Wearable Sensors in Ecological Rehabilitation Environments

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UbiComp '14 Adjunct, September 13-17, 2014, Seattle, WA, USA
ACM 978-1-4503-3047-3/14/09.
http://dx.doi.org/10.1145/2638728.2638737

Abstract
Rehabilitation after injury or stroke is a long process towards regaining function, mobility, and independence. Changes exhibited in these areas tend to be subtle and highly dependent on the patient, their injury, and the intensity of rehabilitation efforts. 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 therapy services 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, pervasive technology can be implemented to provide therapists with objective, quantitative measures to detect additional changes that are not easy to observe. These supplementary measurements can identify subtle performance changes during rehabilitation, providing finer-grained information about an individual's progress.

Inertial Measurement Units (IMUs) have been utilized quite extensively in the healthcare community and various other application domains [1,2,3,4]. This is due to their low cost, portability, and success rate. IMUs are ideal candidates for tracking changes in movement because they can be easily attached to anatomic features of the body [1]. Several studies have used IMUs for analyzing gait and movement as an inexpensive and unobtrusive substitute to other technologies [2,3,4]. Performances on common clinical assessments, such as the timed up-and-go test, have been characterized with IMUs [4]. These studies have illustrated that additional information provided by IMUs can be useful in a clinical setting.

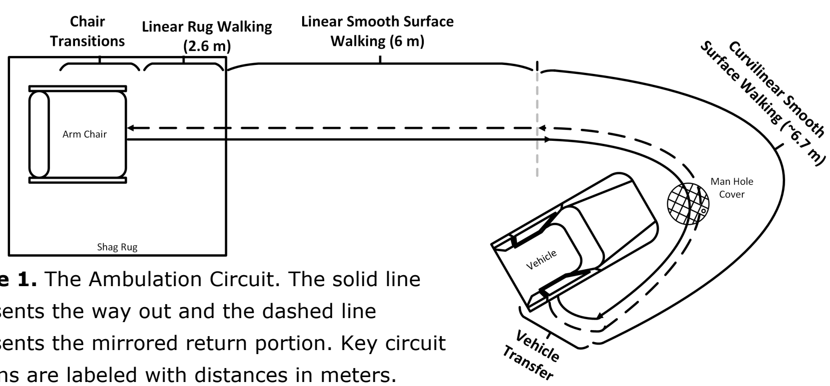

Figure 1. The Ambulation Circuit. The solid line represents the way out and the dashed line represents the mirrored return portion. Key circuit sections are labeled with distances in meters.

Wearable IMU protocols in clinical settings provide valuable information, but may not readily transfer to post-discharge environments [1]. To better understand movement in an ecologically valid setting, a novel 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. Adding ecological context has been proven to better represent an individual's functionality than a controlled laboratory environment [5]. We developed a software system to process the AC data and compute metrics describing recovery. We also derived new features that are unique to simulated settings. The results of these metrics provide a foundation for engineering potential future applications 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

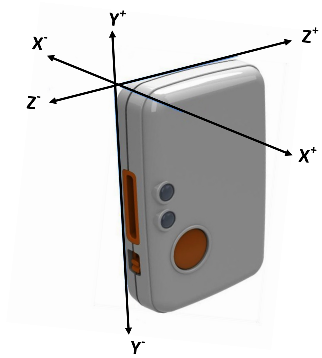

Figure 2. The Shimmer3 IMU. The alignment of the IMU axes are shown.

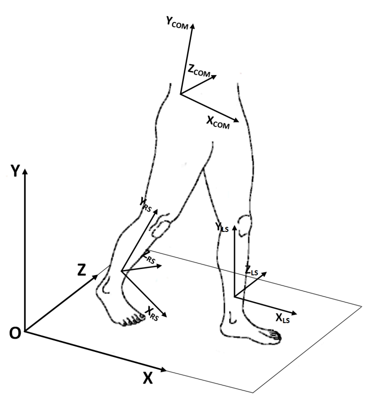

Figure 3. Three IMU sensors were placed on the body. One sensor on the center of mass (COM) and one sensor on each shank (LS and RS).

position in a simulated hotel lobby module. After standing, the 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 a sport utility vehicle (SUV) module. Finally, the participant performs a vehicle transfer into and then out of the SUV front passenger seat, and returns to the chair in the hotel lobby. Figure 1 illustrates the facility layout and the AC. A repeated measures design was used to test consented participants on the AC two times at two different testing periods, for a total of four trials. The first test session was conducted shortly after the participant was physically able to perform the circuit, as determined by the physical therapist. The second test session was conducted one week later, a date close to discharge from the inpatient hospital.

Instrumentation
Commercially available Shimmer3 IMUs were used to collect movement data. Figure 2 shows the IMU with axes corresponding to limb motion. 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) [2,3]. The other two IMUs were placed on the legs; one sensor on each shank [4], 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. During the trials, data were annotated with a stopwatch denoting section transitions and key events as the participant ambulated through the AC. These included: start time, end time, module events, and unexpected stops, if any occurred. These annotations were used to partition the collected data during processing.

Metrics Computed
Metrics obtained from the AC data characterized 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. Ambulation was also quantified with the following metrics: index of smoothness, stride and step regularity, step symmetry, and shank range of motion. Metrics for measuring performance on the sit-to-stand and stand-to-sit included: duration, root mean square (RMS), and peak angular velocities. In addition to computing these metrics, we proposed several new features that are unique to the ecological environment. These features included: SUV transfer duration, SUV transfer RMS, SUV transfer peak angular velocities, surface transitions between a rug and smooth flooring, ratio of linear velocity to curvilinear velocity, AC duration improvement, and intra-session variability.

Preliminary Results

Metrics related to gait and activities of the AC were computed with custom software [1,2,3,4]. 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) to frame patient improvement and performance.

Preliminary results indicate that changes in movement can be detected with metrics calculated from IMUs.

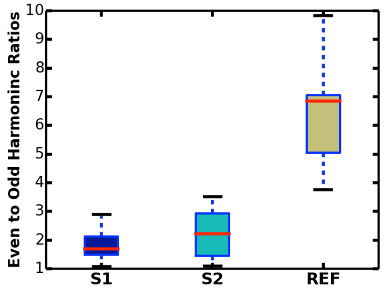

Figure 4. Smoothness index metric.

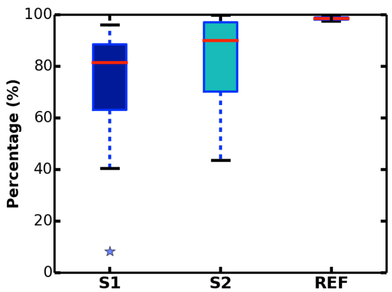

Figure 5. Step symmetry metric.

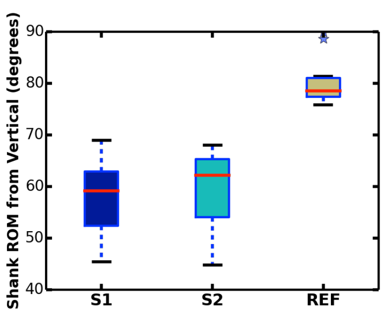

Figure 6. Range of motion metric.

Figures 4-6 show select metrics used for quantifying ambulation. Trial data from the first session is indicated by S1 and data from the second session as S2. Outliers beyond the interquartile range are denoted with a star. The data collected from the reference population are denoted with REF. S1, S2, and REF are represented in the x-axis of the Figures. Changes in the metrics from S1 to S2 occur at varying rates for individuals. Initial results suggest that IMUs are suitable for distinguishing between healthy and patient populations, as illustrated by the absence in S1, S2, and REF distribution overlaps.

Figure 4 shows patient averages for the smoothness index metric, the ratio of even to odd harmonics in the frequency domain [2]. A higher value on the y-axis indicates a smoother pattern. 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 [3]. A higher value on the y-axis indicates a higher regularity in step timing and length. The reference group can easily be distinguished from the patients by its small variability. Figure 6 shows patient averages for the shank range of motion (ROM) metric. ROM, a measurement of combined hip and knee joint movement, is calculated by integrating the shank angular velocity of the gyroscope signal to yield angular position [4]. Decreased joint ROM is often associated with aging or a decline in mobility. This can be seen in Figure 6 where the reference group exhibits a higher ROM than the study participants.

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 engineering systems for ubiquitous movement monitoring. Such a monitoring system has multiple possibilities for the advancement of healthcare technology. Future work can focus on providing individualized, mobile post-care assessment.

Acknowledgements

We wish to thank our therapist collaborators at St. Luke's Rehabilitation Institute. This work is supported in part by National Science Foundation grant 0900781.

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