Capturing Human Motion One Step at a Time

The design, construction, and deployment of a pressure-enhanced IMU system that fits in the bottom of your shoe.

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Digitizing human motion can provide deeper insight into both the physical and mental properties of a subject. Once captured, the motion of different body parts can be quantified, analyzed, and related to one another to extract useful information. In medicine, doctors try to augment diagnoses, or even base new diagnoses, on objective motion data. Sports and biomechanics focus on objective measures of physical properties from motion data, e.g., angles, accelerations, rotations, and torque. In this article, we provide a focused view on the development and deployment of our motion-sensing device and discuss our use of the system in both a medical setting and in experiments with athletes.

INTRODUCTION

We aimed to create a wearable sensor system that tells us more about mobility than a single accelerometer or pedometer, but is as unobtrusive as possible. Initially, we wanted to assess data to determine gait patterns, fitness, or mobility of elderly people. The fitness of a subject is defined depending on context: The time required to run 100 meters might be used as a fitness indicator for an athlete, whereas a mobility index (MI) is often employed for elderly people.

There are an abundant number of mobility indices used in practice. The Barthel-Index, for example, captures everyday activities like eating and drinking, but also more specific activities like climbing stairs and sitting on chairs. A more focused and widely used index is the timed-up-and-go (TUG) test: The time required for a subject to rise from a seated position in a chair and to walk five meters is measured and compared with a normative score [1]. The longer it takes the person, the lower the score. Prior studies have shown TUG correlates very well with a subject's risk of falling. Since injuries caused by falls are usually more severe for elderly people, falls should be prevented as often as possible.

Motivated by prior research [2], we knew important information could be obtained from analysis of temporal gait patterns in (elderly) subjects: Step frequency, stance time, swing time, anterior-posterior, and medio-lateral sway, are important statistical features affected by a subject's fitness or mobility. These features can be captured with inertial measurement units (IMUs) comprised of an accelerometer, a gyroscope, and often a magnetometer. On the other hand, balance, posture, TUG scores, center-of-pressure characteristics, are also established measures that assess different parts of a subject's mobility. These features could be estimated using an IMU-based system, but not possible if you only use a single-sensor device. After evaluating possible existing alternatives (multi-IMU systems, optical systems, pressure sensitive flooring or device, etc.) we decided to create our own device: A pressure-enhanced IMU system that can be worn unobtrusively in a shoe.

A NOVEL DEVICE

Our first task was identifying key features. Unobtrusiveness was an important design goal. This requires small packaging and no wires; it should be unnoticeable to the user. Our lab had previously developed a small IMU sensor with a wireless communication channel; the missing piece was the pressure-sensitive part. There are pressure-sampling systems that use thin polymer foils and incorporate

Image by Wave Break Media

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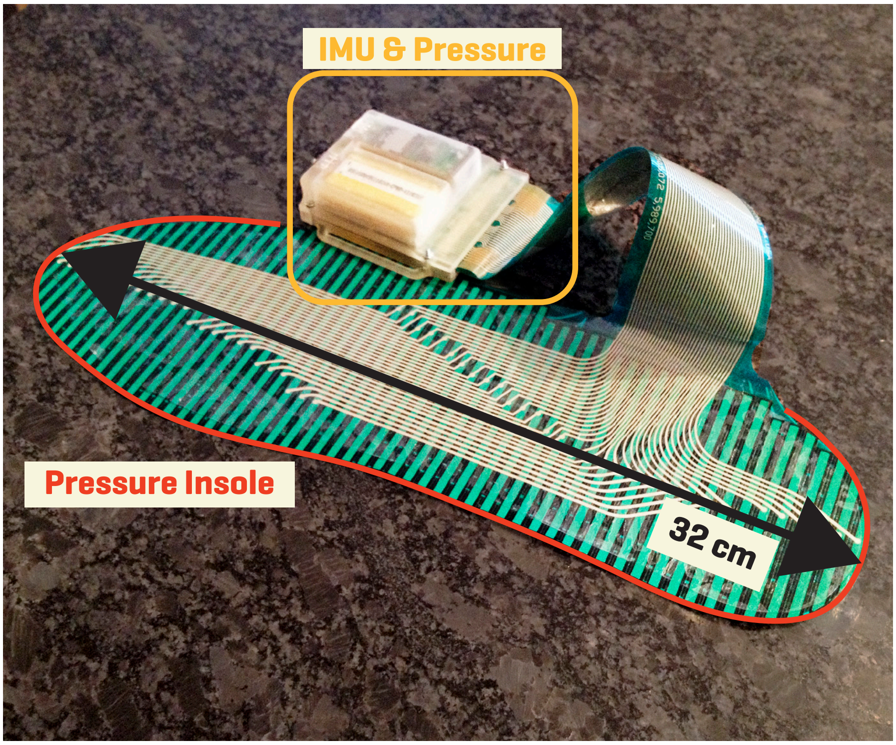
Figure 1. The PIMU device showing the electronics with casing and the pressure insole.



pressure-sensitive electronics. For example, TekScan builds tethered systems where the sampling circuitry communicates to an aggregator device attached to a subject's waist. Via a wired connection to a base station, the pressure insoles can be sampled at about 100 Hz.

We concluded that a combination of both devices—an IMU and a pressure-sensitive insole—would fit our needs perfectly. Not only would such a device assess temporal features from steps of a subject, but the pressure insole would allow assessment of a high-resolution time series of pressure maps. Tests, like TUG, could be performed automatically by detecting situations of standing, sitting, and walking, and of estimating distance walked. With wireless communication, not only are per-foot center-of-pressure (COP) calculations possible, but a body-COP assessment is also feasible. We decided to call our device PIMU, for pressure-sensing IMU.

The layout and population of the circuit board turned out to be straight-forward. The pressure-sensitive insole was constructed in a matrix-style layout: On one side the force-sensing resistors (FSR), which are the sensor elements, are connected in a column order; on the other side of the foil, there is a row-like connection. The FSRs change their resistance relative to the applied pressure. In a nutshell, we connected the pins of the central processing, which could be configured as outputs (e.g., the columns) to one side of the sensor foil. The other side was connected to the rows of the sensor foil. At runtime, the sensor board enables one output pin and then samples the voltage for all input pins. A complete set of pressure readings, i.e., one sole, is sampled if every output pin was once assigned high.

The remaining obstacle was enabling communication between the IMU and the pressure system. There are multiple communication standards for electronics; a very prominent one is the inter-integrated circuit, or I^2C. The processor on the IMU already uses I^2C to talk to the sensors. Since it is a bus system, adding a new party to the communication was straightforward. The only things needed were a wired connection from the pressure system to the I^2C wires of the IMU and software adaptions on the inertial sensor in order to enable communication with the other system.

Without going into detail, both operating systems on the two sensors are designed in an interrupt-driven philosophy. That means instead of polling for answers from external sensors or communication chips, the processors are notified whenever something new happens). This design principle reduced power consumption on both systems by more than 60 percent and relaxed the system load so complex calculations could be implemented in real time on the sensor boards. Our system can run continuously for more than 12 hours sampling IMU data at 128 Hz and pressure data at 100 Hz.

TURNING MULTIPLE MODULES INTO ONE SENSOR SYSTEM

We used a 3D-printer to print housings receiving both sensor modules, a battery, and the insole-connector in a small volume. PIMU incorporates an ANT+ enabled wireless communication chip. It is compatible with heart-rate belts and similar sports equipment by Garmin and other manufacturers. ANT is a very low-power communication protocol and is implemented by specific types of smart phones. Additionally, an ANT USB dongle enables this communication channel on a regular PC. We decided to use a smartphone to control the sensors and display sensor data. The application runs on Android OS and enables the operator to start and stop the sensors, display real-time data, and configure sampling parameters.

Often in a multi-device setup, good inter-device synchronization is difficult or even unattainable and has to be performed offline. Our setup allows us to have a very accurate synchronization between any two sensors; the difference between two sensors at the beginning of sampling is at most four microseconds. We achieved this high accuracy with a carefully designed interrupt mechanism in the sensor's operating system. The communication interrupts are assigned a high priority within an interrupt context. Only if a sensor is currently in another interrupt context could there be a delay (at most four microseconds). The clocks on the sensor boards exhibit a maximal drift of 10 parts per million. In our configuration, this results in a maximal drift between any two sensors of about 36 milliseconds over a 60-minute time period.

DEPLOYMENT

Once the hardware was built and wired and the operating system and back-end applications were programmed, the system was ready to be used. Presented here are increasingly complex tasks that were performed by our system in deployment.

Gait analysis. In geriatric medicine, it is well known that gait performance decreases with increasing cognitive load for many elderly people. Hence, affected subjects tend to walk more irregularly and have more difficulties maintaining a straight path when asked to perform a cognitive task. However, it has been hypothesized that mental training, as well as physical training, could reduce the impact of cognitive load on gait patterns. Consequently, this would also lower the risk of falling. For a study evaluating training effects on elderly people, we used both PIMUs and commercial IMUs that were attached to the subjects' legs while they were walking on a treadmill. For each of the 16 subjects, we recorded three sessions: The first prior to any training, the second to assess performance in the middle of training, and the last once training was complete. The training period occurred over 14 weeks. Our results showed with high statistical significance that training is beneficial to the gait performance of elderly people. Furthermore, even training just once a week improves overall gait performance and reduces possible impacts of increased cognitive load on gait performance [4]. Our gait analysis showed the IMU part of our system (i.e., no pressure data) is useful for the assessment of slow movements.

Athlete-centric motion analysis. We next decided to tackle a more challenging problem: Exploiting the high-accuracy synchronization between any two PIMU sensors. For this purpose, we took a scientific detour into a new domain: weight lifting. In many sports, the synchronization between different body parts is of high importance for good performance. This is especially true for weight lifting, where a very heavy mass, e.g., a barbell, is moved externally to the body. Weight-lifting athletes practice exploiting the momentum they created in every phase of a movement. For example, a barbell is initially accelerated upwards with lower-body muscles until it reaches a certain height, at which point the athlete tries to switch as smoothly as possible to upper-body muscles.

We used our system to test whether beginner athletes are easily distinguishable from more experienced athletes by looking at the synchronization between lower-body and upper-body movements. We asked 12 athletes of different experience levels to wear our sensor system while they performed front squats with a consecutive overhead press (an exercise called a "thruster"). We were very pleased with the results. Analyzing the power generated by hip and arm movements measured using our PIMU device, enabled us to to classify individual athletes by experience level with more than 90 percent accuracy.

Balance assessment. So far, we validated our PIMU component for performing motion analysis in two different settings. Our main focus, however, is posture and stability anal-

Figure 2: An athlete wearing three PIMUs in the start position of a "thruster."

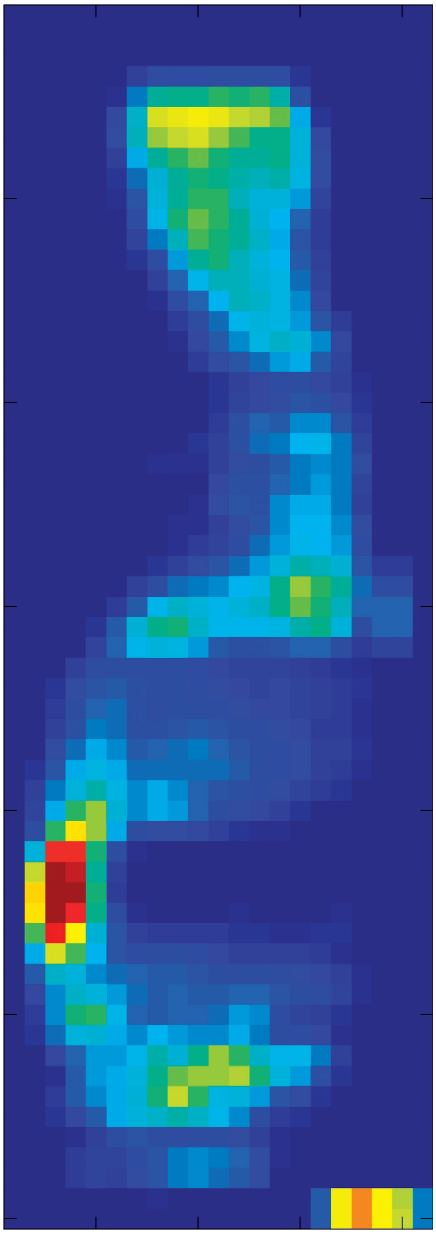
ysis of elderly patients. In more recent studies, we used our system to assess postural stability of patients with balance deficiencies.

There are uncountable medical causes that eventually lead to difficulties maintaining a balanced posture. The human balance system comprises three main components: proprioception (the sense of the relative position of neighboring parts of the body), the visual system, and the vestibular system. If any of these body systems are affected by a medical condition, the overall sense of balance (equilibrioception) can be reduced.

In collaboration with a local hospital, we attended several functional gait analysis (FGA) sessions. This analysis screens patients to determine if they need physiotherapy to improve their posture stability. The sessions seldom incorporate technical tools; usually, a medical doctor or physiotherapis tasks patients to perform several items from a test battery and estimates the score on an ordinal scale. This assessment is frequently difficult even for well-experienced experts with 10-plus years of practice. We wanted to create a tool for medical experts to better—objectively and quantitatively—assess the patient's movements.

Typical tests in an FGA include a) walking on a line with closed eyes and b) standing heels together with eyes closed. The former is rated according to an estimated maximal drift from the optimal line. The latter would be harder to assess, because an objective statement about a patient's stability can only be made if a patient needs to take a step. However, stability is not a binary entity; it can be modeled as a function of the coordinates of a subject's center of mass (COM). Measuring the COM and its projection on the ground can give an accurate assessment of the subject's balance. If that point falls inside the base support spanned by a person's feet, his or her posture is stable. Assessing the COM requires accurate knowledge of the mass distribution of a subject's limbs, as well as the ability to track the trunk and all limbs with high accuracy. Optical motion capture systems are very good at that task. Measuring the COP does not unveil the distribution of mass, but it does tell us about the applied forces. These forces result from body movement initiated by a subject trying to maintain balanced posture.

Figure 3: Pressure data from PIMU device.



Prior research has shown by analyzing the time series of COP displacements for a standing subject, the stability of the subject can be estimated very accurately without knowing the location of the COM. An intuitive explanation could be a stable person shows less sway in his or her COP than a subject fighting for stability. The technical term for that proxy is stabilogram diffusion analysis, or SDA [6].

We implemented algorithms on the PIMU sensors that track the COP of a subject in real-time. For validation, the performance of our device was compared to that of a medical treadmill with incorporated pressure sensors. The comparison proved our system is a valid alternative to a static COP-assessment system. For those FGA items assessing static posture stability, our system can report an objective measure to a medical expert, quantitatively aiding in score assignment.

CONCLUSIONS AND OUTLOOK

Human motion is an amazing source of information for answering many questions in sports and medicine, as well as in everyday life. In our journey designing the PIMU system—from the first step of problem identification, to the device's design, creation, and, finally, deployment—our results have shown that even a single device can enable multifaceted, motion analysis research in a variety of different problem domains.

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Biography

Rolf Adelsberger has a M.Sc. in computer science from ETH Zurich. His first steps in research were in the area of computer graphics where he was looking into motion capture, 3-D imaging / 3-D video and related projects. He is currently pursuing a Ph.D. in electrical engineering and works with the wearable computer lab at ETH.