The Instrumented Multitask Assessment System (IMAS)

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Abstract— This work introduces a closed loop virtual reality platform for rehabilitating members of the armed forces after concussion or lower extremity musculoskeletal injury. Subjects perform a virtual variable-speed foot patrol designed to bring the subject's heartrate up to an operator-designated value. Relevant biometric measurements are timestamped and recorded for post-hoc analysis, including heart (ECG), brain (EEG), and movement kinematics of the hands, feet, hips, and head. The long-term goal is to use these data to guide return-to-duty decision making and to support efficient rehabilitation protocols. The platform is physically compact for ease of deployment and has been designed in a modular fashion to allow easy integration of new sensors in future designs.

I. Introduction

It has been estimated that between 5% and 35% of the 1.6 million US troops deployed in Operations Enduring Freedom and Iraqi Freedom (OEF/OIF) since October 2001 have sustained concussions (about 28,000 annually) [1]. Both moderate traumatic brain injury (TBI) and mild TBI are associated with a myriad of physical and psychological symptoms, many of which can interfere with service members' (SMs) occupational duties [2] and quality of life [3]. Repeated concussions can result in the progressive degenerative condition termed chronic traumatic encephalopathy (CTE), which is characterized by dementia-like symptoms.

Within the military, there is a critical need for ecologically valid measures of recovery of function in TBI injured service members [4]. For example, for patients with non-critical symptoms that persist beyond seven days post-injury, the standard of DoD care is not to re-evaluate the patient until the 90-day mark [5]. The long delay is necessitated because of the lack of proper testing paradigms that are sufficiently specific and sensitive to military-specific performance criteria. Common concussion tests such as ImPACT and ANAM are specifically contraindicated beyond the initial 30 days post-injury because there is insufficient evidence they that they correlate to simple self-reported measures such as the Neurobehavioral Symptom Inventory (NSI) and Patient Global Impression of Change (PGIC) [5].

This inability to properly evaluate recovering service members represents a significant lost opportunity: personnel who are ready to be re-deployed may be kept out of service longer than is necessary, or conversely, injured personnel may be reactivated before they are ready. A lack of validated metrics also makes it difficult to determine the efficacy of various physical and cognitive therapies in SMs. Traditional measures of balance, gait, working memory, and executive function that are applicable in civilian environments are inadequate predictors of the multimodal stressors associated with being a deployed service member [2].

In response, multitask testing paradigms have emerged as a staple of Return-To-Duty (RTD) testing for military personnel rehabilitating from traumatic brain injury. Multitask paradigms typically include one or more tasks that entail decision-making (correctness of choice), memory (correct recall), response to visual/auditory (correctness of target identification), and/or one or more movement tasks (speed and accuracy of movement). Although valuable, these testing paradigms can be difficult to routinely administer outside of a dedicated research setting. Scherer [2] posited that robust RTD assessments can be performed either in immersive virtual reality settings such as CAREN [6] or realistic real-life combat drills. Neither of these are cost or space-efficient, and therefore not appropriate for routine use in forward or garrison-based military settings.

The purpose of this work is to develop and test a system that quantifies TBI-related impairments in service members and supports return-to-duty decision making. The Instrumented Multitask Assessment System (IMAS) leverages recent technological breakthroughs in virtual reality, wireless instrumentation, and physical therapy to create a system that is compact and ecologically valid, can be operated without a clinician on hand, and can be easily deployed in myriad military settings. The IMAS will be pre-programmed to administer a novel test of occupational readiness that requires physical and cognitive multitasking. However, it will also be extensible enough to easily incorporate new sensors, and flexible enough to allow for other tests developed by third parties.

The IMAS implements a compact virtual reality system that combines wireless body tracking sensors with a multidirectional treadmill and a head-mounted display that exploits real-time eye tracking. This platform can be used to implement any number of ecologically valid physical therapy tests that are more rigorous than existing field measures of TBI impairment and recovery. Whereas earlier applications of VR for ecological TBI assessment have required costly room-scale installations or have been limited in scope, the proposed system occupies a mere 2m x 2m footprint and can be operated without expert knowledge of engineering or physical therapy.

This study presents a system that can be used to assess service members' suitability for return to service after a traumatic head

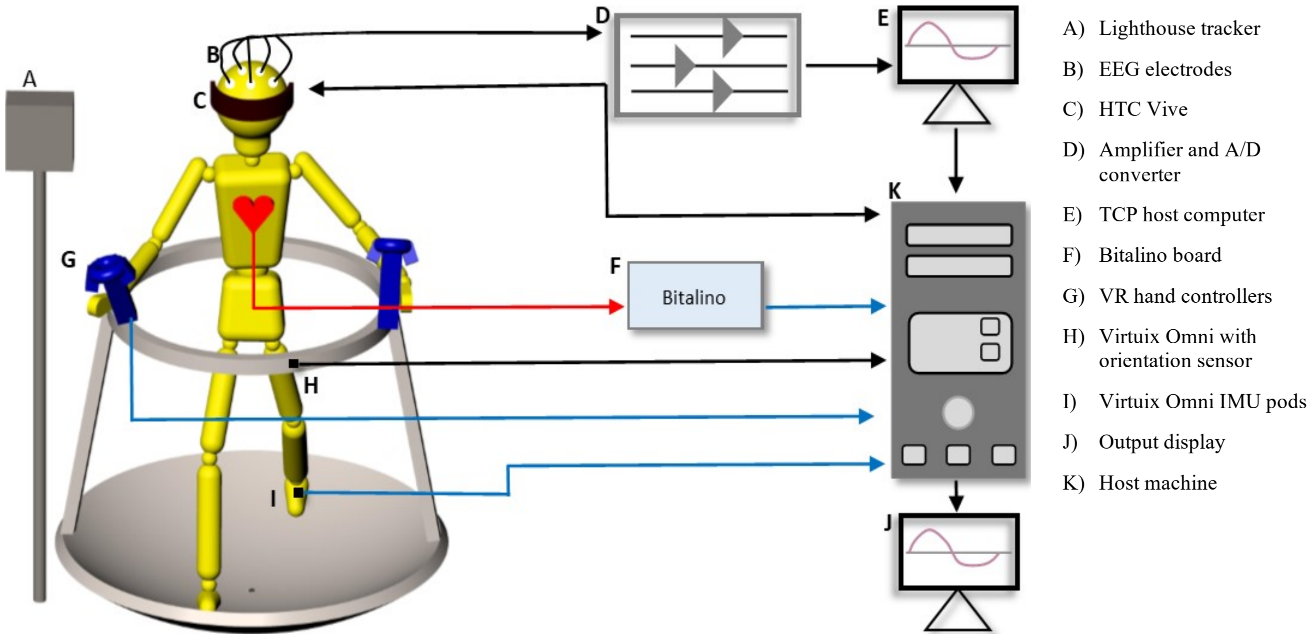

Figure 1: Top-level block diagram of the IMAS system. The user ambulates in a 360 degree treadmill while participating in a virtual foot patrol. Movement kinematics and biomedical signals are recorded for post-hoc analysis.

injury and/or lower extremity injury. The current system in place for testing these injuries can lack accuracy due to human error, require a trained clinician to administer the test and can require costly room-scale installations. IMAS would replace the current system and would allow for a more accurate and quantitative diagnosis, while being more cost and spatially efficient. By using medical grade sensors, the system removes the need for a trained onsite clinician.

Recovery from concussions are made in numerous of ways. Concussion assessments range from a battery of psycho-analytic tests to physical examinations (balance/BESS) to full neuropsychological workups. Recently, emerging sensor and computational technology has been leveraged to create systems that can more accurately measure deficiencies in balance, reaction time, mobility, and memory. Systems such as Automated Assessment of Postural Stability (AAPS) have been developed to quantify balance and mobility of a subject specifically in a military context. Using various sensor technologies, several versions of AAPS were implemented, each designed for diagnosing stability issues and brain injuries in a military setting.

This work describes the creation of a new platform that integrates virtual reality with a suite of biomedical and biomechanical sensors and a closed loop feedback system that allows the operator to control difficulty and stress levels in the simulation. The platform is hardware-extensible and easily re-programmable in order to accommodate any number of pre-existing or novel tests of field performance.

II. Methods

The purpose of the IMAS system is to present a realistic and challenging patrol environment to a service member while making a complete recording of all relevant biomedical and kinematic variables. These data can then be used to quantify injury recovery and to assess suitability for returning to duty. A top-level block diagram is shown in Figure 1. Briefly, the subject stands in an omnidirectional treadmill while wearing an immersive virtual reality headset that simulates a patrol environment. Although the VR environment is programmable, a typical application will require the subject to follow a variable-speed foot patrol leader while responding to environmental stressors and distractors. The speed of the patrol leader is determined through closed loop feedback in order to achieve a target heart rate in the user. Biomedical recordings including brain (EEG), heart (ECG), and movement kinematics are synchronized and stored for post-hoc analysis. The system is managed by a central host computer that generates the virtual reality and collects and synchronizes data from the various peripherals. The system is extensible through a standardized interface that can easily accommodate new peripherals.

A. Host Machine

The host computer creates the real-time virtual reality environment while also synchronizing and logging data from the biomedical peripherals. The host runs the SteamVR (Valve Corp., Bellevue, WA) application, which renders and runs the virtual reality patrol environment created in the Unity development environment (Unity, San Francisco, CA). Peripheral data streams are collected via Bluetooth (IMU trackers, hand controllers, ECG), serial USB (headset, treadmill) and TCP (EEG data). Owing to the graphically intensive nature of the system, the host machine is an Alienware Aurora R7(J) with a GeForce GTX 1080 GPU, 16 GB of RAM and an Intel i7 8700k 6-core CPU.

B. VR Tracking and Head Position Collection

The Vive headset (HTC, New Taiwan, Taiwan) is used to render a custom-designed virtual reality environment for the user. The host computer running SteamVR generates a pair of stereoscopic images which are then displayed in the headset

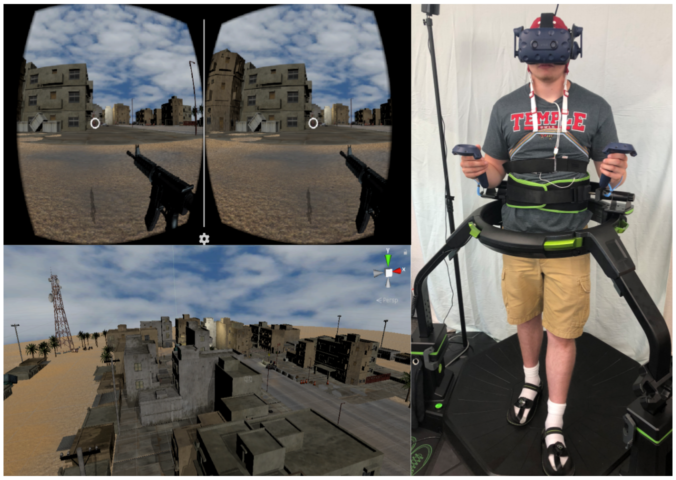

Figure 2: Example of the VR Environment from IMAS as a user walks through the environment to follow the patrol unit. User is harnessed into the Virtuix Omni with the HTC Headset and is now able to freely move in any direction.

(Figure 2). The headset's orientation in three-dimensional space is determined by an embedded inertial monitoring unit (IMU). The IMU's orientation is determined with respect to two infrared emitters (lighthouses, Figure 1A) that are part of the Vive system. Head orientation is not only used to inform the real-time virtual reality display but is also logged on the host computer as part of the recorded kinematics. Similar IMU sensors in the two handsets are used to determine hand position in real-time for the VR environment and are also logged.

C. Motion Collection

The Virtuix Omni (Figure 1H) is an omnidirectional VR treadmill used to create an immersive and realistic experience in which the user may move freely around the environment and follow the patrol leader. The Omni tracks the user's motion in real time with two inertial measurement units (IMU) (Figure 3-left) strapped to the user's feet (see Figure 1I). The user's orientation is determined with a harness sensor around the waist. These measurements are processed by the application and then used to move and position the user in the VR environment; they are also recorded for later post-hoc analysis. The data is sent serially to the host machine at the start of every frame to allow for smooth and natural movement.

D. Electrocardiogram Collection

Electrocardiogram (ECG) data is collected in real time throughout the run time of the application. A Bitalino data acquisition board (Figure 3-right, and Figure 1F, Plux Wireless Biosignals, Arruda dos Vinhos, Portugal), with a 3-lead ECG extension collects a single lead heart signal from the user as they move and patrol through the environment. The data is streamed via Bluetooth to the host computer and read at each frame with a corresponding time stamp from the application. The Bitalino board allows for accurate data collection even in the presence of additional artifacts such as muscle noise. As the data is streamed, the heart rate of the user is computed in beats per minute. The calculated heart rate acts as a feedback control system to adjust the speed and difficulty of the patrol in order to achieve an operator-programmable target heartrate.

E. Electroencephalogram Collection

IMAS collects electroencephalogram (EEG) data in real time so the user's brain activity may be analyzed. Using a 20-channel EEG recorder (Grass Model 2, NeuroNatus, Middleton, WI; Figure 1D), the operator sets each channel to a reference configuration of their choosing. Electrodes connected to the user (Figure 1B) are linked to the EEG machine where standard EEG signal conditioning is applied. Using a National Instruments (Austin, TX) analog-to-digital converter (PCI 6224) these signals are converted and processed by a secondary machine (Figure 1E) which acts as a TCP Listener. The host computer (the TCP Client) sends time stamps to the secondary computer application on each frame, which toggles a sample reading from all 20 channels. To minimize effects of network traffic, these readings are saved locally on the secondary machine and then transferred serially back to the host machine after the application is complete.

F. Time Synchronization

The system allows for multiple generic sensors to be integrated seamlessly into the environment. To keep the sensors as generic as possible, standard serial data transfers are utilized. However, with multiple sensors, each with independent clock speeds and sampling frequencies, the sensors must be synchronized with a common clock. The host machine records the data from each of the serial ports at the beginning of each new frame in the VR environment. While sensor data may be generated or transmitted faster than once a frame, only one sample per sensor is kept at the start of each new clock edge. This effectively down samples each sensor while synchronizing the data to the run time of the environment. While it is technically possible that some data may be lost in this manner, the effective sampling rate for most biomedical signals of interest such as movement, heart, muscle artifact, etc., will obey the Nyquist Theorem since the system frame rate is nominally 90 frames/sec. Information generated by the body is generally less than 45 Hz, thus the down-sampling rate of 90 Hz will be enough to accurately acquire this information. Even with the effects of time synchronizing, all necessary data is recorded.

III. Results

The result of each trial is a plaintext data file in CSV format containing all aggregated data. Each line shows the time at which the reading occurred, and the time elapsed from the

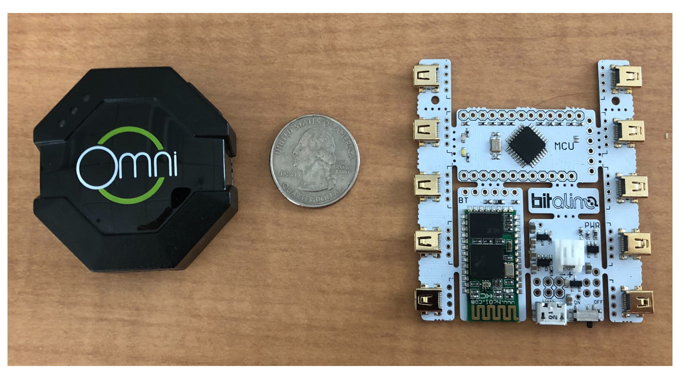

Figure 3: The Omni IMU Pod clips to the front of the shoe to allow for natural movement and gait [left]. Bitalino board is attached to a belt around the user and does not prohibit movement [right]

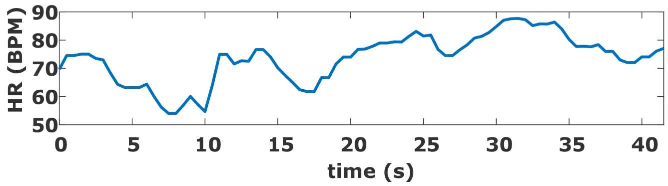

Figure 4: Heart rate vs. time

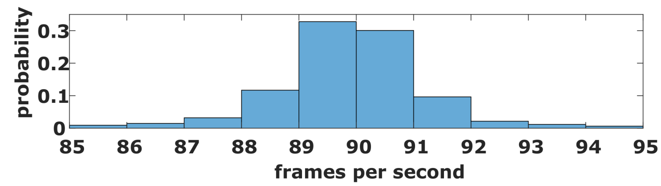

Figure 5: Histogram of system throughput.

previous reading (for calculating sampling period variability). All sensor readings, calculations and event descriptions are paired with their respective time stamps.

The system was tested with a single healthy subject walking on the treadmill while immersed in the virtual reality environment. Heart and motion data were all captured during the trial, thereby placing a significant burden on data acquisition system.

Figure 4 shows the heart rate measured by the system during a single trial. The raw recorded data were single-lead ECG measurements which were then converted post hoc into heart rate using a 2.5 second moving average. The range of beats per minute values is consistent with a healthy subject and the heart rate can be seen increasing after the subject has been walking steadily for ~17 seconds.

Figure 6 shows sample kinematic data from the IMAS system from a single trial of a healthy subject. The linear accelerations of the left (blue) and right (orange) feet are clearly seen to alternate in a manner consistent with smooth walking gait. The black trace shows the angular direction of the body as measured with the waist-mounted sensor. The small fluctuations are consistent with normal body sway during walking. The large shift starting around t=8 seconds shows the subject making a 90-degree right turn in order to continue following the patrol leader.

Figure 5 shows a histogram of the resulting system-wide frame rate from a single trial. Theoretically, the frame rate was expected to be 90 frames per second, although the empirically observed value was expected to fluctuate depending on the real-time computational burden on the VR rendering host computer (see Figure 1K). The observed frame rate (n=3978 frames) was 90.3±5.3 frames/sec.

IV. Discussion

The overall system allows for biomedical signal data to be recorded synchronously in real time from an arbitrary number of sensors. The goal is for the data to be used by clinicians or other experts as a tool to assess an individual's suitability for returning to duty after injuries such as concussion or musculoskeletal trauma. The system can also be used as a rehabilitation tool with quantifiable metrics that accurately document changes in performance over time. Further evaluations and data collections are necessary to ensure the overall system quality. However, based on the current status of the IMAS and the data that has been collected, the results demonstrate feasibility. Future work will seek to implement such functionality in concert with our partners in the US Armed Services.

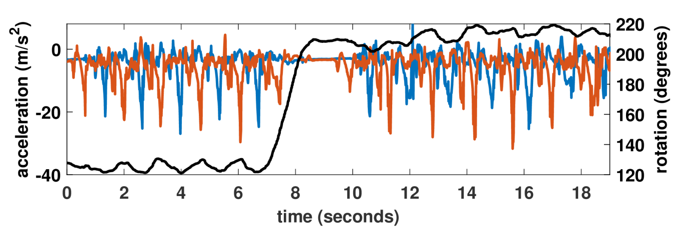

Figure 6: Linear acceleration for left (blue) and right (orange) feet. Body rotation (measured at the waist) is shown in black.

Future versions of the system will benefit from enhancements to the data acquisition format. The current system was designed to accommodate most generic serial communication sensors. However, not all sensors may be compliant with the generic communication protocol in place. Some sensors may require additional configuration, set up, or initialization triggers, which the software suite currently does not support. We will continue to evaluate these on an as-needed basis.

The non-constant sampling rate, while not ideal, has been demonstrated to be reasonably stable under significant data acquisition conditions. This has only been possible owing to the high-performance, graphics-intensive host computer that was custom specified to work with the Vive VR system. Host computers with different specifications should be expected to perform differently and should be evaluated individually. The existing system is optimized to remain as stable as possible to reduce fluctuation.

While the system provides large potential benefits to medical professionals for diagnosing patients within a controlled environment, there is further room for expansion, improvement, and evaluation. The generic sensor interface may be further developed for more sensor accommodations. The software suite currently offers one environment with limited testing options. Ideally, additional environments with more test options would be designed to give the subject multiple evaluation options.

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