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Vestibular Balance Deficits Following Head Injury: Recommendations Concerning Evaluation and Rehabilitation in the Military Setting

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Vestibular pathology has been documented following barotrauma and/or head acceleration associated with exposure to explosions. The usual symptoms include dizziness and headache, with dizziness and associated imbalance contributing disproportionately to disability. Several agencies have noted the need for better vestibular evaluation and rehabilitation following exposure to improvised explosive devices (IEDs). The authors asked subject matter experts to assist in formulating recommendations for initial assessment and rehabilitation of balance problems following IED exposure, focusing on strategies that are either available or in development. This report summarizes feedback obtained from approximately 50 vestibular researchers, scientific advisors, clinicians, and biomedical engineers working for government agencies, universities, clinics/hospitals, and businesses. Tests appropriate for early (post-injury) functional assessment in the military setting are considered, along with the optimal application of novel tactile balance feedback technologies being developed to augment vestibular rehabilitation.

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Summary

Exposure to Improvised Explosive Devices (IEDs) may cause head injury, leading to central and/or peripheral deficits. Causes of injury from IEDs include blast-induced barotraumas, head acceleration, and/or head impact with environmental objects or flying fragments. Harmful head and neck acceleration also commonly occurs due to falls or vehicle accidents. The most frequent symptoms are dizziness and headache, with dizziness/imbalance contributing disproportionately to disability. The vestibulocochlear organs are exquisitely sensitive to pressure and acceleration, the main sources of injury from IEDs. Vestibular pathology has been documented following barotraumas and head acceleration, and is known to be associated strongly with dizziness, disequilibrium, and headache. Several agencies have noted the need for better vestibular evaluation following IED exposure. There is also a need for better tools for balance rehabilitation following vestibular insults. It is important to develop technologies and protocols which will meet the needs of clinicians. Subject matter experts should be consulted early in the process so that the most relevant and useful tests and treatments are delivered. The authors asked balance experts to assist in formulating recommendations and analyzing alternatives for initial assessment and rehabilitation of balance problems following IED exposure, focusing on strategies that are either available or in development. This report summarizes the findings of two rounds of consultation (one held at a workshop in the U.S. and another at an international conference in Europe) and comprises feedback from approximately 50 vestibular researchers, scientific advisors, clinicians, and biomedical engineers working for government agencies, universities, clinics/hospitals, and businesses. Tests appropriate for early (post-injury) functional assessment in the military setting are considered, along with the optimal application of novel tactile balance feedback technologies being developed to augment vestibular rehabilitation. In the first round of consultations (the minutes of which are summarized in this report), experts were invited to a workshop in Rockville, MD. The experts agreed that better balance/vestibular tests definitely are needed following IED exposure and other sources of head injury. It was recommended that tests emphasize dynamic, functional, and military-relevant aspects of standing balance, gait, visual acuity, perceived visual vertical, and/or perceived dizziness. Preference was given to the development of portable, field-ready tests which would be semi-automated and hence capable of administration by a medic/corpsman rather than a specialist. The meeting participants evaluated a prototype tactile balance testing and feedback technology and found it to be promising for early evaluation and rehabilitation. Suggestions for future modifications tended to focus on ergonomics, human-computer interface (e.g., error proofing), and ideas for additional automated capabilities (e.g., tests). A second round of consultations was solicited at an international vestibular conference (Reykjavik, Iceland). This additional expert feedback (summarized in this report) largely supported the findings of the first workshop, although a few differences emerged concerning tests of preference. The authors noticed an increase in presentations concerning tactile balance cueing compared to past conferences, although much of the research still focused upon healthy normal subjects. The authors recommend further research on efficacy of tactile balance testing and feedback for patients recovering from balance complaints following mild head injury. Further details concerning testing and rehabilitation recommendations from both consultations are provided in this report. Recommendations are also

made for a research and development effort to extend tactile balance cueing technology into clinical and ambulatory applications.

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Introduction

Military personnel may suffer head trauma due to falling, vehicle collisions, head accelerations/impact, sudden pressure changes, or explosive blasts, etc. (Office of the Surgeon General, Traumatic Brain Injury Task Force, 2007). Improvised Explosive Devices (IEDs) have received special attention as a major source of head trauma during current military operations (Taber, Warden, & Hurley, 2006). IEDs cause mixed injuries due to blast pressure and acceleration (including head/neck acceleration, impact against objects, and impact from projectiles). Injuries and syndromes associated with IED exposure have been described by a complicated set of overlapping constructs, including Traumatic Brain Injury (TBI), concussion, post-concussion syndrome, labyrinthine concussion, whiplash injury, and vestibular migraine (Lawson & Rupert, 2010). Although many definitions of TBI exist, in recent common usage, TBI often has become a general phrase which describes explosive blast and acceleration/impact-related polytraumas to the head or brain, associated with multiple, complex injury types (Scott, Belanger, Vanderlploeg, Massengale, & Scholten, 2006; Ruff et al., 2009).

Dizziness and headache (often of migrainous type) are among the most frequent symptoms reported by sufferers of concussion or mild TBI (MTBI) (Luxon, in Baloh & Halmagyi, 1996; Terrio et al., 2009; Gottshall, Drake, Gray, McDonald, & Hoffer, 2003; Lawson & Rupert, 2010). In fact, the majority of concussion/MTBI patients in the military setting show evidence of vestibular pathology and balance problems (Balaban & Hoffer, 2009; Hoffer, Gottshall et al., 2010). This is understandable, since the vestibulocochlear organs and central vestibular systems are exquisitely sensitive to pressure and acceleration. Vestibular pathology has been extensively documented following concussion, MTBI, and barotraumas and vestibular injury is known to be associated strongly with dizziness, vertigo, and disequilibrium (Nashner, in Jacobson, Newman, & Kartush, 1997; Scherer & Schubert, 2009; Lawson & Rupert). Dizziness has been described as a nonspecific sense of disorientation, whereas vertigo has been characterized as an illusion of self-motion (Luxon, in Baloh & Halmagyi). The two terms are not distinguished rigorously in this report. The patient will use the terms interchangeably but the clinician can distinguish them during an exam by careful questioning and evaluation (Herdman, 2007; Hoffer, Gottshall et al.; Hoffer, Balaban et al., 2010).

Dizziness and vertigo are symptoms which contribute disproportionately to a person's degraded performance or disability following head injury (Luxon, in Baloh & Halmagyi, 1996; Terrio et al., 2009). This may be because few people feel able to perform when they are experiencing episodes of vertigo which prevent them from confidently standing or walking, whereas many other common signs and symptoms of mild blast injury (e.g., headache, tinnitus, partial hearing loss) might be tolerated more readily under routine circumstances.

The ability to balance and coordinate while moving is fundamental to nearly all military duties. Disruption of balance can harm readiness (or fitness-for-duty) resulting in prolonged inability to return-to-duty and increasing the risk of further injury (e.g., due to falling or vehicle accidents) (Sylvia, Drake, & Wester, 2001). Hoffer, Gottshall, & Balough (2009) estimated that assessment, treatment, and follow-up of balance patients costs the U.S. military over 500M

dollars a year in lost equipment and lost mission accomplishment, results in the medical discharge of valuable personnel, costs billions of dollars a year in re-training and medical benefits, and strains an already tight personnel pipeline. Cumulative costs for the U.S. and its coalition partners obviously will be much greater than for the U.S. alone. Such balance disorders have dramatic effects on the lives of those who suffer from them, severely limiting their activities and contributing to depression. All coalition allies have been adversely affected by manpower issues associated with blast/concussive events in both Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF). Balance research is ongoing in coalition countries, in part because falls continue to be the leading cause of accidental death in the elderly (over 75). The UK, through its National Health Service (NHS), has a long standing tradition of strong support for preventive medicine research, especially in the area of falls in the elderly.

Recently, a number of authors and agencies have noted the need for better screening tools following TBI (Tanner, 2007; Megna, 2007), and in particular, for improved vestibular evaluation following IED exposure (Scherer & Schubert, 2009; Myers, Wilmington, Gallun, Henry, & Fausti, 2009; Lawson & Rupert, 2010). There is a need for easy-to-use tools which allow rapid and earlier (i.e., further forward) testing to assist with decisions concerning return-to-duty versus referral for additional evaluation and treatment. Such tools should allow automated administration and scoring to yield better consistency than is presently common among many subjective tests used in the clinic. There is also a need for better tools for rehabilitation and assistance following vestibular and balance insults. Many technologies are being developed for evaluation of TBI, but few focus on vestibular and balance functioning. Such a focus seems advisable, since nearly all military missions require good balance and healthy gaze control. Another problem with current systems used to assess TBI effects is that they generally are developed separately from systems for TBI rehabilitation. It would be advantageous if systems could be developed which had assessment and physical therapy rehabilitation capabilities integrated into one unit or one closely coordinated suite of tests with consistent and well-designed procedures and interfaces. Careful consideration and planning is necessary to achieve these goals. It is important to develop solutions with the needs of the clinician firmly in mind from the outset. It is advisable to consult subject matter experts early in the process so that the most relevant and useful tests and treatments are delivered. Such a consultation process should reach out as widely as possible to various international military services and healthcare providers (e.g., otolaryngologists, physical therapists [PT]), to ensure the widest acceptance and successful transition of clinical technologies. This report solicited expert recommendations for technologies designed to meet the need for a modular balance assessment and rehabilitation technology. Many forms of initial vestibular/balance assessment were considered, while treatment discussions centered on tactile balance rehabilitation technologies and protocols. Background on tactile balance cueing is provided below.

A technology for preventing aircraft disorientation mishaps (Rupert, Mateczun, & Guedry, 1990; Rupert, Guedry, & Reschke, 1994; Raj, Suri, Braithwaite, & Rupert., 1998; Rupert, 2000) recently resulted in “spinoff” prototypes which measure and cue balance and may help with the rehabilitation of balance impairments by providing enhanced body sway cues through the sense of touch (Mortimer & Dutta, 2010; Atkins, 2010a; Rupert & Lawson, 2011). The authors

believe that such systems (Asseman, Bronstein, and Gresty, 2007; 2008) may help address some of the military's needs for testing and rehabilitation. Despite the high incidence and severity of balance problems associated with concussion and MTBI, there is no standardized approach for assessing or treating dizziness/balance following such injuries (Gottshall et al., 2003). The current approach to TBI-related balance rehabilitation involves different equipment and methods from site to site (which challenges continuity of care and comparison of outcomes), requires extensive contact time with a PT, and is usually provided at tertiary care facilities. There is a need for greater standardization and site-to-site compatibility of equipment and methods, permitting the comparison of multi-site treatment outcomes and promoting better continuity of care as the patient moves from one treatment site to another (e.g., Department of Defense [DoD] to Veterans Administration [VA]; or from one country to another). Such technology also should enable increased patient throughput by PTs and make balance rehabilitation tools more widely available outside of the Continental U.S. (OCONUS) and in field- and home-based settings. The recognized need for such tools by providers will be a strong driver pulling the technology to the user community. A portable, field-able technology would be well-suited for transition, since it would align with the Navy concept of extending medicine "to the deckplates" and the VA concept of "care where you live" by promoting field- and home-based healthcare. Any rehabilitation method which promotes faster return-to-duty and reduces travel and treatment costs (vice referral to tertiary care centers) will be a useful addition. The clinical and operational impact of this technology would be to improve the quantification and treatment of disequilibrium, vestibular dysfunction, and to improve recovery strategies following concussion/MTBI or whiplash injury.

Balance or visual-vestibular dysfunction has appeared or persisted even in cases where an office exam, brain scan, or cognitive test appears normal. Yet, despite the high incidence and severity of balance problems associated with concussion, there is no standardized approach for assessing or treating dizziness/balance following MTBI (Gottshall et al., 2003). The clinical and operational impact of this project would be to improve the detection and quantification of disequilibrium, vestibular dysfunction, and recovery following concussion, MTBI, or whiplash injury. This initiative will also provide improved rehabilitation strategies incorporating enhanced sensory feedback.

The tactile feedback device which is the focus of this study was originally developed for prevention of spatial disorientation in flight (Rupert et al., 1990; Rupert et al., 1994; Raj et al., 1998; Rupert, 2000; McGrath, Estrada, Braithwaite, Raj, & Rupert, 2004; Curry, Estrada, Grandizio, & Erickson, 2008), with recent help from the Coalition Warfare Program (CWP) sponsor. The aviation hardware and software were adapted to create an initial prototype device suitable for cueing sway in persons with balance problems. This prototype adapted from the aviation setting has shown promise for balance rehabilitation (Mortimer & Dutta, 2010; Atkins, 2010a), but it needs to be transformed into a true clinical tool. This requires input from subject matter experts. Experts should evaluate device requirements and treatment protocols necessary to transform the current prototype balance cueing devices into optimal sensory feedback systems to improve the balance rehabilitation training of patients suffering from postural instability. An initial consideration of several available touch-cueing systems for balance was

conducted by a small group of six balance experts in 2009, the results of which were reported by Rupert and Lawson (2011). The Rupert and Lawson report describes how an aviation orientation cueing system supplying vibrotactile feedback (through the clothing) to the circumference of the torso came to be employed for balance cueing and why it was selected as the technology most ready for further evaluation compared to two other systems (one of which supplied electrotactile cues to the top of the tongue and the other of which supplied electrotactile cues to the bare skin of the abdomen). This preliminary expert evaluation was merely a beginning, and a more complete evaluation was needed to ensure that tactile cueing technologies were developed in a way that would render them optimal for transition to widespread clinical trials of efficacy. This report summarizes that additional evaluation effort.

The impetus for this report came from Mr. John Noulis of the CWP, who experienced a demonstration of the prototype balance cueing system and recognized its potential. He alerted the authors to an opportunity for possible studies group funds to carry out expert consultations which would aid the design and transition of the technology. The authors then proposed a consultation plan to COL Kathleen Hithe of CWP, who gave her approval. This report summarizes the evaluations of clinicians, researchers, and biomedical engineers to optimize balance testing and enhance the suitability of tactile balance testing/cueing systems for military clinical applications and full clinical trials. The authors assembled a group of well-known, highly-experienced clinicians, researchers, and biomedical engineers, who made recommendations for military-appropriate balance tests for early assessment after injury, and recommendations concerning tactile balance testing and cueing, particularly any changes they felt might enhance the successful transition of a final clinical product. This group was tasked with providing expert advice to the sponsor concerning the optimal design and implementation of tests and protocols intended to enhance Warfighter balance recovery following TBI. The recommendations of this group were then discussed with approximately 30 additional experts at an international conference and refined accordingly. Thus, counting the authors, this report represents feedback from approximately 50 people with experience in the area of human balance and vestibular function. The list of people consulted includes researchers, scientific advisors, otolaryngologists/ear, nose, and throat doctors (ENTs), PTs, audiologists, and biomedical engineers. Consultants who have extensive experience working in academia, industry, and/or the government (e.g., National Institutes of Health [NIH], DoD, National Aeronautics and Space Administration [NASA]) are included.

This effort was designed to ensure that the U.S. and its coalition partners provide the best care to wounded Warriors and minimize the present and future risk of them experiencing vertigo, disequilibrium, or falling. To this end, national and international experts formed a working group to discuss the current state of balance testing and cueing, to analyze alternatives for testing and rehabilitation, to directly experience the current tactile balance testing and feedback devices, to provide advice to the authors concerning Small Business Innovative Research (SBIR) topics/programs, to recommend improvements and guide the direction of future changes to the device, to provide guidance on locations of pilot experiments, and to advise on institutional review for the necessary protocol applications for multi-center clinical trials. The key liaison among all participants (i.e., the expert consultants, the sponsor, the

meeting site personnel, and the in-house administrative personnel) was maintained by principal investigator (PI), Dr. Rupert (USAARL), associate investigator (AI), Dr. Lawson (USAARL), and research associate, Ms. Legan (Henry Jackson Foundation), who coordinated all working group communications, meeting agendas, and reports to the sponsor. The present report is a summary of our findings concerning two rounds of expert consultation. The first round of deliberations summarized in this report entailed a formal, dedicated working group meeting held domestically. The second round of deliberations was carried out in Europe and consisted of multiple discussions with participants at two preeminent international symposia on vestibular neuroscience and vestibular clinical topics. The results of these group consultations are discussed in the remainder of this paper. The purpose of this report is not to transcribe all discussions, meetings, presentations, or demonstrations attended by the authors. Rather, this report focuses on specific balance testing and rehabilitation recommendations the authors can make, based on their consideration of the extensive feedback they received from various experts, starting with an expert working group meeting, which is described below.

First round of deliberations: Minutes from an expert working group meeting

Group considerations began with an invited workshop on balance assessment and tactile rehabilitation, held 2 June 2010 at the Henry Jackson Foundation Headquarters in Rockville, MD. The meeting was sponsored by the CWP Office of the Undersecretary of Defense for Acquisition, Technology, & Logistics (AT&L). The meeting was organized and led by members of the U.S. Army Aeromedical Research Laboratory (chair, Dr. Rupert; co-chair Dr. Lawson). The workshop opened with several presentations on the subject topic, but presentation time was limited to allow the group to focus on a roundtable discussion leading to specific recommendations concerning balance assessment and rehabilitation. The presentations and recommendations are summarized here. The workshop attendees are listed in alphabetical order, in table 1.

Table 1.
Workshop participants.

Name	Degree	Title	Affiliation
Atkins, Karen	PhD, PT	Director	BalanceSense, LLC
Balaban, Carey	PhD	Professor	University of Pittsburgh
Gottshall, Kim.	PhD, PT	Director, Vestibular Assessment & Rehab.	Naval Medical Center San Diego (NMCSD)
Holden, Maureen	PhD, PT	Associate Professor	Northeastern University
Lawson, Ben	PhD	Research Scientist	USAARL
Merfeld, Daniel	Ph.D.	Associate Professor	Harvard Medical School
Mortimer, Bruce	Ph.D.	Director, R&D	Engineering Acoustics Inc.
Nashner, Lewis	ScD	President & CEO	Interactive-Motion Technologies, Inc.
Platt, Christopher	PhD	Program Director	CNS Hearing & Balance, National Institute on Deafness and Other Communication Disorders (NIDCD)/NIH
Rine, Rose Marie	PhD, PT	Research Scientist - Physical Therapist	Specialty Therapy Source, LLC
Rupert, Angus	MD, PhD	Research Scientist	USAARL
Shelhamer, Mark	ScD	Associate Professor	Johns Hopkins University School of Medicine
Sklare, Daniel	PhD	Director, Assessment & Management of Hearing/Balance Disorders; Research Training Officer	Division of Scientific Programs, NIDCD/NIH
Stith, Dettrick	PhD	Senior Principal Scientist	General Dynamics Info. Technol. for Clinical & Rehab. Medicine Research
Wall III, Conrad	PhD	Professor	Harvard Medical School
Wood, Scott	PhD	Senior Scientist	Universities Space Research Association (USRA)

The meeting began with a presentation by Dr. Rupert which outlined the goals of the workshop and provided an overview of the various relevant streams of research the participants have carried out which are relevant to those goals. Dr. Balaban then reviewed recent findings

concerning vestibular effects of TBI. Next, Dr. Atkins summarized the results of her dissertation research on tactile balance rehabilitation. Presentation slides from Drs. Rupert, Balaban, and Atkins are shown in appendices A through C.

After the presentations, the bulk of the meeting was dedicated to a roundtable discussion concerning suitable tests for early evaluation of vestibular deficits due to MTBI. Earliest possible evaluation and treatment was considered important for improving early determinations concerning return-to-duty and for improving therapeutic outcomes (Scherer & Schubert, 2009; Balaban & Hoffer, 2009)

Next, Dr. Mortimer demonstrated a prototype system for tactile balance cueing, which the meeting participants experienced. This was a later generation of the system Dr. Atkins used in her dissertation. The group then provided feedback about the device and considered its optimal applications for tactile balance testing and rehabilitation.

At the end of the day, the group briefly considered general treatment needs (beyond the tactile device) and discussed potential assistance devices for those in need of prolonged balance cueing in their daily lives. Brief comments concerning the three presentations are provided immediately below, with notes concerning the roundtable discussion appearing after the presentations.

Highlights from "Tactile sway biofeedback" by Rupert and Lawson

Dr. Rupert kicked off the meeting with a brief presentation concerning the goals of the workshop, recent research efforts of relevance, and future research needs (slides shown in appendix A). He described the relevance of subsequent planned speeches, demonstrations, and discussions to the most important issues of the workshop. He also provided background concerning how tactile balance cueing grew out of the various streams of research many of the attendees had carried out in postural equilibrium, vibrotactile displays, and TBI. Dr. Rupert stressed that following an exposure to an IED or a concussive event, there are frequently vestibular symptoms. Due in part to the lack of personnel familiar with subtleties of vestibular function, these symptoms have not been adequately evaluated or treated in the past. Unless the Soldier has an injury which requires him/her to be sent to the emergency room, the Soldier is likely to be initially assessed by an enlisted Army/Air Force combat medic or Navy hospital corpsman[1]. For this reason, there is the need for a simple, objective test with a small footprint in order to determine whether the injured person goes back to his unit or receives additional care. This is the first issue of concern in the workshop. Dr. Balaban and his colleagues have gathered evidence in the operational setting which implies that 80 to 90% of personnel experience vestibular problems following IED exposure. Such problems currently are detected only by experienced ENTs and detection requires access to sophisticated tests and the ability to interpret them. The goal of recent efforts by Dr. Rupert, his colleagues, and Phase I Office of the Secretary of Defense (OSD) SBIR-funded researchers has been to develop fairly simple,

[1] Hereafter, collectively referred to as "medic/corpsman."

portable, objective tests and rehabilitation devices (examples of various SBIR and non-SBIR devices are shown in appendix D.)

Tactile cueing has proven helpful to the improvement of gait performance (Dozza, Wall, Peterka, Chiari, & Horak, 2007) and standing balance among healthy young and old persons (Peterka, Wall, & Kentala, 2006; Verhoeff, Horlings, Janssen, Bridenbaugh, & Allum, 2009); it has also helped patients with central or peripheral vestibular pathology (Wall & Kentala, 2005; Danilov, Tyler, Skinner, Hogle, & Bach-y-Rita, 2007). Over the past several years, the military has provided funding via various SBIRs to develop the tactile stimulators (e.g., vibrating tactors), balance platforms, algorithms, and related multisensory systems to improve standing balance and sit-to-stand tasks. For example, prototypes have been developed (Atkins, 2010a; Mortimer & Dutta, 2010) for the treatment of balance dysfunction using vibrotactile feedback to provide center-of-pressure information derived from patients standing on balance platforms.

It is anticipated that with continued technology development (SBIRs, Small Business Technology Transfers [STTRs], and Multidisciplinary University Research Initiatives [MURIs]), it will be possible to advance this sensory feedback technology to include the ambulatory condition. The ultimate goal is to provide real-time multimodal sensory cueing to prevent falls while engaging in everyday activities (i.e., walking and moving quickly while carrying objects). To accomplish this task it will be necessary to link multiple miniaturized accelerometers and pressure measuring devices together to provide real-time information on center-of-pressure and center-of gravity which can be used to develop algorithms to predict falls and compensate using combinations of tactile, visual, and auditory cues. This issue is dealt with later in this report (under “Group evaluation of tactile sway detection and cueing for ambulatory assistance”).

Dr. Rupert provided a short history of tactile cueing systems developed operationally for maintaining orientation in aviation and clinically for patients with disequilibrium (see also Rupert & Lawson, 2011). The first application of artificial tactile vibration cueing[2] for balance and orientation was developed for the aviation community, since loss of orientation presented a huge operational cost to the U.S. military both in terms of loss of lives as well as equipment (Gillingham, 1992; Lawson, Kass, Kennedy, Muth, & Smith, 2003). In 1991, under an In-House Laboratory Independent Research (ILIR) project, Dr. Rupert developed and flight-tested a vest torso garment to provide pitch and roll information to pilots of fixed-wing aircraft. Pilots frequently become disoriented as a result of maintained forces experienced in flight. The solution was to present on the torso an accurate sensation using tactile stimulators (tactors) to intuitively indicate the direction in which the pilot and aircraft were “leaning” (via veridical pitch and roll cues).

The first clinical demonstration of tactile cueing to correct a balance problem was the indirect result of research on balance effects associated with simulator sickness. In the early 1990s, the U.S. Navy provided funds to design and demonstrate an objective test to detect which pilots after a simulator session had experienced simulator sickness and thus, were at risk of

[2] In contrast to natural touch cues, e.g., provided by a PT.

experiencing simulator sickness after-effects. Pilots who experience simulator sickness should be temporarily restricted from flying (Department of the Army, 2007; Department of the Navy, 2004). Pilots are loathe to report if they have simulator symptoms so the Navy requested development of an objective test. Dr. Rupert proposed using the Neurocom Equitest balance platform[3] to examine pilots after they had experienced a simulator session of at least 2 hours. Dr. Frederick Guedry suggested using a more controlled stimulus rather than simply testing pilots following a long simulator session. The Coriolis Acceleration Platform, a large rotating room 20 feet in diameter, was used to provide a more controlled/measured condition to which postural and reflex responses must adapt in order to maintain balance and steady gaze responses (Rupert & Lawson, 2011; Rupert, Lawson, McGrath, & Wood, 2011). The protocol involved seated subjects making head movements (HMs) and then walking to another chair, resting until 1 minute after beginning HMs and then repeating the sequence. After 10 minutes, effects could be seen on Neurocom Sensory Organization Test, Condition 5 (SOT5), but only if an HM was made during the SOT5 test. The effect was easily "erased" if just a few HMs were made. In effect, this experimental paradigm was eliciting a temporary, acute vestibular insult which could be examined experimentally.

Pilot testing indicated that the sensory rearrangement created by the rotating room could be adapted to rapidly and when subjects made an HM on SOT5, they would invariably fall, unless they were provided a tactile cue (based on center-of-pressure from the posture platform) to provide corrective action, in which case the fall could be prevented (Rupert & Lawson, 2011; Rupert et al., 2011). Many people were invited to the lab to experience the tactile solution to the imbalance induced by the acute vestibular insult of adaptation to a rotating environment. The rotating room research led directly to a modification of the Neurocom SOT5, in which the manufacturer added head movements to the standard protocol. NASA adapted this protocol to examine astronauts to determine their time course of readaptation upon returning to earth (Jain, Wood, Feiveson, Black, & Paloski, 2010). This is an objective measure used to determine astronaut fitness for return-to-flight status. The pilot tests also became the basis for important experiments by Dr. Wall (e.g., Kadkade, Benda, Schmidt, Balkwill, & Wall, 1999; Wall & Kentala, 2005).

Dr. James Atkins (an ENT in Orlando) and Dr. (Karen) Atkins (a PT in Dr. James Atkins' clinic) invited Dr. Rupert to present to ENTs and PTs from the Southeastern U.S. a lecture on applications of the tactile aviation technology for patients with balance dysfunction. Dr. Rupert described the algorithms he developed (using a 5 by 8 matrix of tactors in a vest-like garment) for pitch and roll and wing-leveling. The same matrix used for wing leveling (a 1 by 8 matrix of tactors) is the current algorithm used in balance applications by Engineering Acoustics, Inc. (EAI) and BalanceSense. Dr. Rupert pointed out that he started with aviation because spatial disorientation was a deadly problem for aviators and touch looked like a useful way to provide intuitive orientation information in high workload environments. Also, the aircraft possessed the sensor information required for orientation cueing (using existing aircraft instruments), while

[3] A description of the device is at: http://resourcesonbalance.com/neurocom/products/SMARTEquiTest.aspx, while publications concerning the methods are at: http://resourcesonbalance.com/clinical_info/library/cdp.aspx.

the type of sensor technology needed for the patient population was not readily available. Through the recent development of micro-electronic mechanical (MEM) systems, the long-term goal of ambulatory balance assistance devices based on non-invasive tactile cueing became a realistic consideration.

Dr. Rupert pointed out that the tactile displays that are currently available are extremely limited due to the non-availability of tactors with wide frequency and amplitude characteristics. Tactile display capabilities will be advanced significantly by the development of new tactors which can take advantage of the observation made by Dr. Hans-Lukas Teuber, namely "the number of dimension of perception exceeds that of the stimuli." Teuber pointed out that by varying only frequency and amplitude, it was possible to create effects in four psychophysical variables. The solution to improving balance will be to imitate nature by providing continuous skin-muscle-joint orientation information as the basis upon which it adds the other sensory information of hearing and vision.

Dr. Rupert concluded by summarizing the three main goals of the workshop.

a. Provide group recommendations for initial assessment after injury (the primary focus).

b. Provide recommendations concerning strategies for rehabilitation of vestibular/balance functioning, especially strategies pertinent to the tactile balance testing/cueing technology (secondary focus).

c. Recommend future applications of tactile balance/cueing for ambulatory balance assistance devices/prostheses (tertiary focus).

Highlights from "Mild traumatic brain injury and balance control" by Balaban, Hoffer, and Gottshall

Dr. Balaban summarized the many criteria for TBI, among which are loss of balance and sensory deficits. He indicated that hearing loss and/or tinnitus were present initially in 70% of individuals, while dizziness was present in 98% initially, along with evidence of vestibular abnormality (head thrust, Romberg balance test). In such a situation, he suggested that balance measures may be the most sensitive approach to testing. He distinguished dizziness (unsteadiness during head thrust or Romberg) from vertigo (reported sensation of illusory motion) and noted that vertigo tends to be more unilateral and to appear later after injury. Dr. Balaban briefly described the pathophysiology of closed head injury, which may disrupt message transfer along the "balance pathway" in the brain, leading to altered vestibular reflexes which may account for disequilibrium.

Dr. Balaban introduced his recent research, which was intended to determine if differences exist in the vestibular effects of blast-induced versus blunt force-induced head injury. He described the extensive evaluations carried out by the presentation authors, including a

specialized vestibular history, evaluation by several clinicians, audiogram, magnetic resonance imaging (MRI) scan, and a battery of neuro-vestibular tests, etc. (see appendix B). Many of the findings are detailed in Hoffer et al. (2010), Hoffer et al. (2009), and other reports cited in the presentation slides (appendix B). Briefly, the recent studies found that blast-induced TBI patients had more significant headache, disequilibrium, and hearing loss than blunt trauma patients. However, Dr. Balaban stressed that vestibular disorders are a dominant clinical feature in all types of head trauma and that vestibular disorders from both types of patients are often treatable in specialized centers.

Dr. Balaban presented recent evidence from the military setting concerning the relation between MTBI and balance control. He noted that TBI is a common neurological injury resulting from operations in Iraq, and that the frequency of TBI has increased over time. He summarized statistics concerning the millions of people affected by TBI in the U.S. and the billions of dollars the problem costs annually. He discussed the definition of TBI (slides in appendix B) developed by the Military Traumatic Brain Injury Task Force (Office of the Surgeon General, 2007), which (paraphrased) involves structural injury or disruption of brain function due to an external force and includes such clinical symptoms as altered consciousness, amnesia, disorientation, change in vision, and sensory loss.[4]

Dr. Balaban applauded the workshop's effort to foster meaningful collaboration among agencies and called for continued collaboration among DoD, NIH, and other agencies (such as VA) concerning this important problem. Second, he stressed that certain objective balance tests (e.g., Sensory Organization Test) indicate that symptoms of blast-induced dizziness can sometimes become worse over time and balance testing may be useful for distinguishing sub-acute from chronic MTBI patients. Therefore, he emphasized, the workshop's goal of fostering rapid field tests for initial screening and follow-up is important. Dr. Balaban made several additional recommendations to the working group, including wider communication of the classification system he and his colleagues employ, and pre-deployment baseline assessments of vestibular/balance functioning in the military.

The group was receptive to Dr. Balaban's affirmations and recommendations concerning inter-agency cooperation, increased use of objective and rapid field tests (either pre-post deployment versus post-injury, or relative to a normative database), regular follow-up tests post-injury, and wider communication of consensus criteria.

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[4] The authors of the present technical report note that the criterion "disorientation" may require refinement, since the word can describe a disruption in the awareness of place (e.g., "Where am I?"), geographical direction (e.g., "Which way do I go to get back to my base?"), gravitational orientation (e.g., "Which way is up?"), or temporal awareness ("What time/day is it?"). Moreover, the use of the phrase "external force" in the definition may benefit from elaboration, since it is possible that readers would infer that "external force" refers to a mechanical impact to the head, while the definition is intended to encompass force-without-impact, as occurs due to blast pressure to the head or due to body acceleration without head impact.

Dr. Lawson asked for further clarification concerning the false +/- error rates in the rotator tests performed by Hoffer et al. (2010), since they did not appear to perform as well as some of the other balance/vestibular tests. Dr. Balaban said there is not enough evidence to know whether rotator tests are optimal, but that such tests were included in Hoffer et al. (2010) because they are accepted as part of full-scale vestibular evaluations outside of the context of portable field testing.

The group discussed tests of cervical and ocular vestibular evoked myogenic potential (cVEMP; oVEMP), which are portable and rapidly administered, but may require further development and automation before they can be administered and interpreted readily by a non-specialist, such as a medic/corpsman. The rationale for including c/oVEMP among portable tests of balance conducted following head injury sustained in the military setting is described by Lawson and Rupert (2010), while the array of vestibular problems detected by c/oVEMP is described by Curthoys, Manzari, Smulders, and Burgess (2009). Both tests are useful, with the oVEMP being considered easier for the clinician and patient.

Dr. Conrad Wall mentioned the possible benefits of portable oculometrics, and briefly described a saccadic field test that he was developing. In reference to the prolonged balance decrements observed by Balaban and colleagues, the group noted that DoD/VA guidelines (Management of Concussion/TBI Working Group, 2009) and various other papers focus on the need to consider psychological causes if the injury has not resolved in 4 to 6 weeks, but the vestibular systems can take a long time to recover, and such data should be reconciled against current guidelines. Dr. Gottshall further described the recovery process with military TBI patients and introduced the group to the typical forms of PT rehabilitation her center offers.

Highlights from “Vibrotactile postural control in patients who fall and have sit-to-stand balance deficit” by Atkins

Dr. Atkins described some background work from her dissertation (Atkins, 2010b[5]), which she noted was the first attempt to integrate a vibrotactile balance testing/cueing device into functional activities within the context of a standard physical therapy practice. She noted that while past laboratory studies suggest that vibrotactile cueing improves balance test scores, most investigations were limited to upright stance in non-clinical settings. Furthermore, it is not known whether transitional movements are facilitated by vibrotactile cueing, such as the forward lean and rise movement necessary for the frequent daily activity of rising from a sitting to a standing posture (“sit-to-stand”).

Dr. Atkins studied elderly patients with multiple sensory/neural deficits presenting with balance complaints. A prospective case/control study was used to determine the relationship between standard of care physical therapy plus vibrotactile force platform device treatment and standard of care physical therapy only. A repeated-measures design investigated the relationship between force platform vibrotactile intervention and balance test scores, sit-to-stand and falls. Dr. Atkins described 14 participant inclusion/exclusion criteria for the study, e.g., ensuring

[5] Available on-line at: http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA528706.

adequate visual and mental functioning and confirming the presence of a balance problem (slides in appendix C). The subjects were 30 community-dwelling adults, aged 60 to 79 years, with abnormal NeuroCom Sit-to-Stand test results and two or more self-reported falls within the last 6 months. Subjects were quasi-randomly assigned to 1 of 3 groups: 1) 10 as off-site controls, 2) 10 as on-site controls, and 2) 10 as on-site device intervention subjects. In all cases, the subjects engaged in either standard-of-care physical therapy twice per week (controls) or standard of care augmented by the tactile sway cueing device intervention.

Dr. Atkins described the methods of the study and the main measures and then presented the main findings. Since methodological information is available in detail in her dissertation (Atkins 2010b), which has also been disseminated widely as a government technical report (Atkins 2010a), this section will merely summarize the overall findings. The study found a significant beneficial effect in the device intervention group, which showed better scores on the Berg Balance Scale, the Dynamic Gait Index, and the Functional Independence Measures-Motor test, as well as a decrease in self-reporting of falls. In particular, the device group (but not control groups) showed significant post-therapy improvement (versus pre-therapy) on the main sit-to-stand measure (see results for Functional Independence Measurement FIM).[6] Dr. Atkins concluded that older adults with abnormal sit-to-stand performance and self-reports of falling were able to improve faster and more when standard care was augmented with vibrotactile testing and balance cueing.

Dr. Atkins noted that vibrotactile technology was readily incorporated into the physical therapy plan of care and workflow and that it appeared to benefit the outcome of physical therapy. She also noted in her dissertation that the impressions the patients had of the vibrotactile device were overwhelmingly positive. She described potential advantages and limitations to her research and especially noted the need for further research with larger samples concerning the benefits of tactile rehabilitation for fall prevention confirmed by objective indicators. She also felt it would be worthwhile to take advantage of the opportunity afforded by such a device to standardize evaluation and treatment protocols into skill sets with progressive levels of difficulty based on postural control of sway. Finally, she noted that the beneficial outcome of the present study should encourage further investigations on other populations, such as military TBI patients. A brochure concerning the testing/rehabilitation system Dr. Atkins is developing under the OSD SBIR is shown in appendix D.

Some discussion followed Dr. Atkins's presentation. The workshop participants agreed that PT care varies widely and that the tactile device may help to standardize care, while still allowing some flexibility concerning software settings and exercise choices consistent with the PT model of individualized/tailored care treatment. The group agreed that it was wise to go beyond static standing to incorporate functional activities, such as sit-to-stand, gait, lunge, and especially duty-related activities applicable to military rehabilitation. Further automating of testing, diagnosis, and rehabilitation methods are particularly needed in the military setting to standardize care for applications where non-specialists will be involved and/or multi-site research protocols will be carried out.

[6] See, p. 81, Atkins' (2010) dissertation.

Dr. Balaban suggested that supplying tactile cues to the torso is a good approach because it provides a consistent, body-centric frame of reference, whereas visual, auditory, and vestibular cues change rapidly with head motion and sometimes tend to be more head-referenced in perception. Dr. Nashner noted that balance control is highly automated and hence very accessible via intuitive (rather than abstract/symbolic) interfaces, such as the spatially-referenced waist circumference vibrotactile belt employed by Dr. Atkins, Dr. Mortimer, and others. Dr. Atkins replied that she had obtained some pilot data (outside the scope of her dissertation) which looked at a subgroup of stroke patients with Pusher(s)[7] Syndrome (Karnath & Broetz, 2003) and the trends implied these patients had trouble using visual and auditory cues, but could use the tactile feedback readily. Dr. Lawson noted that the discussion of the benefits of this approach are particularly hopeful, considering that Dr. Atkins obtained her findings after relatively few PT sessions (two sessions per week for 6 weeks) compared to many physical therapy studies in the literature, which employ approximately 8 to 42 sessions over a period of 8 to 14 weeks (Whitney & Morrris, in Poe, 2005). Drs. Rupert and Lawson mentioned that during their recent visit to Dr. Gottshall's well-equipped PT center at NMCSD, it appeared that the TBI-related balance therapy was not always a matter of slow, incremental, monotonic brain reorganization over 2 or more months, but rather appeared to occasionally take larger "leaps" in the form of a fairly rapid process not unlike a patient who suddenly realizes which muscles to innervate to control the grasping hooks of an arm prosthesis, or a healthy person who, after many unsuccessful attempts, suddenly realizes which muscles to innervate in order to successfully wiggle his/her ears. Dr. Gottshall agreed with the general outlines of this viewpoint and elaborated on some of the therapeutic interventions used in her practice.

Group analysis of alternatives for simple field testing

The three presentations above described the purposes and current state of tactile balance cueing (Rupert and Lawson), introduced recent evidence concerning vestibular/balance effects of TBI in the military setting (Balaban, Hoffer, and Gottshall), and described the first attempt to bring tactile balance rehabilitation into a physical therapy practice (Atkins). These presentations were intended to set the stage for the main order of business, which was to conduct a roundtable discussion concerning balance testing. Test recommendations were solicited concerning vestibular/balance tests suitable for initial screening after a TBI in the military setting, especially blast TBI following IED exposure.[8] "Tests" were defined as important variables to be tested, rather than named/established tests. Participants were encouraged to consider existing, established tests, but not to limit themselves strictly to existing tests if they felt that new tests (or modifications of existing tests) were necessary.

The authors attempted to "bound and scope" the problem by summarizing the features of an optimal test, so that these requirements would be firmly in mind during subsequent group discussions. These features of an optimal test would be:

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[7] The words "Pusher" or "Pushers" Syndrome are both used in the clinical literature.

[8] A separate consideration has been made concerning a more comprehensive battery of tests which are appropriate mainly for tertiary care centers (appendix E), due to the time and equipment required.

1. Sensitive.
2. Reliable.
3. Fairly specific.
    a. But need not be diagnostic.
    b. Designed for initial screening/evaluation, to determine if additional testing/care is needed.
4. User-friendly (e.g., usable by a medic/corpsman after one hour of training).
5. Rapidly administered and interpreted.
6. Portable (i.e., small and light).
7. Rugged (i.e., hardware) and stable (i.e., software).
8. Militarily-relevant (e.g., clear face validity for return-to-duty decisions [RTD] (can perform necessary tasks).
9. Clinically-relevant (e.g., relevant to procedures and standards of clinical practice).
10. Semi-automated.
11. Multi-functional (e.g., does testing and rehabilitation).
12. Accepted by users (e.g., comfortable, non-invasive).
13. Fairly mature.

Many of the optimal criteria of a MTBI balance test are the same as those which would be desired by the military for a neurocognitive test (McCrea et al., 2008). Based on these criteria, the participants agreed that the emphasis of discussion would be on simple functional tests and less on sophisticated, comprehensive, or less portable test devices, such as the Neurokinetics Neuro-otologic Test Center (NOTC) or the Neurocom Equitest. Nevertheless, such established tests serve as important gold standards for comparison as new field tests are developed. Several functional abilities are critical to a service member and may be adversely affected by vestibular aspects of head injury. The group first identified and categorized three main functional abilities, which are listed below, along with an example of one or more “gold standard” tests of each ability:

1. Head-gaze coordination to maintain good visual processing.
    a. Gold standards = Dynamic Visual Acuity Test (DVAT), head thrust, visual-vestibular tests of Neurokinetics NOTC.
2. Balance functioning to maintain coordination during standing and locomotion.
    a. Gold standard = Equitest Sensory Organization Test, condition number 5 (SOT5).
    b. No clear, established gold standard yet for gait tests in young military TBI patients.
3. Maintenance of accurate spatial orientation perception.
    a. Gold standard = Neurokinetics NOTC Dynamic Unilateral Centrifugation test.

It would be ideal if a test or test battery measured all three of these functional abilities and met all 13 of the optimal test requirements listed above, but it was acknowledged that this was not likely and that failure to do so should not be considered a reason to eliminate an otherwise good test. Similarly, no current test was deemed likely to meet all of the criteria of an optimal

test listed above. It was decided that discussion would center on which functional tests were best (requirements number 1 through 3) for rapid field screening by a non-specialist (requirements number 4 through 5), with the other criteria (requirements number 7 through 13) being used as additional bases for inclusion.

A lively discussion ensued. Dr. Nashner mentioned that the DVAT may be useful for measuring the functional outcome of poor head-gaze coordination (i.e., loss of visual acuity). Dr. Lawson agreed and pointed out that DVAT has good test properties (Herdman, 2007) and may offer the additional benefit of distinguishing blast versus blunt trauma (in Hoffer et al, 2010). Overall, dynamic visual acuity is relevant to military and transportation operations (see Lawson & Rupert, 2010). Dr. Nashner agreed, but stressed that we should avoid measuring just one aspect of vestibular function if possible, and the group agreed. Dr. Rine said we should discuss very simple tests such as visual observation of head-shake nystagmus. Several such tests were added to the group list. Some discussion ensued concerning how much expertise was needed for some of the simpler in-office tests an ENT might administer, and whether neck status would be a constraining factor for some head movement tests. There was some concern that a head impulse test, while very useful, should be avoided with any patient whose neck status is unknown or unfavorable, since the test requires small but rapid and unpredictable movements of the patient's head by another person.

The group wished to more carefully define the initial, secondary, and tertiary screening and evaluation situation in the military. Drs. Gottshall and Balaban briefly described the recent state of affairs for medical screening (see also Helmick, 2010; Tanner, 2007), in which the very first screening following TBI during military operations is an evaluation by a medic/corpsman, based on observations of altered consciousness, often without much in the way of a true neurological test. Such evaluations are supplemented by the Glasgow Coma Scale (GCS) (Teasdale & Jennett, 1974), and more recently, the more comprehensive Military Acute Concussion Evaluation (MACE) (French, McCrea, & Baggett, 2008; Scherer & Schubert, 2009). The MACE includes a brief history, symptom checklist, and several short paper-and-pencil cognitive screens.

The medic/corpsman is the first on the scene, either initally present or arriving via ambulance or medical evacuation (medevac) helicopter. His or her assessment is done and then any patients deemed to need further attention are typically sent to a battalion aid station to be seen further by medics/corpsmen, nurses, physicians, etc. If necessary, they will be referred to a specialist for further testing or rehabilitation (e.g., an ENT, a PT), which may require transfer to a central location, such as a hospital. Based on this description, it was agreed that tests most suitable for initial (Level 1) screening by a medic/corpsman would be rated as "primary," while tests most likely to be administered at least at the level of a battalion aid station (after the patient has been cleared to make head movements) would be considered "secondary" (i.e., applicable to secondary or follow-on care.)

Some discussion ensued concerning the role of technology in testing at the primary level. Should a primary test be limited to a questionnaire or something like a field sobriety test

requiring no equipment? The group applauded simplicity, but recommended that technology was acceptable at the primary level, presuming it was useful, portable, field-ready, and user-friendly. In fact, technology would enhance automation which would increase testing capability and standardization while reducing human error. The appropriate level of technology was discussed. For example, Dr. Wall discussed several gaze-related parameters, such as pursuit, saccades, and memory saccades, which could be evaluated simply with a laptop. He also mentioned the critical tracking task, which is a test of psychomotor eye-hand coordination that is analogous to the actions required during body sway and vehicle operations (Wall, Weinberg, Schmidt, & Krebs, 2001; Lawson et al., 2003). It was agreed that simple eye-movement tests could be very useful, provided they were not the sole features of the primary test. For example, abnormalities of saccadic eye movement control can help to localize central deficits (Herdman, 2007). Such tests are useful but fall somewhat outside the scope of the present report's emphasis on vestibular injury and tests of functional disability.

Tests of standing balance were featured prominently in the group discussion. Drs. Lawson and Rupert (2010) described the rationale for including posturography testing following mild head injury. Inability to stand or walk normally has clear relevance to functional readiness for many military duties. Drs. Balaban and Gottshall recommended that static platform posturography should be considered, especially if the subject was required to stand during head movement or head shake (to make the test more difficult and overcome some of the limitations of not having a dynamic platform such as Equitest). An example is Dr. Rupert's head movement protocol which makes Equitest SOT5 more difficult for high-performing aviators and variants of which are in use by Drs. Varsha Jain, Scott Wood, and other colleagues (Jain et al., 2010) for evaluating astronaut readiness post-flight.

Other ways of sharpening static posturography were discussed, such as testing sway under external perturbation, testing after physical exertion, testing on a compliant surface, testing during increased cognitive workload, etc. (Hanes & McCollum, 2006; Scherer & Schubert, 2009). Various advantages and disadvantages of these additional test features were discussed. Dr. Lawson mentioned that compliant surfaces not only make the test harder, but may help to reveal changes in sway strategy (hip versus ankle). Dr. Mortimer pointed out that testing on a compliant surface, while relatively well-accepted, creates alterations in the center-of-pressure signal which cause deviations from the inverted pendulum model and complicate the analysis of rapid changes in sway. Dr. Atkins pointed out that the manufacture of compliant surfaces (foam products) is not standardized either, which makes test standardization and interpretation more difficult. Of the various methods of making static posturography more difficult, the group favored head movement and cognitive tasking the most. It was agreed that the following lists of methods should be considered as a possible augmentation of simple field tests, where applicable to the test:

1. Simultaneous head movement.
2. Simultaneous cognitive tasking.
3. Testing during external perturbation.

4. Testing following physical exertion[9].

Several participants recommended that we not limit ourselves to standing balance, but that we also consider functional gait scales (also see Shumway-Cooke, 2007). As an example, Dr. Balaban mentioned the Dynamic Gait Index (DGI) and Dr. Gottshall mentioned the Functional Gait Assessment (FGA). The FGA is a version of the DGI which was developed by Wrisley, Marchetti, Kuharsky, & Whitney (2004), partly to avoid ceiling effects occurring when young vestibular patients do the DGI.

Dr. Stith mentioned the Timed Get Up-and-Go test. Dr. Lawson said this last test performed well relative to a number of other gait tests, showing good test properties and requiring very little time to administer (Lueckenotte & Conley, 2009). Nevertheless, several of the PT participants (Drs. Holden, Gottshall, etc.) were concerned that some otherwise good tests such as this may not be optimal for young military service-members with mild head injuries, because the tests may prove too easy. A similar concern was voiced for the Berg Balance Scale, which performs well but was conjectured to be susceptible to a ceiling effect for the target sample. Dr. Atkins suggested that walking while counting and turning the head would be a difficult task, which is part of the FGA. Dr. Holden described military-specific tasks which may be included in balance and gait assessment of military members, e.g., standing in tandem, then turning to shoot. Regardless of the details of the task, the key idea would be to turn one's head rapidly and focus visually on different targets while trying to balance. This ability should be disrupted by vestibular injury. Dr. Holden thought that focusing visually while driving should also be difficult under such circumstances. The group enthusiastically supported the idea of tailoring tests to military tasks and a discussion ensued concerning the shooting task in particular. Dr. Wall suggested consideration of a task which involves moving and shooting, perhaps with the additional cognitive load created by shoot/no shoot decisions. Dr. Lawson agreed that shoot/no shoot decisions would increase the cognitive loading and mental stress of the testing and would add to military relevance, but he also noted that the task is essentially a choice reaction task, and that a measurement limitation of laboratory versions of choice reaction time tests is that they tend to be less reliable and take longer to stabilize than simple reaction tests (Lawson et al., 2009). They also are very susceptible to instruction set (subject motivation, etc.), while not adding all that much scientifically to the understanding of different specific aspects of neurological functioning, e.g., compared to a test which taps a totally different aspect of neurocognitive performance (such as visual pattern memory). Nevertheless, combined tasks involving simple shooting tasks while balancing or moving should be included in military testing, because they are a key aspect of warrior skills. While shooting well in a simulation is not proof of readiness to shoot well in combat, shooting poorly in a simulation should be of great concern. Simply put, clearly abnormal performance in a dynamic shooting task should be an important consideration in the RTD decision. Moreover, since some neuropsychological tests have been criticized for their lack of relationship to day-to-day functioning (Saatman et al., 2009), it would be desirable to include some vestibular/balance tests with a clear relationship to shooting.

[9] Testing under exertion prior to RTD is already included in general DoD guidelines for RTD (Scherer & Schubert, 2009).

The group discussed the pros and cons of low versus high-technology approaches to such testing and the use of various shooting postures. Dr. Lawson informed the group that while proxy shooting tasks take longer to reach test stability than simpler cognitive tasks (e.g., matching to sample) and often require technology that is difficult to maintain (Lawson et al., 2009), they have tremendous face validity, such that if a practically significant decrement in shooting is detected, there will be little question concerning whether the deficit is relevant to military performance. Dr. Lawson informed the group that USAARL developed a test with many of the features being mentioned, and briefly presented some of the features of a funded U.S. Army Medical Research and Materiel Command research project led by principal investigator Ms. Catherine Webb of USAARL, in which he is involved as an associate investigator (appendix G). The project evaluates shooting performance in normals and MTBI balance patients using a series of functional balance and gait tests which also involve shooting. The tests require participants to shoot just after turning quickly in yaw or bending down to pick up a rifle from the floor. They also require participants to shoot while kneeling, traverse a narrow path, and turn to shoot while walking. Many of the tasks are based on aspects of existing functional tests and exploit those aspects of balance and movement known to be difficult for persons suffering from vestibular injuries. For example, one task is roughly similar to the abilities required by the FGA, in that it requires walking straight forward while swiveling in yaw. However, instead of walking normally and swiveling just the head, the subject walks forward, then swivels his/her head, upper torso, and rifle periodically to acquire and shoot a target. Further details are provided in appendix G. The group agreed that the incorporation of military skills such as shooting was useful and that the general approach was interesting, provided a test could be developed which was also portable, inexpensive, and easy-to-maintain.

Dr. Rine informed the group of a test battery she was helping to develop, known as the NIH Toolbox. This involves a series of tests which she says can be conducted by a non-specialist. The test battery is relatively fast, portable, and inexpensive. It is a functional screen, not a diagnostic test. Current work is underway to compare the toolbox against other standards. The group agreed that the NIH Toolbox (or aspects of it) should be studied further. Additional information about the tests is shown in appendix H. The NIH Toolbox is based around a low-cost, computerized version of the DVAT (but not the same device as the Neurocom DVAT nor the clinical bedside DVAT), along with various standing postures with eyes open or closed and without or without a foam substrate.[10] This latter task is called the Balance Accelerometer Measure (BAM).

Dr. Merfeld stressed that dizziness is a perceptual problem that has profound consequences for the sufferer and that we need to go beyond gaze and balance and discuss a good perceptual test, since orientation perception is the third main function of the vestibular system. The group agreed that perceptual factors such as dizziness and disorientation were important. The group recommended that spatial orientation should be evaluated and discussed possible ways to do so. Examples included questionnaires and orientation perception tests. Evidence from Muir, Berg, Chesworth, Klar, and Speechley (2010a,b) indicates that self-report of falls is a good predictor

[10] Some potential advantages and disadvantages of foam testing are discussed earlier in this report.

of actual falls in older adults, but it is not certain how well self-reporting will work among young military MTBI patients. Nevertheless, it stands to reason that multiple measures of different types may yield better results than one type of measure (S. W. Muir, personal communication, 6 May, 2010), so if a suitable questionnaire can be added to other objective measures, this may be of benefit. Moreover, self-reporting is fast, cheap, and demands few resources. Of the available questionnaires, the Dizziness Handicap Inventory (DHI) was favored by the group. A few approaches to the measurement of perceptual orientation were considered, such as nulling of felt motion and subjective visual vertical (Baloh & Halmagyi, 1996; Baloh & Honrubia, 2001), but it was agreed that this area has not received enough attention in the literature (Guedry, 1993). Dr. Rupert described an idea for a very simple field test that could detect asymmetric vestibular otolith function, such as might be caused by a blast occurring to one side of the patient. The test would involve setting a line of light in the darkness to the perceived gravitational vertical. The rationale for this test is described in Friedmann (1970), Herdman (2007), and Lawson and Rupert, (2010), and further discussion is provided in appendix F. Dr. Rupert is working on this test and recently submitted the protocol for the study. The test is one of the simplest ways to measure utricular otolith function, it is very useful for detecting vestibular neuritis, it is reproducible, and it is specific (Herdman, 2007, but note she recommends estimating the visual horizontal).

Participant recommendations and group reactions are summarized below. The authors attempted to summarize the tests which received most serious attention, based on cross-referencing the separate notes taken by Drs. Lawson, Rupert, and Rine during the meeting. The initial list of tests and/or balance challenges were as follows, with those tests most suitable for primary (medic) or secondary (battalion aid station) testing noted by “primary test post-injury” or “secondary test post-injury.” Similarly, tests which could benefit from further automation are indicated by “needs more automation.” Finally, tests whose quality or suitability was questioned after being proposed are indicated by “suitability questioned.”

1. Head-gaze coordination tests (visual acuity and nystagmus during head movement).
    a. Neurocom computerized DVAT.
        i. Primary if neck not compromised.
    b. NIH Toolbox DVAT.
        i. Possibly primary if neck not compromised.
    c. Head shake with frenzel lenses (observed nystagmus).
        i. Secondary.
        ii. Needs more automation.
    d. Head thrust/impulse.
        i. Secondary.
        ii. Needs more automation.
    e. Other types of “positional” tests, e.g., Dix-Hallpike, side-lying, rolling over.
    f. Vestibulo-Ocular Reflex (VOR) nulling.
    g. Vestibulo-Ocular Reflex (VOR) noise.

2. Balance tests (sway/coordination during standing or locomoting).
    a. Computerized static posturography (as in mini-SOT).
        i. Secondary.
            1.) With head movement.
                a. Under perturbation.
                b. Needs more automation.
            2.) Jump down and hold steady.
                a. Suitability questioned.
            3.) Functional reach.
                a. Suitability questioned.
    b. Balance Accelerometer Measure of the NIH Toolbox.
        i. Possibly secondary.
    c. Gait.
        i. Bat spin.
            1.) Suitability questioned.
            2.) Needs more automation.
        ii. Weave step.
            1.) Suitability questioned.
            2.) Needs more automation.
        iii. Move and shoot.
            1.) Secondary.
            2.) Suitability questioned.
            3.) Needs more automation.
        iv. Medial-lateral root-mean-square error during gait.
        v. Path integration (eye close + gait + turns).
            1.) Secondary.
            2.) Needs more automation.
        vi. Plyometrics.
            1.) Suitability questioned.
            2.) Needs more automation.
        vii. Dizziness Gate Index.
            1.) Secondary.
            2.) Needs more automation.
        viii. Functional Gait Assessment.
            1.) Primary.
            2.) Needs more automation.
        ix. Gait aspects of NIH toolbox.
        x. Timed Up-And-Go.

3. Spatial orientation tests (perceived visual vertical, questionnaires concerning dizziness).
    a. Questionnaires:
        i. Dizziness Handicap Inventory.
            1.) Primary.
            2.) Needs more automation.

        ii. Illness Behavior Questionnaire.
            1.) Suitability questioned.
            2.) Primary.
            3.) Needs more automation.
    b. Subjective visual vertical.
        i. Primary.
        ii. Needs more automation.

4. Other.
    a. c/o VEMP.
        i. Secondary.
    b. Laptop oculometrics.
        i. Primary.
        ii. Needs more automation.
    c. Vestibular thresholds.
        i. Secondary.
        ii. Suitability questioned.
        iii. Needs more automation.
    d. Simulated driving
        i. Secondary.
        ii. Needs more automation.
    e. Critical tracking task.
        i. Secondary.
        ii. Suitability questioned.

From the initial list above, the authors selected (based on the group discussion) a subset of tests or balance challenges which they considered the best fit to the optimal test requirements, especially during primary or secondary testing:

1. Head-gaze coordination tests (visual acuity and nystagmus during head movement).
    a. Computerized dynamic visual acuity.
    b. Head shake.
        i. Automated for administration and interpretation by non-specialist and real-time recording/playback/analysis to avoid need for uncomfortable test repetitions and allow later review by specialists (Bronstein & Magnusson, 2010).
    c. Head thrust/impulse.
        i. Automated version developed (e.g., Head Impulse Test video-oculography (HIT-VOG) developed by Autronic Medizintechnik, described later in this report).

2. Balance tests (sway/coordination during standing or locomoting).
    a. Computerized static posturography (as in mini-SOT).
        i. With head movement.

        ii. Under perturbation.
        iii. Jump down and hold steady.
        iv. Functional reach.
        v. Balance aspects of NIH toolbox.
    b. Gait.
        i. Move and shoot.
        ii. Medial-lateral RMS during gait.
        iii. Path integration (eye close + gait + turns).
        iv. Functional Gait Assessment.

3. Spatial orientation tests (perceived visual vertical, questionnaires concerning dizziness).
    a. Questionnaires:
        i. Dizziness Handicap Inventory.
    b. Subjective visual vertical.

4. Other.
    a. c/o VEMP.
        i. Secondary.
    b. Laptop oculometrics.

Group evaluation of a testing/treatment device employing posturography and tactile cueing: Demonstration by Dr. Mortimer

Dr. Rupert concluded discussion of tests and prompted the participants to consider balance rehabilitation. He started by inviting participants to experience tactile balance cueing directly. Dr. Mortimer of Engineering Acoustics demonstrated the second generation of Engineering Acoustics' Sensory Kinetics tactile balance testing/cueing device as part of an SBIR project (appendix D). He demonstrated the device's ability to measure center of pressure, limits of stability, symmetry of stance, sit-to-stand performance during eyes-open (visual) or eyes-closed (tactile) feedback, etc.

Dr. Mortimer explained how the tactile feedback is provided by small, powerful vibrators (tactors) that are mounted to a belt and placed around a patient's waist. Eight tactors were used to achieve good localization accuracy (Cholewiak, Brill, & Schwab, 2004). Eight signal directions on the body intuitively corresponds to the compass rosette (N, NE, E, SE, S, SW, W, NW) for operators of vehicles, while being fewer tactors to keep track of than 12 (e.g., clock positions), which yielded no appreciable improvement in accuracy and added to weight, bulk, and system complexity.

The patient's position is measured and calculated using a force plate sensor. The computerized system is used as part of physical therapy balance training to improve the patient's balance and potentially reduce their risk of falling. Since physical therapy is individually tailored, the system allows for great flexibility in settings.

The device is designed to follow the usual PT workflow and task expectations. Initial assessment of the patient provides the PT with information as to where any sensory deficits may be localized, and provides an opportunity to customize functional activities for the particular subject. Patients must master static skills before moving on to dynamic movement tasks. The prototype device follows a similar strategy to a PT, who will group functional training activities into a hierarchy, concentrating on basic activities which are then refined through training by modulating variables such as the quality of the sensory information, adding extra tasks, etc. Physical therapists need to stay focused on the patient rather than the technology, so the interface has been made as simple and intuitive as possible. The system is designed to allow PTs to operate hand-free (rather than holding a controller or mouse) when needed, e.g., in order to guide or spot the patient. From the patient's perspective, the feedback should be intuitive so as not to require extensive learning. Dr. Mortimer demonstrated how these requirements were met with the system.

After everyone received a demonstration of the device, Dr. Rupert invited the group to identify any desired modifications. Feedback was sought from the PTs especially, since they would be the intended users. The PTs saw the utility of the device and felt it could help them with patient recovery; they expressed no major concerns or criticisms. Dr. Gottshall captured the consensus attitude of the PTs succinctly when she stated that she would like to borrow the device for treating patients as soon as possible instead of waiting for further modifications.[11]

Individual comments were also solicited from each participant separately during his/her demonstration with Dr. Mortimer, and these provided an additional source of user feedback. After the meeting, Dr. Mortimer and Dr. Lawson summarized these comments, which confirm that the second generation of the technology was received well by the experts, with the following minor comments for consideration during future development:[12]

1. Human factors of tactor belt should make aligning front reference tactor to body more intuitive and less prone to human error (e.g., upside-down or inside-out placements).
2. Tactors should be more firmly fixed inside belt.
3. Tactor controller could be smaller and more out-of-the-way.
4. Patient identification entries should allow mixed letter/number entries (e.g., for research experiments).
5. Initial familiarization with feeling of tactor would be good to avoid surprise and minimize hyper-sensitivity.
6. Default tactile cueing limits could be based on the subject's height and age to decrease set-up time.
7. Suggestions were made concerning whether to include velocity feedback about sway and whether to cue sway more strongly as the angle of sway increased.

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[11] As of this writing, Dr. Gottshall has done some initial evaluation of prototype balance feedback devices from EAI and Balance Sense and has provided preliminary feedback concerning device strengths and suggestions for improvement.

[12] Some comments must be kept general to avoid exposing intellectual property during an ongoing SBIR competition.

8. Some minor usability suggestions were made concerning the text labels on the screen and the user's virtual buttons.

Dr. Rupert concluded the discussion of Dr. Mortimer's prototype and opened the discussion to considerations of treatment recommendations not specific to a tactile balance cueing device, i.e., treatment which may or may not eventually be incorporated such a device. The group identified the following types of vestibular rehabilitation (Herdman, 2007) that should be most useful in returning military MTBI balance patients to duty:

- DVA training.
- Gaze plus movement.
- Head shake.
- Balance training (Romberg, weight shift, one-leg stand, sit-to-stand).
- Gait training.
- Dynamic training in weapons proficiency.
- As normal performance returns, adding exertion, stress, or cognitive load to the above.

Group evaluation of tactile sway detection and cueing for ambulatory assistance

Dr. Rupert asked the workshop participants to conclude with a brief consideration of future ambulatory applications of tactile cueing for assistance devices. Dr. Rupert asked Dr. Wall to lead off this discussion, since he has the most experience in this area. Dr. Wall said drift is the main problem that is expensive to deal with in accelerometers, but says we can deal with drift problem now if appropriate filters are used, as described by Wall & Kentala, 2005. A discussion ensued concerning orientation/sway modeling versus fall prediction relative to the dynamic control of the center of gravity of the body. Dr. Wall described his current approach to this problem and what might be needed for future systems. Dr. Wall currently tests limits of stability for Romberg stance tasks which mainly elicit lateral sway then sets warning limits in lateral sway when people go to greater levels of tilt. However, for fall cueing, one might use displacement and velocity together and provide predictive warning signals.

Dr. Rupert introduced an SBIR topic he is considering involving solutions for multi-segmental fall sensing and prediction. The objective would be to develop and optimize the integration of networked wireless sensors located on the torso and appendages of the body to develop accurate center of gravity and center of pressure measures in real time. A collection of as many as 15 small acceleration/pressure sensors spread across the head, torso, and limbs should be capable of providing similar information that the distributed biological sensors of the human body provide the brain to carry out complex mobility tasks. Dr. Rupert envisioned that a full-capability system might employ one sensor on the head, one on each shoulder, elbow, wrist, hip, knee, and ankle, and one on the ball of each foot. A key objective for study would be determining the minimal number, location and type of sensors required to provide real-time balance information to an integrative device which uses an appropriate algorithm to provide assistive cueing to prevent falls. Just as important would be determining the optimal algorithm for integrating the sensors to predict falls. For example, the software should be able to

distinguish normal dynamic walking conditions (walking is essentially controlled falling) from abnormal falling conditions. Dr. Rupert asked for group feedback about this idea.

Drs. Wall and Nashner cautioned that it is important to avoid unnecessary proliferation of sensors, since an excess would make the device cumbersome and complicate the algorithm. There was considerable discussion among the engineers and scientists present as to the minimum number of sensors required to perform the task of computing real time center-of-pressure and center-of-gravity. The suggested number varied from three to 15 acceleration sensors (not including the possibility for additional pressure sensors on the soles of each foot). Drs. Wall, Merfeld, Shellhamer, Balaban, and Lawson agreed that the necessary number of sensors may prove to be less than 15.

Dr. Rupert pointed out that during normal balance, our central nervous system obtains information from tens of thousands of sensors; this information is integrated centrally to provide appropriate responses with minimal cognitive effort required. This function is semi-automated. Dr. Rupert offered some examples where compensation during a fall involves reflexive motions of the arms or other body parts, thus requiring sensors on the arms. He also gave some examples of the generative (non-one-to-one) nature of movement control, to make the point that certain intentional movements and postures would “look like” unintentional falls to a “dumb” system, unless it had enough sensors and a proper algorithm.

Dr. Balaban hypothesized a fall prediction system must be able to account for all sorts of intentional movements while relatively few sensors may be needed for a simple fall prediction/warning system during regular standing and walking, whereas more sensors and a more complicated system may be required for appropriate augmentation of balance during the full range of dynamic human activities. Dr. Balaban stressed the need to define the problem carefully, e.g., via a stability map. Discussion ensued concerning the theoretical and quantitative modeling of sway and falling. Drs. Merfeld, Wood, Shelhamer, and Balaban in particular discussed the modeling of orientation and sway and how best to provide prediction and feedback with such a system as Dr. Rupert proposed, and in a way that is optimal for the user.

Dr. Nashner raised a counter point to the effort to carefully model and cue orientation for optimal signaling. He agreed that this is an important and complicated undertaking, but asked whether human motor control can be meaningfully cued even by a very simple system. Drs. Nashner, Balaban, and Rupert opined that the plasticity of our postural control may allow us to adapt to user signals which are not optimally predictive of falling, provided they are accurate reflections of sway. One may even be able to get away with fairly raw cues concerning simple body tilt. Dr. Nashner offered the example of early cochlear prostheses for deafness which yielded a low resolution signal not at all like regular hearing, but was still usable because the signal varied meaningfully with variations in the external noises coming to the user. Dr. Lawson suggested that the question of whether a raw signal is sufficient or only a refined, user-friendly signal will suffice may be answered similarly to the way such questions have been answered in other areas of sensory science, i.e., by figuring out what aspects of the signal are invariant and reliable and concentrating on those. Much has been done along these lines in the visual

sciences. The idea would be to discover the unique signature of sensor-transmitted signals which reliably precedes different common types of falls.

Dr. Merfeld acknowledged the importance of plasticity, but said that his implant research implies that there are limits to what the human can process without some degree of optimization. Dr. Merfeld recommended that we operate under the initial assumption that we will try to provide the information the brain expects to receive and can best interpret. The group agreed but pointed out that it can be difficult at times to predict what information to provide.

Dr. Atkins pointed out that prediction of falls can be tricky and that surrogate measures have not done that well in predicting falls so far. Dr. Lawson distinguished overall fall risk prediction factors (Brady & Lamb, 2009; Muir et al., 2010a, b) from temporal prediction of an imminent fall in a given person, which are overlapping but distinct concepts. Regarding the former issue, he recalled reading that mis-stepping was a good predictor of a future fall (Srygley, Herman, Giladi, & Hausdorff, 2009), so perhaps that variable would be one upon which to focus. Dr. Atkins said that this sounded reasonable, but will take time to be ready for transition in the form of a predictive technology. Drs. Atkins and Wall mentioned that a good approach to fall prediction is to monitor patients while they carry our routine activities of daily living (Weiss, Shimkin, Giladi, & Hausdorff, 2010).

Dr. Nashner suggested that in addition to early sensing of falls and cueing to prevent them, it may be beneficial to enhance the compensatory motor reaction to the fall. The group discussed motor response augmentation strategies, such as triggering of reflexive muscular activity. The group also considered direct assistance to a weak muscular response via an exoskeleton which would “spot” the user and also provide kinesthetic force feedback. Systems in development were considered, some of which are for assisting unhealthy persons and some of which are for assisting healthy military personnel to carry heavy loads. It is agreed that such systems are promising for fall prevention, provided they can be made light, comfortable, unobtrusive, and drivable via small batteries.

In considering the discussion, Dr. Rupert concluded that the complexity of the algorithm and prediction side of this effort may imply that it is best to break the idea up into two SBIRs, one on sensors/technology (which are close to ready for use) and one on algorithms (which will take more work and become an STTR). Dr. Rupert concluded the group discussion by asking whether there are any other thoughts concerning the applications of tactile ambulatory cueing. Dr. Balaban wondered whether the group thought that tactor input regarding movement could be given to the stump of an amputee in order to help get rid of phantom limb sensation, which he granted is not an ambulatory application, per se. No conclusive answer was provided regarding this question, but Dr. Stith mentioned that his office is interested in future programs of research to help amputees. He informed the participants that some of the vestibular discussions being held at the meeting may fit within the U.S. Army Medical Research and Materiel Command’s (USAMRMC’s) Research Area Directorate 5 (RAD 5), which is the Clinical and Rehabilitative Medicine Research Program. He encouraged the participants to contact this office should they wish to explore research opportunities with this agency.

Authors' test recommendations based on workshop findings

Following the workshop, the authors of this report met again to evaluate tests from the group-approved list above and consider which were most ready for use. The authors envisioned a portable battery of tests that would be supported for accelerated development and rapid delivery, based on exploitation of near-term capabilities. The tests should include aspects of each of the three categories of function (head-gaze, balance, orientation), should meet the key requirements from the first workshop (e.g., portable, medic-friendly, laptop-based administration and test results), and should be capable of integration with one another into a single system or compatible suite of tests. Possible tests are provided below:

1. Subjective visual vertical (automated goggles, primary test without head movement, secondary retesting to include head movement).
2. Dizziness Handicap Inventory (DHI) (primary and secondary, but requires modification for military use).
3. Static posturography with additional stressors (e.g., cognitive tasking and/or external perturbation at primary level, addition of head movement and/or pre-test exertion at secondary level).
4. Functional Gait Assessment (FGA) (automated version without head movement at primary level, with head movement at secondary level).
5. Dynamic visual acuity (secondary level testing).

A test which bears further discussion is the DHI, which came up frequently in the first round of consultation and is widely used. Unfortunately, further review by the authors suggests that while the DHI is a useful scale for predicting falls in older adults, its specific number of construct factors is still in question (Kurre et al., 2010). More importantly, the scale is designed to assess general dizziness experienced in everyday civilian life over a longer period of time that would be typical if it were applied as a scale to assess state immediately after head injury. Five of the 18 items in the scale specifically ask about dizziness or disability associated with situations which are not likely to be encountered in a military field setting (e.g., walking down supermarket aisles or sidewalks, going to the movies, doing household chores). Approximately 6 of the 18 questions would require at least a couple days of self-observation in order to answer accurately, since they pertain to sleeping difficulties, avoiding heights or travel, etc. For these reasons, the entire DHI in its present state should probably not be administered immediately post-injury in the military field setting, but it could be useful at the secondary level (battalion aid station) or it could be developed into a military-specific state scale for immediately after injury. Since some of the other tests also require development before field use (e.g., automation of the FGA), the DHI could be included in the list above.[13]

The FGA also requires modification. The test is administered and scored manually according to observer judgments concerning whether the subject has complied with the protocol

[13] Other potentially useful questionnaires and tests not mentioned by the experts are presented by Herdman (2007) and at web.missouri.edu, some of which appear applicable to military needs and may merit further consideration.

sufficiently (concerning stepping, turning, and moving his/her head according to instruction) and how far the subject has strayed from a straight walking path. At the Vestibular Assessment & Rehabilitation unit of the Naval Medical Center, San Diego, one therapist has added a series of measured tape lines on the floor to allow quicker and more accurate scoring of amount of deviation from a straight path, but it is not known whether this provides an additional visual stability cue. No provision has been made yet for fully-automated FGA of the patient's stepping, head movement, etc. This may be a factor in a recent recommendation against the FGA (Cohen et al., 2011). We recommend the development of an automated FGA which allows laptop tracking of movement (test compliance, movement characteristics) and immediate scoring of path deviations, without the need for making additional scoring lines on the walking surface.

The authors next considered the sequence in which such tests should be used following a mild head injury in the military setting. They recommend that if all the tests immediately above were adopted, they should be practically applied as follows:

1. Primary field testing by medic/corpsman post-injury: complete SVV and then FGA (all subtests not requiring head movement) as soon as possible after MTBI. Total time ~10 minutes. Tests can be carried in a small tote bag and administered anywhere with a level surface. If scores are abnormal, proceed to battalion aid station.
    a. It may be possible to proceed with tests requiring head movement if the patient shows no signs of neck injury and can easily move his/her head around voluntarily (good cervical range of motion). If there is any doubt, head movements can be deferred for secondary testing.

2. Secondary testing at battalion aid station by MD, nurse, and/or PT: Check neck further as needed, do posturography, then do DVAT. Total time ~30 minutes. All tests can be carried in the rear seat of a vehicle and administered anywhere with a level surface and where there is not too much noise. If scores are abnormal, proceed to specialist if needed, or begin therapy at aid station using the same dual-use portable testing/rehab device. Therapy should involve vestibular rehabilitation and other appropriate physical therapy <u>at least</u> twice per week for at least 8 weeks, checking recovery progress against a gold standard, if feasible. If feasible, more frequent sessions are likely to be beneficial to rapid recovery.

3. Tertiary testing and care by specialists (e.g., ENT, otololaryngologist) at comprehensive care center: standard set of full tests (appendix E), including oVEMP, Equitest SOT5, and Neurokinetics NOTC Dynamic Unilateral Centrifugation.

<u>Second round of deliberations: Feedback from attendees of an international conference focusing on vestibular clinical problems</u>

The goal of the authors at the first workshop (summarized above) was to stage an invitation-only meeting near Washington, DC, attended by top experts on vestibular/balance testing and

rehabilitation, then ask them to generate recommendations concerning the most suitable tests for vestibular screening following head injury in the military setting. Some time was also spent discussing the period following screening, i.e., full clinical evaluation, rehabilitation, and the application of assistance devices. The main emphasis of the first meeting was on identifying candidate tests for initial screening as close to the time and place of the injury as possible. It was agreed that the optimal tests for this purpose should be easy and rapid to set up and administer. The initial screening tests need not offer a definitive diagnosis; rather, they should merely be sensitive (and fairly specific) to a vestibular or balance impairment which merits further evaluation before the individual should be cleared to RTD.

The present section summarizes additional feedback gathered at a second meeting. Further information regarding vestibular testing and rehabilitation was obtained by soliciting feedback from a larger and more geographically dispersed group of vestibular and balance experts than were present at the first workshop in Rockville, MD. This information was gathered by the authors during two international vestibular and balance research conferences held from 14 to 21 August 2011 in Iceland. The first conference was "The Vestibular System: Current Research and Future Directions" (Reykholt, Iceland) which tended to focus on the latest findings in vestibular and postural neuroscience, but also covered some basic aspects of clinical vestibular/balance science. The second, larger conference was the XXVI Bárány Society Meeting (Reykjavik, Iceland), which is considered the preeminent international conference for vestibular research and has a heavy focus on clinical problems related to vestibular function and balance. Soliciting feedback at these two conferences allowed the authors to reach as many additional experts as possible on the same set of questions as the first workshop, but with a minimal additional expenditure of money and time. The two meetings being held in Iceland were ideal in this respect, since they were well attended by the top experts in the field, enabling the authors to reach many experts. Moreover, the location between the East Coast of the U.S. and Western Europe was deemed perfect for increasing the amount of information the authors could gather from non-U.S. scientists and clinicians because of the lesser travel distance (versus another U.S. conference) for many of the experts traveling from locations abroad. Finally, the international prestige of the meetings and the interesting qualities of the host sites were thought to ensure good attendance by distant experts (e.g., from Australia or Japan) who may not be able to travel so far unless they were presenting their scientific findings at an important conference and attending many interesting sessions.

The authors sought to amplify the findings from the first meeting in three ways:

1. Meeting with experts outside the sessions to solicit their opinions concerning the specific problems being tackled by our studies project (viz., vestibular screening, assessment, and rehabilitation, especially using tactile cueing systems).
2. Attending relevant presentations, making inquiries during the question-and-answer period or immediately after the session, and reading abstracts which may assist our studies project.
3. Experiencing some of the latest testing/treatment devices being demonstrated at the conference by conference exhibitors.

This section will summarize some of the information gained from speaking to the experts, considering their latest research findings, and experiencing commercial testing/rehabilitation systems. This last source of information is limited, since only a few systems were exhibited in a small area in the lobby, and the vast majority of the authors' time was spent on the first two items.

A number of experts were consulted in person via conversations outside the conference sessions. We especially sought contact with clinical personnel such as ENTs, otololaryngologists, PTs, occupational therapists, and audiologists. Since these conversations were informal and the experts would not necessarily expect to be quoted, the experts will remain anonymous in this report. A few of the broad characteristics of the experts are summarized below:

Table 2.
Characteristics of the Experts.

Total Number Consulted	Approximately 30 (not counting additional contact with persons already named from the first workshop)
Broad Geographical Regions of Practice	Scandinavia, United Kingdom, Continental Europe, Middle East, Asia, Australia / New Zealand, United States
Specialties Represented	ENTs, otolaryngologists, PTs, audiologists, vestibular researchers.
Advantages of the Information Obtained	Feedback was obtained from a greater number of people than in the first workshop, as well as a greater proportion of clinicians, and a greater number of non-U.S. citizens
Limitations of the Information Obtained	The feedback usually was provided by people who treated vestibular diseases caused by a wide range of factors (not just head injury or blast from an IED) and who were not necessarily seeking to develop portable applications for the military

Most of the recommendations from the first workshop were corroborated by this second round of feedback. First, the conference participants with whom we spoke unanimously agreed that the three main categories of functional ability identified in the first workshop (viz., head-gaze coordination, balance function, and orientation perception) were critical to human performance and likely to be affected by vestibular aspects of head injury in the military setting. Second, the participants generally agreed that the Neurocom DVAT was a suitable standard for testing of dynamic visual acuity, the Neurocom Equitest SOT5 was a suitable standard for

standing functional balance deficit following vestibular injury, and the Neurokinetics NOTC Dynamic Unilateral Centrifugation (DUC) test was a suitable standard for altered orientation perception following unilateral vestibular injury, although several participants added that the oVEMP may soon become more popular for testing certain types of otolith asymmetry than the DUC. The oVEMP test is considered in more detail later in this section.

The conference participants with whom we spoke generally recommended the same vestibular/balance screening tests (i.e., DVAT, posturography, FGA, DHI, SVV) listed in the author's final recommendations from the first workshop. This section provides further feedback concerning these tests, followed by additional tests worth considering. The participants felt that the recommended tests could be made useful for the stated purpose (with one exception concerning DVAT noted below). The main suggestions for improving and transitioning these tests for initial military field testing are shown below, along with the most relevant new conference findings concerning the tests.

1. Computerized dynamic visual acuity.
    a. Participant recommendations.
        i. Determine neck status before test.
            1.) DVAT requires rapid voluntary head movements of moderate angle. Patient must be cleared for head movement.
        ii. Confirm that established norms will work for young healthy military personnel.
        iii. Consider shorter version of test.
        iv. Consider doing tests involving head movement last in battery to avoid confounding other tests (e.g., due to sickness or vertigo).[14]
        v. One conference participant questioned the clinical usefulness of dynamic visual acuity for reasons other than the need for head movements.
            1.) The authors agree that while its use for specific diagnosis in the clinic is limited, it should be preserved as a screening test, because (according to Herdman, 2007), its reliability is good, normative data is available, it has good sensitivity/specificity (85% / 55%) for vestibular deficits, it is a functionally relevant vestibulo-ocular test, and it is available in an automated version.
    b. Relevant presentation findings.
        i. Pijnennurg et al. (2010) reported at the Bárány conference that dynamic visual acuity only weakly correlates with severity of a patient's oscillopsia, which leads the authors to infer that simple observation of oscillopsia does not capture the extent of functional limitation of visual acuity caused by vestibular deficit.

[14] The authors note that Herdman (2007) lists positional and head movement tests first in the clinical evaluation sequence, followed by balance/gait tests.

2. Computerized static posturography during head movement (secondary until neck check automated).
    a. Participant recommendations.
        i. Determine neck status or consider other ways of making test harder (difficult stance, cognitive load).
            1.) This test may require voluntary, moderate-speed, moderate angle head movements in pitch, roll, and/or yaw. Speed of head movement is less than DVAT but movement out of yaw axis is a concern. Patient must be cleared for head movement.
        ii. Consider doing standing balance tests involving head movement towards end of battery to avoid confounding other tests (e.g., due to sickness or vertigo).
        iii. Confirm that established norms will work for young healthy military personnel.
        iv. When ambulatory applications are anticipated, compare platform to accelerometer-based posturography to determine relative false +/- errors.
        v. Some participants wondered whether enough useful information could be obtained from a simpler test, such as one of the Romberg variants.
            1.) A conference presentation by Bergquist Larsson, Kammerlind, & Ledin (2010) noted that many previous studies have found that feet-together Romberg, sharpened Romberg, and a number of other "floor" tests have good test-retest and inter-rater reliability when applied consistently.
            2.) However, the presentation by Szmulewicz, Waterson, & Storey (2010) found little consistency in the method or interpretation of the Romberg among neurologists.
            3.) One of the authors of the present report (in Lawson et al., 2009) has used a difficult rail-standing task derived from a sub-test of the Fregly Ataxia Test Battery (Fregly, 1974) and has found it to be fairly variable according to experimenter instructions, subject compliance, and subject footwear. In general, the variability seemed too high even among healthy normal persons for the test to be very sensitive to potential balance-disrupting effects.
            4.) For these reasons, while the authors of the present report are interested in automated versions of simple floor-based balance tests, they will not alter their recommendations concerning the need for some form of posturography in the field.
    b. Relevant presentation findings.
        i. Zhang, Fan, Han, and Wang (2010a) reported that dynamic posturography was more sensitive than caloric testing for diagnosis of acute vertigo. Dynamic posturography helped to confirm the presence of abnormalities in selected patients with peripheral vertigo whose caloric tests are normal. There were some different characteristics of the results of dynamic posturography between peripheral and central vertigo,

suggesting that dynamic posturography is a complementary test aiding in the differential diagnosis of peripheral and central vertigo.

ii. Zhang, Fan, Han, and Wang (2010b) found that, among 23 cases of Benign Paroxysmal Positional Vertigo (BPPV), the abnormal rates estimated by the caloric test, static posturography, and dynamic posturography were 26.1%, 34.8% and 73.9%, respectively, before the canalith repositioning maneuver (CRM). The abnormal rate of dynamic posturography was much higher than that of caloric test or static posturography. After the CRM, the abnormal rates of caloric test, static posturography, and dynamic posturography were 17.4, 8.7 and 21.7%, respectively. Dynamic posturography has clinical value in confirming the presence of impaired balance in patients with BPPV. Treatment of BPPV using the CRM results in improved postural stability in dynamic posturography.

3. Functional Gait Assessment (primary).
    a. Participant recommendations.
        i. Needs automation to get consistent results with non-specialist.
        ii. Consider doing gait tests involving head movement towards end of battery to avoid confounding other tests (e.g., due to sickness or vertigo).
            1.) Some sub-tests of the FGA require large, voluntary head movements of moderate speed in yaw and pitch (including pitch up/back) while walking, so patient must be cleared for head movement.
4. Dizziness Handicap Inventory (primary).
    a. No new comments.
5. Subjective visual vertical (primary).
    a. Participant recommendations.
        i. Needs further testing and clinical validation of abnormals against gold standard DUC.
    b. Relevant presentation findings.
        i. Ogawa et al. (2010) reported that, among the abnormal SVV subjects, the SVV tilt was directed toward the affected ear in 96.0% of vestibular neuritis (VN) patients and in 47.6% of unilateral sudden deafness, (uSD) patients. Among VN, VEMP was normal in 21 patients, and was abnormal in 15 patients.
        ii. Bos, Winters, Klis & Grolman (2010) argued that using head tilt only instead of dynamic unilateral centrifugation will yield a simpler and more unbiased test of unilateral utricular function.

In general, perceptual reports of orientation appeared to be well accepted. Many conference participants were exploring various aspects of orientation perception for clinical applications. For example, Beaton, Ying, Roberts, and Shelhamer (2010) and Guinand et al. (2010), reported that assessing perception thresholds could be more sensitive than testing vestibular reflexes to evaluate residual vestibular function. In fact, substantial perception thresholds were found in

patients with complete abolished vestibular reflexes (Guinand et al). Hullar, Olomu, Mallery, and Uchanski (2010) reported that psychophysical testing is much more sensitive than conventional reflexive tests of vestibular function for identifying canal hypofunction in the elderly. They said that the prevalence of age-related peripheral vestibular loss may be underestimated using conventional measures of vestibular function. Ruff et al. (2009) reported that psychophysical techniques have shown to be extraordinarily sensitive in detecting pathology in the auditory and other sensory systems. These techniques have not been explored as methods for evaluating vestibular function in subjects with imbalance.

Due to the nature of the conference (latest scientific and clinical research findings from specialists) and the setting (informal discussions between conference sessions), it was somewhat difficult to restrict discussions to the quickest and simplest tests for initial field screening following explosive blast or other sources of head injury in the military. Since this was a research symposium, attention naturally gravitated towards the newest tests under development even if they had not had full clinical validation yet or were presently only usable by specialists. While the authors did not intentionally ignore new tests and did not require tests to be fully validated, they did seek medic-ready field tests which had promise outside the setting of a full clinic and had been tested on persons other than elderly patients with vestibular anomalies.

The authors encountered some screening tests which would require more time and expertise than was desirable for the military setting anticipated. For example, although Cohen et al. (2010) have developed relatively simple functional tests for initial and post-flight screening of astronauts, they employ tests whose set-up time may need to be shortened dramatically for the primary military setting. Nevertheless, the finding of Cohen et al. that foam-based testing conditions were potentially useful was in agreement with the first author's suggestion (above) at the Rockville, MD meeting of experts. Finally, Cohen et al. made a recommendation to consider the Dix-Hallpike test (described in Herdman, 2007) as a screening test for use by non-specialists, an idea which had not been strongly advocated at the Rockville meeting, possibly due to considerations concerning the status of the neck and the specific expertise of the medic/corpsman. Some of the ideas from Cohen et al. should be considered further in future, but since the authors already have gathered a lengthy list of potential tests and recommendations from experts, no additions will be made at this time.

In general, the authors felt that many of the rapid screening tests they encountered may be useful for secondary testing at a battalion aid station, but should be made quicker and easier in the future and should not require semi-permanent testing sites (since these cannot be disturbed or dismantled). These changes would ensure optimal transition of field tests to medics/corpsmen who are seeking to conduct tests near the time and place where the injury occurs.

A few modifications of the findings from the first workshop were suggested. For example, the head impulse test and head shake tests were repeatedly recommended for consideration, although concerns about neck status during testing had been raised in the first workshop. It was pointed out by the conference attendees that such concerns applied to some extent to the head shake test and the DVAT also, which had been recommended in the first workshop.

Nevertheless, the experts consulted in the U.S. and Iceland unanimously agreed that head movements are a very important feature of early testing for vestibular dysfunction. For example, the head impulse test is a key early test for vestibular diagnosis (Herdman, 2007). Similarly diagnosis of BPPV, a common malady caused by dislodged otoliths, involves detection of positional nystagmus during the Dix-Hallpike or supine roll maneuvers (Herdman), which requires some degree of neck flexion or stress.

Therefore, the problem of determining neck status prior to screening or diagnosis is a key consideration in making any vestibular tests involving head movement field-ready. Since head movement is such an important challenge to an injured vestibular system, the authors recommend that at least one of the following options be pursued for military testing:

1. Near term recommendations:
    a. If neck status is in doubt, continue to conduct tests <u>not</u> requiring head movement as soon as possible after the injury (field test by medic).
    b. Consider whether neck status can be safely determined by the medic/corpsman in the field under certain circumstances (e.g., patient has been walking around, moving his/her head and acting normally, despite having been near a blast or having suffered a head blow).
        i. It may be possible to proceed with tests requiring head movement if the patient shows no signs of neck injury and can easily move his/her head around voluntarily (good cervical range of motion). If there is any doubt, head movements can be deferred for secondary testing.
    c. Determining neck status as early as possible (e.g., battalion aid station) for any uncertain cases, and then doing all head movement tests (DVAT, head impulse test, etc) as soon as possible after the patient is cleared for head movement.
2. Long term recommendations:
    a. Make the head impulse test administration and interpretation as automated as possible.
        i. During the Bárány Teaching Day (see Bronstein & Magnusson, 2010) at the conference, the test was demonstrated repeatedly and clearly was simple to administer, but some degree of experience would be needed to detect the abnormal eye movements without repeating the test, and a specialist would be needed for fully exploiting such “bedside” tests to reach specific diagnoses. Overall, the authors felt this test was very suitable for automation and early use by medics/corpsmen, provided the patient was cleared for head movement.
            1.) A system was exhibited which automates the eye tracking and interpretation aspect of the test (but not the head movement itself) (see HIT–VOG, by Autronic Medizinetechnik).
            2.) Some attendees felt that an automated system of this type could detect eye movement abnormalities even during much less vigorous head motions than are typical for a clinical head impulse test, and if the subject can move their head around voluntarily, it

should be safe for him or her to perform a relatively small/mild head impulse sufficient to be registered by a video-based system.

b. Developing methods for definitively determining neck status in the field following injury.
c. Developing portable tests which achieve the same ends as the head impulse test without any need for body movement.
d. Developing portable tests which move the head without moving the neck, e.g., via a head-locked-to-torso impulse.
    i. At the Bárány conference, Hegemann, Vital, Straumann, Bockisch, and Probst (2010) reported that passive head impulses were significantly better than active, exhibiting 100% sensitivity and 94% specificity in distinguishing normal patients versus patients with bilateral or unilateral pathology. Of course, much development would be needed to get the same results in the field as Hegemann's 40 passive impulses using a rotating chair.

The authors noted that research efforts to develop and refine vestibular tests featured prominently at the formal presentations from these conferences. In fact, this seemed to be a major focus of clinical vestibular research. The majority of the tests being reported were for diagnosis rather than initial screening. Also, while many of the tests being studied were portable, few could be administered or interpreted quickly or by a non-specialist. Finally, many of the tests had not been tried on IED blast patients. A number of tests did not make the final list of recommended author-recommended tests for initial screening following the first workshop, but are worth considering for inclusion in secondary (battalion aid station) or tertiary (hospital) testing. Foremost among these are the cVEMP and oVEMP. The oVEMP is particularly interesting since it is rapidly administered, easy to tolerate, and requires no special tasks on the part of the subject. Recent Bárány findings concerning VEMP variants (mainly oVEMP) are provided below.

Selected Bárány findings concerning oVEMP

1. The test-retest reliability of oVEMP was found to be good-to-excellent (Buytaert, Blaivie, Van de Heyning & Wuyts, 2010).
2. Certain responses to oVEMP could be used as clinical indicators of superior canal dehiscence (SCD) (Manzari, Burgess, McGarvie, & Curthoys, 2010), Meniere's syndrome (Shepard & MacPherson, 2010; Winters, Klis, & Grolman, 2010; Manzari, Burgess, & Curthoys, 2010), affected side in canal paresis (CP) (Taylor, Wijewardene, Gibson, Halmagyi, & Weggampola, 2010), and post-surgical management of patients with vestibular scwhannoma (Yavor et al., 2010).
3. Adding oVEMP and cVEMP to traditional caloric testing improved the detection of vestibular impairment in MD (Taylor, et al., 2010).
    a. oVEMP compared favorably to DUC (SVV during centrifugation). DUC-related SVV and VEMP testing were frequently the only abnormalities found on the non-traditional groups of patients (many of whom have symptoms that

are debilitating, but no signs of vestibular disease on examination or in everyday life) (Mallinson & Longridge, 2010).

4. Compared to the subjective visual vertical during tilt and eccentric rotation, the oVEMP was easier to administer, less demanding on patients, and useful for identifying chronic unilateral vestibular loss than visual vertical measurements. (Hegemann et al., 2010).
    a. Note, however, that Mallinson & Longridge (2010) asserted that SVV and VEMP assess two different otolithic structures.

Another interesting finding from the conference was a multi-test battery for TBI, in development by Gottshall and Hoffer (2010). This battery consisted of four tests administered in the acute stage: standing on foam[15] with eyes closed, standing on one leg with eyes closed, visual analogue scale (VAS) rating of vertigo at rest, and EuroQol rating of health-related quality of life. A prediction model was created based on the results of these tests. The model identified subjects at risk of having symptoms after 6 months with a sensitivity of 86% and a specificity of 79%. Given that a VAS may be more applicable to the immediate post-injury period in the military setting than the DHI (faster, easier to program/score, not as specific to civilian-only questions), the authors believe such a rating system should be explored further, if its test properties are good.

As for the standing tests in the Gottshall and Hoffer's (2010) Bárány presentation, some of the participants of the original workshop in Rockville (attended by Gottshall) expressed concerns with foam-based tests, but standing on one leg is a suitable test for military field applications, provided control and standardization of the patient's test compliance to the test requirement can be achieved. Of course, prediction of long-term symptoms is a different goal from determination of immediate readiness for duty (versus need for further care).

Selected Bárány findings concerning tactile cueing for balance

There were several research groups exploring the usefulness of tactile balance cueing. The authors briefly summarize relevant findings below[16]. A number of studies featured the Vertiguard system, which is mentioned in the next section of this report and is shown in appendix D.

1. Lee, Bechly, and Sienko (2010) reported that a low-fidelity cell-phone-based tactile balance feedback system could reduce medial-lateral sway in four vestibular patients during Semi-Tandem Romberg stance.
2. Bechly, Carendar, and Sienko (2010) compared various visual and vibrotactile sway feedback conditions using five vestibular patients performing Tandem Romberg. They

[15] Advantages and disadvantages of foam testing are discussed earlier in this report. The mechanisms of foam-based sway perturbation are discussed by Patel, Fransson, Johansson, and Magnusson in their 2010 Bárány presentation, which recommends standardization of foam testing surfaces or factoring foam properties into testing.

[16] Dr. Atkins also presented findings which have already been discussed in this report and are not reiterated.

reported that all feedback conditions reduced sway compared to normal feedback (control), and that discontinuous visual (only) feedback did not differ from discontinuous tactile (only) or from discontinuous visual + vibrotactile feedback, while continuous visual feedback worked best. (There was not continuous tactile feedback condition). Vibrotactile feedback was said to offer more flexibility for future treatment applications than visual feedback.

3. Bechly, O'Connor, and Sienko (2010) investigated whether vibrotactile feedback can counteract destabilizing visual perturbations in six subjects with unilateral vestibular deficits. They tested a number of different conditions, generally finding that vibrotactile feedback counteracted trunk tilt variability caused by a moving virtual display, but at the cost of increasing center-of-pressure variability.
4. Allum (2010) reported that vibrotactile and auditory sway feedback led to reduction (relative to regular balance training) in angular trunk displacement in 32 healthy young and 32 healthy elderly adults and that the effects remained after training for up to 6 weeks.
5. Harada et al. (2010) found reduced body sway with vibrotactile feedback (versus norms) among 16 presbyvertigo patients during 2 weeks of performing various vestibular rehabilitation training conditions. Goto et al (2010) also tested 15 patients with unilateral semicircular canal dysfunction, finding that patients decreased their body sway during vestibular rehabilitation training in 75 of 90 training conditions.
6. Janssen et al. (2010) studied vibrotactile cueing using 30 patients with vestibular areflexia. They found vibrotactile improvements in balance during stance and gait tasks and increased confidence in balance, but the improvement was only observed in those subjects where an improvement was present in placebo mode as well, which may suggest that confidence in the therapy is a factor in outcomes.
7. Basta and Ernst (2010) studied 17 patients with unilateral otolith dysfunction. They found that vibrotactile tilt feedback helped 13 of the patients show reduction of body sway in > 60% of the vestibular rehabilitation training conditions, with the greatest benefits seen for standing or walking on foam and walking while moving the head.
8. Rossi-Isquierdo et al. (2010) and Lee et al. (2010) tested vibrotactile feedback on patients ($N = 5$, $N = 20$, respectively) with Parkinson's Disease, finding that all showed reduced body sway in 23 of 25 vestibular rehabilitation training conditions and improvement of subjective ratings of daily balance (Rossi-Isquierdo et al.), but no improvement in stepping abnormalities (Lee et al.)

Preliminary evaluation of two exhibitor's devices at Bárány

This last source of information is limited, since only a few exhibitors were present at this conference and the vast majority of the authors' time was spent on the first two planned goals described on page 38, viz., meeting with experts outside the sessions and gathering information during the sessions. Nevertheless, the authors' list their impressions from a preliminary evaluation of two devices being demonstrated by exhibitors at the Bárány conference. No endorsement by the authors is implied.

Vertiguard RT

The first two authors tried the Vertiguard system (VestiCure), which supplies vibrotactile sway feedback from a belt around the waist, based on angular accelerometers (appendix D). The device was used in research presented by Harada, Basta, Rossi-Izquierdo, Goto, and others, with generally favorable results. The authors had the following initial impressions from receiving a system demonstration:

1. The system is aesthetically pleasing, small, and streamlined.
2. The system has a large and thoughtful library of clinical capabilities. The authors did not try all the capabilities, but the user windows looked well designed.
3. The system is based on accelerometer sensors, which will enhance its portability and suitability for ambulatory applications.
4. Like many other accelerometer-based systems, the system could be made to give erroneous body tilt signals by movements other than body tilt (e.g., torso yaw).
5. The tactor cues were discernable, but did not seem as strong or immediate as the cues from the EAI Sensory Kinetics system (appendix D).
6. The belt was initially placed incorrectly on one of the authors. If this can be done by a company representative, then, of course, it can be done by a PT. This is a surprisingly common problem with tactile cueing belts, and was mentioned in the author's recommendations earlier in this report. The authors recommend that all companies consider the human factors of tactor belts so that upside-down, inside-out, or wrongly positioned tactor errors are eliminated.

Users will soon have a choice between platform-based tactile balance systems and accelerometer-based systems. Accelerometer-based systems continue to improve and will be attractive to users because they are extremely portable and applicable to a wide range of needs. Platform-based systems are attractive to users because of their accuracy (e.g., greater avoidance of false cues) and their potential for more direct comparison against existing platform-based standards. The authors hope that both types of systems will improve and fill unique needs of the user market.[17]

Head Impulse Test –VOG

The first two authors tried the HIT–VOG system (Autronic Medizintechnik), which automated measurement (but not stimulus) aspects of the head impulse test, and performs/augments other tests as well. Initial impressions:

1. The representative seemed very knowledgeable about the system and the science behind it.

[17] The authors have already disclosed that they have engaged in early pilot testing using accelerometer-based systems and have initiated platform-based SBIR projects. The authors are government employees technically supervising SBIR efforts from which they do not stand to gain financially.

2. The system could be donned and calibrated quickly.
3. The system was relatively comfortable and lightweight compared to many systems the authors have tried.
4. The observable outputs were clear and easy-to-interpret. The authors did not experience the data analysis features or the various clinical capabilities beyond a self-generated proxy of the head impulse test.
5. The system has been used for testing children, which is a positive sign for the ease and rapidity of its use.
6. The system locked well to the head during motion.
7. The leads running from the system could be bundled and positioned better to avoid them getting in the way or being accidentally damaged.
8. The system will have the vulnerability any mirror-based system has to fragility and cost of the mirrors.
9. The system did not appear to be too finicky about various users' eye colors, etc.
10. Future systems may wish to exploit smaller cameras being continually developed.

Overall, the authors felt this system was worth consideration and further comparison to similar systems. The system makes the head impulse test more automated, but no head impulse system presently deals with all the potential military-application challenges outlined in this report.

Conclusions and recommendations

The authors expect that implementation of tactile balance testing/cueing technology will decrease the number of patient falls internationally, increase patient and caregiver satisfaction with balance diagnosis and treatment, decrease the incidence of "no shows" by balance patients, and increase throughput of balance patients in the local care system. The successful implementation of some of the testing and treatment recommendations in this report would reduce the cost of balance deficits associated with falling beyond the military. Overall, the cost of medical care for patients with balance disorders exceeds $1 billion per year in the United States, while patient care costs for falls are more than $8 billion per year (NIDCD, 2008). Direct costs alone will exceed $32 billion by 2020, according to the Elder Fall Prevention Act of 2003[18]. Better tests and treatments would reduce the growing costs associated with tragic falls by identifying at-risk persons earlier and targeting them for improved balance rehabilitation therapy using the latest techniques.

For initial testing in the field by a medic/corpsman, the authors recommend the development of a portable[19] system which permits automated entry and immediate interpretation of orientation perception and balance testing results. Several aspects of such an automated system are in development, but some aspects have not been fully automated yet, nor have all aspects been bundled.

[18] www.theorator.com/bills108/s1217.html
[19] E.g., driven by a laptop, tablet PC, or PDA.

The authors also considered testing needs immediately after referral (by the medic/corpsman) for initial evaluation (e.g., at a battalion aid station), with the most interesting tests and treatments identified by experts being used as a point of departure. The authors devised a group of desired testing capabilities which could be readily incorporated into near-future generations of a tactile balance testing/cueing device suite. The authors gave special consideration to testing capabilities which also could serve as treatment capabilities, e.g., by using the same basic hardware but having different user interfaces for testing or treatment. The device capabilities listed below are deemed most desirable for testing and treatment at a single portable clinical workstation which could be located as far forward as a battalion aid station. Some of these capabilities are emerging from ongoing SBIR efforts, although much work in automation and testing remains to be done.

1. Balance performance.
    a. With or without visual, auditory, and/or tactile cueing.
        i. Using different stances.
        ii. During paced head movements.
            1.) With or without simultaneous attempts to control gaze or read a display.
        iii. While cognitively tasked.
        iv. After external mechanical perturbation (e.g., unpredictable, small measured push).
2. Related functional activities.
    a. With or without visual, auditory, and/or tactile cueing.
        i. One-legged standing.
        ii. Lunging.
        iii. Partial proxies of gait.
            1.) E.g., heel-to-toe walking, stepping.
        iv. Squat / sit-to-stand.
        v. Simulated dynamic weapon skills.

While this report focuses on military applications of tactile balance testing/cueing, it is important to note that falling is a major problem in civilian society (Lawson & Rupert, 2011). The growing number of elderly persons implies there will be a surge in demand for balance testing and training systems. Moreover, it should be remembered that not only can head injury cause disequilibrium which makes falling more likely, but falling is also a major cause of head injury (Faul, Xu, Wald, & Coronado, 2010). Thus, it could be argued that, in certain cases, a properly-designed balance testing and training system could be employed both as a treatment for MTBI effects and a preventive measure against TBI.

References

Allum, J. 2010. Trunk sway reductions in young and older adults using multi-modal biofeedback: Randomized controlled trials [Abstract]. Journal of Vestibular Research. 20(3-4): 236.

Asseman, F., Bronstein, A. M., and Gresty, M. A. 2007. Vibrotactile feedback of instability for triggering a forward compensatory stepping response. Journal of Neurology. 254(11): 1555-1561.

Asseman, F., Bronstein, A. M., and Gresty, M. A. 2008. Guidance of visual direction by topographical vibrotactile cues on the torso. Experimental Brain Research. 186(2): 283-292.

Atkins, K. 2010a. Vibrotactile postural control in patients that have sit-to-stand balance deficit and fall. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 2010-18.

Atkins, K. 2010b. Vibrotactile postural control in patients with sit-to-stand deficits and fall. Ph.D. dissertation, Nova Southeastern University.

Balaban, C., and Hoffer, M. E. 2009. Mild traumatic brain injury: Vestibular consequences [Presentation]. Defense Center of Excellence Global VTC, Brain Injury Awareness, 18 March. www.dcoe.health.mil/Training/GlobalVTCs.aspx

Baloh, R. W., and Halmagyi, G. M. 1996. Disorders of the Vestibular System. New York: Oxford University Press.

Baloh, R. W., and Honrubia, V. 2001. Clinical Neurophysiology of the Vestibular System. 3rd edition. New York: Oxford University Press.

Basta, D., and Ernst, A. 2010. Vestibular rehabilitation by vibrotactile neurofeedback in otolith disorders [Abstract]. Journal of Vestibular Research. 20(3-4): 256-257.

Beaton, K.,Ying, H., Roberts, D., and Shelhamer, M. 2010. Assessing vestibulo-ocular function without measuring eye movement [Abstract]. Journal of Vestibular Research. 20(3-4): 187-188.

Bechly, K. E., Carendar, W., and Sienko, K. 2010. Comparison of the effects of visual and vibrotactile feedback on postural stability during balance and rehabilitation exercise training [Abstract]. Journal of Vestibular Research. 20(3-4): 253-254.

Bechly, K. E., O'Connor, S., and Sienko, K. 2010. The effect of vibrotactile feedback on vestibular-deficient postural performance during visual perturbations [Abstract]. Journal of Vestibular Research. 20(3-4): 260-261.

Bergquist Larsson, P., Kammerlind, A., and Ledin, T. 2010. Reference values of static and dynamic clinical balance tests [Abstract]. Journal of Vestibular Research. 20(3-4): 231.

Bos, J., Winters, S., Klis, S., and Grolman, W. 2010. Unilateral centrifugation by head tilt [Abstract]. Journal of Vestibular Research. 20(3-4): 248.

Brady, R. and Lamb, V. 2008. Assessment, Intervention, and Prevention of Falls in Elders With Developmental Disabilities. Topics in Geriatric Rehabilitation, 24: 54-63.

Bronstein, A., and Magnusson, M. 2010. Life demonstration of practical skills in examination and rehabilitation [Presentation]. 2nd Bárány Society Teaching Day, XXVI Bárány Society Meeting, Reyykjavik, Iceland, 18-21 Aug.

Buytaert, K. I., Blaivie, C., Van de Heyning, P. H., and Wuyts, F. L. 2010. Test-retest reliability and normative values of Ocular Vestibular Evoked Myogenic Potentials (oVEMPs) to bone conducted vibration [Abstract]. Journal of Vestibular Research. 20(3-4): 154-155.

Cohen, H. S., Mulavara, A., Peters, B., Mille, C., Bloomberg, J., and Sangi-Haghpeykar, H. 2010. Development of screening tests of the vestibular system for epidemiologica and post-flight studies [Abstract]. Journal of Vestibular Research. 20(3-4), 246-247.

Cohen, H. S., Mulavara, A. P., Peters, B. T., Bloomberg, J. J., Miller, C., and Sangi-Haghpeykar, H. 2011. Behavioral and kinematic measures in simple screening tests of vestibular function [Abstract]. Journal of Vestibular Research. 21(2): 74-75.

Cholewiak, R. W., Brill, J. C., and Schwab, A. 2004. Vibrotactile localization on the abdomen: Effects of place and space. Perception and Psychophysics. 66(6): 970-987.

Cordts, P. I., Brosch, L. A., and Holcomb, J. B. 2009. Now and then: combat casualty care policies for Operation Iraqi Freedom and Operation Enduring Freedom compared with those of Vietnam. Journal of Trauma. 64(2):14-20.

Curry, I. P., Estrada, A., Grandizio, C. M., and Erickson, B. S. 2008. Drift cues from a tactile belt to augment standard helicopter instruments. International Journal of Applied Aviation Studies. 8(1): 74-87.

Curthoys, I. S., Manzari, L., Smulders, Y. E., and Burgess, A. M. 2009. A review of the scientific basis and practical application of a new test of utricular function – ocular vestibular-evoked myogenic potentials to bone-conducted vibration. Acta Otorhinolaryngolica Italica. 29(4): 179-186.

Danilov, Y. P., Tyler, M. E., Skinner, K. L., Hogle, R. A., and Bach-y-Rita, P. 2007. Efficacy of electrotactile vestibular substitution in patients with peripheral and central vestibular loss. Journal of Vestibular Research. 17: 119-130.

Department of the Army. 2007. Temporary flight restrictions due to exogenous factors. Washington, DC. Army Regulation (AR) 40-8.

Department of the Navy. 2004.NATOPS General Flight and Operating Instruction, Chapter 8, Aeromedical and Survival, Section 8.3.2.17, Simulator Sickness. Washington, DC. OPNAV Instruction 3710.7T. www.netc.navy.mil/nascweb/sas/files/3710.7t_ch8.pdf

Dozza, M., Wall, C., Peterka, R. J., Chiari, L., and Horak, F. B. 2007. Effects of practicing tandem gait with and without vibrotactile biofeedback in subjects with unilateral vestibular loss. Journal of Vestibular Research. 17(4): 195-204.

Era, P., Konttinen, N., Mehto, P., Saarela, P., and Lyytinen, H. 1996. Postural stability and skilled performance--a study on top-level and naive rifle shooters. Journal of Biomechanics. 29(3):301-6.

Faul, M., Xu, L., Wald, M. M., and Coronado, V. 2010. Traumatic brain injury in the United States: Emergency department visits, hospitalizations and deaths, 2002-2006. Atlanta, GA: Centers for Disease Control and Prevention, National Center for Injury Prevention and Control.

Fregly, A. R. 1974. Vestibular ataxia and its measurement in man. In H. H. Kornhuber (Ed.). Handbook of Sensory Physiology: Vol VI (pp 321-360). NY: Springer.

French, L., McCrea, M., and Baggett, M. 2008. The Military Acute Concussion Evaluation (MACE). Journal of Special Operations Medicine. 8(1): 68-74.

Friedmann, G. 1970. The judgement of the visual vertical and horizontal with peripheral and central vestibular lesions. Brain. 93: 313-328.

Gómez García, A., and Jáuregui-Renaud, K. 2003. Subjective assessment of visual verticality in follow-up of patients with acute vestibular disease. Ear Nose and Throat Journal. 82(6):442-446.

Gillingham, K. K. 1992. The spatial disorientation problem in the United States Air Force. Journal of Vestibular Research: Equilibrium and Orientation. 24(4): 297-306.

Goto F., Harada, T., Kanzaki, S., Kaoru, O., Ernst, A., and Basta, D. 2010. The application of vibrotactile neurofeedback training in patients with a semicircular dysfunction [Abstract]. Journal of Vestibular Research. 20(3-4): 261.

Gottshall, K., Drake, A., Gray, N., McDonald, E., and Hoffer, M. E. 2003. Objective vestibular tests as outcome measures in head injury patients. Laryngoscope. 113: 1746-1750.

Gottshall, K., and Hoffer, M. 2010. To investigate the influence of acute vestibular impairment following mild traumatic brain injury on subsequent ability to successfully complete a vestibular physical therapy program and remain on active duty one year later [Abstract]. Journal of Vestibular Research. 20(3-4): 222.

Guedry, F. E. 1993. Space vestibulo-neuroscience in the new century: Why proceed in semi-darkness? Journal of Otorhinolaryngology and Related Specialties 55(3): 167-172.

Guinand, N., Geerets, B., Boselie, F., Pijnenburg, M., Van Loo, C., Jannsen, M., et al. 2010. Residual perception of motion and tilt in patients with bilateral vestibular function loss [Abstract]. Journal of Vestibular Research. 20(3-4): 221.

Hanes, D.A., and McCollum,G. 2006. Cognitive-vestibular interactions: a review of patient difficulties and possible mechanisms. Journal of Vestibular Research. 16(3):75-91.

Harada, T., Goto, F., Kanzaki, S., Ogawa, K., Ernst, A., and Basta, D. 2010. Vibrotactile neurofeedback for vestibular rehabilitation in patients with presbyvertigo [Abstract]. Journal of Vestibular Research. 20(3-4): 242-243.

Hegemann, S., Vital, D., Straumann, D., and Bockisch, C., and Probst, R. 2010. Improved dynamic visual acuity testing to assess peripheral vestibular function [Abstract]. Journal of Vestibular Research. 20(3-4): 183.

Helmick, K. (2010). Way forward for TBI care and initiatives [Presentation]. Military Health System Conference, National Harbor, MD Jan 25-28,2010..

Herdman, S. J. (Ed). 2007. Vestibular Rehabilitation. 3rd ed. Philadelphia, PA: F. A. Davis Company.

Hoffer, M. E., Balaban, C., Gottshall, K., Balough, B. J., Maddox, M. R., and Penta, J. R. 2010. Blast exposure: Vestibular consequences and associated characteristics. Otology and Neurotology. 31: 232-236.

Hoffer, M. E., Donaldson, C., Gottshall, K. R, Balaban, C., and Baloh, B. J. 2009. Blunt and blast head trauma: Different entities. International Tinnitus Journal. 15(2): 115-118.

Hoffer, M. E., Gottshall, K. R., and Balough, B. J. 2009. Evaluation and management of dizziness after head trauma [Presentation]. www.med.navy.mil/sites/navmedmpte/nmotc/nami/usnac2009/Documents/Add%20Evaluation%20and%20Management%20of%20Balance%20Disorders%201-13-09.ppt

Hoffer, M. E., Gottshall, K. R., Balaban, C., and Balough, B. J. 2010. Mild traumatic brain injury: What we have learned and implications for space flight [Presentation]. Aerospace Medicine Grand Rounds, San Diego, CA, 26 Jan. www.dsls.usra.edu/archive_2010.html

Hullar, T., Olomu, O., Mallery, R., and Uchanski, R. 2010. Psychophysical responses to earth-vertical rotations in the elderly [Abstract]. Journal of Vestibular Research. 20(3-4): 232.

Jain, V., Wood, S. J., Feiveson, A. H., Black, F. O., and Paloski, W. H. 2010. Diagnostic accuracy of dynamic posturography testing after short-duration space flight. Aviation, Space, and Environmental Medicine. 81: 625-663.

Janssen, M., Aarts, J., Janssen-Potten, Y., Vles, H., Van Lummel, R., Stokroos, R., et al. 2010. The Vibrotactile Labyrinthine Substitution system (VLS): Indications for placebo effects of vibrotactile biofeedback improving balance in bilateral vestibular loss patients [Abstract]. Journal of Vestibular Research. 20(3-4): 255-256.

Karnath, H. O., and Broetz, D. 2003. Understanding and treating pusher syndrome. Physical Therapy. 83(12): 1119-1125.

Kadkade, P. P., Benda, B. J., Schmidt, P. B., Balkwill, M. D., and Wall, C. 1999. Optimizing vibrotactile cues for application to a balance prosthesis [Abstract]. Association for Research in Otolaryngology. Tampa Bay, FL, February 16,1999.

Kurre, A., Bastiaenen, C. H., van Gool, C. J., Gloor-Juzi, T., de Bruin, E. D., and Straumann, D. 15 March 2010. Exploratory factor analysis of the Dizziness Handicap Inventory (German version). BMC Ear, Nose and Throat Disorders. 10: 3.

Lawson, B. D., Kass, S. J., Kennedy, R. S., Muth, E. R., and Smith, S. A. 2003. Vestibular stimuli may degrade situation awareness even when overt spatial disorientation is not experienced. In Spatial Disorientation in Military Vehicles: Causes, Consequences, and Cures, NATO RTO, 43-1 to 43-22. Neuilly-Sur-Seine, Sedex, France.

Lawson, B. D., McGee, H. A., Castaneda, M. A., Golding, J. F., Kass, S. J., and McGrath, C. M. 2009. Evaluation of several common antimotion sickness medications and recommendations concerning their potential usefulness during special operations. Pensacola, FL: Naval Aerospace Medical Research Laboratory. NAMRL Report 09-15.

Lawson, B.D., and Rupert, A.H. (2010). Vestibular aspects of head injury and recommendations for evaluation and rehabilitation following exposure to severe changes in head velocity or ambient pressure. In Turan, O., Bos, J., Stark, J., and Colwell, J., (Eds.), Proceedings of the International Conference on Human Performance at Sea (HPAS). (pp. 367-380). Glasgow, U.K.

Lee, B., Bechly, K., and Sienko, K. H. 2010. Cell phone based vibrotactile feedback system for home-based vestibular rehabilitation balance training [Abstract]. Journal of Vestibular Research. 20(3-4): 234-235.

Lee, P., Gadareh, K., Naushahi, M. J., Bain, P. G., Nandi, D., Gresty, M. A., et al. 2010. The effects of vibrotactile feedback on protective stepping responses in Parkinson's disease patients [Abstract]. Journal of Vestibular Research. 20(3-4): 259.

Lueckenotte, A. and Conley, D. 2009. A study guide for the evidence-based approach to fall assessment and management. Geriatric Nursing. 30(3): 207-216.

Luxon, L. M. (1996). Posttraumatic vertigo. In R. W. Baloh, and G. M. Halmagyi (Eds.), Disorders of the Vestibular System (pp. 381-395). New York, Oxford Press.

Mallinson, A., and Longridge, N. 2010. Does VEMP testing detect vestibular damage related to head trauma and whiplash injury? [Abstract]. Journal of Vestibular Research. 20(3-4): 158-159.

Management of Concussion/MTBI Working Group. 2009. VA/DoD clinical practice guideline for management of concussion/mild traumatic brain injury. Department of Veterans Affairs, Department of Defense, USA, 1 March, Version 1.0.

Manzari, L., Burgess, A., and Curthoys, I. S. 2010. Ocular and cervical vestibular-evoked myogenic potentials (oVEMPs and cVEMPs) to bone conducted vibration (BCV) in Meniere's disease during quiescence vs during acute attacks [Abstract]. Journal of Vestibular Research. 20(3-4): 197.

Manzari, L., Burgess, A., McGarvie, L. A., and Curthoys, I. S. 2010. Ocular and cervical vestibular-evoked myogenic potentials to 500 Hz Fz bone conducted vibration in semicircular canal dehiscence [Abstract]. Journal of Vestibular Research. 20(3-4): 155.

McCrea, M., Pliskin, N., Barth, J., Cox, D., Fink, J., French, L., et. al. 2008. Official position of the Military TBI Task Force on the role of neuropsychology and rehabilitation psychology in the evaluation, management, and research of military veterans with traumatic brain injury. The Clinical Neuropsychologist. 22(1): 10-26.

McGrath, B. J., Estrada, A., Braithwaite, M. G., Raj, A. K., and Rupert, A. H. 2004. Tactile situation awareness systems flight demonstration. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 2004-10.

Megna, J. 2007. Balance and vestibular rehabilitation in the patient with acquired brain injury. In J. Elbaum, and D. M. Benson (Eds.), Acquired brain injury: An integrative neuro-rehabilitation approach (pp. 200-214). New York: Springer.

Mononen,K., Konttinen, N., Viitasalo, J. and Era. P. 2007. Relationships between postural balance, rifle stability and shooting accuracy among novice rifle shooters. Scandinavian Journal of Medicine and Science in Sports. 17(2):180-5.

Mortimer, B., and Dutta, A. (2010). Sensory augmentation in a complex balance task. In Proceedings of the Neuromorphic Cognition Engineering Workshop,Telluride, CO. https://neuromorphs.net/nm/wiki/2010/bmi10/uni

Muir, S. W., Berg, K., Chesworth, B., Klar, N., and Speechley, M. 2010a. Quantifying the magnitude of risk for balance impairment on falls in community-dwelling older adults: A systematic review and meta-analysis. Journal of Clinical Epidemiology. 63: 389-406.

Muir, S. W., Berg, K., Chesworth, B., Klar, N. and Speechley, M. 2010b. Balance impairment as a risk factor for falls in community-dwelling older adults who are high functioning: A prospective study. Physical Therapy. 90(3): 338-347.

Myers, P. J., Wilmington, D. J., Gallun, F. J., Henry, J. A., and Fausti, S. A. 2009. Hearing impairment and traumatic brain injury among soldiers: Special considerations for the audiologist. Seminars in Hearing. 30: 5-27.

Nashner, L. M. 1997. Computerized dynamic posturography: Clinical applications. In G. P. Jacobson, C. W. Newman, and J. M. Kartush (Eds.), Handbook of Balance Function Testing (pp. 308-334). New York: Thompson.

National Institute on Deafness and Other Communication Disorders (NIDCD). Strategic Plan (FY 2006-2008). http://www.nidcd.nih.gov/staticresources/about/plans/strategic/strategic06-08.pdf

Office of the Surgeon General, U.S. Army Medical Department. 2007. Traumatic Brain Injury (TBI) Task Force Report. www.armymedicine.army.mil/prr/tbitfr.html

Ogawa, Y., Otsuka, K., Inagaki, T., Kondo, T., Shimizu, S., and Suzuki, M. 2010. Subjective visual vertical in vestibular neuritis and unilateral sudden deafness [Abstract]. Journal of Vestibular Research. 20(3-4): 297-298.

Patel, M., Fransson, P., Johansson, R., and Magnusson, M. 2010. Foam surfaces and standing balance testing: The balance perturbing effects, the perturbing mechanisms and considerations for clinical and experimental practice [Abstract]. Journal of Vestibular Research. 20(3-4): 161-162.

Peterka, R. J., Wall, III, C., and Kentala, E. 2006. Determining the effectiveness of a vibrotactile balance prosthesis. Journal of Vestibular Research. 16: 45-56.

Pijnenburg, M., Guinand, N., Boselie, F., Loo, C., Janssen, M., Guyot, J., et al. 2010. Dynamic Visual Acuity (DVA) and oscillopsia severity in patients with bilateral vestibular loss [Abstract]. Journal of Vestibular Research. 20(3-4): 182.

Raj, A. K., Suri, N., Braithwaite, M. G., and Rupert, A. H. 1998. The tactile situation awareness system in rotary wing aircraft: Flight test results. In Proceedings of the RTO/HFM Symposium on Current Aeromedical Issues in Rotary Wing Operations. Neuilly-sur-Seine, France. RTO NATO HF, RTO-MP-Vol. 19: 16.1-16.7 (ISBN 9283700082). Presented in San Diego, CA 19-21 Oct.

Rossi-Izquierdo, M., Ernst, A., Basta, D., Soto-Varela, A., Santos-Perez, S., Faraldo-Garcia, A., and Sesar-Ignacio, A. 2010. Vestibular rehabilitation with vibrotactile neurofeedback training in patients with Parkinson's disease [Abstract]. Journal of Vestibular Research. 20(3-4): 258-259.

Ruff, R. M., Iverson, G. L., Barth, J. T., Bush, S. S., Broshek, D. K., et al. 2009. Recommendations for diagnosing a mild traumatic brain injury: A National Academy of Neuropsychology Education Paper. Archives of Clinical Neuropsychology. 24: 3-10.

Rupert A. H. 2000. Tactile situation awareness system: Proprioceptive prostheses for sensory deficiencies. Aviation, Space, and Environmental Medicine. 71: A92-A99.

Rupert, A. H., Guedry, F. E., and Reschke, M. F. 1994. The use of a tactile interface to convey position and motion perceptions. In Advisory Group for Aerospace Research and Development (AGARD) Virtual Interfaces: Research and Applications, 20.1-20.7. France.

Rupert, A. H., and Lawson, B. D. 2011. Initial consideration of the feasibility and optimal application of tactile sway cueing to improve balance among persons suffering from disequilibrium. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report 2011-01.

Rupert, A. H., Lawson, B. D., McGrath, E. F., and Wood, S. J. 2011. Computerized posturography incorporating static and dynamic head tilts [Abstract]. Journal of Vestibular Research. 21(2): 74.

Rupert, A. H., Mateczun, A., and Guedry, F. E. 1990. Maintaining spatial orientation awareness. In Situation Awareness in Aerospace Operations (pp. 21-1 to 21-5). Copenhagen, Denmark. AGARD-CP-478.

Saatman, K. E., Duhaime, A., Bullock, R., Maas, A., Valadka, A., and Manley, G. T. 2009. Classification of traumatic brain injury for targeted therapies. Journal of Neurotrauma. 25(7): 719-738.

Scott, S. G., Belanger, H. G., Vanderlploeg, R. D., Massengale, J., and Scholten, J. 2006. Mechanism-of-injury approach to evaluating patients with blast-related polytrauma. Journal of the American Osteopathic Association. 106(5): 265-270.

Scherer, M. R., and Schubert, M. C. 2009. Traumatic brain injury and vestibular pathology as a comorbidity after blast exposure. Physical Therapy. 89: 980-992.

Shepard, N., and McPherson, J. 2010. VEMP threshold response curves in Meniere's Syndrome: Sensitivity / specificity [Abstract]. Journal of Vestibular Research. 20(3-4): 195-196.

Shumway-Cook, A. 2007. Assessment and management of the patient with traumatic brain injury and vestibular dysfunction. In S. J. Herdman (Ed.), Vestibular Rehabilitation. 3rd ed. (pp. 444-457). Philadelphia, PA: F. A. Davis Company.

Srygley, J. M., Herman, T., Giladi, N., and Hausdorff, J. M. 2009. Self-report of missteps in older adults: A valid proxy of fall risk? Archives of Physical Medicine and Rehabilitation. 90: 786-792.

Sylvia, F. R., Drake, A. I., and Wester, D. C. 2001. Transient vestibular balance dysfunction after primary blast injury. Military Medicine. 166: 918-920.

Szmulewicz, D., Waterson, J., and Storey, E. 2010. The clinical utility of Romberg's test [Abstract]. Journal of Vestibular Research. 20(3-4): 305-306.

Taber, K. H., Warden, D. L., and Hurley, R. A. 2006. Blast-Related Traumatic Brain Injury: What is known? Journal of Neuropsychiatry and Clinical Neuroscience. 18(2): 141-145.

Tanner, B. 2007. Traumatic Brain Injury: An Operational Update [Presentation]. United States Marine Corps Combat/Operational Stress Control Conference. Arlington, VA. June 18-19, 2007.

Taylor, R., Wijewardene, A., Gibson, W., Halmagyi, M., and Welgampola, M. 2010. The vestibular evoked-potential profile of Ménière's disease [Abstract]. Journal of Vestibular Research. 20(3-4): 227.

Teasdale, G., and Jennett, B. 1974. Assessment of coma and impaired consciousness. A practical scale. Lancet. 304(7872): 81-84.

Terrio, H., Brenner, L. A., Ivins, B. J., Cho, J. M., Helmick, K., Schwab, K., et. al. 2009. Traumatic brain injury screening: Preliminary findings in a U.S. Army Brigade Combat team. Journal of Head Trauma Rehabilitation. 24(1): 14-23.

Verhoeff, L. L., Horlings, C. G., Janssen, L. J., Bridenbaugh, S. A., and Allum, J. H. 2009. Effects of biofeedback on trunk sway during tasking in healthy young and elderly. Gait Posture. 30(1): 76-81.

Vibert, D. and Häusler, R. 2000. Long-term evolution of subjective visual vertical after vestibular neurectomy and labyrinthectomy. Acta Otolaryngol.120(5):620-622.

Vibert, D., Häusler, R., Kompis, M., and Vischer, M. 1999. Vestibular function in patients with cochlear implantation. Acta Otolaryngol (545): 29-34.

Wall, C., and Kentala, E. 2005. Control of sway using vibrotactile feedback of body tilt in patients with moderate and severe postural control deficits. Journal of Vestibular Research. 15(5-6): 313-325.

Wall, C., Weinberg, M. S., Schmidt, P. B., and Krebs, D. E. 2001. Balance prosthesis based on micromechanical sensors using vibrotactile feedback of tilt. Institute of Electrical and Electronics Engineers (IEEE) Transactions on Biomedical Engineering, 48(10): 1153-1161.

Weiss, A., Shimkin, I., Giladi, N., and Hausdorff, J. M. 5 Mar 10. Automated detection of near falls: Algorithm development and preliminary results. BMC Research Notes. 3: 62. www.biomedcentral.com/1756-0500/3/62.

Winters, S., Klis, S., and Grolman, W. 2010. The air-conducted ovemp in Ménière's disease [Abstract]. Journal of Vestibular Research. 20(3-4): 196-197.

Whitney, S. L., and Morris, L. O. (2005). Vestibular rehabilitation. In D. Poe (Ed.), The Consumer Handbook on Dizziness and Vertigo (pp. 225-248). Sedona, AZ: Auricle Ink Publishers.

Wrisley, D. M., Marchetti, G. F., Kuharsky, D. K., and Whitney, S. L. 2004. Reliability, internal consistency, and validity of data obtained with the Functional Gait Assessment. Physical Therapy. 84(10): 906-918.

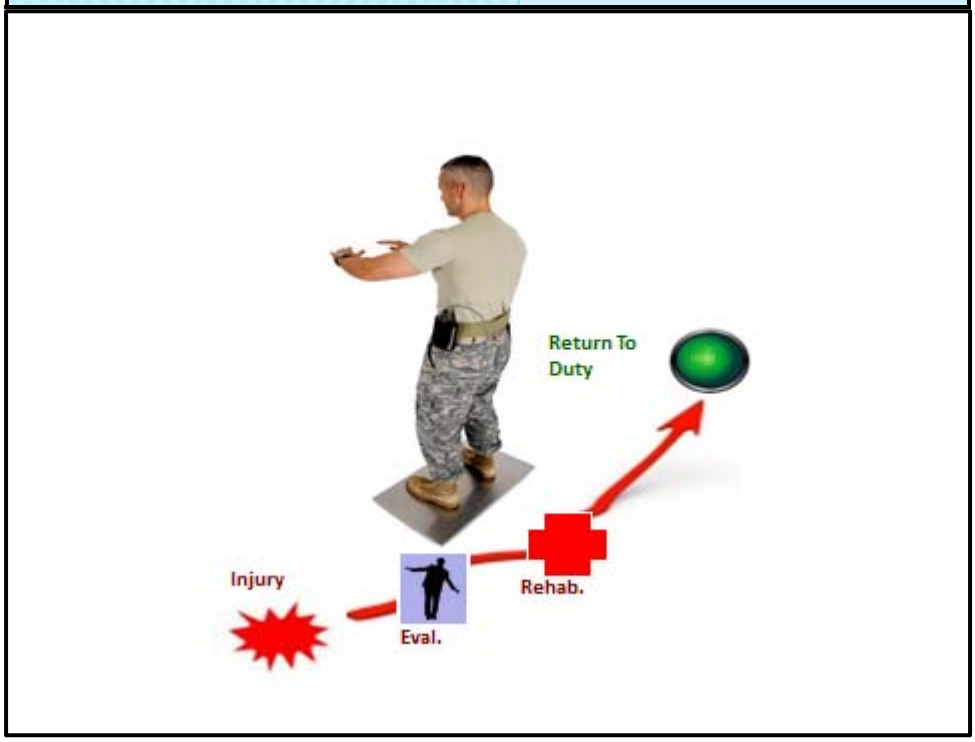
Yavor, R., Taylor, R., Jonker, B., Shivalingam, B., MacDougall, H., Curthoys, I., et al. 2010. Canal and otolith function testing in subjects with Vestibular Schwannoma [Abstract]. Journal of Vestibular Research. 20(3-4): 204.

Yelnik, A.P., Lebreton, F.O., Bonan, I.V., Colle, F.M., Meurin, F.A., Guichard, J.P., and Vicaut, E. 2002. Perception of verticality after recent cerebral hemispheric stroke. Stroke. 33(9):2247-2253.

Zhang, D., Fan, Z., Han, Y., and Wang, H. 2010a. Dynamic posturography: The clinical value in the diagnosis of patients with acute vertigo [Abstract]. Journal of Vestibular Research. 20(3-4): 180.

Zhang, D., Fan, Z., Han, Y., and Wang, H. 2010b. Dynamic posturography: The clinical value in finding balance abnormity of patients with Benign Paroxysmal Positional Vertigo [Abstract]. Journal of Vestibular Research. 20(3-4): 317.

Appendix A.
Rupert and Lawson presentation slides.



CAPT Michael Hoffer MC USN
EN&T

Goals

- Assessment

  Simple, Easy to administer, Corpsman, Objective, Small footprint.
- Treatment Static Balance (SBIRs)
- Ambulatory Prosthesis

  Technology Development (SBIRs, STTRs, MURIs)

THREE STREAMS OF RESEARCH COMING TOGETHER

BASIC SWAY FINDINGS

–Varying sensory conditions alters sway and reveals vestibular pathology (e.g., Nashner et al.)

–Light finger touch as stabilizing as vision in normals (Holden et al)

APPLIED VIBROTACTILE FINDINGS

–Vibrotactile feedback helps pilots maintain spatial orientation (Rupert et al.)

– Post-rotatory dysequilibrium diminished by vibrotactile feedback (pilot tests with Wall)

–Vestibular patients made more stable with vibrotactile sway biofeedback (Wall et al.)

–Standing balance more stable in balance patients following PT augmented by vibrotactile sway biofeedback (Atkins)

RELEVANT TBI FINDINGS

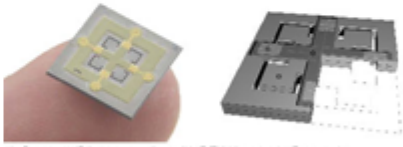
–Balance tests detect deficits associated with MTBI (Goldhall et al.)

–Vestibular rehab. helps with MTBI (Goldhall et al., Herdman et al., etc.)

–Vertigo and disequilibrium are major problems associated with MTBI in Theater (Saleban et al.; Heffer et al.)

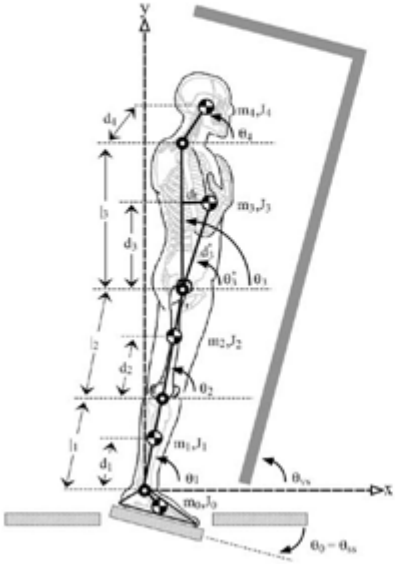
Multi-Site Test of Vibrotactile Sway Feedback for Balance Rehab. Following MTBI

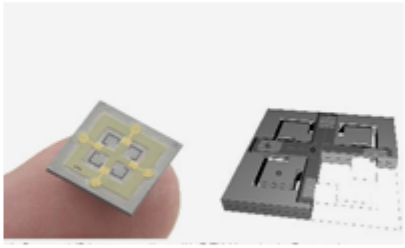
Sensor Technologies



InSensor A/S in cooperation with DTU Nanotech, Denmark

Central Computation



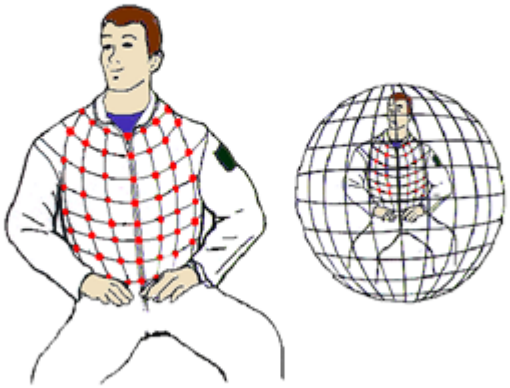


Ambulatory Prostheses to Prevent Falls

Carey Balaban

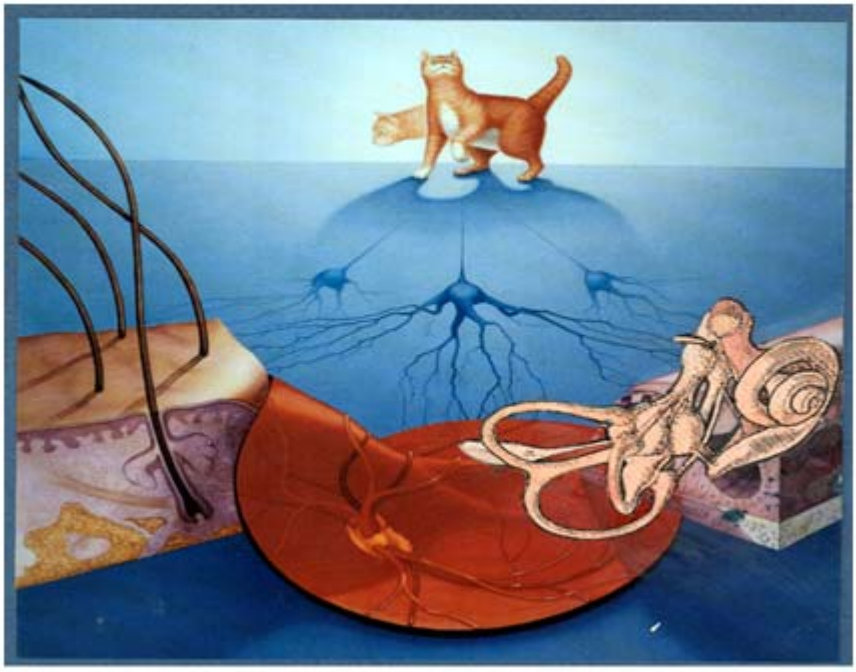
- Magnitude of the balance/vestibular problem in mTBI

Tactile Prostheses

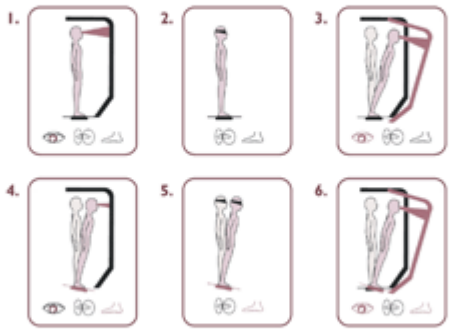


Karen Atkins

- Developed the Physiotherapist application of tactile feedback using basic force plate C-of-G.
- Thesis: Vibrotactile Postural Control in Patients That Have Sit-to-Stand Deficits and Fall
- One of three Phase I SBIRs to enhance the basic system via multimodal feedback.



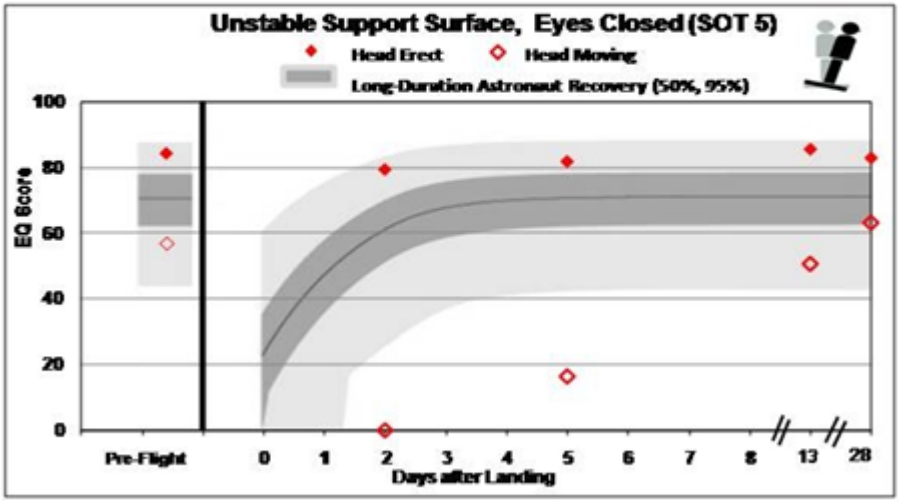
Simulator Sickness Sensory Rearrangement



Sensory Organization Test

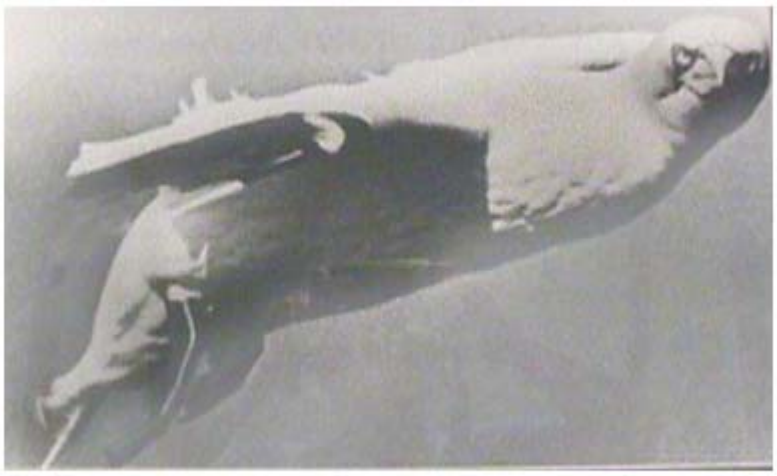
Coriolis Acceleration Platform

Astro Rearrangement

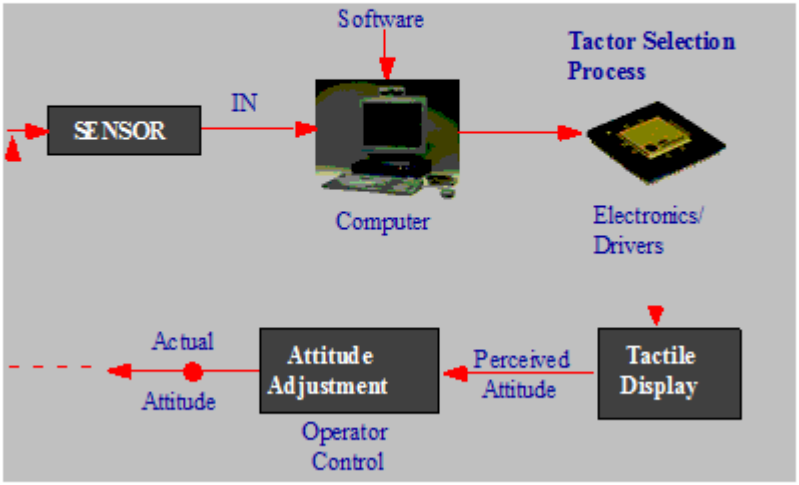


DEMO

- Bruce Artwick

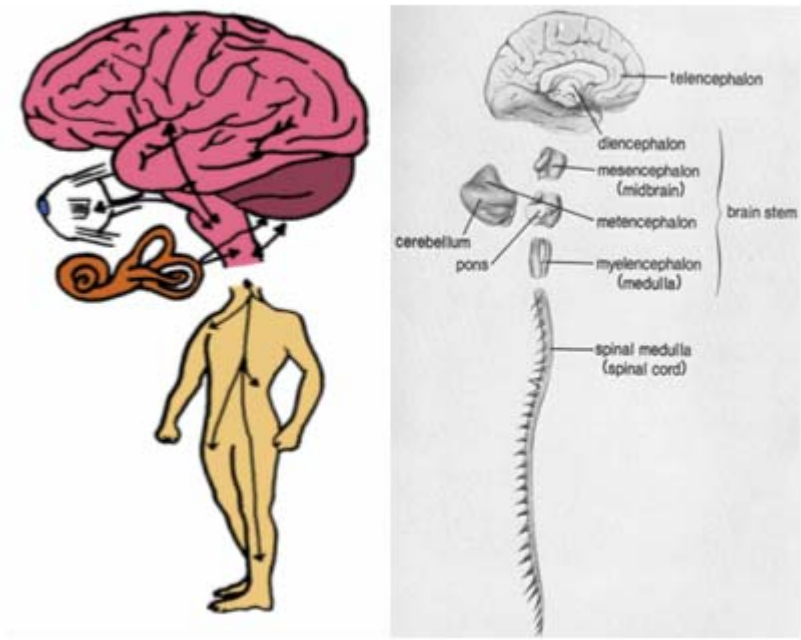


Tactile Display System

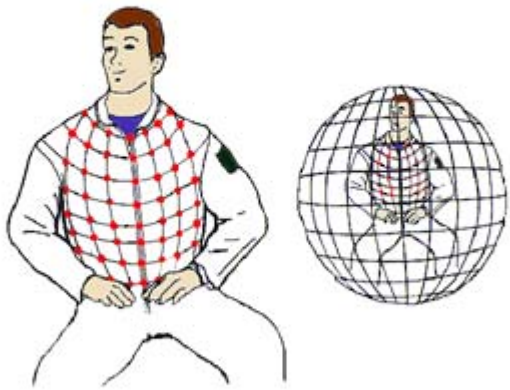


HANS-LUKAS TEUBER

- The number of dimensions of perception exceeds that of the stimuli



Solution --- Continuous Information



Tactile Situation Awareness System

Appendix B.
Balaban, Hoffer, and Gottshall presentation.

Mild Traumatic Brain Injury and Balance Control

Carey D. Balaban, PhD
Michael E. Hoffer, CAPT MC USN
Kim R. Gottshall, PhD, PT, ATC

Disclaimer

- Opinions expressed here are those of the authors
- DoD Policy has been considered in this work but should not be taken as evidence of endorsement
- No commercial disclosures

CAPT Hoffer at TQ Iraq 2008-9

TBI – Significance

- 2nd most common neurological injury
- Increasing in frequency over time
- 1.4 Million people affected annually in the U.S. and 50,000 die from the injury
- TBI costs the U.S. over 48 billion dollars a year
- "Indirect cost" to families and society is difficult to calculate

TBI definition*

A traumatically induced structural injury and/or physiological disruption of brain function as a result of an external force that is indicated by new onset or worsening of at least one of the following clinical signs, immediately following the event:

*As developed by the Surgeon Generals' consensus study group May-July 2007

TBI Definition - Continued

- Any period of loss of or a decreased level of consciousness
- Any loss of memory for events immediately before or after the injury
- Any alteration in mental state at the time of the injury (confusion, disorientation, slowed thinking, etc)
- Neurological deficits
  - Weakness
  - Loss of balance
  - Change in vision
  - Praxis
  - Paresis/plegia
  - Sensory loss
  - Aphasia
  - Etc.
- Intracranial lesion

Traumatic brain injury (TBI)

	Mild TBI	Moderate TBI	Severe TBI
Structural Imaging	Normal	Normal or Abnormal	Normal or Abnormal
Loss of Consciousness	0-30 min	>30 min to 24 hr	>24 hr
Altered Consciousness	Momentary to 24 hr	>24 hr, severity based on other criteria	
Post-Traumatic Amnesia	0-1 day	>1 day to 7 days	> 7 days

Balance, Otolaryngology and mTBI

- Dizziness is the most common symptom of traumatic brain injury occurring initially in 98% of those injured
- Hearing loss and/or tinnitus are present initially in 70% of individuals

Pathophysiology – Closed Head Injury (CHI)

- Consequences of head injury
  - Diffuse Axonal Injury (DAI)
  - Focal Edema
  - Subdural or subarachnoid extravasation or hemorrhage
  - Secondary parenchymal injury
    - Free radical generation
    - Release of excitatory neurotransmitters

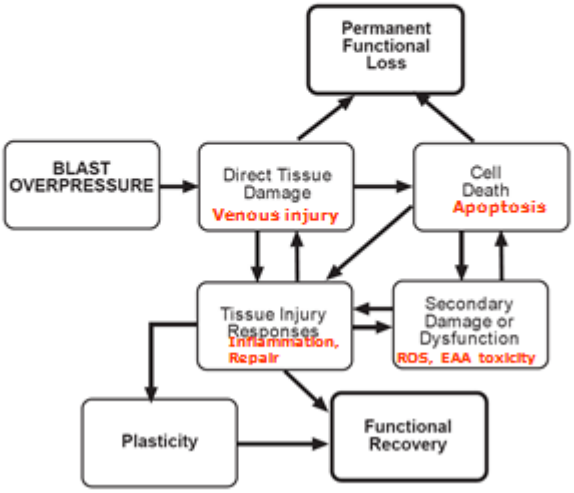
Vestibular effects – CHI

- Altered/disturbed message transfer along "balance pathway" with little initial cell death
  - Altered vestibular reflexes (VOR, VCR, Vestibulo-spinal reflexes)
  - Apoptotic cell death (continuing long after injury) but often only in localized area

Pathophysiology – Blast Injury

- Shock wave effect
  - Microvascular injury
  - Shear injury in vestibular end organ
  - Oxidative cellular stress
  - Significant Release of excitatory neurotransmitters
  - Direct stimulation of apoptotic pathways

Pathophysiology – Blast Injury



Vestibular effects – Blast Injury

- Targeted injury pattern - but may be at multiple sites
- Signs and symptoms
  - Similar to peripheral end organ damage and may be bilateral
  - Central/mixed pattern often seen
  - Hearing loss/tinnitus often present
  - Distinct pattern of cognitive difficulty

Work-up

- Specialized vestibular history and physical
  - Characterization of injury
  - Standard history questions
  - Otolaryngologic and Neurologic Physical exam
- Evaluation by a physician, a physical therapist, and an audiologist
- Evaluation captured in a computer program (AHLTA)

Evaluation - continued

- Audiogram
- Neuro-vestibular testing
- Standardized assessment instruments
- MRI scan

Neuro-vestibular testing

- Dynamic Computerized Posturography
- Rotational chair testing of gain, phase, and symmetry
- Step-velocity testing to determine the vestibular time constant
- High speed head rotation testing for gain

Standardized Assessment Instruments

- Dynamic Gait Index (DGI)
- Dizziness Handicap Index (DHI)
- Activity-Specific Balance Confidence Scale (ABC)
- Vestibular activities of daily living (VADL)
- Balance Error Scoring System (BESS)

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Blast Exposure: Vestibular Consequences and Associated Characteristics

*Michael E. Hoffer, *§Carey Balaban, *Kim Gottshall, *Ben J. Balough, †Michael R. Maddox, and ‡Joseph R. Penta

*Spatial Orientation Center, Department of Otolaryngology, Naval Medical Center San Diego; †1st Marine Expeditionary Group; ‡1st Marine Logistics Group, Camp Pendleton, California; and §Department of Otolaryngology, University of Pittsburgh, Pittsburgh, Pennsylvania, U.S.A.

International Tinnitus Journal, Vol. 15, No. 2, 115–118 (2009)

Blunt and Blast Head Trauma: Different Entities

Michael E. Hoffer,[1] Chadwick Donaldson,[1] Kim R. Gottshall[1], Carey Balaban,[2] and Ben J. Balough[1]

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Classification of primary blunt trauma

- Four Groups
  - Post-traumatic positional vertigo
  - Post-traumatic exertional dizziness
  - Post-traumatic migraine associated dizziness (PTMAD)
  - Post-traumatic spatial disorientation

•Hoffer ME, Gottshall KR, Moore RJ, Balough BJ, Wester DC. *Characterizing and Treating Dizziness after Mild Head Trauma.* Otol/Neurotol, 25(2):135-38, 2004

•Hoffer ME, Balough BJ, Gottshall KR. *Posttraumatic Balance Disorders.* Int. Tin J. 13(1):69-72, 2007

CHI Induced Dizziness

Entity	History	Physical Exam	Vestibular Tests
Positional Vertigo	Positional Vertigo	Nystagmus on Dix-Hallpike test or modified Dix-Hallpike test	No other abnormalities
Exertional Dizziness	Dizziness during and right after exercise	Abnormalities in challenged gait testing	No other abnormalities
Migraine Associated Dizziness	• Episodic Vertigo with periods of unsteadiness • Headaches	• Abnormalities in challenged gait testing • +/-Abnormalities on head impulse testing • Normal static posture tests	• VOR gain, phase, or symmetry abnormalities • High frequency VOR abnormalities • Normal posturography
Spatial Disorientation	• Constant feeling of unsteadiness worsened by standing but still present when sitting or lying down • Drifting to one side while walking • Shifting weight when standing still	• Abnormalities on standard gait tests • +/- Abnormalities on head impulse testing • Abnormalities on static posture tests	• VOR gain, phase, or symmetry abnormalities • High frequency VOR abnormalities • Abnormal posturography • Central findings on rotation chair testing

Blast Induced - TBI

- Slightly different set of diagnoses
- More Cognitive difficulty
- Higher degree of hearing loss

Hoffer ME, Balaban C, Gottshall KR, Balough BJ, Maddox MR, Penta JR. Blast exposure: Vestibular consequences and associated Characteristics. Otol Neurotol, 2010, 31: 232-236.

Hoffer ME, Donaldson C, Gottshall KR, Balaban C, Balough BJ. Blunt and blast head trauma: Different Entities. Int Tinnitus J., 2009, 15:115-118.

Mild Traumatic Brain Injury after Blast - Symptom Distribution

Group	Dizziness	Vertigo	Hearing Loss	Headache	PTSD
Acute (< 72 h)	98%*	4%*	33%*	72%	2%*
Sub-acute (4 -30 d)	76%	47%	43%	76%	20%
Chronic (30-360 d)	84%	36%	49%	82%	44%

Blast Induced Dizziness

Entity	History	Physical Exam	Vestibular Tests
Positional Vertigo	Positional Vertigo	Nystagmus on Dix-Hallpike test or modified Dix-Hallpike test	No other abnormalities
Exertional Dizziness	Dizziness during exercise	Abnormalities in challenged gait test	No other abnormalities
Blast Induced Disequilibrium	•Constant feeling of unsteadiness when standing and walking worse with challenging environments •Constant Headache	•Abnormalities in challenged gait •Abnormalities in tandem Romberg •Abnormalities with quick head motion	•Abnormal posturography •Abnormal target acquisition, dynamic visual acuity, and gaze stabilization •+/- VOR gain, phase, or symmetry abnormalities
Blast Induced Disequilibrium with Vertigo	•Constant feeling of unsteadiness when standing and walking worse with challenging environments •Constant Headache •Episodic Vertigo	•Abnormalities in challenged gait •Abnormalities in tandem Romberg •Abnormalities with quick head motion	•Abnormal posturography •Abnormal target acquisition, dynamic visual acuity, and gaze stabilization •VOR gain, phase, or symmetry abnormalities

Blast Induced Dizziness

Limited objective testing indicates symptoms become aggravated with time

Need sensitive and selective test battery for the field and follow-up

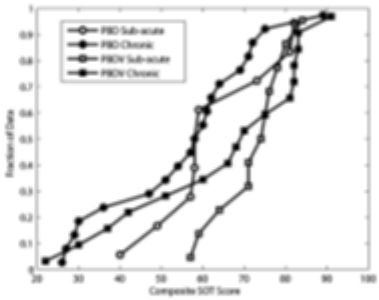


FIG. 2. Scatter plot of SOT scores as a function of dizziness diagnostic classification and time of presentation.

Functional Diagnostic and Rehabilitation Targets

- Vestibular-ocular Reflex (Head and eye interaction)
- Vestibular-spinal Reflex (Head and spine interaction)
- Posture – spatial orientation sense
- Gait – with and without tasks
- General Conditioning – Getting in shape

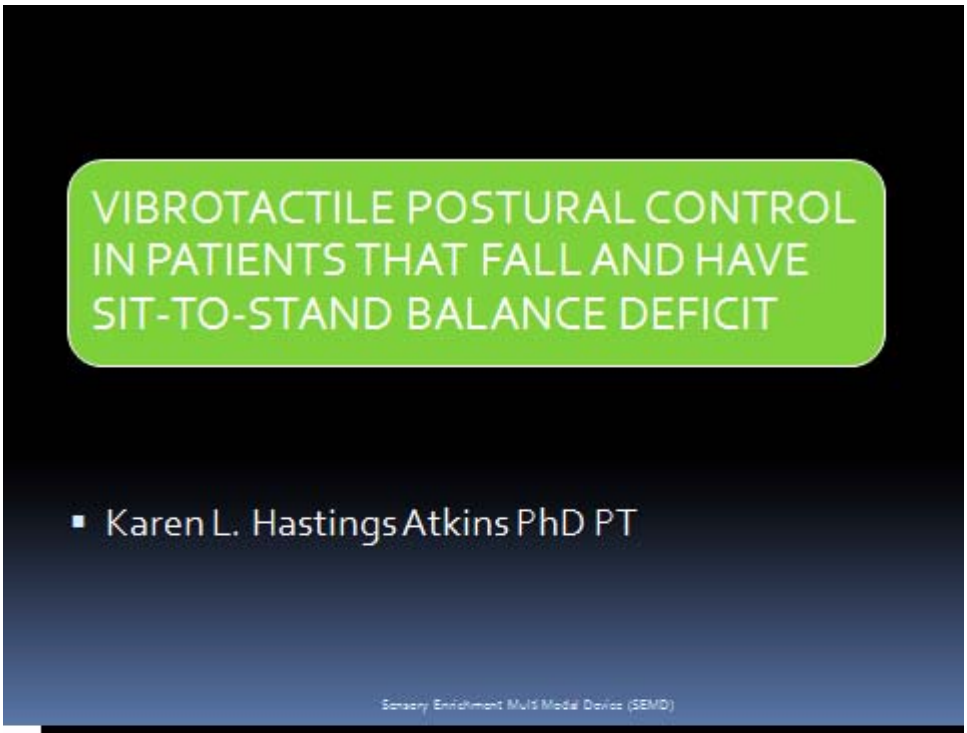
Basic Vestibular Rehabilitation Therapy

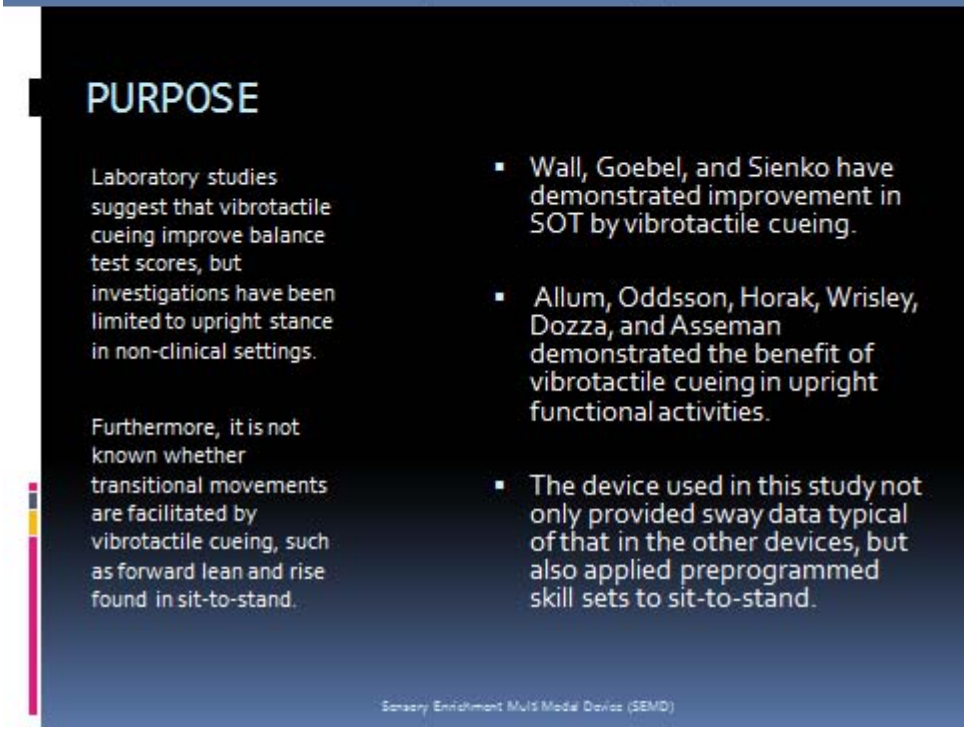
- VOR
- COR
- Depth Perception
- Somatosensory
- Gait Training
- Positional Exercises
- Proprioceptive Neuromuscular Facilitation (PNF)
- Aerobic Conditioning

Conclusions

- Blast vs. Blunt TBI show different diagnostic groups and different test results – they are different injuries
- Understanding the classification system is essential for optimal diagnosis and treatment
- Vestibular disorders are a dominant clinical feature in all types of head trauma
- Vestibular disorders from both groups are treatable in specialized centers

Appendix C.
Atkins presentation.





STUDY DESIGN

A prospective case/control study was used to determine the relationship between standard of care physical therapy plus vibrotactile force platform device treatment and standard of care physical therapy only.

A repeat measure design investigated the relationship between force platform vibrotactile intervention and balance test scores, sit-to-stand and falls.

Session	Activity
1	Initial Evaluation at Florida Ear & Balance Center
1	Physical Therapy Session 1, Week 1
2	Physical Therapy Session 2, Week 1
3	Day 14 Evaluation at Florida Ear & Balance Center
4	Physical Therapy Session 3, Week 2
5	Physical Therapy Session 4, Week 2
6	Physical Therapy Session 5, Week 3
7	Physical Therapy Session 6, Week 3
8	Day 30 Evaluation at Florida Ear & Balance Center
9	Day 90 Evaluation at Florida Ear & Balance Center
10	Day 180 Evaluation at Florida Ear & Balance Center

Participants

Inclusion Criteria

- Prospective subjects must have had the potential to benefit from physical therapy intervention referral by physician.
- Mini Mental State Examination: 25/30 minimum
- Snellen Chart (handheld): 20/60 minimum
- NeuroCom Comprehensive Report: abnormal
- Self-report falls: 2 or more within past 6 months.

Participants
Exclusion Criteria

- less than 20/60 corrected vision
- artificial limbs
- inability to sit unaided for 2 minutes
- inability to stand with a cane or unaided for 2 minutes
- abnormal Mini Mental State Examination (MMSE)
- diagnoses of sarcopenia, Alzheimer's, myasthenia gravis, or Parkinson's
- inability to complete the initial BBS and/or DGI tests
- inability to speak and understand the English language
- internal cardiac devices (pacemakers).

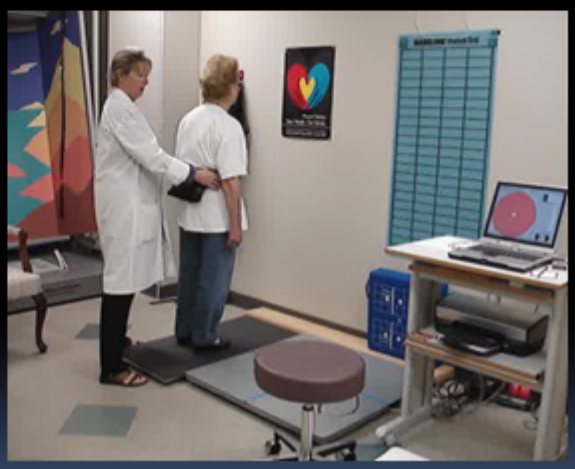
Sensory Enrichment Multi Modal Device (SEMD)

SUBJECTS

30 community-dwelling adults, aged 60 to 79 years, with abnormal NeuroCom Sit-to-Stand test results and 2 or more self-reported falls within the last 6 months.

Subjects were quasi randomly assigned to 1 of 3 groups:

10 as off-site controls, 10 as on-site controls, and 10 as on-site device intervention subjects.



Sensory Enrichment Multi Modal Device (SEMD)

METHODS

Instruments

The Berg Balance Scale (BBS), Dynamic Gait Index (DGI), Functional Independence Measure-Motor (FIM-Motor), NeuroCom Sit-to-Stand normative ratios, NeuroCom Comprehensive Report, and self-reported falls.

Protocol

Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Romberg Eyes open Eyes closed Weight Shift Gait Strategies Sit-to-Stand Initiate Home Program.	Sharpened Romberg Muscle Strengthening Hip Weight Shift Strategy	Tandem Walk Weight Shift Accuracy Speed Sway On Target Deceleration Ball Toss	Dynamic Activities Weave Step Forward Reach Step-up Pivot Turn Eyes Closed with Sharpened Romberg	End Range of Weight Shift Unilateral Stand Head Shakes with Static Stand Activities	Review of all previous activities. Solidify home exercise program.

RESULTS

The study found a significant beneficial effect in the device intervention group which realized

- 39.5/56 to 51.2/56 mean score increase in Berg Balance Score.
- Increase in mean Dynamic Gait Index from 11.7/24 to 19.8/24.
- Mean increase in FIM-Motor from 16.4/21 to 19.5/21.
- Decrease in self-report falls from 4 to 2 by intervention Day 14.

Relationship to Medical Resource Utilization

- Berg scores of 36/56 or lower are predictive of falls.
- Dynamic Gait Index score of 19/24 or lower are predictive of falls in the elderly.
- 1 point in FIM-Motor represents 3.5 minutes of direct care giver time.

RESULTS

Summary data compared pretest to day 14 and found the on-site device intervention group had achieved the most beneficial average increase when comparing a *summed* score of BSS plus DGI plus FIM-Motor.

The sum of the 3 these interval scales is similar to the reporting format in a clinical setting, which in a practical way displays variance between means and Wilcoxon signed ranks narrative.

Average Summed Score Increase per Group

- On-site Device: 21.2/101
- Off-site controls: 7.8/101
- On-site controls: 13.8/101

DISCUSSION

The results of this study show that vibrotactile technology can be effectively incorporated into a physical therapy workflow and treatment plan of care.

Of note, but beyond the scope of this study, was the variation in physical therapy standard care for patients that fall.

The device affords an opportunity to standardize evaluation and treatment protocols into skill sets with progressive levels of difficulty based on postural control of sway.

- Introduction of vibrotactile technology into standard care physical therapy is a paradigm shift in treatment strategies.

CONCLUSION

These findings encourage further investigation of vibrotactile force platform devices.

- As a sentinel study, this beneficial outcome encourages further investigation(s) of the effect of vibrotactile force platform intervention in other studies and on other populations.

Sensory Enrichment Multi Modal Device (SEMD)

LIMITATIONS

Small sample size with attrition

Intervention protocols followed a general scheme but were tailored to the individual.

Consistency of intervention at 1 off-site location could not be controlled.

- 56 subjects are required to reach power.
- Specific, pre programmed physical therapy intervention protocols would enhance internal control.

Sensory Enrichment Multi Modal Device (SEMD)

DELIMITATIONS

Participants appear to be representative of older community-dwelling populations.

Extending the study over 7 months allowed comparison of falls to the pretest time frame.

A similar study design could be reproduced at another location and in other populations.

- Older subjects presented with multiple sensory/neural deficits.
- Knowledge transfer and retention was demonstrated.
- Function within the domain of "activities of daily living" was the basis for improvement.

Sensory Enrichment Multi Modal Device (SEMD)

Appendix D.
Tactile cueing systems.

This section presents additional information concerning a few manufacturers of tactile balance cueing systems, some of whom are mentioned in the body of the paper. No endorsement by the authors is implied. Brochures start on the next page, in no particular order.

Force plates

Force sensors

Multi-axis testing machines

Instrumented biomechanics equipment

AMTI
FORCE AND MOTION
www.amti.biz

Force plates

AMTI force plates represent the culmination of years of research and refinement. Each is designed to measure the three forces and three moments applied to its top surface as a subject stands, steps, or jumps on it.

Our force plates have a proven track record of excellent performance and durability that has earned them a place in hundreds of gait and biomechanics laboratories around the world. We offer many standard designs and also regularly partner with individual researchers to create custom solutions for highly specific applications.

Common applications include:

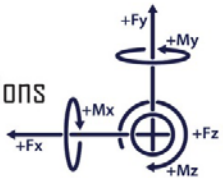
- Human and animal gait
- Sports performance analysis
- Balance assessment and training
- Ergonomics studies
- Underwater force measurement

Force sensors

AMTI has more than 30 years of experience designing and manufacturing six-axis force sensors. Our sensors measure the three force components along the x, y, and z axes as well as their corresponding moments. The sensors are ideal for research and testing environments as they provide high stiffness, high sensitivity, low crosstalk, excellent repeatability, and proven long-term stability.

AMTI general strain gage sensor specifications	
Excitation	10V or less (Recommended source: AMTI amplifier)
Crosstalk	Less than 2% on all channels
Temperature range	0 to 125°F (-17 to 52°C)
Fx, Fy, Fz hysteresis	± 0.2 % full scale output
Fx, Fy, Fz non-linearity	± 0.2% full scale output

The global leader in multi-axis force measurement and testing solutions



Instrumented biomechanics equipment

AMTI integrates its force measurement technology into a variety of biomechanics research equipment, such as treadmills, parallel bars, computerized dynamic platforms, stairs, walkers, canes, and crutches.

Each product allows for the accurate measurement of the three forces and three moments generated by the subject.

MCW Walker Sensors

Available models include:

- Pediatric anterior walker
- Pediatric posterior walker
- Adult anterior walker
- Pediatric crutches
- Adult crutches
- Canes

Compact Tandem Force-Sensing Treadmill

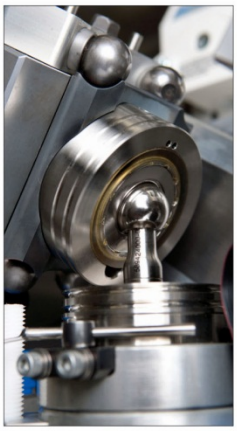
- Tandem belt design eliminates loss of data caused by "double support" during walking
- One force plate located under each belt
- Speed: 0-20 kph, adjustable in .06 kph increments
- Elevation up to 25% grade
- Reversible belt direction for uphill and downhill walking and running
- Vertical force plate capacity: 8800 N
- Horizontal force plate capacity: 4500 N

FP-Stairs

- Innovative design isolates the forces and moments produced on each step
- Attaches to two new or existing force plates

Multi-axis testing machines

AMTI provides the world's most advanced, most reliable, most accurate joint motion simulators. Each year more than 80 percent of the hip and knee implants produced are manufactured by companies that rely on AMTI simulators for the critical phases of implant evaluation.



Available machines:

12-station hip motion simulator

6-station knee motion simulator

Single-station multi-axis testing machine

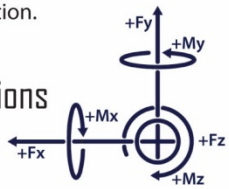
Multidirectional pin-on-disc machine

Key features:

ADL-capable: AMTI simulators are designed to replicate physiological conditions and come equipped with the full range of motion needed to simulate activities of daily living.

ACT: Adaptive Control Technology achieves new levels of tracking performance and ease of use.

VST: Virtual Soft Tissue control uses software to apply the influence of the knee's constraining tissues to the simulation.



The global leader in multi-axis force measurement and testing solutions

Engineering Acoustics, Inc.

406 Live Oaks Boulevard · Casselberry · Florida · 32707 Phone 407.645.5444 Fax 407.645.4910 sales@eaiinfo.com

Sensory Kinetics: Balance Training and Assessment System

Sensory Kinetics

Vibrotactile Guided Rehabilitation Training

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The Military Problem: mTBI Injury

- About 25 % of deployed soldiers are estimated to have been directly exposed to a blast/concussion injury, and many are reporting balance issues. The military has addressed operational protocols to minimized repeat concussion exposure, and is investing heavily in new, beneficial approaches to assessment and therapy.
- Quick and effective battlefield assessment and treatment is difficult. Misdiagnosis and delayed intervention present significant short and long-term risks to personnel and the mission. Long-term care and rehabilitation of military personnel exposed to IED's is a significant problem for the military hospital and VA system.

Civilian Balance Needs

- Motor and balance control dysfunction are associated with aging, stroke, TBI, neurological disorders and disease.
- One of every three adults over the age of 65 experiences a fall each year, which results in direct costs of over $20 billion annually and is responsible for 87% of the fractures in the aged population.

Current Treatment Approaches

- Assessment of mTBI/concusion injury and fall risk is difficult – measures are often "surrogates" and are not good predictors of falls.
- Current intervention strategies include combinations of medical, surgical, education and rehabilitation options.
- Rehabilitation is often remedial physiotherapy (PT) which is time consuming and patient specific, and standards of care are variable.
- In spite of considerable fall intervention programs, the rate of fall occurrence has not decreased.

Sensory Kinetics Approach

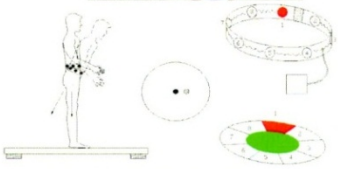
EAI has developed a **vibrotactile** guided rehabilitation training system **(Sensory Kinetics Balance System)** and protocol that can assist in the assessment and rehabilitation of subjects with balance deficits. The system provides real-time tactile cues that can be used to augment sensory information and improve posture control. The system follows existing PT workflow and is scalable and configurable, but can dramatically increase the efficacy of physical therapy compared to current best practices.

Theoretical Basis

- The sense of touch is intrinsically linked with the neuro-motor channel, both at the reflex and higher cognitive regions, which makes it uniquely tied to orientation and localization.
- We can integrate tactile information with conventional therapy without significantly impacting the cognitive bottleneck.
- Tactile cueing yields significantly faster and more accurate performance than comparable spatial auditory cues.
- Sensory integration is able to rapidly use additional tactile/proprioceptive information and there is evidence for transference of skills and retention (brain plasticity).

System Description

The **Sensory Kinetics Balance System** uses a lightweight, portable force platform to measure the center of pressure of subjects. Movement and posture data is recorded and processed using the Sensory Kinetics software, and mapped to a wearable vibrotactile belt array. *Vibrotactile cueing provides continuous and instantaneous feedback to the patient that compliments their postural and mobility decisions.* This vibrotactile feedback greatly improves spatial awareness and, consequently, mobility. Repetitive treatment while performing functional tasks achieves rehabilitation goals sooner than standard care, and the "technological intervention" has strong appeal to both patient and therapist. The system is scalable in terms of hardware and functional activities. There are many uses for the system: Postural awareness, ankle and hip postural positioning, movement planning, vestibular ocular exercises and correcting verticality.



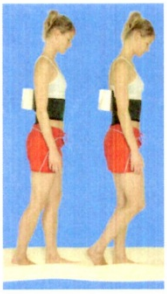
Engineering Acoustics, Inc (EAI) has over 15 years experience in vibrotactile system and application development in the biomedical, military and commercial fields. We are the leader in providing tactile hardware and systems, with multiple awarded and pending patents. We have active, military funded R&D programs in biomedical and tactical application of vibrotactile feedback .

Technical Contact:
Dr. Bruce J.P. Mortimer
EAI Director of Research and Development
email: bmort@eaiinfo com / Phone: 407 645-5444

SwayStar™ (CE approved)

For balance examinations, orthopaedic gait tests, and monitoring patient improvements. A clinical and research tool in one instrument.

SwayStar™ was developed to provide a simple, rapid and highly accurate tool for use in the examination of a patient's stance and gait capabilities, especially when these are compromised by balance or orthopaedic problems that occur with ageing, vestibular loss, neurological deficits, whiplash injuries or hip joint weakness.



The SwayStar™ unit is strapped around the waist at the level of the lumbar spine. Its sensors register angular deviations and angular velocities of the trunk in a highly sensitive manner. The level of precision (<0.01 deg/s) used is sufficient to register the earth's rotation. The Bluetooth™ link to the PC allows unlimited mobility during gait tests.

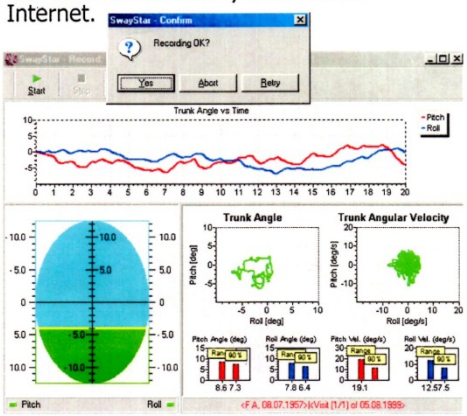
- Completely portable, quick and easy to use
- One exact instrument for stance & gait tests
- Normal reference values are included for almost all standard clinical tests
- Stance test analyses similar to those of computerized dynamic posturography
- Bluetooth (no cables) communication to PC
- User-defined tests can be configured in addition to pre-configured protocols
- Graphics can easily be transferred via "clipboard" to other programs
- Vibro-tactile & auditory rehab. protocols
- Analog signal sampling as add-on.

Posturography examinations, monitoring equipment, and research tool all in one system

The summary report generated at the end of the stance and gait tests, together with the individual test results, permits easy differentiation of a patient's balance and gait problems. Such reports provide a useful basis for follow-up examinations.

For stance and gait tests, the support surface can be firm (a normal floor) or flexible -- such as on foam. Recording trunk sway during the get-up-and-go test or walking up stairs or over barriers is also possible.

Features include standardized reference data over an age range of 6 – 80 years. The software is multilingual, and contains an export function allowing data interchange with other users. Latest software updates can be obtained at any time via the Internet.



References:
-Allum JHJ, Carpenter MG
A speedy solution for balance and gait analysis: angular velocity measured at the centre of mass.
Current Opinions in Neurology 18:15-21,2005
-Van de Warrenburg BPC, Bakker M, Kremer HPH, Bloem BR, Allum JHJ
Trunk sway in patients with spinocerebellar ataxia.
Movement Disorders 20:1006-1013,2005
-Majewski M, Bischoff H, Grüneberg C, Dick W, Allum JHJ
Improvements in balance after total hip replacement.
J Joint Bone Surgery 10:1337-1343,2005
-De Hoon EWJ, Carpenter MG, Salis C, Allum JHJ, Bloem BR and Bischoff H
Quantitative assessment of the "stops walking while talking test" in the elderly.
Arch Phys Med and Rehab 89:838-842, 2003
-Sjöström H, Allum JHJ, Carpenter MG, Adkin AL, Honegger F, Ettlin T
Trunk sway measures of postural stability during clinical balance tests: effects of a cervical whiplash injury.
Spine 28:1725-1734, 2003
-Allum JHJ, Adkin AL
Improvements in trunk sway observed for stance and gait tasks during recovery from an acute unilateral peripheral vestibular deficit.
Audiology and Neuro-Otology 8:286-302, 2003

Need more information?
Look at www.b2i.info
email to info@b2i.info
***

VertiGuard®

VestiCure

Balance Training

Diseases of the vestibular (balance) system, stance, gait and motor disorders cause vertigo with different subjective sensations. Balance training can help to reduce the sensations of dizziness by decreasing body sway and improving vestibular compensation. The efficiency of this type of balance training is based upon the additional vibrotactile (neurofeedback) stimulus which is applied during the exercises done by the patient. This is the working principle of the VertiGuard RT® system, a CE-certified medical device.

VertiGuard-RT® is a vibrotactile, neurofeedback system. It is a battery-driven, body-worn device (with a belt around the hip). It consists of a control unit, four vibrotactile stimulators arranged along the belt. The control unit records body sway of the upper trunk of the body during balance training and activates the stimulators at the direction of maximum body sway accordingly. The force of the vibratory stimulus is increased with body sway, but can be adjusted individually (by programming).

The control unit has a data store. This enables to store all recorded data, compare them with age- and gender-related normative data and use the 6 tasks of the analysis (SBDT) with the poorest performance for a later training. This is done automatically for each patient (tailored approach for individualized training). If someone does not exceed the normative range of body sway despite the fact that she/he complains of vertigo, no balance training program will be created by the system.

Individual exercises can additionally be selected during the training sessions by pushing program buttons on the display of the device. The sensitivity of the neurofeedback signal (threshold adjustment) can also be adapted to meet the actual patient's (physical and mental) needs at each day of the training. The selection of exercises is based on the results of the Standard Balance Deficit Test (SBDT, see VertiGuard®D). The system evaluates the individual vestibular deficits, selects the six most appropriate exercises for training and stores the required neurofeedback thresholds within the data storage section of the device. The neurofeedback thresholds are adjusted with controls at the display of the device so that the patient is able to correct its body position according to the vibrotactile impuls.

VertiGuard® RT

The exercises done at each day of training are stored and should be printed as protocol to monitor the training effects. The individual threshold adjustment can be documented at each day of training on the protocol. An increase in sensitivity is positively correlated to the therapeutic success.

The VertiGuard®RT system can be used for individual balance training in clinical departments, but also in the ambulatory care (medical doctors, physical therapists) as group and/or home training.

With VertiGuard®RT, the postural control shows significant improvements already in the first week of training. It is particularly obvious in elderly patients that they try to avoid the onset of vibration by subtle regulation of body sway. Based on the present study results, daily training sessions should go on for about 10 days, interrupted by one weekend (for physical regeneration). The training can be repeated after about 6 months if required. During a training session, the patient repeats the exercises 5x consecutively with the vibrotactile neurofeedback turned on. It is most likely that this kind of balance training initiates the formation of specific somatosensory memory traces in the brain which provides the long-term postural stability as found in the scientific studies.

It is recommended to repeat the balance tests (SBDT) after finalizing the balance training to monitor the therapeutic success by comparing the pre- and post-traing results. This protocol can be directly generated through the system's software.

BalanceSense, LLC

BalanceSense Pro

Sensory Enrichment Multimodal Device (SEMD)

- Multimodal Sensory Enrichment (vibrotactile, visual, auditory)
    - Tactile, visual, and sound cues are used to enrich balance control activities
    - Relearn postural control after injury or disease
    - Learn new postural control skills such as used in sports or industry
- Sway and Velocity Biofeedback for Human Postural Control
    - Center of Gravity (COG) data is collected from the force platform
    - Vibrotactile belt is worn around the torso to relay COG sway and rate of sway
    - Computer Screen shows pre set boundaries of test or rehabilitation activity
    - Auditory signals are used to pace activities
- Static Stance, Limits of Stability, Sit-to-Stand, Locomotion, Stepping, Pivot Turning
    - Small movement control of static sway when standing still
    - Postural control of sway when weight shifting
    - Transitional postural control movements necessary for activities of daily living both symmetrical and asymmetrical
- Physical Therapy and Rehabilitation
    - Clinical study found faster increase in balance test scores and decrease in fall occurrence over usual physical therapy intervention
    - Patients found multimodal activities helpful and engaging

    - Many patients were able to acquire skills with multimodal sensory enrichment that they were unable to obtain with usual physical therapy
    - Mild Traumatic Brain Injury (MTBI) and Vestibular/Balance rehabilitation responds to multimodal sensory enrichment. The most common complaint from MTBI blast and blast-plus is disequilibrium.
- Vestibular, Proprioception, Visual, Neural, Musculoskeletal, Cognitive, Spatial Learning
    - Suitable for all ages
    - Baseline and pre/post rehabilitation postural control testing with pass/fail scoring
    - Pre-programmed theory based rehabilitation protocols
    - Ability to save individual patient data and individualized rehabilitation programs

Appendix E.
Tests for vestibular evaluation at tertiary care centers.

Below is a list of tests the authors would recommend for consideration if more comprehensive vestibular evaluation is needed at a tertiary care center. This section is not intended to describe or reference each test. This abbreviated list is partly based on testing recommendations made to the Warrior Resiliency and Recovery Center (WRRC) at Fort Campbell, KY in June 2010. WRRC was considering performing a battery of assessments on a group of Soldiers pre- and post-deployment and wanted to know what vestibular assessments USAARL recommended. LTC Kristen Casto of USAARL responded to WRRC's question based on her experience as an audiologist and inputs received from her colleagues (e.g., Drs. Melinda Hill and Ben Lawson). The intent of her communication was to informally convey a range of testing options depending on time and equipment available.

A comprehensive evaluation in an ENT/audiology diagnostic center / hospital might take 2 to 3 hours, and include:

1. Auditory tests:
    a. Audiogram.
    b. Tympanogram.
    c. Acoustic reflexes.
2. Vestibular/balance tests:
    a. Calorics.
    b. Positionals (e.g., head thrust, Dix-Hallpike).
    c. Hallpike.
        i. Rotary chair tests (especially VOR, e.g., phase leads/lags).
        ii. Spontaneous nystagmus.
        iii. Gaze test.
        iv. Saccade test.
        v. Pursuit test.
        vi. Optokinetic test.
        vii. Sinusoidal harmonic acceleration (three frequencies).
        viii. Step test visual enhancement.
        ix. Visual suppression.
        x. Subjective Visual Vertical (SVV) Unilateral centrifugation.
    d. Equitest Sensory Organization Test (SOT).
    e. Dynamic Visual Activity Test (DVAT).
    f. Ocular Vestibular Evoked Myogenic Potentials (oVEMP).
    g. Subjective Visual Vertical (SVV).
    h. Gait testing (e.g., FGA, DGI).
    i. Various questionnaires (e.g., DHI).

Appendix F.
Further rationale for a test of the subjective visual vertical.

In this section, Dr. Rupert provides further rationale for testing of subjective visual vertical to reveal vestibular dysfunction:

The otolithic organs in the vestibular system sense gravity. Both the utricle and saccule contribute to the sense of verticality. After injury to the otoliths, or to the nerve that transmits impulses from the otoliths and other parts the ear to the brain, judgment of vertical may be altered. The inner ear may falsely suggest that the head is tilted while the eyes and somatosensory systems suggest that one is upright. Thus there is a sensory conflict. There can be an interaction between vision and the otoliths in that an otolith imbalance may transiently cause the eyes to counter-roll, which literally tilts one's vision.

Friedman, in 1970, studied subjective vertical in a variety of clinical situations. It is well known that normal subjects can adjust an illuminated rod in an otherwise completely dark room to vertical within a mean error of less than 2 degrees. Friedman concluded that severe derangement of this test is confined to brainstem lesions and the immediate postoperative period of peripheral vestibular lesions. The SVV tilts toward the side of lesion.

Persons with vestibular lesions may orient the bar tilted as much as 10 degrees (Garcia and Jauregui-Renaud, 2003; Vibert, Hausler et al. 1999). The SVV reverts to normal in labyrinthectomy by one year. In vestibular nerve section, a small deviation may persist after neurectomy even after 4 years (Vibert and Hausler, 2000). In patients with Menieres Disease, operated with labyrinthectomy, a marked deviation toward the operated side was found acutely, with resolution over weeks.

Patients with bilateral loss of vestibular function can also adjust the vertical on average, but show greater individual differences. Patients with cerebellar lesions generally showed good accuracy of the subjective vertical, suggesting that in patients with spontaneous nystagmus, the lack of a deviation of the subjective vertical substantiates a cerebellar lesion. Patients with brainstem lesions, however, frequently show extremely profound deviations, some as great as 8 degrees.

The test of subjective visual vertical and the ocular counter-rolling response has been advanced in recent years with the use of off-center rotation. While rotating at high rotations per minute (rpm) (greater than 70 rpm), it is possible to lateralize the effects of the utricle and saccule on eye movement by placing either the left or right vestibular organ directly over the center of rotations so that all ocular counter-roll movements are a result of the off-center vestibular apparatus. This off-center rotation technology is currently only available in highly specialized tertiary research centers.

Otolithic information from the utricle and saccule perform several biological functions including: (1) the perception of verticality and linear motion, (2) generation of eye movements

to compensate for linear acceleration of the head and (3) providing the coordination of movement and balance. By testing these functions it is possible to identify otolithic impairment. (1) Evaluation of the subjective visual vertical, as estimated by adjustment of the visual vertical, identifies otolith dysfunction either the peripheral or central level; (2) otolith signals generate ocular reflexes in response to linear head translation as well as counter-rolling eye movements in response to head tilt; and (3) computerized dynamic center of gravity measurements form the basis of several commercial devices to measure overall balance function. Currently two tests to measure evoked responses for the saccule and the utricle are being evaluated by the vestibular clinical community: the cVEMP measuring primarily saccular function and the oVEMP which is believed to measure primarily utricle function. A review of the literature shows that certain tests can indicate generalized loss of peripheral function while others demonstrate a lateralizing of peripheral function.

Deployed clinicians would like a simple, relatively inexpensive, easy-to-administer test that can identify otolithic dysfunction and that is sufficiently sensitive to provide an indication of clinical improvement or deterioration between testing. We will focus on the SVV used in conjunction with ocular counter-roll to provide a test to meet these criteria. The purpose of the SVV is to detect abnormal subjective tilt. In normal conditions and subjects, the ability depends on the visual, vestibular and somatosensory systems. It also depends on a functioning central nervous system (Yelnik, Lebreton et al. 2002).

Dr. Rupert and colleagues are developing a pair of light-occluding goggles that can present to each eye a stimulus of a faint line against a black background. This device will allow for portable, automated field testing of SVV without the need for a light-proof room, a rotating device, or extensive training to administer and score the test. The patient will be asked to rotate the line with a rotary control until it appears to be vertical. The line will be reset to a random non-vertical position and the test will be repeated up to six times. The extent of counter-roll of the non-stimulated eye will be monitored as a covariate with a camera incorporated into the second eyepiece. The new SVV tests will subsequently be validated against the existing standard, which is off-center rotation (a unilateral otolith stimulus). The protocol for this research has been submitted for approval.

Appendix G.
USAARL's military-relevant balance skills task.

This section contains a brief description of a combined shooting/balance test being developed and evaluate by PI Catherine Webb and her colleagues at USAARL (Lawson, Kelley, Athy, and Cho), and at the William Beaumont Medical Center (Livingston). This test could be carried out at any training command which uses the Engagement Skills Trainer (EST) weapons simulator, or could be set up for testing and training rehabilitation at a tertiary care center. This section describes the rational for the approved research experiment, which began data collection in April 2011:

Weapons utilization is a global task required of all Soldiers, regardless of their military occupational specialty (MOS). Not much is known about the effects of MTBI on marksmanship abilities, although it is believed that MTBI will lead to poor marksmanship (Cordts, Brosch, & Holcomb, 2008). The present study seeks to better understand the effects of MTBI on marksmanship abilities, including accuracy, reaction time, shot radius (of distance of the shot from center of mass [CM] of the target), and root mean square (RMS) distance from target CM as a measure of aiming drift.

In addition, the present study will develop a novel dynamic marksmanship battery, based on dynamic vestibular assessments like the Berg Balance Scale (BBS), Dynamic Gait Index (DGI), and Functional Gait Assessment (FGA), which may be more sensitive to the effects of MTBI than the standard static marksmanship qualification. Current weapons qualification tasks are relatively static, in that Soldiers fire from one of three shooting positions at a time and are not changing positions or deciding upon which target to engage. Dynamic shooting tasks, such as shooting after picking up a weapon or shooting while walking, and friend/foe identification scenarios are more representative of weapons utilization in combat situations. Such tasks also are more likely to detect balance deficit after MTBI. The development of a dynamic marksmanship battery that is sensitive to the effects of MTBI will provide more useful information for RTD determinations.

Anecdotal reports from occupational therapists and PTs indicate that Soldiers recovering from MTBI are experiencing physical and cognitive difficulties with weapons utilization. Occupational therapists at the Center for the Intrepid at Brooke Army Medical Center have observed that Soldiers who have sustained MTBI have significant difficulties with weapon usage. These difficulties include balance impairment, fine motor movement (i.e., adjusting rear site and loading a new magazine), and cognitive endurance (i.e., mentally fatigue easily, unable to concentrate/focus on single and multiple targets, differentiate targets; Personal communication with Jim Ferneyhouth, OT, and MAJ Jay Clasing, OT, 24 February, 2009). In addition, these Soldiers also display physical impairments, inasmuch as they have difficulty firing in the three primary positions (i.e., kneeling, prone, and standing), as well as steadying a weapon and taking aim at a given target (Personal communication with Navy LT John Fraser, PT, 1 March 2009). A review of the available literature has failed to find research documenting the effect of MTBI on marksmanship abilities.

Previous research has shown that psychomotor factors impact marksmanship abilities. Expert shooters have been found to hold a rifle steadier than novice shooters (Mononen, Konttinen, Viitasalo, & Era, 2007) as well as produce smaller body sway amplitudes compared to novice shooters (Era, Konttinen, Mehto, Saarela, & Lyytinen, 1996). A common limitation among these studies is the use of relatively static shooting positions. While the measurements used required the use of stationary positions (i.e., force plates), static shooting positions are not representative of the shooting positions used in combat situations. More research is needed examining marksmanship in dynamic environments.

The dynamic battery is based on the EST 2000. The EST 2000 is a United States Army small arms training device. This device is used in the United States Army Infantry Schools Basic Rifle Marksmanship (BRM) strategy and allows for weapons training in a controlled (simulated) environment. The tasks selected for the dynamic marksmanship battery are shown below. They were chosen based on the types of balance challenges imposed by established clinical vestibular assessments, including the DGI and FGA (Herdman, 2007). Most established vestibular and gait assessments involve rapid head movements, challenges to gaze stability, timed locomotion, and/or a reduction of useful non-vestibular cues (e.g., visual, somatosensory). We are introdcuing such challenges by asking the participant to perform shooting tasks during or immediately after head movement, with reduced visual cues (e.g., darkened glasses, darkened screen), while stepping over small obstacles (e.g., shoe boxes), and/or while standing on a compliant surface (e.g., a foam mat) to reduce ankle kinesthesia. Five shooting tasks are used (see below), with pilot tests determining the best procedures used to challenge balance within each task. Participants perform the shooting task using a rifle. The order of the tasks in the dynamic battery will be counterbalanced to reduce order effects. The task categories and possible procedural variants are shown below. Participants perform the shooting tasks using a rifle.

Dynamic marksmanship battery.

Task	Description
1. Turn to Shoot	Face 180° away from target, execute yaw turn to engage.
2. Kneel & Shoot	Kneeling with a narrowed stance plus engaging multiple targets left and right.
3. Pick up Rifle & Shoot	Pick up weapon from floor, aim and shoot. Weapon down and repeat.
4. Walk, Swivel, & Shoot	Walk parallel to target, 90° yaw right/left yaw swivel to engage targets on every other step, fire at target whenever facing screen on left.
5. Traverse Beam & Shoot	Walk on straight/constrained path parallel to screen, fire to left side -- as many accurate shots as possible while moving

Appendix H.

Supplemental information from first expert meeting (Rockville, MD) regarding certain tests or approaches being developed by meeting participants (sent to the authors following the meeting)

Brief excerpt from a paper in progress sent by Dr. Rose Marie Rine, regarding a test she is developing:

> Based on a comprehensive review of available tests and the literature, the Toolbox vestibular team decided to include one test that isolates the vestibular system's contribution to gaze stability (VOR) and one that isolates the vestibular system's contribution to postural control (VSP). Tests were excluded due to: 1) reliance on self report of symptoms, 2) high cost, 3) requirement of expertise, and/or 4) lack of sensitivity, validity, or reliability.
>
> The team selected two tests: the Dynamic Visual Acuity (DVA) test and a modification of the Clinical Test of Sensory Interaction for Balance 19. Furthermore, it was agreed that the DVA and vestibular balance measures would be used as part of Vision testing (acuity) and the Motor Domain balance measure, respectively. While these measures have a well-established history of use clinically and for research, the clinical versions require expertise and have limited sensitivity and specificity. Computerized versions are expensive. Thus, new versions of these tests were developed, modified and validated for inclusion in the Toolbox.
>
> Dynamic Visual Acuity Test. A low-cost, computerized test that minimizes motor, language and cultural effects was developed. During the validation phase, the age at which letters versus symbols is most effective, valid, and reliable for testing acuity was determined, as was the protocol that would yield reliable and valid data for identification of vestibular hypofunction (VH). The test requires that an individual identify an optotype (letter or symbol) presented one at a time in progressively smaller sizes, at eye height, first with the head kept stationary (static visual acuity test) and again with the head moving to the left or right. The preliminary data supports that this test is low cost, easy to administer, and yields valid and reliable results for testing static and dynamic visual acuity.
>
> Balance Accelerometer Measure (BAM). A low-cost tool that quantifies postural sway using an accelerometer was developed by investigators at the University of Pittsburgh (Redfern, Whitney, and Musolino). Subjects were asked to stand still for 90 seconds, in double limb feet together stance (DS) or tandem stance (TS) under six conditions: 1) eyes open solid floor DS, 2) eyes closed solid floor DS, 3) eyes open dense foam DS, 4) eyes closed dense foam DS, 5) TS eyes open, and 6) TS eyes closed. Sway was measured by an accelerometer placed anteriorly, attached to a gait belt. Preliminary data imply that BAM provides a reliable and valid measure

of balance and the identification of vestibular impairment for individuals three through 85 years of age.

Brief excerpt from a proposal by Dr. Wall which describes a saccadic velocity field test he is developing:

> The long-term goal of this pilot proposal is to improve the diagnosis of "mild" TBI in our soldiers and veterans. The feasibility of our approach to this goal will be achieved by: 1) developing a novel and portable eye movement recording system; 2) testing the validity of this new system by comparing its sensitivity and reliability against traditional, laboratory-based (i.e. non-portable) tests in normal subjects; and if successful, 3) performing a feasibility test with the new eye movement system in 10 veterans with TBI.
>
> Traditionally, eye movement recordings are made in dedicated laboratories that have specialized professionals and equipment to obtain and interpret the recordings. The VA has a rich history in this type of translational science at the Daroff-Dell'Osso Ocular Motility Laboratory at the Louis Stokes Cleveland VA Medical Center. A laboratory of this type receives patients with a wide variety of eye movement and balance problems who are then studied with the specialized equipment housed within the laboratory setting. The novelty of the current proposal is the creation of an easy-to-administer and portable method to capture eye movement recordings without specialized laboratory equipment. The opportunity to employ this type of test relates to the availability of sophisticated and lightweight monitors that can be used to administer certain tests without having to use traditional equipment that either is not portable or would require placement of wires or contact lenses on the eyes of a patient to obtain recordings.
>
> This proposal seeks to customize some traditional laboratory test methods to create the new portable testing method. Following validation studies, the new test paradigm will be given to patients who have received a clinical diagnosis of TBI. The intent is to determine the degree to which the eye movement test results correlate with the severity of TBI. If an acceptable level of concordance is established by our clinical study proposed herein, our long range intent, which is beyond the time period of this proposal, would be to administer our eye movement tests to soldiers pre- and post-deployment. For soldiers who experience TBI, the eye movement recordings should, in the majority of cases, provide an objective parameter to corroborate the clinical diagnosis of TBI.

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