Clinical Observational Gait Analysis to Evaluate Improvement of Balance during Gait with Vibrotactile Biofeedback

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Abstract

Background and Purpose. This study explores the effect of vibrotactile biofeedback on gait in 20 patients with bilateral vestibular areflexia using observational gait analysis to score individual balance. Methods. A tilt sensor mounted on the head or trunk is used to detect head or body tilt and activates, via a microprocessor, 12 equally distributed vibrators placed around the waist. Two positions of the tilt sensor were evaluated besides no biofeedback in three different gait velocity tasks (slow/fast tandem gait, normal gait on foam) resulting in nine different randomized conditions. Biofeedback activated versus inactivated was compared. Twenty patients (10 males, 10 females, age 39–77 years) with a bilateral vestibular areflexia or severe bilateral vestibular hyporeflexia, severe balance problems and frequent falls participated in this study. Results. Significant improvements in balance during gait were shown in our patients using biofeedback and sensor on the trunk. Only two patients showed a significant individual gait improvement with the biofeedback system, but in the majority of our patients, it increased confidence and a feeling of balance. Conclusion. This study indicates the feasibility of vibrotactile biofeedback for vestibular rehabilitation and to improve balance during gait. Copyright © 2011 John Wiley & Sons, Ltd.

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Keywords
biofeedback; observational gait analysis; postural balance; posture; rehabilitation; vestibulopathic gait

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**Introduction**

The vestibular labyrinths play a key role in posture and balance, retinal image stabilization and spatial orientation that are all affected in case of substantial vestibular deficits and lead to a major handicap (oscillopsia, postural imbalance) in patients with a bilateral vestibular areflexia. A potent aid for these patients might be an artificial labyrinth to restore the feedback of linear and angular accelerations of the head or body to the brain. Several researchers are currently engaged with the development of such a device. Some of them try to improve performance in posture and balance in humans using (non-implantable) sensory substitution — galvanic vestibular stimulation (Orlov et al., 2008), auditory feedback (Hegeman et al., 2005), visual feedback (Hirvonen et al., 1997), electrotactile stimulation of the tongue (Tyler et al., 2003) or vibrotactile feedback to the trunk (Kentala et al., 2003). Others try to restore image stabilization by implanting electrodes to restore the input to the brain in animals (Lewis et al., 2002) or in humans (Wall et al., 2007). See Janssen et al. (2010) for a recent overview.

Vibrotactile feedback through the trunk is a very intuitive approach and has been used as support orientation for blind people (Ram and Sharf, 1998), in industrial telemanipulators (Dennerlein et al., 1997) and in virtual environments (Okamura et al., 1998). Therefore, an ambulatory vibrotactile biofeedback (AVBF) system to reduce body sway and increase postural stability for patients with vestibular dysfunction was developed (Janssen et al., 2010), based on the approach used by Wall et al. (2001). In a placebo-controlled study, we previously showed the AVBF system to be effective during quiet stance in 40% of our patients with bilateral vestibular loss (Janssen et al., 2010).

In this study, we focus on the use of the AVBF system to increase postural stability during gait in patients with severe bilateral vestibular losses. To our knowledge, only two studies on the effect of biofeedback on gait have been published (Hegeman et al., 2005; Dozza et al., 2007). Hegeman et al. (2005) measured trunk sway during different gait tasks using two angular velocity transducers, while Dozza et al. (2007) measured motion kinematics using a motion analysis system. We assess gait performance, of patients with divers pathologies (including spasticity and severe vestibular hyporeflexia), in our clinical movement laboratory with a Sybar system (Harlaar et al., 2000) to register and interpret gait and to evaluate treatment based on observation. In this paper, a description of the AVBF system will be given, along with an evaluation of the effect of the AVBF system on gait using observational gait analysis.

**Materials and methods**

**AVBF system**

The AVBF system, schematically shown in Figure 1, consists of four major components:

1. a DynaPort MiniMod (McRoberts, 5.5 mG [1 mG = cm s⁻²] or 0.30° resolution at a sample frequency of 50 Hz) drift-free sensor, small and lightweight (64 × 62 × 13 mm, 55 gram), containing three orthogonal linear (piezo)capacitive accelerometers, which can be mounted on the patient’s head or high on the trunk;
2. an elastic belt with 12 equally distributed actuators (ZUB.NO32.VIB, eccentric vibra-motors like applied in Nokia 3210 at 300 Hz and an amplitude of 0.5 mm; Jones and Sarter, 2008) around the waist, mounted with a Velcro fastener;
3. an ATMEGA128 (Atmel) processor to translate sensor output into activation of correct actuators with a delay of <1 ms;
4. a LiPo battery pack (11.1 V, 3,270 mAh) to supply power to all components, thus making the AVBF system an ambulatory, comfortable and simple system;

![Figure 1 Schematic overview of the AVBF system. The processor and battery pack can be detached from the upper belt and, for example, fastened on the trousers, having the upper belt only containing the sensor. AVBF = ambulatory vibrotactile biofeedback](image)
The battery pack and processor unit dimensions are 12 × 7 × 3 cm, weighing 330 gram and 240 gram, respectively. The battery can power the processor, actuators and sensor for 72 hours continuously and can be recharged within 8 hours, making sure that patients can use the AVBF system for several days and recharge it overnight even without the explicit need of a spare battery.

A patient wearing the AVBF system can set a reference vector at any desired moment, simply by pressing a button on the processor unit. Setting this reference vector is necessary for the AVBF system to know its sensor orientation. Subsequently, the processor calculates the vector difference between the reference vector and the current sensor orientation. This difference is the patient’s tilt angle (size/angle and direction) and is translated into the activation of specific actuators; see Figure 2, in order to code the amount of body tilt (tilt angle) and the direction of body tilt (tilt direction). One actuator is activated in the direction of a patient’s body tilt if it exceeds a tilt magnitude of 1° (no. 1 in Figure 2 if the patient tilts forward). If the tilt angle increases in the same direction and exceeds 2.5°, the two adjacent actuators (no. 2 and 12 in Figure 2) are activated, and the first actuator (no. 1) is deactivated. If the tilt angle increases and exceeds 4°, two adjacent and the middle actuators (nos. 3, 1 and 11 in Figure 2) and the previous actuators (nos. 2 and 12) are deactivated. Thus, the actuator that is activated between 1° and 2.5° of tilt indicates the tilt direction, whereas the number of actuators (the intensity of tactile stimulation [one, two or three actuators]) indicates the tilt angle. In this way, the AVBF system can code body tilt in any direction. When the patient correctly responds to these actuators, they will be deactivated when the tilt angle drops below 1° in any direction. However, if for example the patient responds by tilting backwards and more than 1° to the right, an actuator on the right side will be activated.

The number of activated actuators is based on the sensor resolution and chosen to avoid sensory adaptation because of continuous vibrotactile stimulation. The activation scheme is based on our observations and knowledge that the limit of stability in healthy subjects is about 6° (Nashner et al., 1989) and that the typical sway angle in healthy subjects is about 0.5° (Horlings et al., 2008).

Patients
Twenty patients participated in this study (10 males, 10 females, age 39–77 years) to assess the effect of the AVBF system on postural stability during gait. All patients had severe balance problems with frequent falls (more than five times per year) and showed no responses to caloric irrigations (30°C and 44°C) and reduced or zero gains (≤0.2) at sinusoidal stimulation of the horizontal and vertical canals on rotatory chair testing (0.1 Hz, \(V_{\text{max}} = 60° \text{sec}^{-1}\)), pointing to a bilateral vestibular areflexia or severe bilateral vestibular hyporeflexia.

Procedure
Each patient had 5 minutes to familiarize with the AVBF system. Thereafter, each patient practiced with the AVBF system for 15 minutes to learn how to use the system and to experience the relation between trunk or head movement and actuators. They were instructed to improve their balance using the vibrotactile biofeedback information, during stance and gait, both on a firm surface, with eyes open and closed.

After practicing, gait was assessed with eyes open in challenging situations (Janssen et al., 2010) in all patients, and performance was scored using three standardized gait velocity tasks in our clinical movement laboratory with a 9-m-long and 1-m-wide horizontal track using the Sybar video system:

1. slow tandem gait (one step every 2 seconds; as described by Dozza et al., 2007);
2. fast tandem gait (more than two steps per second);
3. normal gait on 2-cm foam.

![Figure 2](image_url) Figure 2: Activation scheme of the actuator belt worn around the waist. The different marked actuators are activated at different tilt angles, relative to the reference vector, when the patient moves in the marked piece of the pie. In this case, actuator no. 1 is activated at tilt angles >1° and <2.5°, as well as >4° and <2.6°.
Gait was recorded in the frontal (front and back) and sagittal plane using the Sybar video system (Harlaar et al., 2000). An example video capture of a patient is shown in Figure 3. All gait tasks were performed under three different conditions:

- noAVBF: without biofeedback;
- AVBF\textsubscript{trunk}: with biofeedback on the waist and sensor on the trunk;
- AVBF\textsubscript{head}: with biofeedback on the waist and sensor on the head,

resulting in nine different tasks. Both the gait tasks and biofeedback conditions were randomized. Gait assessment took on average 40 minutes per patient.

**Data analysis**

Blinded as to the vibrotactile feedback condition, balance during gait was specifically scored independently by three expert observers (Y.J., H.V. and H.K.) based on the video recordings. Per standardized gait velocity task, the observers identified the condition with best and worst balance during gait, upon which the three conditions were ranked on a three-point scale (2 = best, 1 = medium, 0 = worst; Scholtes et al., 2007). This resulted in an individual maximum score for one of the biofeedback conditions of 6 for each gait velocity task and a score of 18 for the three gait tasks combined.

Wilcoxon’s signed ranked test was used to determine the effect of the AVBF system activated (AVBF\textsubscript{trunk} and AVBF\textsubscript{head}) versus the AVBF system deactivated (noAVBF) for each gait velocity task and for the three gait tasks combined.

As Bayesian analysis allows for a direct patient-specific statement regarding the probability that a treatment was beneficial (Adamina et al., 2009), classical Bayesian probability statistics was used to determine a patient specific effect of the AVBF system, which was significant for a total score >16 or <2. The level of significance in all tests applied was $p < 0.05$.

Interobserver reliability was assessed by using intra-class correlation coefficients, validated for use with multiple raters and calculated in a two-way random model based on absolute agreement, as described by Brunnekreef et al. (2005).

After having tested a patient, the patient was asked in open question to comment on the functionality of the AVBF system and its effect on balance.

**Results**

The individual total gait scores are shown in Table 1. The inter-observer reliability of gait performance scoring was 0.68 (95% confidence interval: 0.50–0.81), which was substantial. Patients’ balance was significantly better in the AVBF\textsubscript{trunk} condition than the noAVBF condition both during normal gait ($p = 0.04$) and fast tandem gait ($p = 0.03$). AVBF\textsubscript{head} and noAVBF were not significantly different in these gait tasks. During slow tandem gait, no significant differences could be shown. Over the total score, patients’ balance during gait was significantly better in both the AVBF\textsubscript{trunk} ($p = 0.01$) and AVBF\textsubscript{head} ($p = 0.03$) condition than the noAVBF condition. Using Bayesian statistics to determine a patient-specific effect of the AVBF system, two patients (9 and 10) demonstrated significant individual improvements of balance during gait with the AVBF system activated as both performed worst without the AVBF system.

No gender or age relations are apparent as shown in Table 1.

Sixteen patients (80%) commented that they felt more confident regarding their postural stability using the AVBF system, and 14 of them were very interested to acquire a system. Balance improvement, increased confidence, independence, feeling more safe and the ability to perform multiple tasks in stance or during walking (e.g. talking and looking around) were reported. No incidents occurred during the whole procedure.
Table 1. Individual gait performance scores per patient, sorted by the total gait performance score without biofeedback. For each patient, total gait performance (the three gait tasks combined) and performance per gait velocity task is shown.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age</th>
<th>Gender</th>
<th>Total gait performance scores</th>
<th>Slow tandem gait</th>
<th>Fast tandem gait</th>
<th>Normal gait on foam</th>
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<td></td>
<td></td>
<td></td>
<td>noAVBF</td>
<td>AVBF&lt;sub&gt;trunk&lt;/sub&gt;</td>
<td>noAVBF</td>
<td>AVBF&lt;sub&gt;trunk&lt;/sub&gt;</td>
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<td>9</td>
<td>56</td>
<td>F</td>
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<td>18</td>
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<td>10</td>
<td>54</td>
<td>F</td>
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<td>3</td>
<td>52</td>
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<td>12</td>
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<td>1</td>
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<td>11</td>
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<td>58</td>
<td>F</td>
<td>16</td>
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<td>9</td>
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<tr>
<td>Total</td>
<td>129</td>
<td>222 (0.01)</td>
<td>188.5 (0.03)</td>
<td>47.5</td>
<td>66 (&gt;0.05)</td>
<td>66.5 (&gt;0.05)</td>
</tr>
</tbody>
</table>

The green cells indicate the significant patient-specific effects as determined by classical Bayesian probability statistics, values between brackets indicate the p-values as determined by Wilcoxon’s signed ranked test between the AVBF system activated (AVBF<sub>trunk</sub> and AVBF<sub>head</sub>) versus the AVBF system deactivated.

AVBF<sub>trunk</sub> = AVBF system activated with biofeedback on the waist and sensor on the trunk; AVBF<sub>head</sub> = AVBF system activated with biofeedback on the waist and sensor on the head; noAVBF = the AVBF system deactivated; F = female; M = male.
During a follow-up consultation, some patients mentioned that the use of the AVBF system even had improved their balance for several hours after the system had been removed.

Discussion

Vibrotactile biofeedback system outcome

We used video recordings from the Sybar video system and scores from three expert observers to determine performance of balance during gait with and without vibrotactile biofeedback in 20 patients with a bilateral vestibular areflexia. Both during normal gait and fast tandem gait, the patients’ balance was significantly better with biofeedback of the AVBF system on the waist and sensor on the trunk compared with no biofeedback. Additionally, using observational gait analysis as a means to score gait performance, we were able to identify significant individual improvements of balance during gait in two patients with the AVBF system activated.

These improvements are in line with work of Dozza and colleagues. They showed in patients with unilateral vestibular loss that stability during slow tandem gait improved using vibrotactile biofeedback (Dozza et al., 2007). They also showed in their cross-over design that stability improved with repetition of tandem gait trials, thus indicating a learning effect of trial repetition, but that performance was consistently better in the trials with biofeedback than without biofeedback. In our study, we controlled for a possible learning effect by randomizing the biofeedback conditions and gait velocities; thus, the significant improvements in our patients can be attributed to effects of biofeedback. However, as we did not perform a placebo-controlled study (Janssen et al., 2010), the effects might also be because of the patient’s belief (Yardley et al., 2001) or increased alertness (Hegeman et al., 2005; Dozza et al., 2007; Basta et al., 2008).

In contrast to Dozza et al. (2007), we were not able to show significant improvements in balance during slow tandem gait. This might be because of the task (slow tandem gait) being too difficult for bilateral vestibular areflexia patients to show balance improvements using vibrotactile biofeedback with limited practice time. Additionally, Dozza et al. have shown a biofeedback effect in their patients with unilateral vestibular loss using a gait task with eyes closed, whereas our patients performed the gait tasks with eyes open. We expect an increased gait performance with eyes closed as well in our gait tasks, because patients will probably use a biofeedback system more in such a challenging situation. However, more training with the AVBF system is then probably needed.

Hegeman et al. (2005) found only little improvement in a group of patients with bilateral vestibular areflexia performing several gait tasks using auditory biofeedback, but their group may not have been a real at risk group in contrast to our (frequent falls), because none of their subjects had recently suffered a fall. Moreover, our results are in line with work of others showing that vestibular impaired patients are more stable using biofeedback in stance (Kentala et al., 2003; Tyler et al., 2003; Danilov, 2004; Dozza et al., 2005b; Hegeman et al., 2005; Danilov et al., 2006, 2007; Ernst et al., 2007; Basta et al., 2008; Goebel et al., 2009).

Sensor location

Balance improvements during stance have been shown using a sensor on the trunk (Kentala et al., 2003; Dozza et al., 2004; Hegeman et al., 2005; Dozza et al., 2005a; Dozza et al., 2005b; Dozza et al., 2007; Ernst et al., 2007; Basta et al., 2008) as well as on the head (Wall et al., 2001; Tyler et al., 2003; Danilov, 2004; Danilov et al., 2006, 2007; Orlov et al., 2008; Goebel et al., 2009). We know of only one study about optimal sensor location in biofeedback (Janssen et al., 2010), which seems to be the head, but which also showed that the placebo effect of biofeedback might be substantial. The current study appears to indicate that the trunk seems to be the optimal location of the sensor, although not on an individual basis. So the optimal sensor location in biofeedback is yet to be examined in future studies and might even be individually determined.

Implications

Although significant individual gait improvements were only shown in a couple of our patients, vibrotactile biofeedback increased confidence, independence and a feeling of balance and safety in the majority of our patients, as was shown by Kentala et al. (2003) as well. Some patients even mentioned that the use of the vibrotactile biofeedback system had improved their balance for several hours after the device had been removed. This indicates the feasibility of the AVBF system to improve balance during gait, and that the brain is able
to include vibrotactile biofeedback in its predictive behaviour to avoid falls.

Some critical remarks after evaluating our results obtained so far and exploring the literature:

1. Improvement of balance by biofeedback is shown in the minority of patients with balance problems (Ernst et al., 2007; Janssen et al., 2010). The impact of biofeedback might vary among patients, first of all because of differences in the severity of the vestibular deficit and its effect on balance during gait and second because of the dependence on vestibular input for balance during gait compared with the other senses.

2. Training to optimize use of biofeedback seems to be essential (Danilov et al., 2006, 2007; Dozza et al., 2007; Ernst et al., 2007; Basta et al., 2008).

3. Adaptation effects do occur and reduce the impact of biofeedback in time during use (Ernst et al., 2007) but also prolong the impact after use (Danilov, 2004).

4. The placebo effect might be substantial (Dozza et al., 2007; Janssen et al., 2010).

In future studies, it needs to be examined if patient performance in daily life or quality of life indeed increases using biofeedback. No doubt, it will be beneficial for training, rehabilitation and sensory substitution; because biofeedback is a rewarding approach as it gives a positive feeling if no feedback has been given during a task and motivates a patient to be more active and train challenging tasks.

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