KNEE: An Everyday Wearable Goniometer for Monitoring Physical Therapy Adherence

Abstract
To maximize the beneficial effects of physical therapy, patients recovering from injury must perform prescribed exercises correctly on regular daily intervals. We present a fully realized wearable knee brace prototype that passively senses and records exercise quantity. We also discuss how key factors such as understanding of physical therapists’ goals, wearability, and affordability guided the brace’s design.

Author Keywords
Wearable Computing, Health Monitoring, Continuous Monitoring, Activity Monitoring

ACM Classification Keywords
J.3 Life and Medical Sciences: Medical Information Systems

Introduction
At the sunset of ubiquitous computing as a niche discipline [1], we find ourselves in a computing universe that is ready to move beyond the many computers—one user paradigm and toward human–human interactions [5]. By working with a specific set of users and addressing their particular wearable computing needs, the most general question we try to
answer is: given the power and variety of sensing at our disposal, how can we solve a problem in a way that requires the minimum effective performance for a specific domain? More specifically, our thesis is that we can augment an existing relationship between patients recovering from knee injuries and physical therapists (referred here as PT) with simple but highly domain-specific sensing. We followed an iterative human-centered design process (Table 1) to achieve this goal.

**Requirements Gathering: Literature Review**

Our team reviewed related research papers in order to understand how past studies had addressed the questions in this problem space. We found several bioinformatics studies that tracked upper and lower extremities for rehabilitation and health assessment. These studies focused on diverse physical movements, such as Tai Chi movements [6], gait [7, 8, 9], and knee movement [9]. To gather information about these movements, experimenters used various methods, including: body-worn accelerometers and gyroscopes [9]; a Bluetooth system equipped with gyroscopes and accelerometers [4]; Kinesiotape applied directly to the skin for unobtrusive, unsupervised long-term monitoring of human gait [6]; and ear-worn accelerometers to capture mobility and activity data [3]. Using pattern matching and thresholding, these researchers could determine whether or not users performed certain activities correctly.

Past research has mostly focused on accurate sensing and interpretation of physical movements rather than working directly with PTs to learn about what information they would find useful. Few human-centered studies exist like the PT Viz brace, which used detachable bend sensors to determine the position of the knee during rehabilitation exercises and provide real-time visualizations of a patient’s range of motion [2]. Learning from [2], our research explores the problem of tracking compliance and aiding patients during the rehabilitation process from a human-centered approach.

**Requirements Gathering: PT Interview**

We spoke to two physical therapists to learn about their goals when working with patients. We learned that they focus on returning patients’ strength and range of motion to the same level prior to injury. To aid recovery, PTs assign rehabilitative exercises that the patient should complete at home between therapy sessions. Some are isolated exercises, such as “triangle leg lifts”, and some of these are functional activities performed daily, such as standing up from a chair.

PTs mentioned that it is rare for patients to fully adhere to the assigned exercise regimens. Since patients spend the majority of their recovery phase without direct supervision, therapists must make inferences about the quality and consistency of exercises being performed based off of patient-reported information and physical exams during periodically scheduled office visits. Due to this lack of information, it is unclear to PTs what the specific reasons are for a patient failing to do assigned exercises, but the presumable main reason is forgetting to do them.

Often, patients are given a knee brace to wear throughout the day to support the joint. As the knee’s strength returns, PTs encourage patients to wear the brace less often, eventually removing it altogether. Patients often fail to wear these at any stage, usually either because they forget to put the brace on or find it
uncomfortable to wear.

**Design Reflection: Calm Computing**

Given the adherence problems discussed above, one could argue for a solution that requires active user engagement like the PT Viz brace [2]. However, as the PT interviews informed us, even though patients should be wearing knee braces to guide their recovery, patients perceive braces as uncomfortable and are less likely to wear them. Therefore, this active engagement may be inappropriate. Furthermore, there is potential for reinjuring the knee and determining liability in the case of reinjury. For example, a patient with limited mobility may be inconvenienced further while performing exercises if he/she also has to monitor an interface on the brace itself.

Due to the reasons discussed above, as well as a desire to aid PTs in their basic goal of rehabilitation, we built a knee brace that places the locus of control externally with the PT and minimally interferes with patients’ lives, following Weiser’s vision of “calm computing” [11]. We address two goals through the design of a wearable knee brace with embedded sensors:

1) To improve patient adherence, defined as the degree to which a patient follows an assigned care regimen, by addressing issues of wearability and affordability while minimizing required patient effort involving the brace.

2) To achieve a minimum level of functionality that delivers PTs with information that can aid and personalize their interactions with patients, resulting in the desired outcome of better care.

**Prototype 1: Physical Design**

We used a commercially available neoprene knee brace with Arduino Lilypad electronics to build our first prototype (Figure 1). We aimed to reduce the cost of the brace and potential part replacements by using these widely available components. We used conductive thread to connect the components to each other. However, these connections proved to be fragile. In order to experiment with inertial measurement unit (IMU) sensor positions to determine the ideal location for the most precise data gathering, we used Velcro-backed patches of Neoprene and attached the sensors to these patches. This allowed us to move the sensors to different positions on the knee brace as needed.

While using a knee brace was a decision supported by the physical therapist’s feedback, we could have implemented other similar garments such as leggings. However, since men may be less likely to wear these, we would be limiting our potential users. We also designed our brace to be easily removable.

**Prototype 1: Data Sensing and Analysis**

To truly obtain ground truth for muscle movement, we would need to use myoelectric sensors to directly measure muscle activity. However, these sensors are invasive to the wearer since they must be placed directly on the skin of a recently injured joint. Instead, we used more indirect accelerometer sensors to gather data. By measuring the force of gravity with three degrees of freedom (DOF) as measured by one sensor above and below the knee, we detected the angle moved by the joint.

We gathered training data from our four team members while they performed a basic knee extension exercise
(triangle leg lifts). We manually tagged this data, passed it through the Weka machine learning software tool, and generated an algorithm that recognized the gesture transitions for the leg lift (Appendix, page 9). This allowed us to count when a leg lift was completed and then send a single haptic vibratory buzz.

**Prototypes 2 & 3: Physical Design**

For our second prototype, our design goals included creating a sleeker design and incorporating more accurate sensing. To accomplish these goals, we purchased smaller components that included an Arduino Pro Mini (3.3V, 8 MHz), and two InterSense MPU-6050 accelerometers mounted on Sparkfun breakout boards. To enable data storage on microSD cards, we also added a Sparkfun OpenLog. These smaller components allowed us to conceal the circuitry as compared to our first prototype’s open display of components that might intimidate patients.

We designed two additional iterations. The first consisted of a stand-alone pouch that could be attached to the top and bottom of a brace (Figure 2). The pouch contained both the sensors and the circuitry needed to connect the various sensor components. However, the pouch shifted on the knee as the patient moved and also added significant bulk to the brace. To address these issues and in order to get the sensors closer to the skin to gather more accurate accelerometer data, we fabricated a second prototype with a Lycra brace and embedded the sensors in two neoprene bands, one placed at the bottom and one at the top of the brace (Figures 3 and 4).

The brace was designed to be a passive object though we needed to give the user feedback about the brace’s status. In our first design we included haptic feedback. For the second design, we removed the vibration motor providing this feedback since we did not want to apply potentially harmful vibration to a sensitive joint, as well as to reduce the brace’s bulkiness. Instead, we used a single LED light to indicate when the brace was turned on or off, as well as an auditory beeper to inform the user when 10 repetitions of an exercise had been completed.

**Prototypes 2 & 3: Data Sensing and Analysis**

In addition to using the more powerful sensors described above, we addressed several issues from our first prototype, including lack of a generalizable algorithm and precision issues. We manually adjusted our algorithm and transformed the raw Cartesian coordinate data from the accelerometers into spherical polar descriptions of orientation. Manual tuning allowed us to experiment with ranges and wider thresholds in the tree to make the algorithm generalizable to different wearers. Inspecting polar angle representation of accelerometer data was more intuitive when visualizing and tweaking the recognition algorithm.

In summary, we translated raw data into a rough model of knee bend angles and applied filters to greatly improve recognition for leg lifts. We also added the ability for our brace to recognize a functional activity, getting up from a chair. Our model for this second activity was not as precise, however, and we did not include it in the evaluations described below.

**Evaluation: PT Benchmark Task**

To measure the performance of our algorithm, we used a physical therapist’s classification of leg lifts as ground truth by asking them to analyze video of good and bad
exercise repetitions. We recorded video of one of our team members performing leg lifts [10] and showed this video to a physical therapist. Then we compared this evaluation by video with our brace’s automatic recognition. Ten exercises were performed correctly based on our definition obtained from physical therapists: “bringing the flat leg up towards the ceiling so that the foot reaches the height of the bent knee”. The other exercises recorded were performed at varying distances less than the required height.

The physical therapist we interviewed confirmed that the ten exercises we had noted as proper leg lifts, were, in fact, performed correctly. Our brace correctly identified these ten exercises as leg lifts (100% accuracy), but it also incorrectly identified three non-leg lifts as properly performed leg lifts, resulting in 3/18 false positives as opposed to the ideal of 0 false positives. Therefore, while our brace’s algorithm is able to recognize leg lifts when they occur, the thresholds it uses may be too liberal, resulting in the observed false positives. With additional data collected from various users with varying leg shapes, we would be able to develop a more robust algorithm.

**Evaluation: PT Participatory Design**
In addition to asking a PT to get feedback on our brace’s functionality, we spoke with the same PT regarding a user interface (UI) to visualize collected data (Figure 5). We created two different interfaces. The first interface had daily, weekly, and summary views and had a minimal monochromatic design (Figure 5, Appendix pg. 14). The second interface design (Figure 5, Appendix pg. 15) was more colorful and had daily and weekly views. Both displayed quantitative data, allowed patients and therapists to enter notes, and summarized exercise goals. Neither interface used actual data collected from the brace since our goal was to learn how to tailor the design based on what the PT would find most useful as well as her expectations for such a UI. She expressed a preference for the weekly and summary views since these could allow her to view a comparison of a patient’s performance from week to week. She also liked seeing a text list of patient’s goals for each respective exercise since it allowed her to easily review and adjust a patient’s exercise regime.

Some other slight suggested changes included: using a search bar for patients’ names (instead of a drop down or clickable left/right arrow), adding dates where necessary, displaying data in reverse chronological order, and providing information about exercise quality.

Based on the PT’s feedback, we modified the user interface (Appendix pg. 16). Instead of displaying a daily, weekly, and summary view, we only display a weekly summary view. We also learned that prescribed exercises might vary greatly from patient to patient as they regain strength, something we had not considered originally. Therefore, we created a menu to allow PTs to modify prescribed exercises.

**Conclusion**
Through our interviews with physical therapists, we learned that the key issues they face are:

1) getting users to perform their prescribed exercises.

2) collecting data from both rehabilitation exercises and functional tasks such as walking.

Several design alternatives were feasible, but given
that PTs already encourage the use of knee braces, especially at the beginning of a patient’s rehabilitation, we explored this wearable solution. By developing a wearable, convenient, and comfortable knee brace, we hope that recovering knee injury patients will be more likely to wear our brace throughout recovery, resulting in exercise data that is collected and later visualized for review by their physical therapists.

Acknowledgements
We would like to thank: physical therapists Jos Kramer Robine Van Gils-Kramer, and Candice Gray; Georgia Tech Contextual Computing Group members Ceara Byrne, Clint Zeagler, David Quigley, Scott Gilliland, Daniel Kohlsdorf; fellow MS-HCI student Joe Gonzales; and Dr. Thad Starner and Dr. Gregory Abowd.

References


