Designing Wearable Interfaces for Knee Rehabilitation

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ABSTRACT

Patients undergoing physical therapy often receive little feedback when performing exercises away from the clinic. They either have to rely on their memory of their rehabilitation session with a therapist or seek guidance from a paper based exercise tutorial. We address this feedback issue for knee rehabilitation with a wearable electronic device that helps patients visualize knee bend when performing exercises at home. We conducted a usability study of the device with six knee rehabilitation patients to better understand their perceptions of wearable interfaces. Through semi-structured interviews and prototype design activities, we derived design guidelines for future wearable devices in this space.

Categories and Subject Descriptors

H.5.m [**Information Interfaces and Presentation**]: Miscellaneous

General Terms

Human Factors; Design

Keywords

knee rehabilitation, user interface, wearable technology

1. INTRODUCTION

Physical therapy is a crucial part of rehabilitation for patients who recently underwent surgery or suffer from chronic physical impairments. It is often a labor intensive process where patients must consult with medical practitioners who prescribe a course of exercises as therapies. Treatment programs can last anywhere from months to years with weekly or bi-weekly visits to the rehabilitation clinic. In addition, patients must support these clinical sessions with daily exercises performed independently at home. At-home exercise sessions are key to regaining mobility and strength. Despite this requirement, many patients often fail to perform or adhere to at-home therapies. In one study that examined sports related injuries (shoulder, knee, and ankle), over half of the participants failed to comply with the prescribed physical therapy exercises [1]. The result of non-compliance is a longer path to recovery for the patient through prolonged treatments that ultimately places a heavier burden on the medical system.

Indeed, research has found that lack of feedback is one of the three major factors correlated with noncompliance in physical therapy [2]. While patients receive instructions and guidance from the physical therapist at the clinic, they have little feedback on the accuracy and progress of their exercises when practicing at home. Often patients receive a paper based exercise tutorial to accompany their at-home sessions.

Our work addresses the issue of exercise feedback for knee rehabilitation through a wearable electronic device, Physical Therapy Visualization (PT Viz), designed to assist patients in range of motion exercises. We focus on users who are increasing knee extension and flexion by helping them visualize progress through an electroluminescent (EL) display.

We explored the effectiveness of the EL visualization in a user study with six knee rehabilitation patients. The PT Viz prototype provided a starting point for discussing how these devices can support rehabilitation exercise performance at home. As part of the study, we also conducted a paper prototyping session where participants designed custom wearable interfaces to support their recovery needs. The specific contributions of this paper are:

1. A technical description of a simple, portable, electronic knee rehabilitation device that helps users visualize knee extension.
2. An exploration of alternative wearable interfaces for knee rehabilitation.
3. A discussion of design guidelines for wearable interfaces to facilitate at-home rehabilitation.

2. RELATED WORK

Perhaps the most common tool for measuring progress in range of motion exercises is the goniometer, a manual instrument that measures the angle of a joint with respect to

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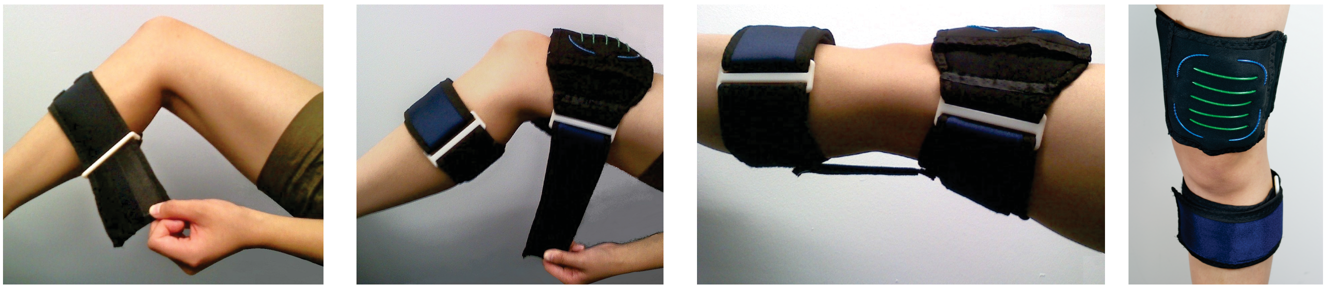
(a) Wearing the calf enclosure (b) Wearing the thigh enclosure (c) Bend sensor secured to the enclosures (d) Front view

Figure 1: Steps for wearing PT Viz

an axis [3]. The electrogoniometer automates this process by replacing the protractor in the traditional goniometer with a potentiometer positioned over the joint being measured. The linear change in resistance is used to automatically determine joint angle. Both these devices however, tend to be therapist-centric and require training to used properly [3]. A more complex device that uses muscle activity (electromyography) is the bioPLUX Clinical System (plux.info). While the bioPLUX is compact and capable of transmitting data wirelessly, it is also primarily designed for physical therapists as a medical device to be used in the clinic.

With the introduction of entertainment consoles such as the Nintendo Wii and Microsoft Xbox Kinect, researchers have designed custom applications that support various rehabilitation therapies including hand rehabilitation for post-stroke patients [4], balance recovery using the Wii balance board [5], and motor rehabilitation for young adults suffering from developmental disabilities [6]. While entertainment consoles demonstrate great promise as rehabilitation tools [7], they are not portable and require a substantial investment in infrastructure requiring users to setup gaming consoles, peripherals and software.

In biomedical literature, there has been abundant research into the use of wearable sensors to monitor therapy. Solutions in this space include classifying limb movements [8], analyzing gait using shoe-integrated sensors [9], and measuring physical activity in specific populations [10]. Most of these solutions however tend to focus on technical aspects such as efficient algorithms, or low power sensors. A number of studies have explored body sensor networks (BSNs) for both local [11] and remote physiotherapy treatments [12], but these systems are invasive in nature, requiring users to place sensors throughout the body and ultimately communicating information primarily to the therapist. While there has been work on interactive methods [13, 14], few have combined the needs of both the therapist and patient.

Perhaps the most relevant research study in line with our work is Thera-Network [15], an electronic knee brace designed to help patients recover from knee pain [15]. Though similar in concept to our work, the authors focus more on the issue of patient motivation through a conceptual social network, while we explore the creation of wearable interfaces from a patient-centric perspective.

Similar to Thera-Network, PT Viz is also a wearable electronic knee brace that assists patients visualize their movements. In previous work with PT Viz, we focused on the need for such wearable devices, how knee rehabilitation participants would wear the device, and how the device could assist with sharing their home rehabilitation progress with health professionals [17]. In this paper, we extend PT Viz by noting the technical considerations and other visualizations.

While many of the approaches presented here are valuable and pertinent to our design - Thera-Network serves as the closest example - we employ a user centered approach that considers the needs of the patient in the rehabilitation process. Our research lies at the intersection of human computer interaction and wearable technologies aiming for designs that are practical, simple, self-contained, and intuitive.

3. SYSTEM DESCRIPTION

3.1 Enclosures

The PT Viz electronic knee rehabilitation prototype consists of a thigh enclosure, a calf enclosure, and a bend sensor (Figure 2a). The thigh enclosure is made of a single curved piece of Neoprene that is lined with polyester on one side and Spandex on the other. We added Spandex to increase flexibility and stretchability that provides users with overall comfort and the ability to accommodate different leg sizes. The ergonomic curvature of the enclosure prevents material bunching and a closer fit to the user's thigh. The associated circuitry for PT Viz is embedded in the thigh enclosure behind the EL wire visualization panel (Figure 2b). The calf enclosure is similar in construction to the thigh enclosure, except not as wide. Both enclosures contain a 3D printed double-slit plastic buckle stitched to one end that is used to secure the device to the leg with Velcro (Figure 1a).

3.2 Bend Sensor

The fabric-based bend sensor (Figure 2a) is constructed from Neoprene, Velostat, and conductive thread[1]. The Velostat is sandwiched between two layers of Neoprene with conductive thread stitching passing through all three layers that terminates at two pieces of conductive fabric at each end. Unlike traditional flex sensors with thick plastic backings that deform over time, the Neoprene bend sensor provides consistent, reliable values even after considerable usage at greater

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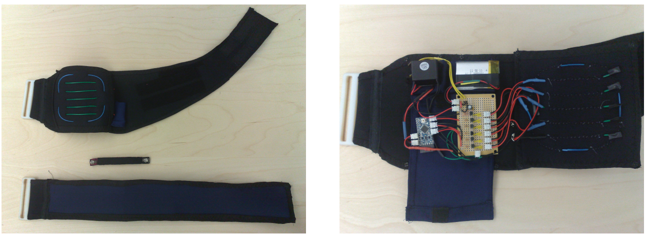
[1] kobakant.at/DIY/?p=20



(a) Thigh enclosure (top), Bend sensor (middle), Calf enclosure (bottom)

(b) Thigh enclosure with electronics exposed

Figure 2: PT Viz: Wearable electronic knee rehabilitation device

than 90 ° bends. A key point with the fabric sensor is that Velostat is piezoresistive (pressure sensing) rather than bend sensing like traditional plastic sensors. Since the Velostat is between two sturdy layers of Neoprene, pressure is exerted while bending, thus producing a resistance value that corresponds with knee bend. The fabric bend sensor runs across the back of the knee and connects to Velcro strips on the thigh and calf enclosures. Values from the bend sensor are measured using a simple voltage divider circuit that is fed to an A/D converter on the microcontroller. Since the hand construction of the sensor produces minor variations in the resulting resistance values, each sensor must be calibrated prior to use. We calibrated the sensor by having participants bend their knee to 90 ° and noting the sensed bend in comparison with the real-world bend measurement. Once the calibration procedure is complete, the sensor provides consistent linearly correlated values across exercise sessions.

3.3 Visualization Panel

The detachable visualization panel consists of 5 green EL wire strips enclosed by a single strand of blue EL wire weaved through the fabric. The green strands represent bend with more strands successively lighting up as the knee bends. The blue strand serves as the power indicator. The strands are stitched to the Neoprene panel with clear nylon thread and the panel is attached to the thigh enclosure with mini snaps. We chose EL wire because it is low power, flexible, and cool to the touch, making it ideal for wearable applications.

A single 1m strand of EL wire that is 2.2mm in diameter consumes on average 90mA on a 3V power source. By comparison a single standard 3mm LED consumes 16 to 18mA. Thus, chaining LEDs together would certainly consume more power. Additionally, EL wire produces a 360° unbroken line of visible light unlike point-based strand lights. However, since EL wire only operates on an AC supply, it requires a DC to AC inverter. This adds an extra external element to the design.

We employed the circuit shown in Figure 3 to control the EL wires individually. It consists of 6 TRIACs gated by the digital output pins from a 3.3V Arduino Mini microcontroller. The TRIAC is used to control the AC power from the inverter to the EL wire load. The entire circuit is powered by a 3.7V, 1000mAh lithium ion battery source with decoupling capacitors between power and ground to reduce noise and stabilize the output voltage. All the components including the battery, inverter, microcontroller, and circuit board are individually insulated in non-conductive spandex pouches. When the circuit is first powered, the Arduino Mini microcontroller first triggers the TRIAC corresponding to the blue strand serving as the power indicator. It then polls the analog input port for values from the bend sensor. Depending on the voltage, it triggers the TRIACs corresponding to the number of green strands. The bend sensor has a range between 0 ° and 140 °, thus a new green strand is illuminated approximately every 28 °. The greater the bend, the more strands are gated.

4. METHODS

PT Viz represents one implementation in a design space that includes a myriad of possibilities. To explore some of the challenges and design considerations of wearable interfaces for at-home rehabilitation, we conducted a user study using our prototype as a starting point for discussion. The user study consisted of a usability session with PT Viz, a semi-structured interview where the participants explored alternative visualizations, and a paper prototyping design activity. Each session was video recorded with participants' consent and lasted approximately 65-75 minutes. A $15 dollar retail store gift card was provided as an incentive to the participants at the end of the session. The study was approved by our university's human subjects review board.

4.1 PT Viz Evaluation

We began the study with a background questionnaire that collected demographic information, information about technology use, rehabilitation history, and overall physical therapy experiences. The questionnaire was followed by a usability session where participants were asked to wear the various components of the device and perform a knee extension exercise. The knee extension exercise consisted of sitting on the edge of a chair and slowly extending the leg straight for 10 repetitions. Participants were encouraged to think aloud while completing the tasks and performing the exercise.

4.2 Alternative Visualizations and Prototype Design Activity

Following the PT Viz evaluation session, we conducted a semi-structured interview to elicit participants' experiences while using PT Viz and its perceived usefulness. During this portion of the interview, we also explored their understanding of the EL visualization along with mockups of alternative visualizations shown in Figure 4. The alternative visualizations consisted of user interface elements that represented session duration, knee bend (angle), repetitions, and progress. We presented four different visualizations for knee angle (Figure 4, left) consisting of: (a) an EL wire knee-shapes display where angle is represented by the shape of the EL wire; (b) a LCD textual display of angle; (c) a LED traffic light where green, yellow, and red LEDs represent stages from full extension to full bend; and (d) a LED semi-circle where angle is proportionally correlated with the number of LEDs. We presented similar alternative representations for sets, repetitions (reps) within a set, and progress (Figure 4, right). We introduced and discussed these visualizations to engage participants in the subsequent design activity because prior work has shown that participants who are not designers should be primed in the domain of interest [16].

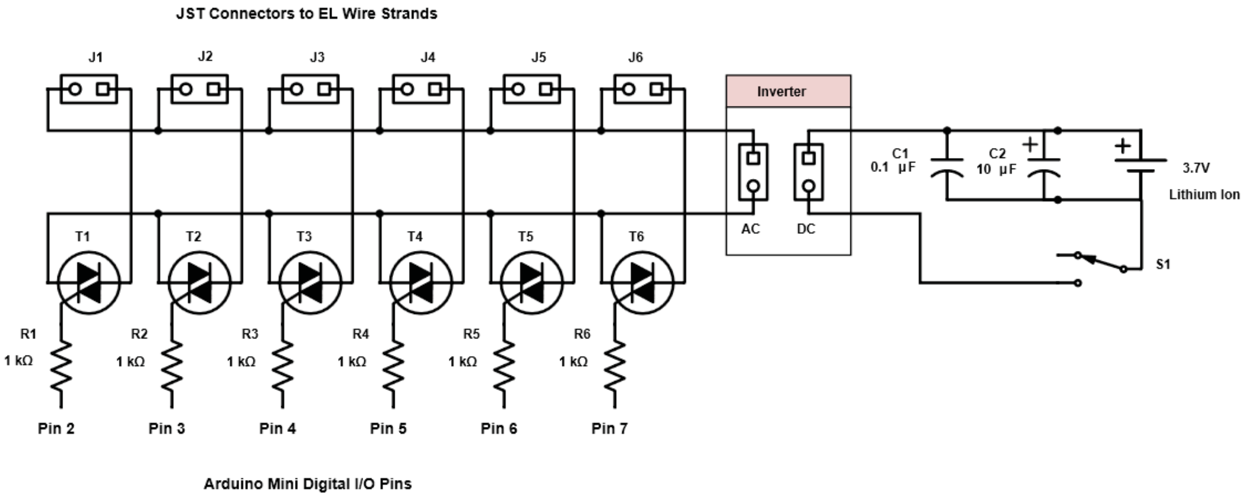


Figure 3: Circuit diagram for EL wire display

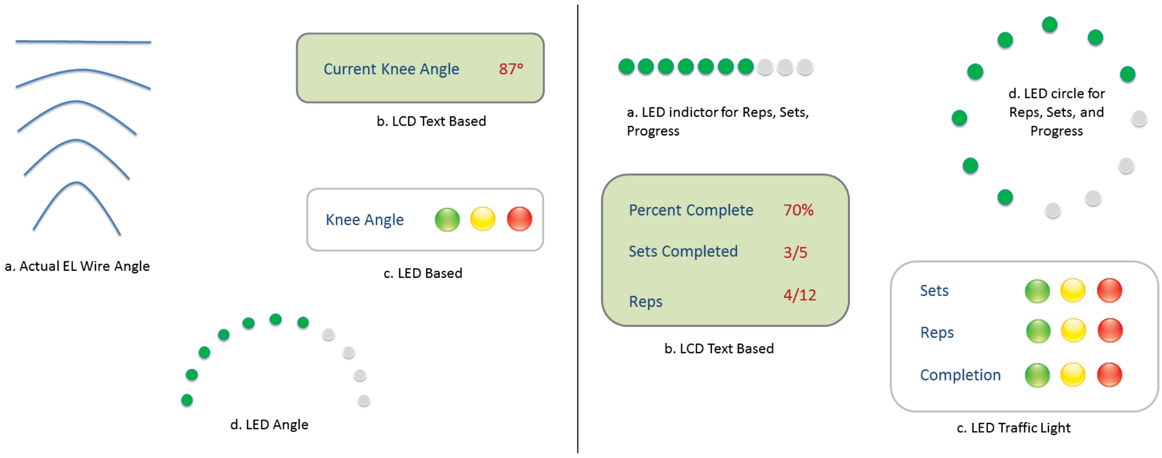


Figure 4: Alternative Visualizations for Knee Angle (left) and Sets, Reps, and Progress (right)

We then asked participants to mockup an interface using paper and pencil that they would find useful for visualizing their at-home physical therapy session.

4.3 Analysis

Quantitative data from the background questionnaire was analyzed using a spreadsheet application. Video recordings were transcribed by the first author and analyzed to identify concepts in the empirical data. Transcriptions and the participants' sketched artifacts were analyzed using both inductive and deductive approaches to identify central ideas. These ideas were then coalesced to inform design insights.

4.4 Participants

We advertised at local rehabilitation clinics and the general campus population for participants who were currently attending or had attended physical therapy for knee rehabilitation. Additionally, we screened for participants who were not allergic to Neoprene to minimize any risks during the usability session. Based on this criteria, we recruited 6 participants, 2 males and 4 females with an age range of 20-37 years old. The participants were all proficient users of modern technologies (e.g., smartphones, personal computers) in their daily lives. Two participants suffered from chronic conditions, with one of the participants having performed physical therapy for over one year and the other for over three years. Four participants had attended physical therapy post-surgery for 6-11 months. Participants reported that their clinic visits were typically once or twice a week and lasted for 30 to 45 minutes. The prescribed home exercise sessions, however, varied among the participants. Depending on the condition or the severity of the injury, the prescriptions ranged from everyday for 25 minutes to 3-4 times a week for an hour.

5. RESULTS

In this paper, we focus on the technical implementation and user interface aspects of PT Viz. We expand on some of the issues participants faced and highlight the issues they considered important. We additionally report participants' reactions to the alternative interfaces and evaluate their preferences through their custom designs.

5.1 Wearable Interface

Participants found the enclosures comfortable and easy to wear. They thought the enclosures would accommodate any difficulties patients might face as a result of their knee condition [17]. As opposed to a single sleeve solution, which is common when using flex sensors for detecting joint angles, participants preferred the distinct thigh and calf enclosures. P6 remarked,

> *"I think it might be harder if it was a full on sleeve. Coming out of surgery it might hurt your knee to pull on a sleeve. Also there is all this extra fabric that comes up in the back when bending your knee. It would be bulkier than the setup you have now."*

P3 also added that with the current design, she was able to visually keep track her knee through the exercise. She considered this especially important for noticing any issues such as shaking. Four participants noted that PT Viz was portable. They remarked how they could "wrap it up and put it in a bag" or how they could take it around with them and perform exercises at work.

While none of the participants had any issues with wearing the enclosures, half of the participants had difficulty attaching the bend sensor - specifically, where to attach the bend sensor. The three participants who successfully attached the bend sensor struggled to find the proper locations.

5.2 Visualization Interface

Overall, participants found the EL wire bar graph visualization intuitive for understanding extent of knee bend. We found that while the concept behind the visualization was simple, especially since patients can immediately see and feel the movement of their knee, the design was nonetheless valuable because patients were less certain about how far to push themselves since they had lost mobility. By breaking the extent of movement into quantifiable EL wire strands, we abstracted away the cognitive burden of remembering and estimating a particular position by providing a visual marker. Indeed, as P1 confirmed,

> *"It probably represents extension. I can see that being good for making sure that I get the full range of motion. I remember when I was injured, it was kind of hard to know how far I could move my leg and how far I actually was able to because of my injury. So this [device] would be good to have."*

P2 commented how PT Viz could serve as an indicator for needing to work harder at home, especially since her therapist pushed her farther than she was willing to during her sessions in the clinic. P2 further remarked about the potentially motivational aspects of the device.

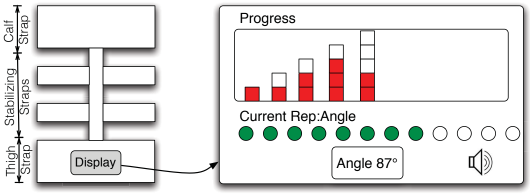


Figure 5: Wearable interface sketched by P2 with audio feedback for reaching goals

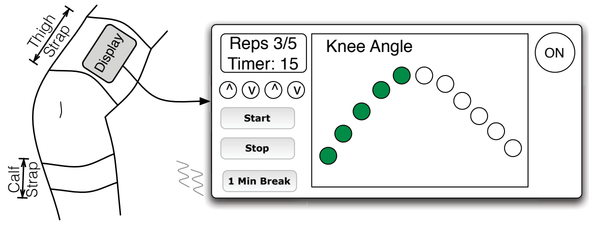


Figure 6: Wearable interface sketched by P3 with vibrotactile feedback for break timer

> *"I think if the pain level isn't an indication of how far you are going then this [referring to PT Viz] can be. And also the number of lights you are lighting up can be a goal and motivator. The first week maybe you only get 1 or 2 lights but the next week you can get 3 and then 4. You can see your progress with the levels and that is really helpful."*

Participants preferred the EL visualization on the upper thigh, even when we suggested other areas of the body or hand held smartphones [17]. With smartphones, participants were too concerned about being interrupted with texts and phones calls, losing focus, and having to prop up the phone for a better viewing angle. P1 vocalized it best when he said,

> *"Yeah I wouldn't move it anywhere else cause it is right in front of you...right there. The knee pad is big enough where you can have a lot more information very clearly. On the iPhone, I can see where it has a lot of appeal but I don't think it will be easier because sometimes you really need to focus and it is hard to look at something else [referring to the iPhone] too. I think it is better to have it all in one."*

While the visualization was intuitive and the EL wire abstraction of knee angle was well understood by all the participants, 4 of the participants echoed the desire to have a textual angle display correlated with the current display. P1 commented how knowing the angle in addition to the EL level would have helped knowing how much farther to go in between the levels. Additionally, all six participants were interested in incorporating the ability to track number of repetitions with the device. Five participants also requested a timer for tracking hold time. Only two participants were interested in tracking the number of sets for a given exercise.

5.3 Alternative Visualizations

Of the four different alternative visualizations we presented from Figure 4 for knee angle, only the text based display and the LED semi-circle were understood by all. In contrast, participants were confused by the simplified traffic light analogy. For example, it was unclear to P2 if it was an indicator of a danger zone or if it was merely indicating that some knee angles were worse than others. The EL wire knee-shapes visualization received a mixed response. While most participants understood the visualization, they preferred the existing visualization by comparison. Some participants commented how the non-linear display was complicated and aesthetically unpleasing. This sentiment was best captured by P3 who said,

"I actually just prefer the straight lines. I don't think the bend actually adds anything to it. I think it might be a little counterintuitive to see that across the thigh and I like the progression in the current interface."

Overall, most of the participants preferred either the semi-circle visualization or the current implementation. The use of an LCD in combination to represent the textual angle received a mixed response. Half the participants thought having a textual angle would perfectly supplement the LED semi-circle or the current visualization, while the other half said that even though the LCD was the most accurate, it was not the best way to visualize knee bend. P5 also mentioned that comprehension of the textual angle might be an issue. In her explanation, she summed it up as,

"LCD is [the] most accurate...but I don't know where that [angle] is in my knee and I don't know if I care [about] the actual number I mean."

Among the alternative visualizations for tracking reps, sets, and progress, participants unanimously preferred the horizontal LED display. They liked being able to glance at the display quickly and evaluate their progress. In contrast, participants found the circular LED display harder to count and calculate. Half the participants also considered the use of an LCD textual display acceptable, mentioning that since the metrics were numerical in nature they would not require an extra visualization. The traffic light visualization was, again, the least understood and preferred visualization.

5.4 Participant Mockups

When participants mocked up their own wearable interfaces, they produced a variety of designs using our implementation and the alternative visualizations as a starting point. Among these drawings, we found two representative samples that encompassed many of the features found in the different designs. The mockups shown in Figures 5 and 6 highlight both enhancements to the enclosure and changes to the visualizations. The images have been digitized from the original paper and pencil illustrations for readability.

With respect to the enclosures, participants were mostly satisfied with the current design. The few recommendations they had consisted of being able to accommodate slightly bigger and thinner than average leg sizes. The only concern participants voiced was with the securing mechanism for the bend sensor. As a suggested solution, P2's mockup (Figure 5) features stabilizing straps to position the sensor securely against the back of the knee.

Participants' drawings of the visual display were true to their preferences from the prior discussion of the alternative visualizations. Though a couple of participants maintained the current PT Viz visualization in their sketches, most participants preferred simpler LED based versions for knee angle. In P2's representative sketch (Figure 5), knee angle is represented through a horizontal LED display while in P3's illustration (Figure 6), a semicircle LED display is employed. The functionality behind the knee angle visualizations however remains the same, with more LEDs successively turning on as knee angle increases. P2 and three other participants further supplemented their knee angle visualization with a numeric display. P2 considered both equally important and remarked,

"I think the LCD would be best because you can quantify it and you can push yourself more measurably outside the physical therapy office. But I think it would be better if you combine that with one of the other visual aids because when I was using the prototype, I wanted to make all the lights light up and it is nice to see your progress."

Participants also included additional metrics as part of their visualization. P3 added a textual display to the left of the knee angle visualization that tracked number of repetitions and hold time (Figure 6) for each repetition. The buttons below the textual display were used to set the respective goals for the two metrics (e.g., 5 repetitions total or 15 second hold time) and the start/stop buttons were used to mark the beginning and the end of a session. P3 also included a break timer button that would vibrate at the end of a minute to help patients accurately track the rest time between sets. The use of interactive elements such as buttons and alternative feedback mechanisms were also present in the other interfaces drawn by the participants. P2's interface drawing included an auditory cue to signal the accomplishment of a goal, in this case a particular knee angle (Figure 5). The knee angle goals were further visualized through a bar graph display so that one could see progress over time.

6. DISCUSSION

We observed that the participants' drawings were heavily influenced by PT Viz and the subsequent interfaces they were shown. As a consequence, we obtained practical interfaces that combined existing interface elements and new alternative feedback mechanisms in novel and useful ways. Based on these findings, we highlight four design considerations for informing future wearable technologies in this space.

6.1 Lifestyle and Portability

The term "at-home rehabilitation" is a misnomer. While some patients might perform their rehabilitation exercises solely at home, it is increasingly common for users to extend their rehabilitation practices to gyms, offices, and labs. Participants in our study often performed their exercises as part of other exercise routines at the gym or in-between classes. We acknowledge that this might be because many of the participants were students, however these away-from-clinic practices might be common considering the increasingly busy lifestyles of users. Moreover, given a prescription such as, "perform the knee extension exercise three times a day for 20 minutes," it is likely that at least one session might occur outside of a home setting. Thus, as designers, it behooves us to consider the lifestyles of users when designing wearable technologies for rehabilitation.

With PT Viz, one of the key ideas discussed by participants was the portability of the device. While this insight seems redundant, considering the already portable nature of wearable technologies, from an implementation standpoint this consideration has far reaching implications. Due to the intimate physical interface between body and device, portability includes taking into account physical effects such as weight, volume, heat, aesthetics, ruggedness, and comfort. All these design guidelines are important because users must carry these devices everyday for the duration of the recovery process, which can often last months to years. If we posit that our device provides feedback that is crucial to recovery [2], then we must also consider the adoption issues surrounding our technology. Issues such as aesthetics are especially important, considering that users might be performing these rehabilitation exercises in the presence of others at work or at a recreation center. A wearable device that is not visually appealing or stigmatizes the user as someone less abled may contribute to less use and noncompliance.

6.2 Support the Recovery Processes of Patients

The fundamental objective of any rehabilitation device is to aid the user in the path towards recovery. As such, the device must support a diverse group of patients' recovery processes with different conditions, diagnoses, prescriptions, recovery times, and treatment goals. The patients we encountered in our study represent a small subsection of this diversity, but even within this limited sample, we discovered that PT Viz is better suited for patients recovering from surgery or acute injury. In hindsight, this result seems somewhat obvious, but how would prior knowledge of the recovery processes affect the wearable interface design?

Let us consider patients recovering from ACL reconstructive surgery. As P2 informed us, her first post-surgery goal was to move her ankles and then straighten her knee. Immediately after surgery, her knee swelled and reduced based on her rehabilitation and self-care routines. Thus, any device created for immediately after surgery needs to support unhindered mobility of the knee and accommodate varying leg sizes. A sleeve based design rather than a two-piece enclosure would be more difficult to slip on. Moreover, the device needs to provide a basic awareness of knee bend in line with the recovery process. In contrast, users performing physical therapy to mitigate chronic pain would place a different set of requirements on the wearable interface since they already have much of their mobility. In this case, wearable interface designs need to detect subtle nuances in muscle activation and address psychological issues around patient motivation.

6.3 Multimodal Feedback

An interesting result of the prototype design activities was the introduction of multimodal feedback mechanisms that were not previously proposed by PT Viz or the alternative visualizations. Apart from visual displays, participants introduced vibrotactile and auditory feedback mechanisms for alerting the user about an event such as the end of break or the accomplishment of a goal. Indeed, research has shown performance improvements in tasks due to bimodal (audio and visual or tactile and visual) and trimodal (audio, tactile, and visual) over visual feedback alone [18]. One feedback strategy is to substitute one sensory channel for another. In the case of knee rehabilitation, one possibility is to use vibrotactile pulses of different frequencies to indicate to the user how close they are to a specified angle. Additionally, as P3 observed the visual display is not always visible when performing exercises. Thus, multimodal feedback mechanisms can support other exercises for knee rehabilitation.

We must acknowledge, however, the tradeoff between degree of automation in data collection, the value of the collection, and the feedback mechanisms used to notify the user. If we do not automate data collection enough, then we place a heavier burden on the user to manually track the information. But if we automate too much, then we rob the user of opportunities for reflection. In our study, we had two participants who eschewed the option to track number of sets when drawing their personal visualizations. They wanted to manually track something to stay attentive. P3 remarked,

> *"I think it is convenient to have something that keeps track of sets, but if you are really not paying that close of attention...that is something you should keep track of while doing physical therapy."*

Similarly, we must also be careful of how we employ the feedback mechanisms and their frequency of use in notifying the user. If we constantly bombard the user with visual, auditory, and vibrotactile cues about their physical therapy session, then users may ignore the feedback or become stressed and possibly have a performance decline. What are the cognitive implications of these feedback mechanisms when performing rehabilitation exercises that require focus and concentration? These issues with automation and user control are not peculiar to wearable technologies. Researchers in the area of personal informatics have faced similar problems when developing tools to help promote physical activity. They found that a fully automated system sometimes hinders users from keeping track of and making sense of their physical activity data [19]. The researchers suggested areas for further study including the need to explore an appropriate balance of automated technology and user control.

6.4 Wearable Affordances

We designed PT Viz with the idea that a user should be able to intuitively grasp the purpose and functionality of the device without needing too many instructions. While this was true for the enclosures and the visualization, participants encountered difficulties in attaching the bend sensor. The two enclosures were designed to resemble common knee braces that one might find in a pharmacy, however the bend sensor was a foreign object that caused confusion among the participants. From critiquing and analyzing our own design, we discovered that the bend sensor did not provide any affordances with respect to its usage. The term affordance refers to the properties of the object that provide strong clues as to how it could be used [20]. For example, if a door does not have a handle and instead has a push plate, then it is visually perceived to be push only. If instead the door has a fixed-handle then it is visually perceived to be pull only.

In our case, we had simply provided Velcro strips on both the thigh and calf enclosures to affix the bend sensor. There were no visual indicators that informed the user on how to attach the sensor. One way to solve this problem by using the concept of affordances is to use paired male-female magnetic snaps which not only provide strong visual cues but have physically attracting ends.

In designing wearable technologies for knee rehabilitation, we must consider the perceived affordances of the parts and materials we use because users will be ultimately interacting with tangible objects. Wearable interfaces in this space need not be complicated to provide value. A simplified wearable interface to accomplish a few carefully selected goals can improve the recovery processes of patients.

7. LIMITATIONS

We acknowledge that the study had a small number of participants - 2 men and 4 women primarily from a college background. Despite our small sample size, this study is valuable to the Pervasive Health community because it forms preliminary design considerations that can inform future research. A good example of such work is described in Mamykina et al.'s paper on diabetes technology where a preliminary health monitoring prototype was deployed and evaluated with 2 participants [21]. We get richer qualitative data with smaller samples to support iterative prototype design.

8. CONCLUSION

In this paper, we described the design and implementation of PT Viz, a wearable electronic knee rehabilitation device for visualizing knee bend through an electroluminescent display. To understand the design issues surrounding wearable interfaces for rehabilitation, we conducted a user study with six participants where we evaluated PT Viz and explored alternative wearable visualizations through prototype design activities. The findings support a wearable technology design that considers the lifestyles of users, supports the recovery processes of patients, employs multimodal feedback, and considers the perceived affordances of the design. We believe these findings provide valuable guidelines for future wearable technologies that serve as mediating artifacts in physical therapy.

Acknowledgments

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