

Title: Visual feedback of the centre of gravity to optimize standing balance

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ABSTRACT

Force platform biofeedback training, whereby concurrent visual feedback of the centre of pressure (COP) is provided, has previously been used for balance training. Since the goal of balance is to maintain control of the centre of gravity (COG), specific feedback of the COG may be more likely than COP feedback to improve overall balance control. The purpose of this study was to compare the effect of concurrent visual feedback of the COP versus COG on postural control during a novel quiet standing task. Thirty-two young healthy adults (20-35 years old) were recruited. Participants were randomly assigned to receive concurrent visual feedback of either the COP or COG while standing on a foam pad. Training occurred over one session (20 30-second trials). Retention and transfer testing (i.e. without concurrent visual feedback) occurred after ~24 hours. Variability of the COG decreased, variability of COP-COG increased, and sample entropy increased with concurrent visual feedback. With practice, variability of COP, COG and COP-COG decreased whereas sample entropy increased. The decrease in variability of COP-COG was greater for those who received COG feedback than those who received COP feedback. Training effects on COP, COG and COP-COG variability were not retained after 24 hours and removal of visual feedback. However, on retention and transfer testing, sample entropy was significantly higher than on baseline testing, indicating more 'automatic' postural control. These results suggest that concurrent visual feedback of neither the COP nor COG is superior for improving quiet standing balance control.

INTRODUCTION

During quiet, unperturbed standing, small ankle and hip adjustments act to maintain balance in the face of continuous postural sway. This quiet standing balance control can be considered a learned feature of the central nervous system¹ that, similar to other learned motor skills, can improve with practice. Studies involving repeated testing of quiet standing balance have observed either short-term (within session^{2,3}) or long-term (across days^{4,5}) reductions in postural sway with repetition of a quiet standing task. Although acquisition of a novel balance skill may be dependent on initial balance capacity,⁶ this improvement putput tcan occur for a relatively simple, presumably well-learned, task (i.e. standing still) among healthy young individuals and without any instruction or experimental strategy to promote learning.

While balance control may not be considered a novel motor skill beyond childhood, the same principles of learning that apply to learning novel motor skills can be applied to continually refine balance control across the life span, or re-learn balance control following neurological injury.¹ Augmented feedback is frequently used to aid learning of novel motor skills by providing learners with information about performance of the skill not appreciated by their own sensory feedback.⁷⁻⁹ One popular option for balance training is to have participants stand on a force platform while providing continuous visual feedback of the centre of pressure (COP) and instructing participants to minimize movement of the COP in quiet standing.¹⁰⁻¹⁵ This type of training appears to be effective for reducing postural sway and improving balance control among older adults.¹⁴

Alternatively, force platform biofeedback could provide individuals with feedback regarding the estimated location of the centre of gravity (COG). Balance control focuses on the outcome of maintaining stability, with less emphasis on how that stability was maintained. The process by which balance control is learned may reflect this distinction. The outstanding question, with respect to balance control, is what feature of balance responses individuals identify in order to learn from experience. In quiet standing when only the feet are in contact with the ground, the goal is to maintain control of the COG, which is accomplished by ankle and hip movements that alter the location of the COP.¹⁵ Therefore, the COP acts as a controlling variable of the true outcome of interest: the *COG*, which is the controlled variable. Previous research has found that visual feedback of the COP can indeed reduce variability of movement of both the COP and the COG.¹⁶ However, given that the COP is simply a controlling variable of the COG, it remains to be determined whether providing direct feedback of the COG, a more accurate indicator of performance, might result in different motor learning strategies that lead to overall improved balance control.

The purpose of this study was to determine the effect of providing feedback the COG versus feedback of the COP on control of a simple quiet standing balance task. It was hypothesized that healthy young adults who receive concurrent visual feedback of their COG during a single training session on an unstable surface will demonstrate a greater ability to minimize their COP-COG compared to a group which receives feedback of their COP. A secondary objective was to explore changes in attentional investment in postural control over the course of the training period.

METHODS

Participants

Thirty-two healthy young adults (16 men, 26 ± 4 years old) participated in this study (Table 1). The study was reviewed and approved by the Research Ethics Board at the University Health Network and all participants provided informed consent prior to participating. None of the participants had any neurologic or musculoskeletal disorders that affected balance control. To ensure that participants could adequately view the visual feedback, participants were excluded if Snellen visual acuity was equal to or worse than 20/80 in either eye, indicating low vision; participants wore their usual glasses or contact lenses, if needed, for all testing. Participants were sub-stratified by sex and randomly allocated into one of two groups, ensuring an equal number of men and women in each group. The COP_f group received

visual feedback of their COP during the feedback trials whereas the COG_f group received visual feedback of their COG during the feedback trials.

Table 1: Participant information. Values are expressed as mean \pm standard deviation, unless otherwise indicated.

	COP _f group	COG _f group
Sex (#M/#F)	8/8	8/8
Age (years)	25 \pm 3	27 \pm 4
Height (m)	1.70 \pm 0.11	1.72 \pm 0.88
Weight (kg)	66 \pm 11	69 \pm 11

Protocol

Participants attended the laboratory on two consecutive days to complete a series of standing balance tasks. Participants stood barefoot or wearing socks only on a 40cm x 50cm foam pad (Balance-pad, Airex AG, Sins, Switzerland). The foam pad was used to provide greater challenge to balance control than standing on a firm surface within this healthy unimpaired group and, thus, to increase the likelihood that training effects would be observed. Feet were placed in a standardized foot position (0.17m between heel centres, with an angle of 14° between the long axes of the feet¹⁷), which was marked on the foam using tape. The foam was fixed on top of a single 50cm x 50cm force plate (Advanced Medical Technology Inc., Watertown MA, USA). A 21 inch computer monitor was placed approximately 60cm in front of the participant at eye level (**Figure 1**).

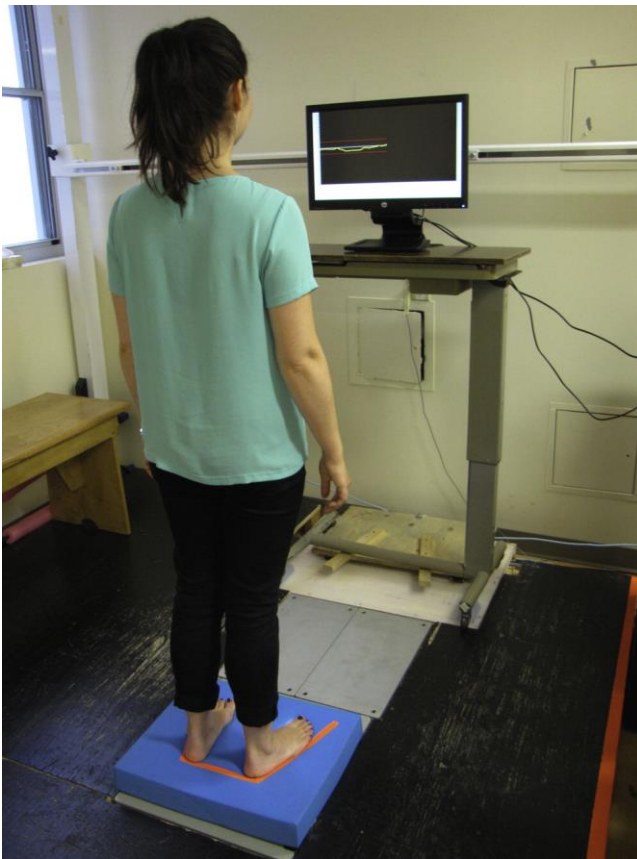


Figure 1: Participant setup. Participants stood on a foam pad in a standardized foot position (marked with orange tape on the pad) on top of a single force plate. During acquisition and retention trial blocks, participants received real-time visual feedback of either their COP or COG, dependent on group allocation.

The trial block order is presented in **Figure 2**. During the first session, participants completed five baseline (B) trials, in which they were instructed to stand as still as possible while maintaining eye contact with a fixed target that appeared on the screen in front of them. All trials were 35s in duration. The average COP and COG and the standard deviations of those measures of each participant were recorded in the baseline trials and were used to tailor the feedback provided to each participant. During the subsequent acquisition 20 trials in the first session (A1-A4), participants were provided real-time visual feedback at 200Hz of either their antero-posterior COP or COG (estimated from equations 1-4),¹⁸ dependent on their group allocation. COP or COG were only presented in the antero-posterior direction to reduce complexity of the feedback and allow participants to only focus on minimizing COP or COG in one direction. Additionally, the real-time estimate of COG (equation 4) can only be used in the antero-posterior direction.

Equation 1: $m = 0.971M$, where M = participant mass in kg

Equation 2: $h = 0.547H$, where H = participant height in m

Equation 3: $I = 0.319MH^2$

Equation 4: $COG = COP - \left(\frac{I}{mgh}\right) * F_y$, where F_y = force in the antero-posterior direction

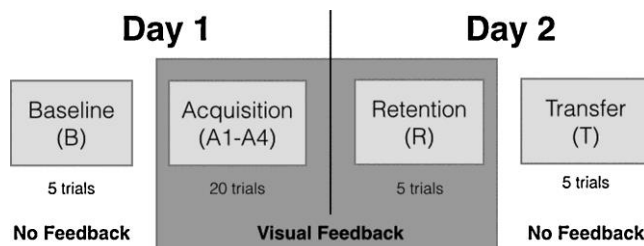


Figure 2: Protocol schematic. Participants attended the lab on two separate days, approximately 24 hours apart. Dark grey shading denotes that trials included visual feedback.

The feedback was presented on the display monitor as a fluctuating horizontal line that moved upwards as the COP or COG moved forwards and downwards as the COP or COG moved backwards. A single, white, horizontal line denoting the average COP or COG for the participant during the fifth trial in baseline testing was displayed on the graph at the midpoint. Two horizontal red lines were also placed on the graph at an upper and lower multiple of the standard deviation of the average COP or COG during the fifth trial of the baseline testing. During acquisition trials, participants were told that the feedback line represented the antero-posterior position of their body and were instructed to keep the line within the upper and lower boundary lines and to stay as close to the centre line as possible. The boundaries were reduced by 0.5 standard deviations of the mean baseline COP or COG every 5 trials, beginning at 3.0xSD.

Session 2 was completed approximately 24 hours after session 1 and participants performed a single retention block of five trials (R) where the upper and lower boundaries were set to 1.5xSD. Following this, participants completed a block of five transfer trials (T) where no feedback was provided and were instructed to stand as still as possible while focusing on an 'X' displayed on the screen in front of them.

Data collection and analysis

Force plate data were collected at 200Hz and stored for offline processing. Data were low-passed at 10Hz with a zero phase-lag dual-pass, 4th order Butterworth filter. A shear correction was applied to the COP to compensate for the height of the foam when depressed with a constant load. COG was recalculated using the zero point-to-zero point double integration method;¹⁹ this method has <1mm error when compared to calculation of the COG from 3-dimensional kinematics.²⁰ The first 5s of each

trial was discarded; thus, each analysed trial was 30s in duration. The primary outcome measures of interest were the root-mean square (RMS) of COP, RMS of COG and root-mean square error (RMSE) of the average difference between the AP COP and the COG. The RMSE provides an index of how closely the COP tracks the COG and has been considered a measure of error in the balance control system¹⁵ or of overall postural stability.²¹

$$\text{Equation 5: RMSE} = \sqrt{\frac{\sum_{i=1}^n (\text{COP}_i - \text{COG}_i)^2}{n}}$$

Sample entropy of the COP was calculated as a measure of regularity of postural control.²² Sample entropy is the negative of the natural logarithm of the conditional probability that a sequence will repeat itself for M+1 points given that it has already repeated itself for M points, within a specified tolerance. Increased sample entropy values indicate reduced COP path regularity and this is interpreted as increased automaticity of postural control (or reduced attentional investment in postural control).²²⁻²⁴ Sample entropy of the resultant COP position was calculated using a routine from PhysioNet;²⁵ using the method described by others²⁶ we determined input parameters M=3 and tolerance=0.04.

Statistical analyses

Statistical analyses focused on differences between groups between acquisition blocks, retention blocks and transfer blocks. Three separate two-way repeated measures analysis of variance (ANOVA) with trial block and group as main effects were completed for each test. Dependent variables were RMS of COP, RMS of COG, RMSE and sample entropy. Initial analysis determined the immediate effect of concurrent feedback on postural control by comparing the first block of trials with no feedback (B) to the first block of trials with feedback (A1). As there were substantial differences between control strategies when feedback was provided versus when no feedback was provided, the remaining analyses compared conditions with feedback to each other and conditions with no feedback to each other. Trial block comparisons were: A1 to A4 (acquisition); A4 versus R (retention); and B versus T (transfer). Where significant group-by-trial block interaction effects were observed, Tukey's range tests were completed to detect pairwise differences between trial blocks and groups.

RESULTS

All participants completed both days of testing without complications. Participant information is located in Table 1. There were no significant differences in age ($t_{30}=1.91$, $p=0.066$), height ($t_{30}=0.67$, $p=0.51$), and weight ($t_{30}=0.85$, $p=0.40$) between the two groups. The primary results are presented in **Figure 3**.

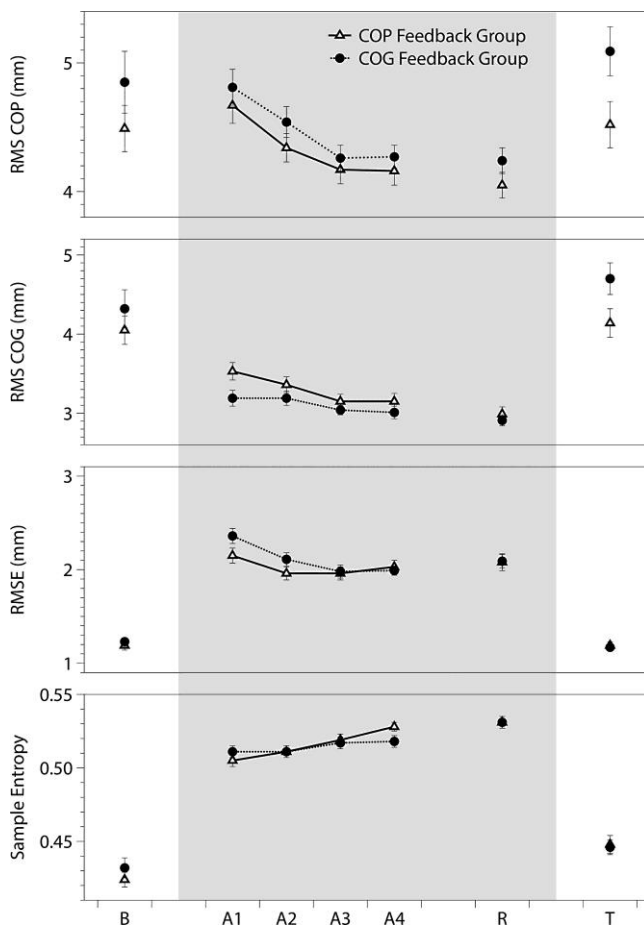


Figure 3: Averaged primary outcome measures by trial block. Grey shading indicates trial blocks that included visual feedback.

Immediate effects of feedback (B versus A1)

When comparing baseline trials (with no feedback) to the first block of trials with concurrent feedback, there were no significant group-by-trial block interactions for any variable ($F_{3,30} < 2.36$, $p > 0.14$). With concurrent feedback (A1), RMS of COG was significantly lower ($F_{3,30} = 17.14$, $p = 0.0003$), RMSE was significantly higher ($F_{3,30} = 344.98$, $p < 0.0001$), and sample entropy was significantly higher ($F_{3,30} = 119.61$, $p < 0.0001$) compared to trials without feedback (B). RMS of COP was not different between blocks B and A1 ($F_{3,30} = 0.11$, $p = 0.74$). Likewise, there were no significant between-group differences in dependent variables for these trial blocks ($F_{3,30} < 0.76$, $p > 0.39$).

Acquisition (A1 to A4)

During the acquisition phase (A1-A4), there were no significant group-by-trial block interactions for RMS of COP, RMS of COG, or sample entropy ($F_{3,90} < 1.55$, $p > 0.21$). There was a statistically significant main effect of trial block for RMS of COP, RMS of COG and sample entropy; RMS of COP ($F_{3,90} = 18.65$, $p < 0.0001$) and RMS of COG ($F_{3,90} = 6.60$, $p = 0.0004$) decreased and sample entropy increased ($F_{3,90} = 6.82$, $p = 0.0003$) for both groups from A1 to A4. There were no significant main effects for group for RMS of COP, RMS of COG or sample entropy during the acquisition period ($F_{1,30} < 0.76$, $p > 0.39$). With respect to RMSE, there was a significant group-by-trial block interaction ($F_{3,90} = 3.27$, $p = 0.025$). Tukey post-hoc testing revealed that RMSE was significantly larger in A1 than all other trial blocks within the COG_f group ($p < 0.05$) and that RMSE was significantly larger in A1 than A2 and A3 within the COP_f group ($p < 0.05$). Furthermore RMSE for was significantly lower for COP_f than COG_f in A1 ($p < 0.05$) but not in the other trial blocks.

Retention (A4 versus R)

When comparing the final block of acquisition trials to the retention block (24 hours later), there was no significant group-by-trial block interaction effect for any variable ($F_{1,30} < 1.71$, $p > 0.20$). Likewise, there were no significant main effects of trial block for RMS of COP ($F_{1,30} = 1.00$, $p = 0.32$) or RMSE ($F_{1,30} = 1.83$, $p = 0.19$). RMS of COG was significantly lower for both groups in R compared to A4 ($F_{1,30} = 6.36$, $p = 0.017$), whereas sample entropy was significantly higher for both groups in R compared to A4 ($F_{1,30} = 5.14$, $p = 0.031$). There were no significant main effects for group for any variable ($F_{1,30} < 0.39$, $p > 0.54$).

Transfer (B versus T)

There was no significant group-by-trial block interaction effect for any variable ($F_{1,30} < 1.08$, $p > 0.31$) when comparing baseline to the transfer test. There was no significant main effect for trial block on RMS of COP, RMS of COG or RMSE ($F_{1,30} < 1.39$, $p > 0.25$). Sample entropy was significantly higher for both groups in T compared to B ($F_{1,30} = 7.71$, $p = 0.0094$). There was no main effect for group on any variable ($F_{1,30} < 1.60$, $p > 0.21$).

DISCUSSION

The primary objective of this study was to explore how concurrent visual feedback of the COG and COP can be used during learning of a simple quiet standing balance task. As the goal of quiet standing is to minimize movement of the COG within the base of support, we hypothesized that visual feedback of the COG would improve learning compared to visual feedback of the COP. Using the RMSE of COP-COG as our primary measure of stability, we observed greater improvements in stability (i.e. greater reduction in RMSE) in the group that received feedback of the COG compared to the group that received feedback of the COP during the acquisition phase, in support of our hypothesis. There was no increase in RMSE from the end of the acquisition period to follow-up testing 24-hours later in both groups, providing evidence of retention of training effects. However, these effects did not transfer to the condition where visual feedback was removed so we cannot conclude that learning occurred.²⁷

When concurrent visual feedback was provided, variability of the COP was slightly lower for those who viewed feedback of the COP, whereas variability of the COG was slightly lower for those who received feedback of the COG. This suggests that the type of feedback provided to individuals while learning a balance task influences subtle differences in the strategy used to maintain balance. Early work exploring the role of biofeedback for the maintenance of postural control in individuals with hemiparesis often categorized COP and COG feedback together because of the lack of literature that distinguished between the two variables.²⁸ Participants in the current study appeared to adopt a strategy to minimize either COP or COG (depending on the feedback provided) by decoupling the two, which served to increase RMSE during feedback trials. While it appears, then, that participants were less stable with feedback, this instability was only apparent during the acquisition phase. Although not apparent in the current study, motor learning studies frequently observe that conditions which impair performance during acquisition can actually result in improved retention and transfer (i.e. learning).²⁷

Contrary to expectations, sample entropy of the COP was higher with concurrent visual feedback than without, indicating less regularity of COP fluctuations with feedback. From prior interpretations of sample entropy,^{22,24} this suggests that postural control demanded less attention with concurrent feedback of the COP or COG than without. It is possible that the visual feedback served to divert attention from balance control to the visual feedback, as with other dual-tasking paradigms;²² however, because the feedback was linked to balance control we would expect this shift in attention would have increased regularity of the COP. Furthermore, the concurrent visual feedback can be used to direct attention internally or externally.²⁹ COG feedback could be considered to promote an internal focus of attention, whereas, because the COP represents the interaction between the participant and the external

environment, COP feedback could be considered to promote an external focus. There were no differences in sample entropy between groups when concurrent feedback was provided, suggesting no differences in attentional investment in postural control with different attentional foci.²⁴ Sample entropy increased in both groups over the course of the acquisition period, from the end of the acquisition period to the retention test 24 hours later, and was higher for the transfer test than the initial baseline test (both without concurrent visual feedback). This suggests that, despite no apparent improvement in overall postural control (i.e. no reduction in RMSE), control was more automatic and less attention-demanding.³⁰ However, we did not include a no-feedback control group and cannot conclude that more automatic control was achieved due to concurrent visual feedback rather than repetition of the quiet standing task.

The healthy young adult population that participated in this study demonstrated a high level of baseline balance control as reflected by low RMSE. This indicates a potential floor effect that might explain the lack of improvement in RMSE following COP or COG training. It is possible that replication of this study with balance-impaired individuals (e.g. older adults or individuals with neurological injury) and/or with a more challenging balance task will yield further insights. While participants who received concurrent feedback of the COG seemed to acquire the skill better than those who received concurrent feedback of the COP, the COG_f group had higher RMSE of COP-COG at the start of the acquisition phase than those in the COP_f group. Thus, the significant finding may have been because the COG_f group had more room for improvement.

To conclude, this study found no differences between training with concurrent visual feedback of the COP or COG on young healthy adults' ability to learn a novel quiet standing balance task. Concurrent visual feedback temporarily induced instability and less regularity of postural control than without visual feedback. This study supports the feasibility of real-time concurrent visual feedback of the COP and COG that can be investigated in more balance-impaired individuals (e.g. older adults).

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