Title: Influence of visual biofeedback and inherent stability on trunk postural control

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Declarations of Interest: None.

CRedit author statement:

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Acknowledgements:

We thank members of the research group (Sara Fitzhugh, Makenna Lommori, Jernique Robertson, and Mark Rowley), for contribution to data collection and data processing. Funding for this study was received from the National Science Foundation (DARE #1803714) awarded to A.D. Goodworth and S. Saavedra.

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Abstract.

Background: For individuals who never achieve independent standing, rehabilitation is focused on trunk posture and balance control. Visual biofeedback has the potential to augment sitting balance training, however previous work in this area has been limited to standing.
Research Question: To what extent do different types of visual biofeedback influence trunk sway in sitting?
Methods: Twelve healthy young adults sat on an articulating bench. During 'sway referencing' trials, the bench tilted up and down in proportion to trunk sway in the frontal plane. This paradigm increased difficulty of the balance task and required participants to rely on visual and vestibular cues. Participants were provided different visual biofeedback through a rotating needle-gage display. Trials lasted 165 s, were ordered randomly, and included either direct feedback (needle rotated in proportion to body sway), inverted feedback (needle rotated in the opposite direction of sway), time delayed feedback (0.5 s), random feedback, eyes closed, or control (eyes open with screen off). To explore the impact of inherent stability, trials were repeated with and without external trunk support.
Results: Body sway depended on feedback type. Specifically, direct and inverted feedback reduced root-mean-squared (RMS) sway the most, time delayed feedback had a smaller effect, and random visual feedback increased participants' RMS sway compared to control. Frequency domain analyses demonstrated direct and inverted visual feedback reduced sway amplitude at the lower frequencies while having minimal effect on (or increasing) sway amplitude at higher frequencies.
Significance: This study extends previous work by showing that visual feedback can have powerful effects on sitting balance, even with external support. Results from the different types of feedback conditions further our understanding of how the brain interprets visual biofeedback. Frequency-based results were similar to previous studies using different modalities and suggest participants interpret biofeedback through sensory addition as opposed to sensory substitution.

Introduction

Trunk postural control is a foundational skill that underlies activities of daily living [1, 2]. Impaired balance of the trunk is prevalent in many populations [3-5] and trunk control has recently gained more attention as a focus in both assessments and training [4, 6-8]. In the current study, we examine how trunk postural control is influenced by different types of visual biofeedback.

Why visual biofeedback? Visual biofeedback studies have consistently demonstrated reduction in postural sway while standing [9-11]. Feedback of a particular segment reduces localized motion supporting the practice of targeted movement [11]. Effectiveness is seen in auditory feedback [12], vibrotactile feedback [13] , and feedback on the tongue [14]. Together, these studies suggest biofeedback has potential to encourage specific movement patterns and use of different sensory cues. Moreover, biofeedback is integrated into most gaming and virtual reality-based standing balance and mobility programs. These training methods have both theoretical and empirical support for increasing motivation and improving outcomes [15-17]. Not surprisingly, biofeedback is growing in research [10, 11, 13].

But for many populations lacking independent standing, training the trunk in sitting or with external trunk support is the only option [2, 4, 18, 19]. Therefore, we investigate sitting trunk postural control using detailed time and frequency domain analyses. An array of different types of visual biofeedback were chosen to broaden our understanding of how visual biofeedback is interpreted and used within the postural control system. Investigating different types of visual feedback also provides practical information for the design of biofeedback protocols. This is novel because previous standing studies either did not vary the type of feedback or only varied a couple types of feedback, typically different magnifications of visual biofeedback. In the current study, our biofeedback types include the following: 1) Direct visual feedback where an arrow on the screen rotates to the same angle as body sway. 2) Direct visual feedback amplified by five to explore the impact of visual cue resolution. 3) Inverted visual feedback where the arrow on the screen rotates in the opposite direction of body sway to test how well participants can transform direction coordinates. This condition gives insight into motor learning and may be a useful assessment tool for populations with impaired neural control. 4) Time-delayed visual feedback to better understand sensorimotor dynamics and to help optimize componentry in future biofeedback studies. 5) Noisy meaningless visual feedback to determine if participants can appropriately “turn off” visual reliance, which may also serve as a useful assessment tool. 6) Eyes closed to compare how postural control differs when altering biofeedback versus altering natural sensory feedback. 7) Eyes open, as a control condition.

In order to highlight the effect of visual biofeedback, our study focuses on an experimental paradigm associated with high visual reliance called surface sway referencing [20]. In surface sway referencing, the bench tilts in direct proportion to trunk sway which diminishes somatosensory cues from the pelvis and trunk. Finally, our study compares responses with and without external trunk support. While most previous studies use a single trunk segment model, the use of external support isolates the sensorimotor processes within different segments of the trunk, which is clinically relevant for many people with impaired motor control [2, 4, 18, 19].

Methods

Participants. Twelve healthy young adults were recruited (6 women and 6 men, mean age 26 ± 5.5 years, height 169.6 ± 6.7 cm, weight 70.9 ± 9.3 kg), provided a written informed consent, and were tested according to a protocol approved by the University of Hartford Institutional Review Board.

Backboard and Trunk Support. Participants were seated on a bench with their feet placed at a comfortable distance on a footrest that moved with the bench (Fig 1). During quiet sitting, the bench was stationary. During sway referencing, the bench tilted up and down in the frontal plane; the angle of bench tilt was equal to the participant's upper body sway angle with respect to upright (about 33 ms delay from the electromechanical equipment). Bench motion was controlled via a servomotor [19, 20]. The bench was limited to ±4.5 degrees. Body sway was measured with a frictionless potentiometer connected to a lightweight rigid backboard. The backboard only rotated in the frontal plane and was tightly attached to participants at the head and upper torso through straps. The backboard rested on a frame so that participants did not need to generate extra force when in an upright position. To ensure the pelvis and bench moved in unison, straps from the bench secured each participant's thighs and pelvis. When the backboard was placed at "Axis 1" (A1), no additional trunk support was used, and the axis of rotation (i.e. pivot point) on the backboard was set to L4/L5 for each participant. For "Axis 2" (A2), trunk support was added using rigid, padded side arms that pressed into the participants' waist at L1/L2 and the axis of rotation on the backboard was lifted upward and set to T12 (Fig. 1B photo). Although the backboard and head rest placed participants in an unnatural position compared to everyday life, advantages of the backboard include: 1) the backboard limited degrees of freedom, thereby providing an unambiguous signal to define as the reference during sway referencing and 2) it enabled a straightforward interpretation of how the trunk and head were oriented and what sensory cues were received. A previous study showed high similarity between a backboard and freestanding with participants who stood on a tilting platform that moved with amplitudes similar to the current [21]. Therefore, we expect our findings with a backboard are relevant to sitting without a backboard.

Protocol. Each participant was tested for 18 total trials: 9 trials at two levels of support (A1, A2). Each trial lasted 165 s, which included 30s of quiet sitting, then 105s of sway referencing, then 30s of quiet sitting. A minimum 60s break occurred after each trial. The 9 trials included 2 control eyes open (EO) trials (screen off) at the beginning and end of the session and 7 randomized trials in between. The randomized trials described in the Introduction and Table 1 included: eyes open with screen off (control), direct visual feedback, amplified direct feedback, inverted feedback, 500 ms time-delayed feedback, random feedback, and eyes closed. Random feedback was generated with low pass filtered (0.4 Hz 3^{rd} order) white Gaussian noise that visually resembled the sway patterns of an average participant during sway referencing. Each participant was instructed to stay as upright as possible and were told that the needle on the screen "might be helpful".

Analyses. Dependent variables included zero-mean root-mean-square (RMS) sway, RMS velocity, and the amplitude spectra. Amplitude spectra provides more detail of sway characteristics by decomposing a single time-domain waveform into its frequency components

[22]. In postural control, low frequency sway corresponds to the slow movements, typically largest in magnitude, whereas high frequency sway (>1Hz) corresponds to fast movements typically not visible to the naked eye. To facilitate analyses, we binned and averaged the amplitude spectra into low (0.05-0.175Hz), middle (0.25-0.85Hz), and high (1.3-2.75Hz) frequencies. Neural processes impact certain frequencies of trunk sway more than others: neural damping is most evident at mid-and high-frequencies, time delays are evident at higher frequencies, while stiffness and sensory reweighting are associated with frequencies below 2.5 Hz [20, 22, 23].

For the sway referencing period, the last 100 s of body sway was analyzed to avoid transient behavior during the first 5 s of sway referencing. The 100 s were divided into five consecutive 20 second periods. Dependent variables were calculated for each 20 s period and then averaged across the 5 periods (all 100 s of data was used).

Statistics. Dependent variables were analyzed using a repeated-measures ANOVA. The model included the following effects: support level (A1 vs. A2), trial type, and interaction of support and trial. Six post-hoc pair-wise comparisons were made between the control and 6 other trials with a Bonferroni correction. There was no significant difference across the three control trials in sway referencing and therefore dependent variables for the three control trials were averaged together for each participant in statistical models. In all main and interaction effects, statistical significance was $p < 0.05$.

Results

Qualitative differences across participants, trials, and support

Figure 2 provides representative sway patterns from two different participants. In Fig. 2A (participant 1), sway amplitude increases at the onset of sway referencing (30 s). Across trials, there is a decrease in sway amplitude from the eyes closed trial to control; and further decrease with direct visual biofeedback. Fig 2B show differences in sway between levels of support (A1-top vs. A2-bottom) for another participant. A2 (higher support) was associated with higher frequency movements. Finally, we found notable variability across participants - some participants had relatively low sway amplitude and others had high sway amplitude, illustrated in the comparison between Fig. 2A and 2B.

Variability across participants

Across all participants, the coefficient of variation (CV) in RMS during sway referencing was 41.8% (averaged across all trials). Eyes closed had the lowest CV across participants of about 27%, while random feedback had the largest CV of about 57%; which means that sway amplitude was most consistent across participants in eyes closed and most variable across participants during random feedback.

RMS sway and velocity results

Figures 3 provides a summary of the mean participant RMS sway and velocity across trials and Table 1 is a statistical summary. Trial type had a significant influence on RMS sway ($P<0.001$) and velocity ($P \leq 0.001$). RMS sway was significantly increased compared to control in eyes closed ($p<0.001$) and random feedback ($p<0.001$), while RMS sway was significantly decreased with direct ($p=0.002$) and amplified ($p<0.001$) visual biofeedback. RMS sway with direct and amplified direct biofeedback was 61% and 62% of control, respectively, in A1 and 79% and 65% of control, respectively, for A2.

In contrast, RMS velocity was less influenced by trial type with most trials either similar to, or larger than, velocity observed during the control. RMS velocity was significantly increased in eyes closed ($p<0.001$) and time delayed biofeedback ($p=0.005$) compared to control.

In the level of support comparison, A2 was associated with a 9% decrease in RMS sway ($p=0.056$) compared to A1 and a 15% significant increase in velocity ($p=0.001$) compared to A1. Importantly, significant interaction effects between level of support and trial were found in the RMS variable ($p<0.001$); meaning that participants' response to different trials was influenced by their level of support. Two notable interaction effects evident in Fig 3A include: 1) trials with eyes closed and random feedback increasing RMS sway more in A1 vs. A2 and 2) the time delayed biofeedback reduced RMS sway in A1 but increased sway in A2.

Frequency domain results

Amplitude spectra are presented in Fig. 4A for sway referencing. Fig. 4B presents body sway amplitude for each frequency point normalized to the control trial. In both A1 and A2, sway amplitude was elevated across all frequencies in eyes closed and random trials. Inverted (white circle) and time-delayed (grey circles) biofeedback reduced sway amplitude at the lowest two frequencies but either had minimal effects or increased sway amplitude across mid- and high-frequencies (~above 0.5 Hz). Direct biofeedback trials (white box and 'x') reduced sway across a wider bandwidth of frequencies.

Low frequencies had the most significant statistical effects: eyes closed ($p<0.001$) and random feedback ($p<0.001$) were significantly higher than control and direct ($p=0.002$) and amplified direct ($p<0.001$) biofeedback trials were significantly lower than control. Level of support also had a significant effect ($p=0.01$) on sway amplitude at low frequencies with A1 associated with larger sway. At mid frequencies, sway amplitude was significantly higher with eyes closed ($p<0.001$) and time delayed biofeedback ($p=0.005$) compared to control. At high frequencies, sway was significantly higher with both eyes closed ($p<0.001$) and random feedback ($p<0.001$) compared to control. At high frequencies, the significant effect of level of support ($p<0.001$) was due to an increase in A2 compared to A1, similar to the larger RMS velocity found in A2.

Discussion

Direct Visual Feedback consistently lowered sway

Our results extend previous research in standing [9-11] to show that people can use visual biofeedback to reduce sway amplitude in sitting. These postures are particularly relevant for populations with limited or impaired balance control who may benefit from new training protocols. Dewar et al. reviewed training studies in cerebral palsy and found positive results and retention with virtual reality and visual biofeedback programs in children who were able to stand but found very little research for children lacking independent sitting [17]. Similarly, a recent review of therapies for children with moderate to severe cerebral palsy summarized the field as lacking appropriate treatments for this population [24].

Direct visual feedback reduced RMS sway to a greater extent than velocity (similar to a previous standing study by Jehu et al.[10]) and sway reductions were most evident at low frequencies (consistent with Halicka et al.[11] in standing). In contrast, altering natural sensory feedback (eyes closed) resulted in increases across a wide bandwidth of frequencies and increased both RMS sway and velocity. Why the difference?

An explanation offered in previous studies is that people adopt a stiffening strategy with biofeedback that increases high frequency movements and muscle activation levels [25]. We offer an alternative explanation based on feedback control theory. Our previous work investigated vibrotactile feedback in standing during pseudorandom tilts of a platform. The normalized amplitude spectra (Fig. 5 in Goodworth et al. 2009 [26]) were similar to the current study showing clear improvements at low frequencies that diminished at higher frequencies. These results were interpreted through a sensory feedback model. The model explored different mechanisms [13] and found the best description for how vibrotactile feedback was used was through “sensory addition”, represented as an additional feedback loop. The same basic model described frequency-dependent changes in body sway with different natural sensory feedback (eg, eyes open vs. eyes closed) [21] and with the addition of biofeedback [26]. The primary difference between the biofeedback loop and natural sensory feedback was a heavy low pass filter within the vibrotactile feedback loop. This filter caused the differential effect of biofeedback at low vs. high frequencies and can be interpreted as “neural integration” which is likely influenced by voluntary control and cognitive effects [11, 20]. Given the similarity between vibrotactile feedback and visual biofeedback results, we suggest this model is useful for interpretating results.

Random and eyes closed consistently increased sway

Eyes closed trials increased sway amplitude across a wide bandwidth of frequencies similar to a previous study suggesting eyes open trials had less sensorimotor noise [20]. Less sensorimotor noise is expected in eyes open because both vision and vestibular cues contribute to a sense of upright. Similarly, random feedback increased sway amplitude across a wide bandwidth, suggesting that random feedback also added sensory noise to the balance system. Most participants in the current study noted an awareness that the biofeedback was meaningless and either looked toward the edge of the monitor or did not focus on the moving needle. The variable response to random feedback caused the high CV across participants with random feedback. Still, participants were not able to ignore the random feedback as it consistently increased sway amplitude. This underscores the powerful effect of visual cues on postural control.

Inverted and time-delayed feedback had mixed effects

Inverted feedback typically improved balance control, especially at low frequencies. Participants were able to adapt using coordinate transformations between direction of sway and direction of biofeedback. Coordinate transformations are part of healthy neural control [27]. Inverted feedback may be a valuable diagnostic test of adaptive control. Still, when considering rehabilitation, the more intuitive feedback (direct) was more effective in reducing sway.

Time-delayed feedback also reduced sway amplitude at the lowest frequencies but there were increases at mid frequencies, especially with A2, similar to previous standing studies [28]. The increases at mid-frequencies are reminiscent of an oscillating system. Control theory shows oscillations and instability with long time delays in a feedback system [29]. Thus, it is likely participants used the time delayed biofeedback and this large time delay contributed to increased sway amplitude at mid-frequencies. A large time delay in componentry should be of concern in biofeedback protocols.

Overall trends in A2 and A1 were similar

Despite a few differences between A1 and A2, the clear similarity in trends across trials should be highlighted. Direct and amplified direct biofeedback improved balance similarly for both A1 and A2. This finding suggests that the presence of visual biofeedback triggered participants to rely on vision similarly regardless of their inherent stability. In fact, the brief periods of quiet sitting could be considered the most inherently stable. We also analyzed the sway data in the first and last quiet sitting period and found the same general trends: RMS significantly increased with random feedback ($p<0.001$) and RMS significantly decreased with direct ($p=0.008$) and amplified direct ($p=0.006$) biofeedback compared to control, while RMS velocity was minimally effected by trial type. One explanation is that the biofeedback changed participants' behavior goal. With visual biofeedback, participants were trying to minimize needle motion and this task required reliance on the biofeedback. In contrast, without biofeedback, typical balance control mechanisms govern and inherent stability does affect sensory reliance [1, 21, 26, 30].

One notable difference between levels of support was the higher velocities and higher sway amplitudes at high frequencies in A2 compared to A1. With A2, the upper body mass and inertia above the axis of rotation was lower which could lead to higher velocities and amplitudes at high frequencies of balance corrections.

Conclusion

We demonstrated a large reduction in sitting trunk sway amplitude at low frequencies with real-time direct visual biofeedback. These improvements were consistent with and without external support, suggesting that visual feedback may be a useful tool to train visual processing in populations who lack the ability for independent standing or sitting. To a lesser extent, inverted visual feedback also reduced sway amplitude, meaning that healthy participants are able to adapt to changes in feedback direction. Random feedback increased sway across a wide range of frequencies.

Figure legends

Figure 1: Schematic and photos of experiment. The photo shows “A2” where the axis of rotation was raised with random visual feedback**.** The side arms moved up and down with the bench so that bench motion did not induce any frictional forces on the torso. The monitor that displayed visual biofeedback was 33 x 52 cm rectangular and the needle was 17 cm in length. One degree of body sway corresponded to about 1 cm horizontal displacement at the tip of the needle during the direct visual feedback trial and about 5 cm horizontal displacement during the trials with 5 times amplification in the display. With the participant 85 cm away from the needle, 5 cm of needle displacement corresponded to a change of 3.4 degrees of the visual field ($\sin^{-1}(5/85)$, top down perspective).

Figure 2: Sample data from two different participants in A) and B). In each trial, quiet sitting was 30 s, followed by 105 s of sway referencing, followed by 30 s of quiet sitting again. In A), the effect of vision and visual biofeedback is clearly evident. In B), the participant showed much higher sway than the participant in A) and also demonstrates the impact of faster movements with additional trunk external support (A2).

Figure 3: Summary root mean square (RMS) and RMS velocity during sway referencing expressed as the mean across participants with error bars equal to one standard error across participants.

Figure 4: A) Summary amplitude spectra across trials for sway referencing (each line represents the mean across participants with one standard error). B) Amplitude spectra across trials normalized to the control trails; where values above one represents sway exceeding the control trails.

Conflict of interest statement

There are no conflicts of interest.

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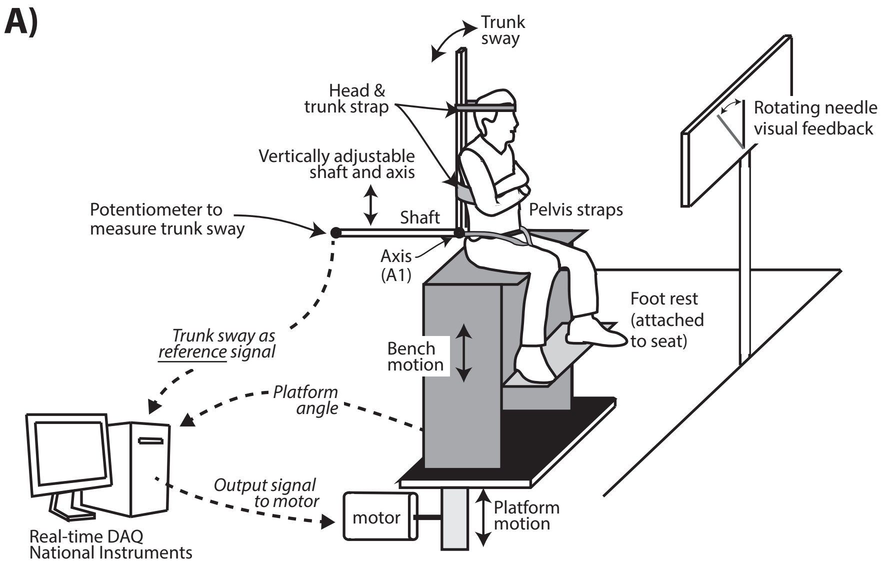
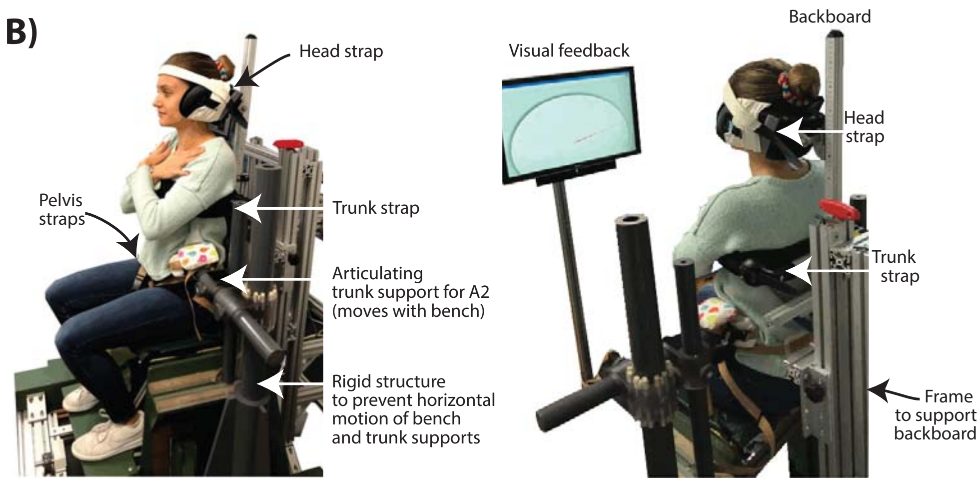
Figure 1

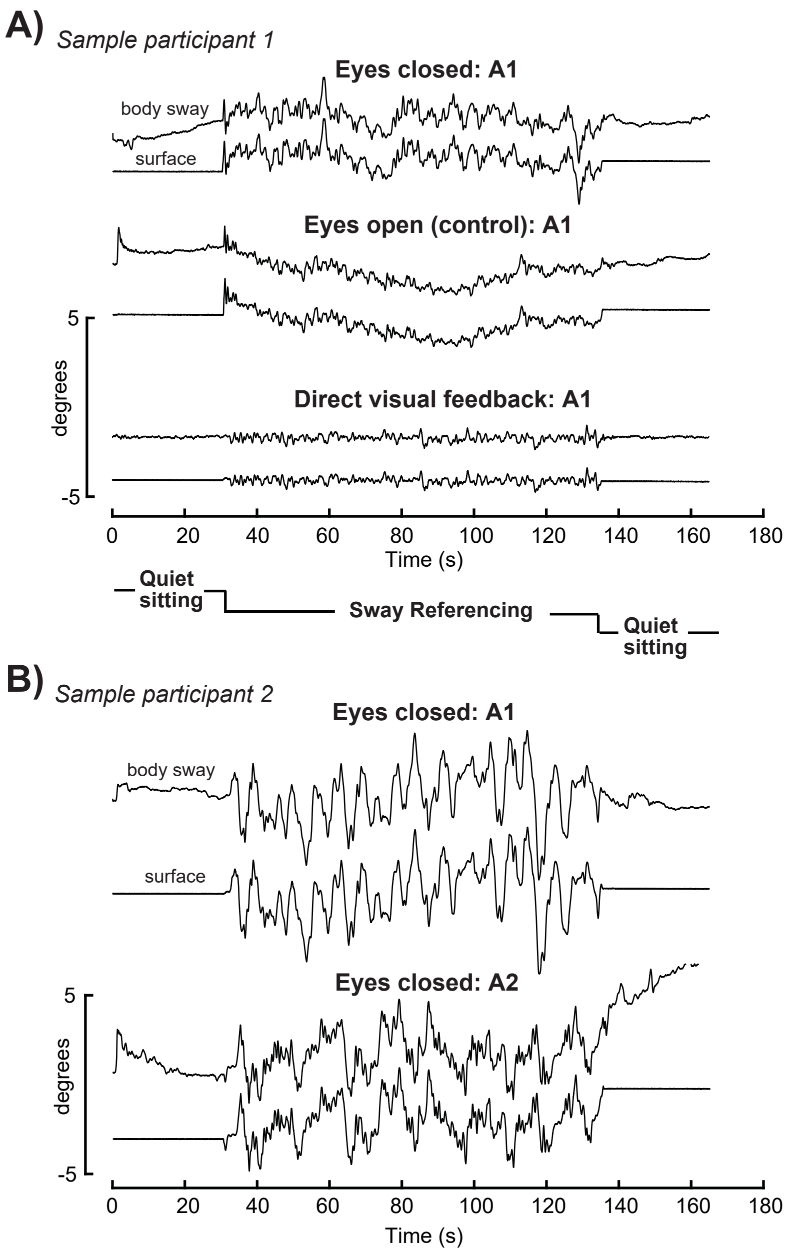


A)
Trunk sway
Head & trunk strap
Vertically adjustable shaft and axis
Potentiometer to measure trunk sway
Shaft
Pelvis straps
Rotating needle visual feedback
Axis (A1)
Foot rest (attached to seat)
Trunk sway as reference signal
Bench motion
Platform angle
Output signal to motor
motor
Platform motion
Real-time DAQ National Instruments



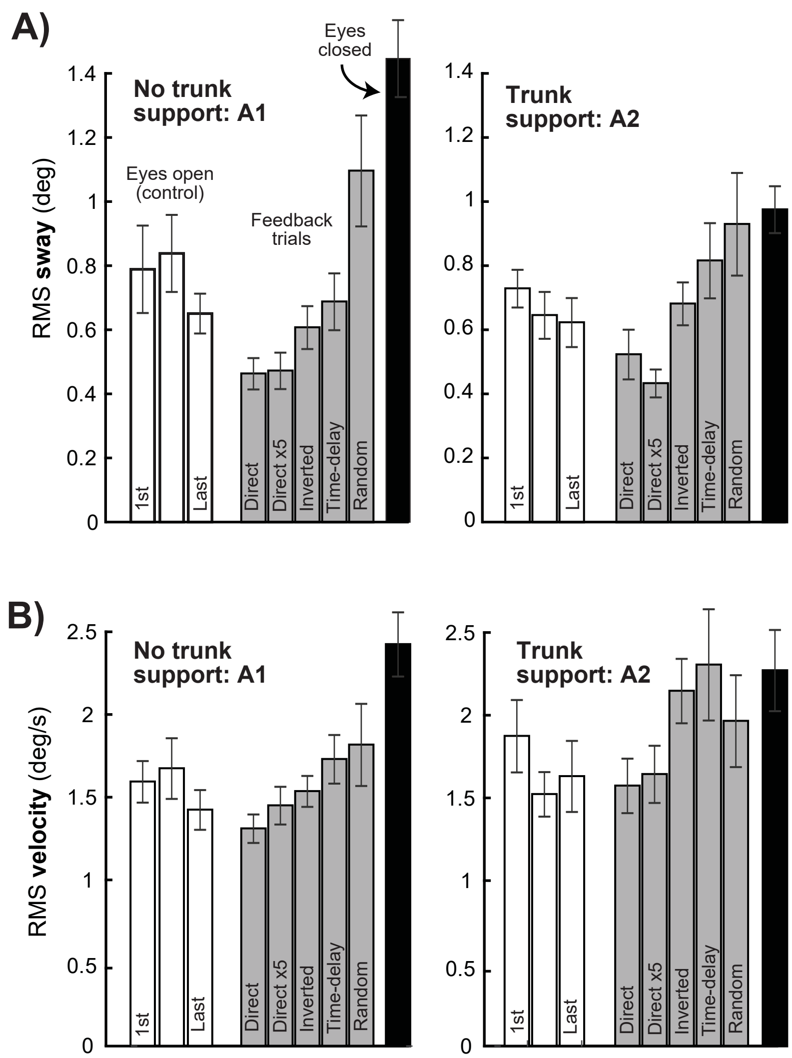
B)
Head strap
Pelvis straps
Trunk strap
Articulating trunk support for A2 (moves with bench)
Rigid structure to prevent horizontal motion of bench and trunk supports
Visual feedback
Backboard
Head strap
Trunk strap
Frame to support backboard

Figure 2



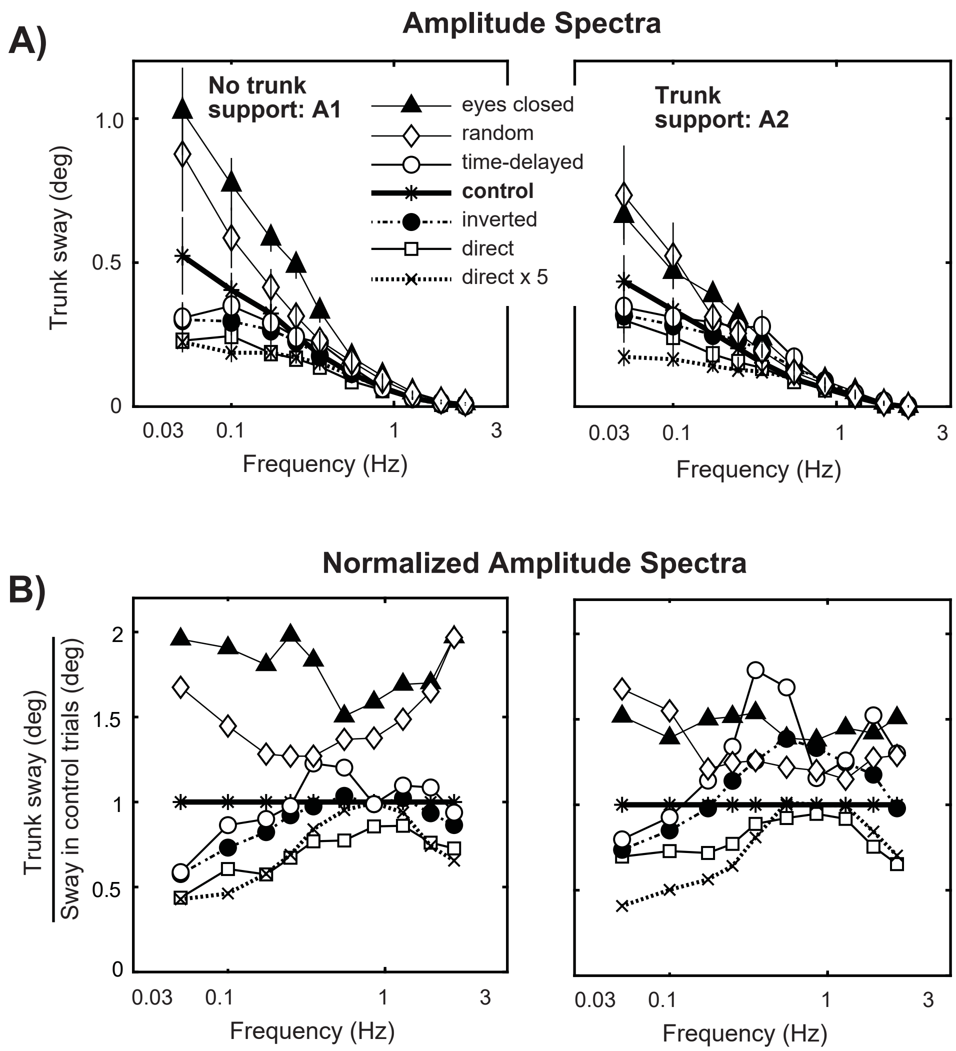
A) Sample participant 1
Eyes closed: A1
body sway
surface
Eyes open (control): A1
Direct visual feedback: A1
5
degrees
-5
0
20
40
60
80
100
120
140
160
180
Time (s)
Quiet sitting
Sway Referencing
Quiet sitting
B) Sample participant 2
Eyes closed: A1
body sway
surface
Eyes closed: A2
5
degrees
-5
0
20
40
60
80
100
120
140
160
180
Time (s)

Figure 3



A)
B)
No trunk support: A1
Trunk support: A2
RMS sway (deg)
RMS velocity (deg/s)
Eyes open (control)
Feedback trials
Eyes closed
1st
Last
Direct
Direct x5
Inverted
Time-delay
Random

Figure 4


A)
Amplitude Spectra
No trunk support: A1
Trunk support: A2
eyes closed
random
time-delayed
control
inverted
direct
direct x 5
Trunk sway (deg)
1.0
0.5
0
0.03
0.1
1
3
Frequency (Hz)
B)
Normalized Amplitude Spectra
Trunk sway (deg)
Sway in control trials (deg)
2
1.5
1
0.5
0

Table

	TIME DOMAIN		AMPLITUDE SPECTRA		
	RMS sway	**RMS velocity**	**Low Freq**	**Mid Freq**	**High Freq**
Support: A1 vs. A2 (P value)	0.056	**0.001**	**0.014**	0.26	**< 0.001**
Support X Trial (P val)	**< 0.001**	0.09	**0.022**	**0.008**	0.09
Trial (P val)	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Eyes closed	* >	* >	* >	* >	* >
Random feedback	* >		* >		* >
Direct feedback	* <		* <		
Direct (x 5)	* <		* <		
Time-delayed feedback (x 5)		* >		* >	
Inverted feedback (x 5)					

Table 1. Statistics of main effects, interaction effects, and post-hoc comparisons for each dependent variable during sway referencing. The “x5” means the needle position was amplified by 5 compared to scaling in Direct feedback. Post-hoc comparisons to control were made with the Bonferroni correction to adjust the P value for the six comparisons. Trials with asterisk were significantly greater than (>) or less than (<) control. Because of frequency-dependent nature of amplitude spectra, the 10 amplitude spectra points were separated into 3 bandwidths: the 3 lowest frequencies (0.05-0.175 Hz), the 4 mid frequencies (0.25-0.85 Hz), and 3 highest frequencies (1.3-2.75 Hz).

There are no conflicts of interest to report for this study.

Abstract.

Background: For individuals who never achieve independent standing, rehabilitation is focused on trunk posture and balance control. Visual biofeedback has the potential to augment sitting balance training, however previous work in this area has been limited to standing.
Research Question: To what extent do different types of visual biofeedback influence trunk sway in sitting?
Methods: Twelve healthy young adults sat on an articulating bench. During 'sway referencing' trials, the bench tilted up and down in proportion to trunk sway in the frontal plane. This paradigm increased difficulty of the balance task and required participants to rely on visual and vestibular cues. Participants were provided different visual biofeedback through a rotating needle-gage display. Trials lasted 165 s, were ordered randomly, and included either direct feedback (needle rotated in proportion to body sway), inverted feedback (needle rotated in the opposite direction of sway), time delayed feedback (0.5 s), random feedback, eyes closed, or control (eyes open with screen off). To explore the impact of inherent stability, trials were repeated with and without external trunk support.
Results: Body sway depended on feedback type. Specifically, direct and inverted feedback reduced root-mean-squared (RMS) sway the most, time delayed feedback had a smaller effect, and random visual feedback increased participants' RMS sway compared to control. Frequency domain analyses demonstrated direct and inverted visual feedback reduced sway amplitude at the lower frequencies while having minimal effect on (or increasing) sway amplitude at higher frequencies.
Significance: This study extends previous work by showing that visual feedback can have powerful effects on sitting balance, even with external support. Results from the different types of feedback conditions further our understanding of how the brain interprets visual biofeedback. Frequency-based results were similar to previous studies using different modalities and suggest participants interpret biofeedback through sensory addition as opposed to sensory substitution.

Introduction

Trunk postural control is a foundational skill that underlies activities of daily living [1, 2]. Impaired balance of the trunk is prevalent in many populations [3-5] and trunk control has recently gained more attention as a focus in both assessments and training [4, 6-8]. In the current study, we examine how trunk postural control is influenced by different types of visual biofeedback.

Why visual biofeedback? Visual biofeedback studies have consistently demonstrated reduction in postural sway while standing [9-11]. Feedback of a particular segment reduces localized motion supporting the practice of targeted movement [11]. Effectiveness is seen in auditory feedback [12], vibrotactile feedback [13] , and ~~tactile~~ feedback ~~of~~ on the tongue [14]. Together, these studies suggest biofeedback has potential to encourage specific movement patterns and use of different sensory cues. Moreover, biofeedback is integrated into most gaming and virtual reality-based standing balance and mobility programs. These training methods have both theoretical and empirical support for increasing motivation and improving outcomes [15-17]. Not surprisingly, biofeedback is growing in research [10, 11, 13].

But for many populations lacking independent standing, training the trunk in sitting or with external trunk support is the only option [2, 4, 18, 19]. Therefore, we investigate sitting trunk postural control using detailed time and frequency domain analyses. An array of different types of visual biofeedback were chosen to broaden our understanding of how visual biofeedback is interpreted and used within the postural control system. Investigating different types of visual feedback also provides practical information for the design of biofeedback protocols. This is novel because previous standing studies either did not vary the type of feedback or only varied a couple types of feedback, typically different magnifications of visual biofeedback. In the current study, our biofeedback types include the following: 1) Direct visual feedback where an arrow on the screen rotates to the same angle as body sway. 2) Direct visual feedback amplified by five to explore the impact of visual cue resolution. 3) Inverted visual feedback where the arrow on the screen rotates in the opposite direction of body sway to test how well participants can transform direction coordinates. This condition gives insight into motor learning and may be a useful assessment tool for populations with impaired neural control. 4) Time-delayed visual feedback to better understand sensorimotor dynamics and to help optimize componentry in future biofeedback studies. 5) Noisy meaningless visual feedback to determine if participants can appropriately “turn off” visual reliance, which may also serve as a useful assessment tool. 6) Eyes closed to compare how postural control differs when altering biofeedback versus altering natural sensory feedback. 7) Eyes open, as a control condition.

In order to highlight the effect of visual biofeedback, our study focuses on an experimental paradigm associated with high visual reliance called surface sway referencing [20]. In surface sway referencing, the bench tilts in direct proportion to trunk sway which diminishes somatosensory cues from the pelvis and trunk. Finally, our study compares responses with and without external trunk support. While most previous studies use a single trunk segment model, the use of external support isolates the sensorimotor processes within different segments of the trunk~~. The external support also increases the inherent stability of the trunk by lowering its unstable mass and inertia against gravity and reducing the trunk segments to be controlled against gravity,~~, which is clinically relevant for many people with ~~is needed in some patients with~~ impaired motor control [2, 4, 18, 19]. ~~In conclusion, the current study advances the field by examining trunk postural control with different external support and different types of visual biofeedback in sitting.~~

Methods

Participants. Twelve healthy young adults were recruited (6 women and 6 men, mean age 26 ± 5.5 years, height 169.6 ± 6.7 cm, weight 70.9 ± 9.3 kg), provided a written informed consent, and were tested according to a protocol approved by the University of Hartford Institutional Review Board.

Backboard and Trunk Support. Participants were seated on a bench with their feet placed at a comfortable distance on a footrest that moved with the bench (Fig 1). During quiet sitting, the bench was ~~horizontal and~~ stationary. During sway referencing, the bench tilted up and down in the frontal plane; the angle of bench tilt was equal to the participant's upper body sway angle with respect to upright (~~with an estimated~~about 33 ms delay from the electromechanical equipment). Bench motion was controlled via a servomotor ~~, described previously~~ [19, 20]. The bench was limited to ±4.5 degrees~~ in each direction~~. Body sway was measured with a frictionless potentiometer connected to a lightweight rigid backboard. The backboard only rotated in the frontal plane and was tightly attached to participants at the head and upper torso through straps. The backboard ~~was made of a rigid structure and~~ rested on a frame so that participants did not need to generate extra force when in an upright position. To ensure the pelvis and bench moved in unison, straps from the bench secured each participant's thighs and pelvis. When the backboard was placed at "Axis 1" (A1), no additional trunk support was used, and the axis of rotation (i.e. pivot point) on the backboard was set to L4/L5 for each participant. For "Axis 2" (A2), trunk support was added using rigid, padded side arms that pressed into the participants' waist at L1/L2 and the axis of rotation on the backboard was lifted upward and set to T12 (Fig. 1B photo). Although the backboard and head rest placed participants in an unnatural position compared to everyday life, ~~there were several~~ advantages of the backboard include: 1) the backboard limited degrees of freedom, thereby providing an unambiguous signal to define as the reference during sway referencing and 2) it enabled a straightforward interpretation of how the trunk and head were oriented and what sensory cues were received. A previous study showed high similarity between a backboard and freestanding with participants who stood on a tilting platform that moved with amplitudes similar to the current [21]. Therefore, we expect our findings with a backboard are relevant to sitting without a backboard.

Protocol. Each participant was tested for 18 total trials: 9 trials at two levels of support (A1, A2). Each trial lasted 165 s, which included 30~~-~~s of quiet sitting, ~~followed by~~then 105~~-~~s of sway referencing, ~~followed by~~then 30~~-~~s of quiet sitting. A minimum 60~~-~~s break occurred after each trial. The 9 trials included 2 control eyes open (EO) trials (screen off) at the beginning and end of the ~~test~~ session and 7 randomized trials in between~~ (Table 1)~~. The randomized trials described in the Introduction and Table 1 included: eyes open with screen off (~~as a~~ control), direct visual feedback~~ where the arrow on the screen rotated to the same angle as body sway~~, amplified direct ~~visual~~ feedback~~ amplified by five~~, inverted ~~visual~~ feedback~~ where the arrow on the screen was amplified by 5 and rotated in the opposite direction of body sway~~, 500 ms time-delayed ~~visual~~ feedback~~ amplified by 5~~, ~~noisy, meaningless~~ random ~~visual~~ feedback, and eyes closed. Random feedback was generated with low pass filtered (0.4 Hz 3rd order) white Gaussian noise that visually resembled the sway patterns of an average participant during sway referencing. Each participant was instructed to stay as upright as possible and were told that the needle on the screen “might be helpful”.

Analyses. Dependent variables included ~~standard time domain measures~~ zero-mean root-mean-square (RMS) sway, ~~and~~ RMS velocity, and ~~along with~~ the amplitude spectra ~~in the frequency domain~~. Amplitude spectra provides more detail of sway characteristics by decomposing a single time-domain waveform into its frequency components [22]. In postural control, low frequency sway corresponds to the slow movements, ~~that are~~ typically largest in magnitude, whereas high frequency sway (>1Hz) corresponds to fast movements ~~that are often~~typically not visible to the naked eye. To facilitate analyses, we binned and averaged the amplitude spectra into low (0.05-0.175Hz), middle (0.25-0.85Hz), and high (1.3-2.75Hz) frequencies. Neural processes impact certain frequencies of trunk ~~body~~ sway more than others: ~~. For example, in trunk posture control,~~ neural damping is most evident at mid-and high-frequencies, ~~neural~~ time delays are evident at higher frequencies, while ~~neural~~ stiffness and sensory reweighting are associated with frequencies below 2.5 Hz~~, while neural integration is typically most evident at the lowest frequencies below 0.2 Hz~~ [20, 22, 23].

For the sway referencing period, the last 100 s of body sway was analyzed to avoid transient behavior during the first 5 s of sway referencing. The 100 s were divided into five consecutive 20 second periods. Dependent variables were calculated for each 20 s period and then averaged across the 5 periods~~. This method~~ (~~used~~ all 100 s of data was used ~~and improved confidence in dependent variables by averaging across periods.~~).

Statistics. Dependent variables were analyzed using a repeated-measures ANOVA. The ~~statistical~~ model included the following ~~model~~ effects: support level (A1 vs. A2), trial type, and ~~the~~ interaction of support and trial. Six post-hoc pair-wise comparisons were made between the control and 6 other trials with a Bonferroni correction. There was no significant difference across the three control trials in sway referencing and therefore dependent variables for the three control trials were averaged together for each participant in statistical models. In all main and interaction effects, statistical significance was $p < 0.05$.

Results

Qualitative differences across participants, trials, and support

Figure 2 provides representative sway patterns from two different participants. In Fig. 2A (participant 1), ~~there is an increase in~~ sway amplitude increases at the onset of sway referencing (30 s)~~ and a decrease in sway amplitude at the end of sway referencing (135 s)~~. Across trials, there is a decrease in sway amplitude from the eyes closed trial to ~~the~~ control ~~trial~~; and further decrease with direct visual biofeedback. Fig 2B show differences in sway between levels of support (A1-top vs. A2-bottom) for another participant. A2 (higher support) was associated with higher frequency movements. Finally, we found notable variability across participants ~~in how they responded to the different trials~~ - some participants had relatively low sway amplitude and others had high sway amplitude, illustrated in the comparison between Fig. 2A and 2B.

Variability across participants

~~The large difference between participants in the top plots of Fig. 2A vs. 2B were representative of the entire data set.~~ Across all participants, the coefficient of variation (CV) in RMS during sway referencing was 41.8% (averaged across all trials). Eyes closed had the lowest CV across participants of about 27%, while random feedback had the largest CV of about 57%; which means that sway amplitude was most consistent across participants in eyes closed and most variable across participants during random feedback.

RMS sway and velocity results

Figures 3 provides a summary of the mean participant RMS sway and velocity across trials and Table 1 is a statistical summary. ~~The different trials~~Trial type had a significant influence on ~~body~~ RMS sway (P<0.001) and velocity (P≤0.001). ~~In sway referencing,~~ RMS sway was significantly increased compared to control in eyes closed (p<0.001) and random feedback (p<0.001), while RMS sway was significantly decreased with direct (p=0.002) and amplified (p<0.001) visual biofeedback. RMS ~~S~~sway with direct and amplified direct biofeedback was 61% and 62% of control, respectively, in A1 and 79% and 65% of control, respectively, for A2.

In contrast, RMS velocity was less influenced by trial type with most trials either similar to, or larger than, velocity observed during the control. RMS velocity was significantly increased in eyes closed (p<0.001) and time delayed biofeedback (p=0.005) compared to control. ~~in sway referencing.~~

In the level of support comparison, A2 was associated with a 9% decrease in RMS sway (p=0.056) compared to A1 and a 15% significant increase in velocity (p=0.001) compared to A1. ~~The cause of this result was more apparent in the interaction effect analysis.~~Importantly, ~~S~~significant interaction effects between level of support and trial were found in the RMS variable ~~during sway referencing~~ (p<0.001); meaning that participants' response to different trials was influenced by their level of support. Two notable interaction effects evident in Fig 3A include: 1) trials with eyes closed and random feedback increasing RMS sway more in A1 vs. A2 and 2) the time delayed biofeedback reduced RMS sway in A1 but increased sway in A2.

Frequency domain results

Amplitude spectra are presented in Fig. 4A for sway referencing. ~~Trends were consistent with RMS results.~~ Fig. 4B presents body sway amplitude for each frequency point normalized to the control trial. In both A1 and A2, sway amplitude was elevated across all frequencies in eyes closed and random trials. ~~Direct, i~~Inverted (white circle)~~,~~ and time-delayed (grey circles) biofeedback ~~all~~ reduced ~~body~~ sway amplitude at the lowest two frequencies but~~. But time-delayed biofeedback (grey circles) and inverted (white circle)~~ either had minimal effects or increased ~~body~~ sway amplitude across mid- and high-frequencies (~above 0.5 Hz). ~~In contrast, d~~Direct biofeedback trials (white box and 'x') reduced sway across a wider bandwidth of frequencies.

Low frequencies had the most significant statistical effects: eyes closed (p<0.001) and random feedback (p<0.001) were significantly higher than control and direct (p=0.002) and amplified direct (p<0.001) biofeedback trials were significantly lower than control. Level of support also had a significant effect (p=0.01) on sway amplitude at low frequencies with A1 associated with larger sway. At mid frequencies, sway amplitude was significantly higher with eyes closed (p<0.001) and time delayed biofeedback (p=0.005) compared to control. At high frequencies, sway was significantly higher with both eyes closed (p<0.001) and random feedback (p<0.001) compared to control. At high frequencies, the significant effect of level of support (p<0.001) was due to an increase in A2 compared to A1, ~~. This high frequency increase is ~~similar to the ~~significantly ~~larger RMS velocity found ~~with higher support (~~in A2~~)~~.

Discussion

Direct Visual Feedback consistently lowered sway

Our results extend previous research in standing [9-11] to show that people can use visual biofeedback to reduce sway amplitude in sitting. These postures are particularly relevant for populations with limited or impaired balance control who may benefit from new training protocols. ~~For example, ~~Dewar et al. reviewed ~~posture ~~training studies in cerebral palsy and found positive results and retention with virtual reality and visual biofeedback programs in children who were able to stand but found very little research for children lacking independent sitting [17]. Similarly, a recent review of therapies for children with moderate to severe cerebral palsy summarized the field as lacking appropriate treatments for this population [24].

~~Also, d~~Direct visual feedback reduced RMS sway to a greater extent than velocity (similar to a previous standing study by Jehu et al.[10]) and sway reductions were most evident at low frequencies (consistent with Halicka et al.[11] in standing). In contrast, altering natural sensory feedback (eyes closed) resulted in increases across a wide bandwidth of frequencies and increased both RMS sway and velocity. Why the difference?

An explanation offered in previous studies is that people adopt a stiffening strategy with biofeedback that increases high frequency movements and muscle activation levels [25]. We offer an alternative explanation ~~below ~~based on feedback control theory. Our previous work investigated ~~the impact of ~~vibrotactile feedback ~~on ~~in standing ~~posture sway ~~during pseudorandom tilts of a platform. ~~The vibrotactile feedback was based on either body sway or velocity or combinations of sway and velocity. ~~The normalized amplitude spectra (Fig. 5 in Goodworth et al. 2009 [26]) were similar to ~~those reported in ~~the current study showing clear improvements at low frequencies that diminished at higher frequencies. These results were interpreted through a sensory feedback model~~ of sensory integration~~. The model explored ~~several ~~different mechanisms [13] and ~~ultimately ~~found the best description for how vibrotactile feedback was used was through "sensory addition", represented ~~in the model ~~as an additional feedback loop. The same basic model ~~was able to ~~described frequency-dependent changes in body sway with different natural sensory feedback (eg, eyes open vs. eyes closed) [21] and with the addition of biofeedback [26]. The primary difference between the biofeedback loop and natural sensory feedback was ~~the presence of ~~a heavy low pass filter within ~~ed interpretation of~~ the vibrotactile feedback loop. This filter ~~gave rise to~~caused the differential effect of biofeedback ~~on ~~at low vs. high frequencies and can be interpreted as "neural integration" which is likely influenced by voluntary control and cognitive effects [11, 20]. Given the similarity between vibrotactile feedback and visual biofeedback results, we suggest this model is useful ~~in the~~for interpretating ~~on of~~ results.

Random and eyes closed consistently increased sway

Eyes closed trials ~~resulted in greatly~~ increased sway amplitude across a wide bandwidth of frequencies ~~. This result is~~ similar to a previous ~~experimental and modeling sitting sway referencing~~ study ~~that suggested~~ suggesting eyes open trials had less sensorimotor noise [20]. Less sensorimotor noise is expected in eyes open because both vision and vestibular cues contribute to a sense of upright. Similarly, random feedback increased sway amplitude across a wide bandwidth, suggesting that random feedback also added sensory noise to the balance system. Most participants in the current study noted an awareness that the biofeedback was meaningless and either ~~. Many self-reported that they~~ looked toward the edge of the monitor or did not focus on the moving needle. ~~There was particularly high sway amplitude with random feedback in the first period of quiet sitting which we speculate was due to some participants "trying out" the biofeedback to see how it corresponded to their sway.~~ The variable response to random feedback caused the high CV across participants with random feedback. Still, participants were not able to ignore the random feedback as it consistently increased sway amplitude. This underscores the powerful effect of visual cues on postural control.

Inverted and time-delayed feedback had mixed effects

Inverted feedback typically improved balance control, especially at low frequencies. ~~Thus, participants~~ Participants were able to adapt ~~and make~~using coordinate transformations between direction of sway and direction of biofeedback. Coordinate transformations are part of ~~a~~ healthy neural ~~system~~ control [27]. ~~Thus, the i~~Inverted feedback ~~trial~~ may be a valuable diagnostic test of adaptive ~~neural~~ control. Still, when considering rehabilitation, ~~it is noteworthy that~~the more intuitive feedback (direct) was more effective in reducing sway ~~amplitude~~.

Time-delayed feedback also reduced sway amplitude at the lowest frequencies but there were ~~clear~~ increases at mid frequencies, especially with A2~~. This frequency dependence is~~, similar to previous standing studies [28]. The increases at mid-frequencies are reminiscent of an oscillating system. Control theory shows oscillations and instability ~~when~~ with long time delays ~~are introduced to~~in a feedback system [29]. Thus, it is likely ~~that~~ participants used the time delayed biofeedback ~~when it was time delayed~~ and ~~it was the~~ this large time ~~-~~delay ~~within the posture feedback loop that~~ contributed to increased sway amplitude at mid-frequencies. ~~The presence of a~~A ~~notable~~ large time ~~-~~delay in componentry should be of concern in ~~future~~ biofeedback protocols.

Overall trends in A2 and A1 were similar

Despite a few differences between A1 and A2, the clear similarity in trends across trials should be highlighted. Direct and amplified direct biofeedback improved balance similarly for both A1 and A2. This finding suggests that the presence of visual biofeedback triggered participants to rely on vision similarly regardless of their inherent stability. In fact, the brief periods of quiet sitting could be considered the most inherently stable. We also analyzed the sway data in the first and last quiet sitting period and found the same general trends: RMS significantly increased with random feedback ($p<0.001$) and RMS significantly decreased with direct ($p=0.008$) and amplified direct ($p=0.006$) biofeedback compared to control, while RMS velocity was minimally effected by trial type. ~~(only random feedback was significantly increased compared to control).~~ One explanation is that the biofeedback changed participants' behavior goal. With visual biofeedback, participants were trying to minimize needle motion and this task required reliance on the biofeedback. In contrast, without biofeedback, typical balance control mechanisms govern and inherent stability does affect sensory reliance [1, 21, 26, 30].

One notable difference between levels of support was the higher velocities and higher sway amplitudes at high frequencies in A2 compared to A1. With A2, the upper body mass and inertia above the axis of rotation was lower which could lead to higher velocities and amplitudes at high frequencies of balance corrections.

Conclusion

We demonstrated a large reduction in sitting trunk sway amplitude at low frequencies with real-time direct visual biofeedback. These improvements were consistent with and without external support, suggesting that visual feedback may be a useful tool to train visual processing in populations who lack the ability for independent standing or sitting. To a lesser extent, inverted visual feedback also reduced sway amplitude, meaning that healthy participants are able to adapt to changes in feedback direction. Random feedback increased sway across a wide range of frequencies.

Figure legends

Figure 1: Schematic and photos of experiment. The photo shows "A2" where the axis of rotation was raised with random visual feedback**.** The side arms moved up and down with the bench so that bench motion did not induce any frictional forces on the torso. The monitor that displayed visual biofeedback was 33 x 52 cm rectangular and the needle was 17 cm in length. One degree of body sway corresponded to about 1 cm horizontal displacement at the tip of the needle during the direct visual feedback trial and about 5 cm horizontal displacement during the trials with 5 times amplification in the display. With the participant 85 cm away from the needle, 5 cm of needle displacement corresponded to a change of 3.4 degrees of the visual field ($\sin^{-1}(5/85)$, top down perspective).

Figure 2: Sample data from two different participants in A) and B). In each trial, quiet sitting was 30 s, followed by 105 s of sway referencing, followed by 30 s of quiet sitting again. In A), the effect of vision and visual biofeedback is clearly evident. In B), the participant showed much higher sway than the participant in A) and also demonstrates the impact of faster movements with additional trunk external support (A2).

Figure 3: Summary root mean square (RMS) and RMS velocity during sway referencing expressed as the mean across participants with error bars equal to one standard error across participants.

Figure 4: A) Summary amplitude spectra across trials for sway referencing (each line represents the mean across participants with one standard error). B) Amplitude spectra across trials normalized to the control trails; where values above one represents sway exceeding the control trails.

Conflict of interest statement

There are no conflicts of interest.

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