Biomechanic analysis using wearable sensors during an immersive foot patrol task in a virtual environment performed on a circular treadmill

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This work extends our earlier research into novel tools for training and rehabilitating servicemembers (SM). We are specifically focused on developing a multitask assessment platform that quantifies SM ability to make decisions or remember information under physical duress. Our base system is an extensible platform built around a 360-degree dish treadmill. Virtual reality (VR) is used to present realistic field conditions to the user, who must engage in tasks such as following a fast-paced foot patrol while deciding which potential targets to engage. Multi-modal sensors are used to quantify biometric data ranging from heart rate to brain activity, to foot, trunk, hand, and head motion. The platform is extensible, allowing new sensors to be interfaced.

Aim: Here, we seek to evaluate new tools with the goal of expanding the system beyond the 360-degree treadmill. Although the dish treadmill has a small footprint and can be deployed in as little space as 2m x 2m, it places physical restrictions on the user. For example, the user may be forced to adopt a modified stride motion to accommodate the dish treadmill, lateral movement may be hard to implement, and non-ambulatory validated movement assessments, such as the Run-Roll-Aim (Scherer *et al.*, 2013), are difficult to implement.

In this work, we 1) evaluate the use of a new wireless sensor for measuring gait and movement; and 2) describe impact force symmetry in the device. The sensor is validated against our existing VR movement sensors, and then evaluated for additional, novel functionality. If successful, this will allow for the implementation of VR-based multi-tasks tests that are not confined to the dish treadmill, but that can also be deployed in a room-scale VR environment where the user can move freely in three dimensions. Specifically, we investigate use of the "IMU Sensor" device (IMeasureU, New Zealand). IMUs can be attached to one or both ankles and record up to +/- 200G of force in linear and rotational dimensions at up to 1600 frames per second. Raw data can be exported for post-processing or can be analyzed in the cloud using web-based tools.

Methods: Nine subjects healthy subjects (5 female, ages 20-45) were placed in the 360-degree treadmill and donned the virtual reality gear. The VR system was configured to measure foot acceleration (linear and rotational) and trunk orientation. IMeasureU sensors were also placed on both ankles. Subjects were asked to follow a virtual foot patrol at a medium-fast pace for 180s. Since the goal of this task was solely to assess gait and movement kinematics, no cognitive tests were incorporated. All subjects successfully completed the task, and the work was performed with Institutional Review Board oversight.

Results: Offline analysis was performed to compare foot acceleration as measured using the VR sensors with the IMeasureU sensors. Signals were manually aligned and downsampled to a common sampling frequency (80Hz). Linear accelerations were compared using Pearson's R as a measure of similarity. Of the three linear dimensions (front-back , side-side, up-down), the best agreement between the two sensors was front-back, for both feet. R-values were 0.516 and 0.506 for left and right feet, respectively. The side-side and up-down were not found to be strongly correlated ($r < 0.1$).

We also used the IMeasureU sensors to evaluate step forces including asymmetries between left and right feet. The average difference in intensity between feet was 0.54G, corresponding to a difference of 5.8% (range 1.6 – 10.8% difference in force between feet). Since subjects were all healthy with no recent history of lower extremity injury, this range of asymmetry is normal and typical of what is found in more conventional ambulation tasks on regular treadmills or overground.

Discussion: This work introduces the use of the IMeasureU sensor for recording ambulatory kinematics and kinetics. Used in the context of our VR-based multitask assessment system, it will allow flexibility in using our VR tasks in both the restrictive dish treadmill and expanded room-scale implementation of existing and novel tests of movement and cognition. Such tests have already been demonstrated by others to be valuable both for training as well as for tracking and directing injury recovery in SMs (Gottshall *et al.*, 2012; Scherer *et al.*, 2017; Fain *et al.*, 2019). Our goal is to create tests that are simultaneously more immersive and that yield more actionable data to drive optimization of recovery and training for SMs.

Although the IMeasureU sensor was observed to be adequately accurate and sensitive, its correlation to foot accelerations as measured by the VR sensors was only strong in one dimension (front-back). There are at least two inter-related reasons for this observation. Most critically, the sensor locations are not identical. Whereas the VR sensors are placed on the top of the foot, the IMeasureU sensor is designed to be worn on the leg, just at the ankle. Because of this difference in location and the considerable rotational movement of the ankle during walking and running, the sensors can be expected to produce different measurements. The second (related) reason is that the differences in the signals complicated the time-alignment process which consequently degrades the degree of correlation. This is especially true in the side-side dimension in which there is little movement to start with.

Measures of step impact load, including asymmetries, have the potential to be especially helpful in quantifying injury recovery and performing return-to-duty assessments. Our measurements suggest a range of normative values in the context of VR tasks on the dish treadmill. Given that the ambulatory task is different in the dish treadmill, the symmetry of foot forces in adults without injury suggests that user can accommodate their bipedal gait to the dish treadmill. Future work will seek to perform a more complete sensor integration and a comparison of step loads and speeds, especially as a function of fatigue, pain, and injury recovery.

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