Vestibular Substitution for Posture Control

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1. Introduction.

The Electro-tactile Vestibular Substitution System (EVSS) is an example of the highly efficient fusion of advanced electrical engineering, computer science and progressive developments in neuroscience and rehabilitation medicine, to recover one of the most “unrecoverable” disabilities – those of the vestibular system. Training with the EVSS leads to greatly improved posture, not only during use of the system, but for increasing periods of time after training sessions.

The EVSS system combines the information transmission capacity of the human skin (the largest human sensory organ and the most evolutionarily advanced and histological sophisticated tissue that is saturated with multiple modality sensors), with the human brain plasticity.

1.1 Historical development. The EVSS has evolved from tactile sensory substitution studies that began in 1963, resulting in the development of the Tactile Vision Substitution System (TVSS). The TVSS delivered information from a TV camera to arrays of mechanical stimulators in contact with the skin of one of several parts of the body, including the abdomen, back, thigh, forehead, and fingertip [1, 2, 3].

After sufficient training with the TVSS, blind subjects reported experiencing the images in space, instead of on the skin. They learned to make perceptual judgments using visual means of analysis, such as perspective, parallax, looming and zooming, and depth judgments. The TVSS has been sufficient to perform complex perception and “eye”-hand coordination tasks. These have included facial recognition, accurate judgment of speed and direction of a rolling ball with over 95% accuracy in batting the ball as it rolls over a table edge, and complex inspection-assembly tasks [1, 2, 3, 4].

Electrotactile stimulation supplanted the vibrotactile stimulation because it is simpler lighter, consumes less energy, and can control the stimulus more easily. Various improvements have lead to the current EVSS system. It is an example of a new generation of sensory substitution devices based on computer controlled electrical stimulation of the human skin in the most densely innervated tactile areas: the tongue and the fingers.

1.2 Vestibular Substitution. The vestibular system detects head movement by sensing head acceleration with specialized peripheral receptors in the inner ear that consist of semicircular canals and otolith organs.

The vestibular system is important in virtually every aspect of our daily life, because head acceleration information is essential for our adequate behavior in three-dimensional space not only through vestibular reflexes that act constantly on somatic muscles and autonomic organs (see Wilson and Jones 2002 for review [5], but also through various cognitive functions such as perception of self-movement [6,7,8,9,10,11], spatial perception and memory [12,13,14,15], visual spatial constancy [16,17], visual object motion perception [18,19], and even locomotor navigation [13,20]. Vestibular input functions also include: egocentric sense of orientation, coordinate system, internal reference center, muscular tonus control, body segment alignment [21].

Bilateral vestibular loss can be caused by drug toxicity, meningitis, physical damage or a number of other specific causes, but is most commonly due to unknown causes. It produces multiple problems with posture control, movement in space, including unsteady gait and various balance-related difficulties, like oscillopsia [22]. Unsteady gait is especially evident at night (or in persons with low visual acuity). The loss is particularly incapacitating for elderly persons.

Oscillopsia, due to the loss of vestibulo-ocular reflexes, is "…a distressing illusory oscillation of the visual scene" [23]. Oscillopsia is a permanent symptom. When walking, patients are unable to fixate on objects because the surroundings are bouncing up and down. In order to see the faces of passerby they learn to stop and hold their heads still. When reading, such patients learn to place their hand on their chin to prevent slight movements associated with pulsation blood flow [22, 23].

For the current project of vestibular rehabilitation we chose subjects with bilateral vestibular loss, the most severe damage possible to the balance sensory system. All of them were identified as disabled or handicapped.

2. Methods

2.1 Device. A miniature 2-axis accelerometer (Analog Devices ADXL202) was mounted on a low-mass plastic hard hat. Anterior-posterior and medial-lateral angular displacement data (derived by double integration of the acceleration data) were fed to a previously developed tongue display unit (TDU) that generates a patterned stimulus on a 144-point electrotactile array (12 x 12 matrix of 1.8 mm diameter gold-plated electrodes on 2.3 mm centres) held against the superior, anterior surface of the tongue [24] .

Subjects readily perceived both position and motion of a small 'target' stimulus on the tongue display, and interpreted this information to make corrective postural adjustments, causing the target stimulus to become centered.

Signals from the accelerometer, located in the hat on top of the head, deliver position information to the brain via an array of gold plated electrodes in contact with the tongue. Continuous recording from the accelerometer produced the head base stabilogram (HBS). The HBS is the major component of our data recording and analysis system.

2.2 Subjects. Ten individuals with bilateral vestibular dysfunction (BVD) tested and trained using the EVSS. Five participants were female and five were male. The average age of the female group was 51.4 years with the average age of the male group being 64.4 years.

Of both groups, the dysfunction of seven of the participants was a result of ototoxicity from the use of the aminoglycoside antibiotic gentamycin. One subject had Mal de Debarkment syndrome, one patient had vestibular dysfunction as a result of bilateral surgery to correct perilymphatic fistulas, and one subject's loss of vestibular functions bilaterally was a result of an unknown phenomenon.

2.3 Testing and training procedure. To determine abilities prior to testing, each subject completed a health questionnaire as well as a task ability questionnaire, along with the required informed consent forms. Prior to testing each individual was put through a series of baseline tests to observe their abilities in regards to balance and visual control (oscillopsia). These baseline tests were videotaped.

Prior to undergoing any 20 minute trials each individual underwent a series of data captures with the EVSS designed to obtain preliminary balance ability baselines as well as to train them in the feel and use of the system. These data captures included 100, 200 and 300 second trails both sitting and standing, eyes open and eyes closed.

Upon completion of the balance ability baselines and confirmation from them that they fully understood the EVSS system and how it operates, each individual proceeded into the 20 minute trails and/or were trained to stand on soft materials or in tandem Romberg posture. For all patients both conditions were "unimaginable" to perform. Indeed, none of the subjects could complete more than 5-10 seconds stance in any conditions.

Typical testing/training included 9 sessions 1.5-2 hours long (depending on patient stamina and test difficulty). The shortest series a patient completed was 5 sessions, while the longest was 65 sessions.

3. Results

As a result of training procedures with the EVSS, all ten patients demonstrated significant improvement in balance control. However, speed and depth of balance recovery varied from subject to subject. Moreover, we found that training with the EVSS system demonstrated not one, but rather several different effects or levels of balance recovery.

We can separate at least two groups of balance recovery effects of EVSS training: direct balance effects and residual balance effects. In addition to balance recovery effects, we found a multiple effects directly or indirectly related to the vestibular system, for example improvement of vision (oscillopsia and eye movement control) and sleep improvement.

3.1.1 The immediate effect was observed in sitting and standing BVD subjects almost immediately (after 5-10 minutes of familiarization with EVSS) and included the ability to control stable vertical posture and body alignment (sitting or standing with closed eyes) during extended periods (up to 40 minutes after 1-2 experimental sessions) [24] .

3.1.2 Training Effect. Some of our BVD patients, especially after long periods of compensation and extensive physical training during many years, had already developed the ability to stand straight, even with closed eyes, on hard surfaces. However, even for well-compensated BVD subjects standing on soft or uneven surfaces or stances with limited bases such as during a tandem Romberg stance, standing was challenging, and absolutely unthinkable with closed eyes.

Using the EVSS, BVD patients not only acquired the ability to control balance and body alignment standing on hard surfaces, but also the ability to extend the limits of their physical conditioning and balance control. As an example, standing in the tandem Romberg stance with closed eyes became possible. After one training session of 18 training trials each 100 second long (total EVSS exposure time 30 minutes), a BVD patient was capable of standing in the tandem Romberg stance with closed eyes for 100 seconds.

3.2 Residual balance effects also were observed in all tested BVD patients; however strength and extent of effects significantly varied from subject to subject depending on the severity of vestibular damage, the time of subject recovery, and the length and intensity of EVSS training.

At least three groups of residual balance effects were noted: short term residual effects (sustained for a few minutes), long term residual effects (sustained for 1 to 12 hours) and a rehabilitation effect that we observed during several months of training in a single subject. All residual effects were observed after complete removal of EVSS from subject's mouth.

3.2.1 Short term after effect. This effect usually was observed during the initial stages of EVSS training. Subjects were able to keep balance for some period of time, without the immediately developing an abnormal sway; as it usually occurred after any other kind of external tactile stabilization, like touching a wall or table. Moreover, the length of short term aftereffects was almost linearly dependent on the time of EVSS exposure. After 100 seconds of EVSS exposure, stabilization continued during 30-35 seconds, after 200 seconds EVSS exposure 65-70 seconds and after 300 seconds EVSS trial the subject was able to maintain balance for more than 100 seconds. Short term after-effect continued during approximately 30%-70% of the EVSS exposure time [24].

3.2.2 Long term after effects. This group of effects developed after long (up to 20 - 40 minutes) sessions of EVSS training in sitting or standing subjects and continued for a few hours. The duration of the balance improvement after-effect was much longer than after the observed short-term after effect: instead of the expected 7 minutes of stability (if we were to extrapolate the 30% rule on 20 minute trials), we discovered from 1 to 6 hours of improved stability, Figure 1. During these hours BVD subjects were able to not only stand still and straight on a hard or soft surface, but were also able to accomplish completely different kinds of balance-challenging activities, like walking on a beam, standing on one leg, dancing. One subject brought a bicycle to the lab and was able to ride it. However, after a few hours all symptoms returned.

The strength of long term after effects was also dependent on the time of EVSS exposure: 10 minutes trials were much less efficient than 20 minutes trials, but 40 minutes trials had about the same efficiency as 20 minutes. Usually, 20 -25 minutes was the longest comfortable and sufficient interval for standing trials with closed eyes. Sitting trials were less effective than standing trials.

The shortest effects were observed during initial training sessions, usually 1-2 hours. The longest effect after a single EVSS exposure was 11-12 hours. The average duration of long term after effects after single 20 minutes EVSS exposure was 4-6 hours.

3.2.3 Rehabilitation effect. We were capable of repeating two or even three 20 minutes EVSS exposures to a single subject during one day. After the second exposure effects was continued in average about 6 hours. In total, after two 20 minutes EVSS stabilization trials, BVD subjects was capable of feeling and behaving what they described as "normal" for up to 10 - 14 hours a day.

One BVD subject was trained continuously during 20 weeks, using one or two 20 minute EVSS trials a day, Figure 2. This figure demonstrates the systematic improvement and gradual increase of the long term aftereffect for the same subject during consistent training. Moreover, we found that repetitive EVSS training produced both accumulated improvement in balance control, and global recovery of the central mechanisms of the vestibular system.

For the same BVD subject, after two month of intensive training, we completely stopped any EVSS exposure and begin regular checking of the subject's balance and posture control. During the 14 weeks after the last EVSS system training, the subject was able to stay perfectly still with closed eyes, while standing for 20 minutes on hard or soft surfaces. We considered that fact as convincing evidence of the actual rehabilitation capability of the EVSS.

3.3 Summary of ETVS training effects

3.3.1. General balance improvement. Subjects experienced the return of their sense of balance, increased body control, steadiness, and a sense of being centered. The constant sense of moving was disappeared. They were able to walk unassisted, reported increased ability to walk in dark environments, to walk briskly, to walk in crowds, and to walk on patterned surfaces. They gained the ability to stand with their eyes closed with or without a soft base, to walk a straight line, to walk while looking side to side and up and down. They gained the ability to carry items, walk on uneven surfaces, walk up and down embankments, and to ride a bike. They became willing to try new things, and in general became much more physically active.

3.3.2 Posture, proprioception and motor control. Body movements became more fluid, confident, light, relaxed and quick. The stiffness disappeared, limbs, head and body felt lighter and less constricted. Fine motor skills returned, and gait returned to normal. Posture and body segment alignment returned to normal. Stamina and energy increased.

3.3.3. Vision. Vision became more stable, clearer, and brighter. Colors were also brighter and sharper, and peripheral vision widened. Reading became smoother and easier, and it was even possible to read in a moving vehicle. There were strong improvements in adaptation during transition from light to dark conditions. There was a reduction of oscillopsia, and an improved depth perception.

3.3.4. Cognitive functions. There were increases in mental awareness, creativity, clarity of thinking, confidence, multitasking skills, memory retention, and concentration ability, ability to track conversations and to stay on task. Subjects felt more alert and energized, and ceased the constant awareness to balance. There was less “noise” in the head, much improvement in intensity of thinking, problem solving, and decision making.

3.3.5. Emotional conditions. Subjects felt calmer, aware, confident, happy, and quiet, refreshed, relaxed, and experienced a strong sense of well being, with elimination of fear.

3.3.6. Sleep. The majority of BVD patients noticed sleep improvement. Sleep became fuller, longer, and more restful, often with no awakenings during the night.

3.3.7 Other. There was an increased ability to drive both for daytime and night driving. Subjects reported feeling younger and more vibrant, with reduction of stress, lifting and relaxation of the face muscles resulting in “younger look”, brighter eyes. Some subjects reported fewer visits to a chiropractor, increased awareness of surroundings, increased activity, and reduction or elimination of tinnitus.

All these functions ultimately relate to the individual’s ability to maintain employment, personal and social activities, family life and relationships leading to a great improvement in their quality of life. The results emphasized the truly rehabilitation effects of EVSS.

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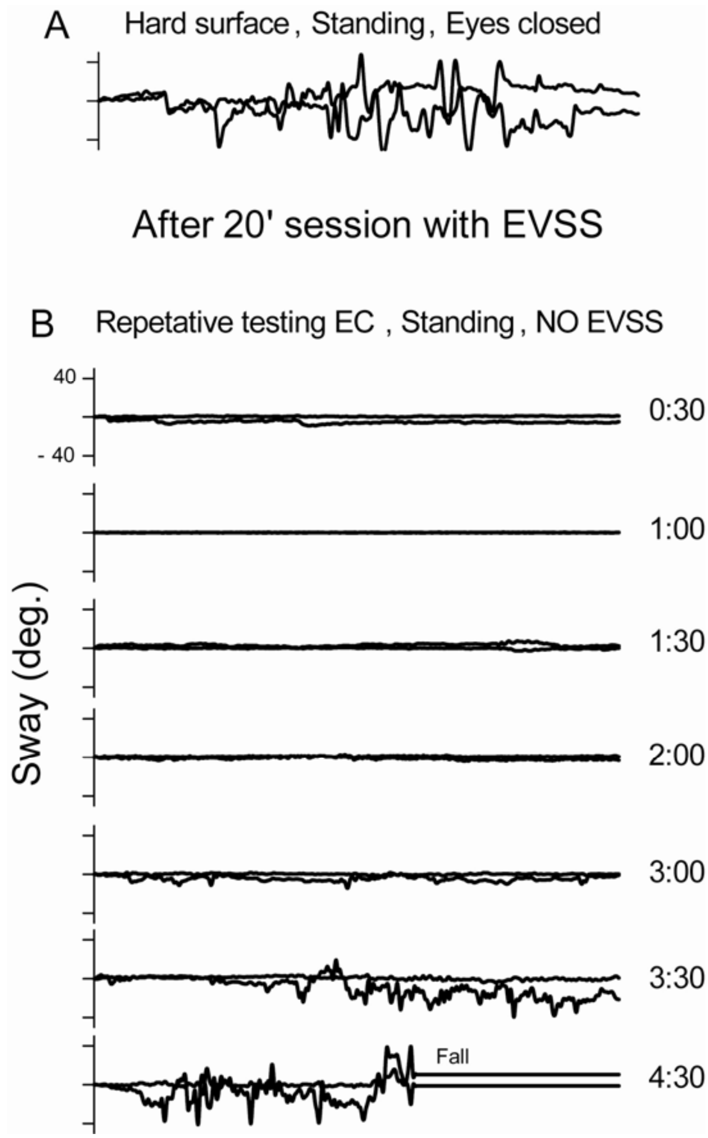

Figure 1. Long term after effect.

Figure demonstrates improvement of the balance control in BVD patients during few hours after EVSS removal.

A- Starting condition, trial of BVD patient standing on the hard surface with closed eyes.

B- Set of BVD patient trial sessions standing on the hard surface, repeated every 30 – 60 minute after 20 minutes session with EVSS system.

Note,

- The balance control improvement was observed during almost 4 hours after EVSS system removal.
- Testing trial recorded 1 hour after EVSS system removal is not an artifact, in opposite – it is 100 seconds of subject’s perfect stability.

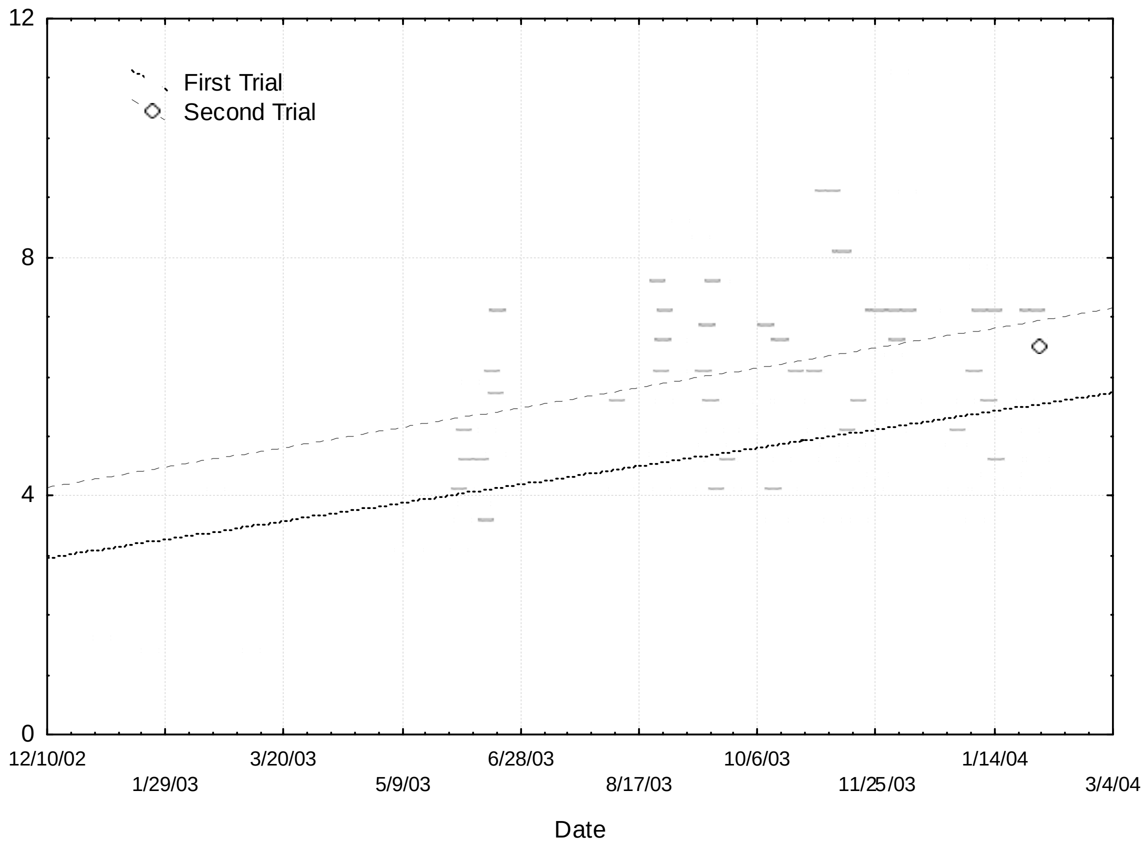

Figure 2. Summary graph of long term after effect for one BVD patient.

Scatter plots demonstrate duration of balance improvement after first (filled circle) and the same day second (empty diamonds) 20 minute trials with EVSS system. Dotted lines represent linear regression lines for fist and second trials recorded during one year training.
Note,

- The length of balance improvement after single trials varied from day to day
- After effect after second EVSS trial was usually 1.5 - 2 hours longer than after first one
- The average length of after effect for both trials gradually increased with regular training.