during balance recovery: does holding an object inhibit compensatory grasping? Exp Brain Res 157:49–58

Bleyenheuft Y, Lefevre P, Thonnard JL (2009) Predictive mechanisms control grip force after impact in self-triggered perturbations. J Mot Behav 41:411–417

Chen B, Aruin AS (2013) Does the type of somatosensory information from the contralateral finger touch affect grip force control while lifting an object? Neurosci Lett 556:196–199

Chen B, Lee YJ, Aruin AS (2015) Anticipatory and compensatory postural adjustments in conditions of body asymmetry induced by holding an object. Exp Brain Res 233:3087–3096

Diermayr G, Gysin P, Hass CJ, Gordon AM (2008) Grip force control during gait initiation with a hand-held object. Exp Brain Res 190:337–345

Flanagan JR, Wing AM (1993) Modulation of grip force with load force during point-to-point arm movements. Exp Brain Res 95:131–143

Flanagan JR, Tresilian J, Wing AM (1993) Coupling of grip force and load force during arm movements with grasped objects. Neurosci Lett 152:53–56

Gordon AM, Forssberg H, Johansson RS, Westling G (1991) Visual size cues in the programming of manipulative forces during precision grip. Exp Brain Res 83:477–482

Gysin P, Kaminski TR, Gordon AM (2003) Coordination of fingertip forces in object transport during locomotion. Exp Brain Res 149:371–379

Horvat M, Croce R, Tomporowski P, Barna MC (2013) The influence of dual-task conditions on movement in young adults with and without Down syndrome. Res Dev Disabil 34:3517–3525

Iyengar V, Santos MJ, Ko M, Aruin AS (2009a) Effect of contralateral finger touch on grip force control in individuals with multiple sclerosis. Clin Neurophysiol 120:626–631

Iyengar V, Santos MJ, Ko M, Aruin AS (2009b) Grip force control in individuals with multiple sclerosis. Neurorehabil Neural Repair 23:855–861

Jeka JJ, Lackner JR (1994) Fingertip contact influences human postural control. Exp Brain Res 100:495–502

Johansson RS, Westling G (1984) Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. Exp Brain Res 56:550–564

Johannsen L, Wing AM, Hatzitaki V (2007) Effects of maintaining touch contact on predictive and reactive balance. J Neurophysiol 97:2686–2695

Kanekar N, Santos MJ, Aruin AS (2008) Anticipatory postural control following fatigue of postural and focal muscles. Clin Neurophysiol 119:2304–2313

Kennedy A, Guevel A, Sveistrup H (2014) Impact of forearm fatigue on the postural response to an externally initiated, predictable perturbation. Eur J Appl Physiol 114:1473–1481

Krishnan V, Kanekar N, Aruin AS (2012) Feedforward postural control in individuals with multiple sclerosis during load release. Gait Posture 36:225–230

Kwok HF, Wing AM (2006) Time-based prediction in motor control: evidence from grip force response to external load perturbations. Exp Brain Res 175:183–190

Lee YJ, Aruin AS (2015) Effects of asymmetrical stance and movement on body rotation in pushing. J Biomech 48:283–289

Li X, Zhou P, Aruin AS (2007) Teager–Kaiser energy operation of surface EMG improves muscle activity onset detection. Ann Biomed Eng 35:1532–1538

Massion J (1992) Movement, posture and equilibrium: interaction and coordination. Prog Neurobiol 38:35–56

Mitra S (2004) Adaptive utilization of optical variables during postural and suprapostural dual-task performance: comment on Stoffregen, Smart, Bardy, and Pagulayan (1999). J Exp Psychol Hum Percept Perform 30:28–38

Morioka S, Hiyamizu M, Yagi F (2005) The effects of an attentional demand tasks on standing posture control. J Physiol Anthropol Appl Hum Sci 24:215–219

Muller ML, Redfern MS, Jennings JR (2007) Postural prioritization defines the interaction between a reaction time task and postural perturbations. Exp Brain Res 183:447–456

Nowak DA, Hermsdorfer J (2006) Predictive and reactive control of grasping forces: on the role of the basal ganglia and sensory feedback. Exp Brain Res 173:650–660

Nurwulan NR, Jiang BC, Iridiastadi H (2015) Posture and texting: effect on balance in young adults. PLoS One 10:e0134230

Plummer P, Eskes G, Wallace S, Giuffrida C, Fraas M, Campbell G, Clifton K, Skidmore ER, American Congress of Rehabilitation Medicine Stroke Networking Group Cognition Task F (2013) Cognitive-motor interference during functional mobility after stroke: state of the science and implications for future research. Arch Phys Med Rehabil 94:2565–2574 **(e2566)**

Reilly DS, Woollacott MH, van Donkelaar P, Saavedra S (2008) The interaction between executive attention and postural control in dual-task conditions: children with cerebral palsy. Arch Phys Med Rehabil 89:834–842

Riccio GE, Stoffregen TA (1988) Affordances as constraints on the control of stance. Hum Mov Sci 7:265–300

Santos MJ, Kanekar N, Aruin AS (2010a) The role of anticipatory postural adjustments in compensatory control of posture: 1. Electromyographic analysis. J Electromyogr Kinesiol 20:388–397

Santos MJ, Kanekar N, Aruin AS (2010b) The role of anticipatory postural adjustments in compensatory control of posture: 2. Biomechanical analysis. J Electromyogr Kinesiol 20:398–405

Serrien DJ, Kaluzny P, Wicki U, Wiesendanger M (1999) Grip force adjustments induced by predictable load perturbations during a manipulative task. Exp Brain Res 124:100–106

Shumway-Cook A, Woollacott M, Kerns KA, Baldwin M (1997) The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. J Gerontol A Biol Sci Med Sci 52:M232–M240

Slijper H, Latash ML, Rao N, Aruin AS (2002) Task-specific modulation of anticipatory postural adjustments in individuals with hemiparesis. Clin Neurophysiol 113:642–655

Stoffregen TA, Smart LJ, Bardy BG, Pagulayan RJ (1999) Postural stabilization of looking. J Exp Psychol Hum Percept Perform 25:1641–1658

Stoffregen TA, Pagulayan RJ, BtG Bardy, Hettinger LJ (2000) Modulating postural control to facilitate visual performance. Hum Mov Sci 19:203–220

Temprado JJ, Monno A, Laurent M, Zanone PG (2001) A dynamical framework to understand performance trade-offs and interference in dual tasks. J Exp Psychol Hum Percept Perform 27:1303–1313

Turrell YN, Li FX, Wing AM (1999) Grip force dynamics in the approach to a collision. Exp Brain Res 128:86–91

Ustinova KI, Langenderfer JE (2013) Postural stabilization by gripping a stick with different force levels. Gait Posture 38:97–103

Weeks DL, Wallace SA, Noteboom JT (2000) Precision-grip force changes in the anatomical and prosthetic limb during predictable load increases. Exp Brain Res 132(3):404–410

Wing AM, Flanagan JR, Richardson J (1997) Anticipatory postural adjustments in stance and grip. Exp Brain Res 116:122–130

Winter DA, Prince F, Frank JS, Powell C, Zabjek KF (1996) Unified theory regarding A/P and M/L balance in quiet stance. J Neurophysiol 75:2334–2343

Woollacott M, Shumway-Cook A (2002) Attention and the control of posture and gait: a review of an emerging area of research. Gait Posture 16:1–14