Application of Wearable Inertial Sensors in Ecological Rehabilitation Environments

Gina Sprint
Washington State University
Box 642752
Pullman, WA 99164-2752 USA
gsprint@eecs.wsu.edu

Vladimir Borisov
Washington State University
Box 642752
Pullman, WA 99164-2752 USA
vladimir.borisov@email.wsu.edu

Diane Cook
Washington State University
Box 642752
Pullman, WA 99164-2752 USA
cook@eecs.wsu.edu

Douglas Weeks
St. Luke's Rehabilitation Institute
Spokane, WA 99202 USA
weeksdl@inhs.org

Abstract

Rehabilitation after injury or stroke is a long process towards regaining functionality, mobility, and independence. Changes exhibited in these areas tend to be subtle and are highly dependent on the patient and their injury. To provide a fine-grained assessment of patient progress, we undertook a study to quantitatively capture movements during inpatient rehabilitation. We utilized wearable inertial sensors to collect data from participants receiving physical therapy at an inpatient rehabilitation facility. Participant performance was recorded in an ecological environment on a sequence of ambulatory tasks. A custom software system was developed to process sensor signals and compute metrics describing ambulation. A comparison of metrics one week apart suggests quantifiable changes in movement.

Author Keywords

Wearable Sensors; Inertial Measurement Unit; Accelerometer; Rehabilitation; Gait Analysis

ACM Classification Keywords

J.3 [Life and Medical Sciences]: Health; I.5.4 [Applications]: Signal processing.

Introduction

Rehabilitation after injury or stroke is characterized by a long process towards functional, mobile, and independent recovery. Changes exhibited in these areas tend to be subtle and are not necessarily improvements. The recovery process is characterized by non-linear trends as general progress is made. Rehabilitation is driven primarily by the therapists' subjective assessments of the patients' state. Therapists use their expertise to adapt and implement the most appropriate regimen to address the patients' needs. At this point, technology can step in to provide therapists with objective, quantitative measures to detect additional changes that are not easy to observe. These additional measurements can identify the subtle changes during rehabilitation, providing finer-grained information about an individual's progress.

IMUs have been utilized quite extensively in the health care community and various other application domains. This is due to their low cost, portability, and success rate. IMUs are ideal candidates for tracking changes in movement because they can be attached to any position on the body. Several studies have used IMUs for analyzing gait and movement as an unobtrusive substitute to other technologies. Common clinical assessments such as the timed up and go (TUG) test and the clinical test of sensor integration of balance (CTSIB) have been instrumented with IMUs [1, 2]. These studies have proven additional information provided by IMUs to be useful in a clinical setting.

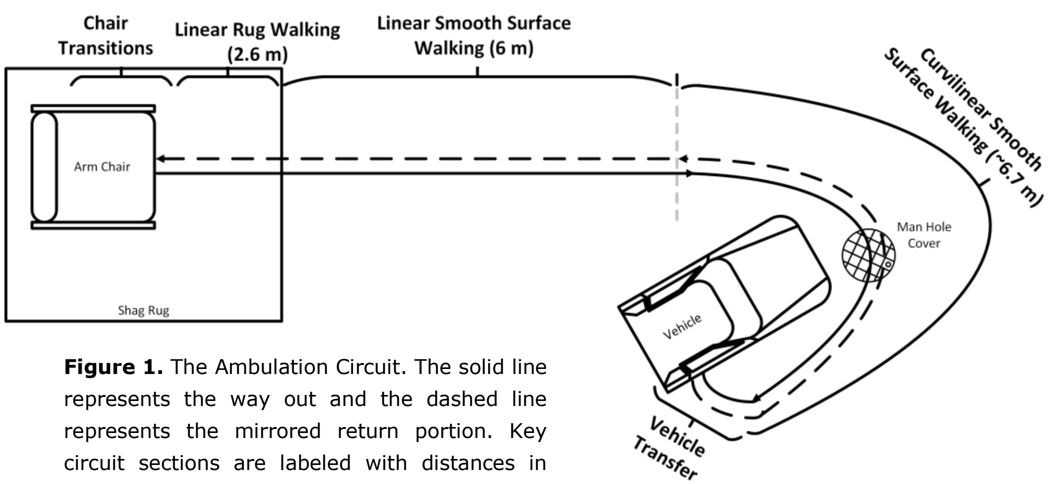

Figure 1. The Ambulation Circuit. The solid line represents the way out and the dashed line represents the mirrored return portion. Key circuit sections are labeled with distances in meters.

Wearable IMU protocols in clinical settings provide valuable information, but may not readily transfer to post-discharge environments. To better understand movement in an ecologically valid setting, an Ambulation Circuit (AC) was developed; utilizing an in-house simulated community at St. Luke's Rehabilitation Institute. By using the community and wearable IMUs, we collected movement profiles of patients in a natural setting. This ecological context has been proven to better represent an individual's functionality than a controlled laboratory setting [3]. Metrics describing recovery in simulated settings provide a foundation for understanding the potential future of continuous IMU monitoring.

Experimental Design

Ambulation Circuit

The AC was designed to assess the mobility and physical ability of the participants as they progressed through physical therapy. The AC is a continuous sequence of activities performed in an indoor facility consisting of several community-based modules. The AC requires a participant to stand from a seated position in the hotel lobby module. After standing, the

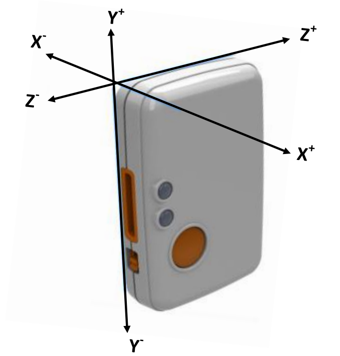

Figure 2. The Shimmer3 IMU. The alignment of the IMU axes are shown.

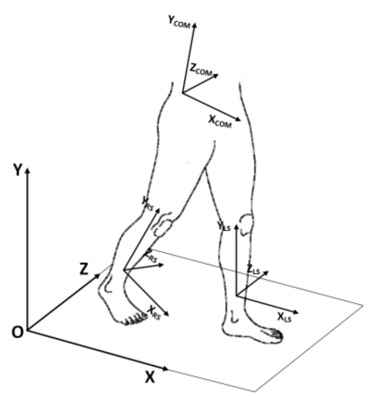

Figure 3. Three IMU sensors were placed on the body. One sensor on the center of mass and one sensor on each shank.

participant begins walking in a straight line, performing a surface transition from a shag rug to a smooth floor. The participant then proceeds in a curvilinear path around the sport utility vehicle (SUV) module. Finally, the participant performs a vehicle transfer and returns to the chair in the hotel lobby. Figure 1 illustrates the facility and the AC.

Testing Protocol

A repeated measures approach was used to test recruited participants for a total of four trials, at two different testing intervals. The first test session was conducted shortly after the participant was physically able to perform the circuit, as determined by their physical therapist. The second test session was conducted one week later, a date close to discharge from the inpatient hospital. During each test session, the participant performed the AC two times, producing two separate trials.

Instrumentation

Commercially available Shimmer3 IMUs were used to collect movement data. Figure 2 shows the IMU and its axes. Each of the three IMUs captured linear acceleration and angular velocity in three dimensions. One sensor was placed centrally on the lumbar spine at the third vertebrae, near the center of mass (COM). The other two IMUs were placed on the legs; one sensor on each shank, above the ankle and in line with the tibia. Figure 3 illustrates the IMU mounting locations and sensor axes. A sampling frequency of 51.2 Hz was set for all sensor platforms.

Data were annotated with a stopwatch, denoting section transitions and key events in the AC. These include start time, end time, module events, and unexpected stops if any occurred. The annotations were used to partition the collected data during processing.

Metrics Computed

Metrics mined out of the AC data characterize participant performance over a one week period. Measurements such as walking speed, cadence, double support time, swing as a percentage of the gait cycle, and number of gait cycles were used to describe spatio-temporal gait parameters. In addition to these gait parameters, ambulation was quantified with the following metrics: index of smoothness, stride and step regularity, step symmetry, and range of motion. Metrics for measuring performance on the sit-to-stand, stand-to-sit, and SUV transfer tasks include: duration, root mean square (RMS), and peak angular velocities, among others.

Preliminary Results

Metrics related to gait and activities of the AC were computed with custom software. Gyroscope and accelerometer signals were filtered, time-aligned, and oriented. To date, ten participants (8 males, 2 females) have completed both AC testing sessions. Preliminary data were also collected from three healthy individuals (2 males, 1 female) for referencing patient improvement and performance.

Preliminary results indicate that changes in movement can be detected with metrics calculated from IMUs. Figures 4-6 show select metrics quantifying ambulation. Data from the first session is indicated by S1 and data from the second session as S2. Data collected from the reference population is denoted with REF. Changes from S1 to S2 occur at varying rates for individuals.

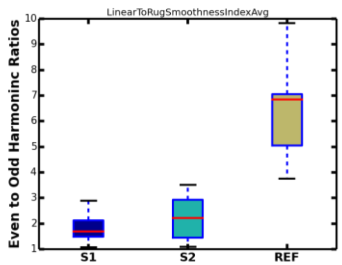

Figure 4. Smoothness index metric.

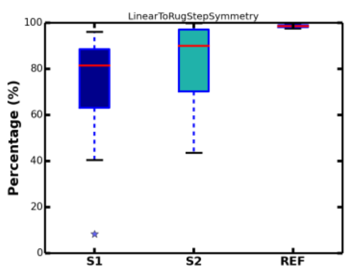

Figure 5. Step symmetry metric.

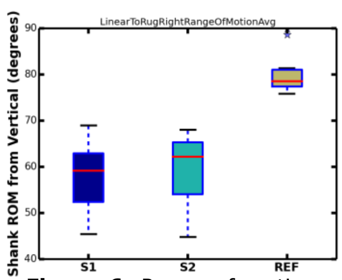

Figure 6. Range of motion metric.

The boxplots presented represent general trends because data from individual trials are combined in each session. As illustrated by the absence in S1, S2, and REF distribution overlaps, the figures also suggest that IMUs are suitable for distinguishing between the healthy and patient populations.

Figure 4 shows patient averages for the smoothness index metric. The smoothness index is calculated as the ratio of odd to even harmonics in the frequency domain [4]. As seen in Figure 4, the patient averages improve slightly from S1 to S2. The difference in smoothness between patients and the reference population is quite large.

Figure 5 shows patient averages for the step symmetry metric. Step symmetry provides an indication of consistency between subsequent steps while walking. The metric is calculated as the ratio of step regularity to stride regularity [5]. The reference group can easily be distinguished from the patients by its small variability.

Figure 6 shows patient averages for the range of motion (ROM) metric. ROM is a measurement of joint movement, which provides information about patient capabilities. ROM is calculated by integrating the shank gyroscope signal [6]. A decrease in ROM is often associated with aging or a decline in mobility.

Conclusions

In summary, metrics derived from motion tracked with IMUs are a powerful, objective method for quantifying changes over the course of inpatient rehabilitation. Utilizing an ecological environment with the AC establishes an important step in the direction of ubiquitous movement monitoring systems. Such a monitoring system has multiple possibilities for the advancement of healthcare technology. Future work can focus on providing individualized, clinically relevant post-care assessment.

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