33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Improving impaired balance function: real-time versus carry-over effects of prosthetic feedback.

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Abstract— **This study investigated whether training with real-time prosthetic biofeedback (BF) of trunk sway induces a carry-over improvement in balance control once BF is removed.**

12 healthy older adults and 7 uncompensated unilateral vestibular loss patients were tested. All participants performed a battery of 14 balance and gait tasks (pre-test) upon their initial lab visit during which trunk angular sway was measured at L1-3. They then received balance BF training on a subset of 7 tasks, three times per week, for two consecutive weeks. BF was provided using a multi-modal biofeedback system with graded vibrotactile, auditory, and visual cues in relation to subject-specific angular displacement thresholds. Performance on the battery of the 14 balance and gait tasks (without BF) was re-assessed immediately after the 2 week training period, as well as 1 week later to examine BF carry-over effects. Significant reductions in trunk angular displacement were observed with the real-time BF, compared to the pre-test trials. The effects of BF persisted when BF was removed immediately after the final training session. BF carry-over effects were less evident at one week post-training. This evidence supports the potential short-term effects of BF training in a limited number of tasks after the BF is removed in healthy elderly subjects and those with vestibular loss. However, the prospect for longer term (>1 week) effects of prosthetic training on balance control remains currently unknown.

I. INTRODUCTION

Previous studies have shown that balance performance measured in terms of trunk sway during stance and gait tests can be significantly improved when real-time prosthetic biofeedback (BF) of trunk sway is available to young and older healthy adults [1-2], and patients with unilateral or bilateral vestibular loss [3-7]. The most common type of feedback employed is vibro-tactile feedback applied at the head or at the waist [1-3, 5-7] with a preference for that at the head possibly because of the shorter neural pathways involved. Auditory feedback has also been employed [4, 8], but tends to impair communication with the patient. Recently, bone-conducting auditory feedback has been used to supplement vibro-tactile BF at the head as a multi-modal feedback with different sway thresholds for each mode [1]. The positive effects of receiving such real-time BF on balance performance are well established. These include a reduction in sway for both stance and gait tasks [1], greater reductions in the plane of most task-dependent instability (eg roll for tandem stance) [9-10] and reductions with dual tasks in the young and elderly [2]. However the extent to which improvements may persist once the BF is removed is currently unknown.

Manuscript received April 14th, 2011. This work was supported in part by a National Swiss Research Fund (320000-117951/1), Swiss KTI grant (7812 LSPP-LS), NSERC and CIHR.
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Knowledge about whether BF for balance control produces carry-over effects will influence both prosthesis design and rehabilitation schedules. If carry-over effects are not to be expected, then design efforts may have to concentrate on making the prosthesis small and cosmetically acceptable with the ultimate goal of making the device implantable [11-13]. Alternatively, if a substantial carry-over effect is present, rehabilitation of balance disorders can concentrate on regimes that extend the effect as much as possible. Thus the aim of the current research was to establish whether carry-over effects exist for the 2 of the 3 largest populations most likely to benefit from BF, otherwise healthy, older adults who because of their age will have a tendency to fall and patients with uncompensated unilateral peripheral vestibular loss (ucUVL). A project with the other large potential population, the frail elderly, is in progress. Here we present preliminary results that short (1-2 weeks) carry-over effects on balance control can be established with BF. We have previously shown that a relatively smaller population, those with bilateral vestibular loss, can benefit from auditory BF [4].

II. METHODS

12 healthy older adults (age range 59-86 years) and 7 ucUVL patients (age range 35-72 years) volunteered for the study. The ucUVL suffered an acute unilateral vestibular loss at least 3 months prior to testing and had remaining complaints of unsteadiness as well as asymmetrical results in tests of vestibular-ocular reflex function based on whole body rotation about an earth vertical axis with an acceleration of 20 deg/sec^2.

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All participants performed a battery of 14 stance and gait tasks (pre-test) upon their initial lab visit:
30 secs standing feet together (eyes open and eyes closed)
30 secs tandem stance (eyes open and eyes closed)
30 secs standing feet together on foam (eyes open and eyes closed)
Walk 8 tandem steps (eyes open and eyes closed)
20 secs standing on 1 leg (eyes open)
Walk 8 m (eyes open)
Walk 3m while rotating head (in pitch and yaw directions)
Get up from a stool and walk 3m (on firm and foam surfaces)
.

For these tasks trunk sway at L1-3 was measured with a SwayStar^{TM} system (Balance International Innovations GmbH, Switzerland). This system consists of two digital angular-rate gyroscopes mounted on a converted motor-cycle kidney belt, in order to measure angular velocity in the roll (side-to-side) and pitch (fore-aft) planes (Fig 1A). Samples were transferred to a PC via Bluetooth^{TM} with a rate of 100 Hz. Participants then received balance BF training, three times per week, for two consecutive weeks on a subset (7 tasks) of the initial assessment tasks. A subset was used in order to quantify a carry-over effect to non-trained tasks [1]. An increased emphasis was placed on the first task for the ucUVL patients as they have most difficulties with eyes closed tasks. The training tasks were:

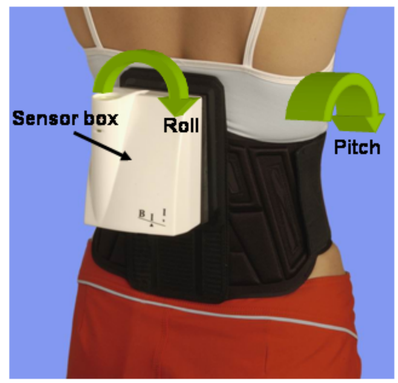
30 secs standing feet together eyes closed (6 times, 3 times for the elderly)
20 secs standing on 1 leg eyes open (3 times)
30 secs tandem stance eyes closed (2 times, 3 times for the elderly)
30 secs standing feet together on foam eyes closed (2 times, 3 times for the elderly)
Walk 8 m eyes open (5 times)
Walk 3m while rotating head (5 times)
Walk 8 tandem steps eyes closed (5 times)

Biofeedback was provided using a BalanceFreedom^{TM} add-on the the SwayStar^{TM} system (Balance International Innovations, Switzerland). This is a multi-modal biofeedback system (see Fig 1B) that provides graded vibrotactile, auditory, and visual cues in relation to subject-specific angular displacement thresholds. The biofeedback thresholds were based on the individual 90% peak-to-peak values for pitch and roll angles, recorded during the first assessment and updated after each week of training. To derive 90% values, a histogram of pitch (or roll) samples of each subject's trial was developed by dividing the peak-to-peak range into 40 bins. The 90% range was then the range with the extreme 5% of values in the histogram excluded. Feedback thresholds increased in order of vibro-tactile, auditory and visual. For example, if the individual 90% peak-to-peak roll angle range was 1 deg, the vibro-tactile roll threshold was set at 0.4 deg for both the left and right directions (factor 40%), the acoustic roll threshold at 0.8 deg (factor 80%) and the visual roll threshold at 1.5 deg (factor 150%). The same factors (40%, 80%, 150%) were used to calculate roll and pitch thresholds across all tasks.

The 90% measures of pitch and roll angular displacements were recorded while subjects trained with BF online, and were compared with pre-test measures to examine the effect of online BF. Performance on the battery of the 14 stance and gait tasks (without BF) was re-assessed immediately after the 2 week training period, as well as 1 week later to examine BF carry-over effects.

Figure 1. (A) Sensor device providing body sway measures for feedback in the directions shown. (B) Young subject wearing the BalanceFreedom^{TM} device comprised of head-mounted feedback transducers for delivering biofeedback. Vibrotactile feedback is provided over 8 vibrators spaced equally around the head, auditory feedback over 2 bone-conducting auditory vibrators placed over left and right mastoids, and visual feedback using a single warning red light emitting diode.

A



B

III. RESULTS

A typical example of the improvement in balance control that may be obtained in a difficult gait task when BF of trunk sway is available is shown in figure 2 for a ucUVL patient 5 months after the initial acute onset of symptoms. When compared with x-y plots of roll versus pitch as shown in figure 2B, it is apparent that the extreme excursions of sway are reduced.

Figure 3 illustrates mean changes for the most difficult task, tandem walking eyes closed. Our preliminary results indicate a similar pattern across tasks, namely that there is a clear reduction when the feedback is present, with the greatest reduction observed in the pitch plane. For example, in both the elderly and ucUVL populations, reductions were present while standing on foam, walking 8 tandem steps eyes closed (figure 3) as well as standing on 1 leg eyes open. When present the effects of BF persisted when BF was removed immediately after the final training session. Except for the most difficult tasks, BF carry-over effects were less evident at one week post-training (week 3). A similar pattern was observed for tasks of the initial assessment that were not trained with BF.

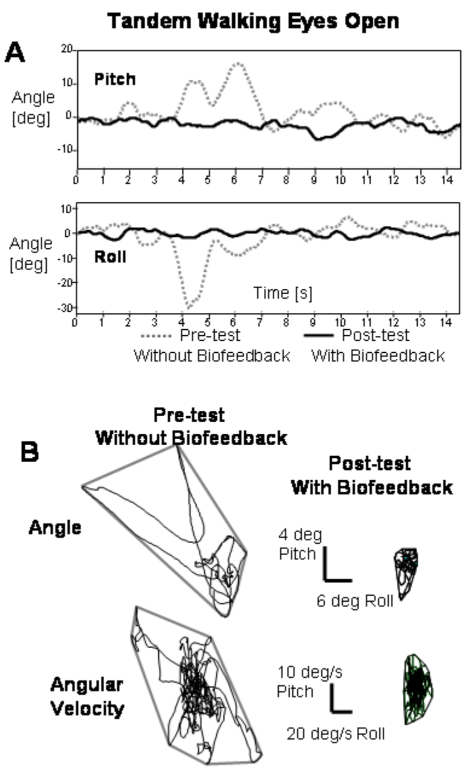


Figure 2. Improvements in trunk sway with biofeedback for an uncompensated unilateral peripheral vestibular loss patient (5 months post acute unilateral peripheral vestibular loss). The improvements are shown for walking 8 tandem steps, eyes open during training. In A, the time traces with and without feedback are shown. In B, angle and angular velocity plots before feedback training and with feedback (after training with it) are shown as x-y plots of roll and pitch deviations. Notice the considerable reduction with feedback. An envelope (the convex hull) has been drawn around the x-y plots.

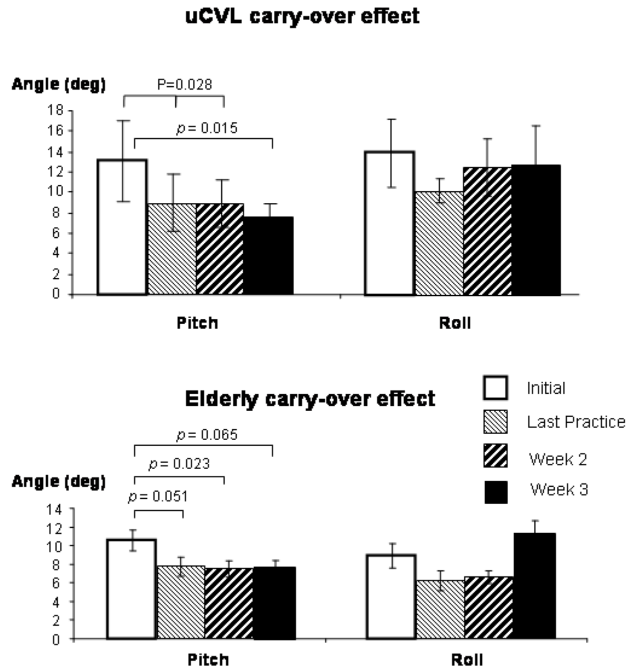


Figure 3. Bar graphs of angular displacement (population means +/- SEM) in the pitch and roll directions for the elderly subjects and ucUVL patients performing the task of tandem walking with eyes closed. Significant reductions in angular displacement with respect to initial test values are marked for the last test session with feedback (after 2 weeks of training), the session immediately following without feedback, and a retest a week later.

IV. Discussion

The available evidence, including the results provided here, clearly supports the potential for BF to be used as a prosthetic device capable of providing real-time sensory information to individuals based on angular trunk sway deviations during stance and gait. Evidence also supports the potential short-term effects of BF training in a limited number of tasks after the BF is removed in healthy elderly subjects and those with vestibular loss. However, the prospect for longer term (>1 week) effects of prosthetic training on balance control remains currently unknown. This suggests that efforts should concentrate on improving real-time feedback devices rather than relying on carry-over effects to improve balance control in those with balance problems. These efforts may also be of use in designing balance prostheses using direct electrical stimulation in the peripheral vestibular system [11-13].

Biofeedback resulted in improved balance control for tasks that were not included in the training regimen. For example, despite not practicing with biofeedback while standing with eyes open, ucUVL patients had significantly reduced ranges of trunk pitch and roll angles when standing in tandem stance or with feet together with eyes open on a foam or firm surface in the training weeks. This finding suggests that training with biofeedback may result in a carry-over effect leading to general balance improvements, provided the training has been recent.

The device used to provide biofeedback in this study is unique compared to existing biofeedback devices because vibrotactile, auditory and visual sensory cues are used together to improve balance control. For the majority of trials, however, participants were provided with two forms of feedback, vibrotactile and auditory signals. Visual feedback was only activated at the extremes of stability for a given task and this rarely occurred. The combination of the vibrotactile and auditory modes as combined contributions to sensory signals controlling balance may be beneficial in eliminating potential errors in sensory integration and delays in sensory transmission that can occur among older adults [14-15]. Further, the observed reductions in trunk angular displacement with biofeedback are likely beneficial to the overall balance performance of older adults considering that reduced trunk sway in older adults is highly correlated with a reduction in falls [16].

The design of the biofeedback system used in this study may serve to better facilitate and improve postural performance in future designs. For example, it has been observed that participants with the largest initial ranges of angular displacement showed the largest reduction in the ranges of angular displacement with biofeedback (Fig 4) when population values were used for thresholds[1]. Thus we had expected greater reductions in vestibular loss patients than the elderly as these have greater initial sway, as observed in figure 3, for the tandem gait task with eyes closed task. The reductions in trunk pitch displacement following intervention translated into a 40% reduction in trunk sway for this task in both the elderly and vestibular loss patients. This is a substantial change and provides strong evidence for the usefulness of providing additional sensory information via biofeedback to help the user control their balance. The question arises though whether using individual rather than single group thresholds in the elderly and ucUVL studies reported here provided an additional improvement in performance. Avoiding the need to calculate individual thresholds would reduce operator time once group thresholds are available. This issue needs to be explored in future studies.

It should be noted that vibrotactile feedback can be perceived as a bone-conducted auditory stimulus for the vibrotactile transducers near the mastoid bones containing the inner ear hair cells of the cochlea. Due to the low threshold sensitivity of the otolith organs to bone-conducted sounds [17] this implies that both bone-conducted auditory stimulus and vibrotactile transducers close to the mastoid may excite vestibular pathways as well.

It should be noted that this study did not include the frail elderly who might have yielded greater effect sizes than seen in the current studies. Future studies will need to assess the applicability of the current BF design to this population.

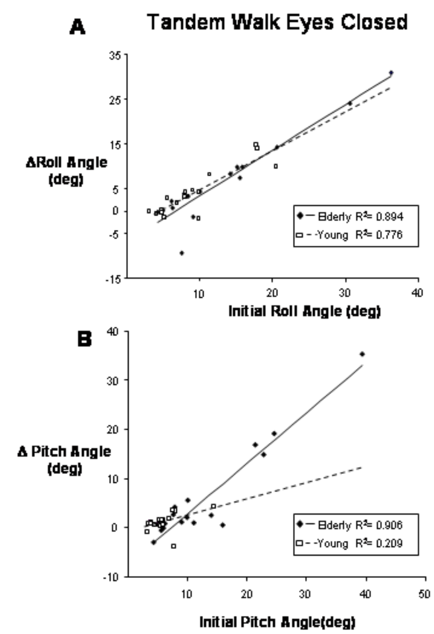


Figure 4. Relationship between pre-test peak-to-peak trunk sway and the reduction in sway achieved with feedback. Roll and pitch angle changes for are shown for walking tandem steps eyes closed (A, roll; B, pitch). Regression lines through the data have been drawn separately for elderly and young subjects. Positive changes means that sway was reduced with feedback (Data from Davis et al 2008 [1]).

One potential limitation of the biofeedback system is that the additional sensory information provided may draw attention resources away from postural control. However, recent studies of older adults engaged in attention demanding tasks while simultaneously performing a balance task and receiving BF have provided findings indicating both improved balance performance and dual tasking ability [2]. Also it has also been demonstrated that attending to an auditory signal during quiet stance does not interfere with balance [18]. This evidence, coupled with the observation that the majority of participants in the current studies had reduced amplitudes of trunk sway with biofeedback, suggests that the possible attention demanding effects of biofeedback are not likely to impair balance control even during dual tasking. This reinforces our main conclusion that efforts should concentrate on improving real-time biofeedback prosthetic balance devices rather than relying on carry-over effects to improve balance control in those with balance problems.

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