Keppi: A Tangible User Interface for Self-Reporting Pain

Alexander T. Adams[1], Elizabeth L. Murnane[3], Phil Adams[1], Michael Elfenbein[1], Pamara F. Chang[4], Shruti Sannon[2], Geri Gay[1,2], Tanzeem Choudhury[1]
[1]Information Science, [2]Department of Communication, Cornell University,
{ata56, pja22, mse56, ss3464, gkg1, tkc28}@cornell.edu
[3]Computer Science, Stanford University, emurnane@stanford.edu
[4]Department of Communication, University of Cincinnati, changpf@ucmail.uc.edu

ABSTRACT
Motivated by the need to support those managing chronic pain, we report on the iterative design, development, and evaluation of Keppi, a novel pressure-based tangible user interface (TUI) for the self-report of pain intensity. In-lab studies with 28 participants found individuals were able to use Keppi to reliably report low, medium, and high pain as well as map squeeze pressure to pain level. Based on insights from these evaluations, we ultimately created a wearable version of Keppi with multiple form factors, including a necklace, bracelet, and keychain. Interviews indicated high receptivity to the wearable design, which satisfied additional user-identified needs (e.g., discreet and convenient) and highlighted key directions for the continued refinement of tangible devices for pain assessment.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces; J.3. Life and Medical Sciences: Health

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Tangible User Interfaces; Pressure-Based Input; Ecological Momentary Assessment; EMA; Self-Report; Chronic Pain

INTRODUCTION
Chronic pain (i.e., persistent, recurrent, or long-lasting pain) has been recognized by the World Health Organization as a serious public health problem around the globe. The worldwide prevalence of chronic pain is over 30% on average [20], and numbers are considerably worse for the aging population: over 50% of older adults and as many as 80% of older adults living in nursing homes experience chronic pain [23, 30]. A wide range of disease and demographic groups are impacted by chronic pain [26], though it is significantly correlated with indicators of poor socioeconomic status (e.g., lower household income and unemployment [40]) and is more common in women than men [24].

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Common chronic pain conditions include osteoarthritis, rheumatoid arthritis, lower back pain, migraines, and headaches as well as injury-related conditions and repetitive stress disorders. Patients with chronic pain are frequently severely debilitated and face major limitations in their ability to function or work. Further, chronic pain is associated with depression, sleep disturbance, fatigue, and decreased cognitive and physical abilities as well as overall reduced quality of life in terms of physical, psychological, and social well-being [5].

Chronic pain is traditionally assessed based on patient recall during doctor visits, typically in the form of a self-report response to one of several standard pen-and-paper or verbal measures. Such an approach faces problems, however, due to retrospective and reconstruction biases [58] and low test-retest reliability, especially for individuals with memory or other cognitive impairments [16]. These issues can be mitigated by Ecological Momentary Assessment (EMA), a data collection method that affords frequent, in-situ assessment of physiological and psychological data [66]. Using momentary reporting to assess pain has been previously validated [65] — though current at-home instruments (typically diaries) still face limitations, as they can suffer from misreporting and poor adherence, especially if cumbersome or inconvenient to use [9]. Aiming to relieve such burdens and improve data fidelity, some HCI researchers are interested in measuring pain through passive sensing [6]. However, "pain is what the patient tells us it is" [46] — i.e., a highly subjective experience; and as such, self-assessment is considered the best and truest descriptor of pain, making self-report instruments essential for its effective measurement and, in turn, treatment.

Altogether, this motivates the development of novel tools for chronic pain measurement that support in-situ, naturalistic self-assessment and remain reliable and low burden to use even over prolonged periods of time. In this paper, we pursue the design of a pressure-sensitive tangible user interface (TUI) that meets these requirements. We took this approach after observing the way people in moments of pain sometimes instinctually grasp the hand of a loved one, the arms of a chair, or some other object nearby. We were further inspired by the uncomplicated action of squeezing a stress ball, which can also be unobtrusive and very private. In seeking to integrate these types of interactions with intentional self-report, we make the following specific contributions:

- A series of identified design challenges and practical trade-offs important to take into account when developing pressure-sensitive user interfaces for pain assessment.
- Detailed hardware design specifications for three different versions of our TUI intended to meet these constraints and other user requirements that surfaced during studies.
- The findings of in-lab evaluations that demonstrate reporting reliability along with insights from interviews that increase understanding of individual characteristics, experiences, preferences, and contexts that can impact technology-mediated chronic pain management.
- A discussion of considerations we discovered in developing a TUI (e.g., pressure perceptions, alternatives to squeeze-based input, and more or less appropriate use cases for a device in light of privacy concerns) together with concrete strategies for addressing such issues going forward.

The remainder of the paper is organized as follows. We begin with background about pain and its assessment, including via technology, along with a review of previous work on pressure-based input devices. We then detail our iterative design, development, and evaluation process to create a tangible device for self-reporting pain, including a more discreet, wearable version. Next, we report quantitative and qualitative results from our user studies with individuals experiencing various types of chronic pain. We conclude by reflecting on the findings from our research, including a discussion of alternative approaches and other opportunities for future work.

RELATED WORK

Assessing Pain

When it comes to assessing pain, there can be multiple dimensions to capture about the experience. Early research suggested three dimensions: discriminative, motivational-affective, and cognitive-evaluative [49] based on the neurophysiology of pain mechanisms, with the words patients use to describe their pain often mapping to these dimensions [48]. More recently, pain has come to be characterized in terms of two dimensions commonly referred to as pain intensity and pain interference. Going beyond the mere presence of pain, intensity represents the severity of that pain (i.e, how much it hurts) while interference reflects how much the pain interferes with functioning, including physical activities, mood, and social relationships (i.e., what the pain prevents a person from doing) [15]. Given a consensus that “intensity is without a doubt the most salient dimension of pain" [67], most of today’s pain assessment scales and methods (including our research presented in this paper) focus on measuring pain intensity.

Specifically, instruments commonly employed for self-reporting pain intensity include the Numerical Rating Scale (NRS) [21], a version of the Faces Pain Scale (FPS) [7, 33], a Pain Body Map (PBM) [37], or a variation of the Visual Analog Scale (VAS) [29, 35]. FPS and PBM use drawings and visual representations to collect pain data, while NRS and VAS are unidimensional measures of pain intensity that typically use a horizontal or vertical line with text descriptors at each end that describe the extremes of the scale (e.g., "no pain" and "pain as bad as it could be"). These instruments are clinically effective and generally straightforward to administer, but they face limitations. For instance, while test-retest reliability is normally high for the Visual Analogue Scale for Pain (VAS-P), this reliability is lower among illiterate patients [22]. Or, while completion of the NRS is usually easy and relatively brief (less than one minute), it may be inadequate for measuring complex changes in pain levels and is not intended for use with all ages [70]. Considering pain fluctuates, it is important to capture this fluidity of pain intensity throughout everyday life, via more quick, frequent, and in-situ self-reporting techniques.

Using Technology to Support Pain Self-Assessment

As time goes on, measures for self-reporting pain are increasingly being incorporated into digital tools. Research typically confirms that measures remain valid when deployed electronically and that the electronic version is preferred by participants (although it is not clear if it is a function of novelty, utility, user experience, or something else) [25]. As a result, there is a broad practice of deploying variations of the above measures or similar descriptive scales via technology.

Many tools focus on utilizing the smartphone medium due to its increasing ubiquity [42]. Smartphone applications developed by the academic community include "ePAL" [2] and "Painometer" [18], which deliver standard pain intensity scales such as FPS and NRS. "Meter" provides a suite of self-reporting interfaces that include both standard instruments (e.g., FPS, NRS, VAS) as well as novel designs (e.g., using pictures or metaphors) [1]. "Pain Squad" [64] is designed to support pain management for adolescents with cancer and provides an electronic pain diary of 20 questions including VAS scales, body maps, selectable words, and free-text. A number of commercial pain assessment apps are available as well [57], although while some are designed in an evidence-based way, they largely remain unevaluated [17, 42]. Research is also increasingly exploring alternative styles of input and interaction to self-report pain. For example, "BodyDiagrams" [38] is an online tool that enables a user to indicate pain intensity through drawings and annotations. Similar work has developed tablet- and web-based programs for marking pain drawings [36]. "PainDroid" [60] is a multimodal smartphone application that augments body-model based pain assessment with virtual reality (VR) functionality.

Such technological advancements are encouraging steps toward enhancing the self-assessment of pain and have been shown to facilitate pain management [47, 69] as well as reduce associated emotional distress [41]. However, scholars have called for more thorough evaluations of such tools to confidently establish both their quality and usability [17, 54]. Further, existing technologies for self-reporting pain still face several barriers to repeated, prolonged usage throughout daily life, in that their employed measures can be too time-consuming to support frequent use; are not discreet enough for individuals to feel comfortable using them in some contexts (e.g., social situations); and can be too burdensome to use [45], especially for individuals with cognitive impairments [62], low digital skills, or functional limitations (e.g., visual deficits) [52].

Addressing these challenges requires the design of novel self-report tools that better support frequent and unobtrusive use through intuitive, natural interactions. We identified a personal device that is portable and tangible (i.e., supports input via touch) as a desirable approach.

Pressure-Based User Input

Speaking to the value of pressure-based interaction, research has identified that pressure sensors are inexpensive, leverage and extend users' familiarity with interaction styles, and, unlike tilt or motion sensors, do not require additional gross physical motions [14]. Numerous studies have explored such pressure-based input actions. For example, "haptic conviction widgets" have been developed for users to convey their degree of conviction in performing an action, such as applying considerable force to permanently delete files from a trash can [13]. A single-handed device made of pressure-sensitive, multi-functional strips found that linear strips afforded a number of interaction techniques, including controlling an on-screen slider or spring wheel, and that participants learned very quickly to exert the proper amounts of pressure [8]. Other work has investigated pressure-based input with a stylus, finding an individual's input control depends on there being a fixed number (at most six) of discrete pressure levels available [53]. This has been confirmed by other research that finds three to seven discrete pressure levels allow accurate control of input [12, 50]. This same work further indicates that greater force degrades the input experience, from both performance and comfort perspectives. Combined with prior research that establishes that four levels of pain intensity are sufficient for assessment [39], we focus in this paper on developing a tool that supports reporting no, low, medium, and high pain, to balance practical hardware constraints with scientific robustness.

Systems are typically based around a single-sided 'push' or 'tap' style interaction. Given our inspiration of squeezing a chair arm, stress ball, or loved one's hand, we focus on two-sided pressure-based input instead — that is, a 'grasp' or 'squeeze' style interaction. Recent research has found that grasping or squeezing outperforms single-sided pressure-based input for tasks such as selecting a target and inputting a desired force [63]. Further, this sort of squeezing has been experimentally confirmed as a viable input technique for device interaction, though similar to single-sided pressure, performance degrades and input errors increase when greater force targets are used over longer time periods (specifically, longer than approximately three seconds) [34].

Regarding the use of pressure to measure health-related information specifically, researchers have used pressure values for assessing emotions or stress. The "Emotion Slider", developed for self-reporting affect, is a long box with a round handle that can be pushed and pulled along the box's main axis and that encounters resistance when pushed toward the ends of the device due to contained springs [43]. As another example, greater typing and mouse pressure have been associated with higher stress levels based on self-report and electrodermal activity [32]. This experiment made us of a pressure-sensitive keyboard [19] and capacitive mouse, and further found through user testing that individuals were able to very quickly learn to control their input pressure. The closest previous work to our own is a project from several decades ago that had subjects squeeze a bag in proportion to their pain severity [35]. More recently, portable "pain meters" that provide buttons to report pain levels have been developed as part of a pain monitoring system designed for use by nurses and patients in hospital and home environments [3]. However, most tangible interfaces used in the context of pain are geared toward health care professionals, rather than patients [56].

Altogether, there is thus a compelling yet unseized opportunity to pursue the development of pressure-based pain self-report interfaces. In addition, novel contributions to the pressure-based user input literature are particularly timely given the widespread interest in and release of commercial devices with variable pressure inputs (e.g., Apple's "Force Touch" and more sensitive "3D Touch" technologies [4]).

METHOD

Ideation and Exploration

As mentioned, our initial idea to design a pressure-sensitive tangible user interface (TUI) for self-reporting pain was inspired in part by a stress ball. Exploring this idea led us to create a compressible stick, which has many of the same affordances as a ball and not nearly as many physical design challenges. The creation of this device, which we call "Keppi", was an iterative, experimental process during which we explored a variety of commodity pressure, flex, piezo-electric, and force sensors, all with numerous different attributes such as flexibility, pressure thresholds, shape, and size.

The primary issues we had with the commodity force-sensitive resistors (FSRs) related to form factor — the cylindrical shape of the stick did not allow the sensor to sit flush against a rigid surface, which caused the signal to be very unpredictable and noisy; plus, in order to cover enough surface area, many sensors would have been required. Another problem we found with commodity FSRs is that they generally cannot withstand the force of a person's grip. We did have some success with flex sensors, but they can be costly and easily damaged. We also saw promise in some piezo-electric ceramic rings; however, they are quite fragile and subject to fracture, which could be harmful (e.g., by cutting a user during squeezing).

After exploring all of these possibilities and weighing their (dis)advantages, we chose to design and experiment with custom FSRs. To engineer a robust FSR that could handle high thresholds of pressure while also having good resolution and sensitivity to lower pressures, we tested out different force-sensitive resistive materials, material amounts, electrode types and designs, and housings and mechanical designs. We concurrently developed and benchmarked these prototypes through a series of tests such as applying constant force with weights and clamps, testing the recovery time for various impacts and surface compressions, and exploring the effect of different types of leads — both how they affect the change in resistance during compression as well as how they hold up physically given they are subject to bending. The next section provides further details of our development process and the hardware specifications for the successive versions of our Keppi TUI.

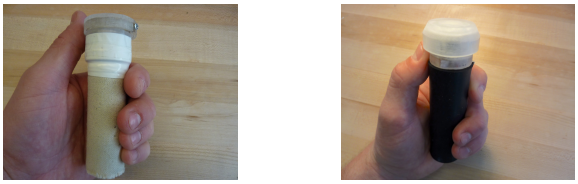

Figure 1. Keppi Version 1 (left) and Version 2 (right)

Hardware Design

After running several pilot studies to decide upon the basic structure (e.g., weight, height, diameter) of our envisioned compressible stick, we produced a fully functional prototype of Keppi. This version 1 (V1) as well as version 2 (V2) can be seen in Figure 1, held with the grip we found individuals typically applied when using the device. While these two versions are very similar, their main differences relate to FSR design and compressibility, as described below.

Force-Sensitive Resistor

The design of the FSR in our first version consisted of a core electrode (copper tape) that covered the core shaft inside of the device, which was covered in medium density conductive foam. On top of this foam was an outer electrode that wrapped all the way around the foam, as seen in Figure 2. The electrodes had industrial grade aluminum foil leads soldered into a board mounted at the top of the core. This entire system was covered in electrical tape to keep it isolated and stable. The outer electrode had a 3V charge pass through it, which traveled through the conductive foam to the core electrode. The output of the core electrode was passed into a signal conditioning circuit, which we describe in the section *Electronics*. When the foam was compressed, the density of the material would change, inherently changing the resistance.

This design provided good resolution (approximately 30 points) and could handle substantial force. However, we found two major drawbacks. Specifically, the outer electrode's lead encountered a great deal of movement, and the outer electrode would cause the conductive foam to temporarily deform when a large change in pressure occurred. This resulted in the output signal sometimes getting stuck or behaving erratically while the material was returning to its neutral state. When heavy or rapid compression took place, the outer electrode would crinkle, deforming its shape and the foam's resistive qualities.

We created V2 to address these problems with V1, with a primary focus on creating a more stable FSR and increasing

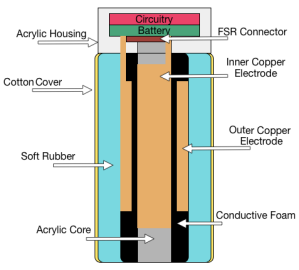

Figure 2. V1 sensor diagram

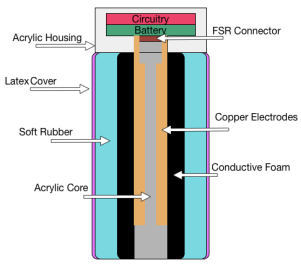

Figure 3. V2 sensor diagram

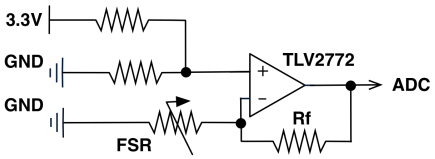

Figure 4. Electronic schematic for Keppi V1 and V2

resolution. We designed the V2 FSR using two core electrode plates, each covering approximately half of the core shaft, as seen in Figure 3. This design immediately resolved the issue of mechanical wear on the FSR's leads. The two electrodes were wrapped with the same conductive foam as V1; however instead of covering this in tape, we used thread evenly wrapped around to gently hold the components in place. This was then covered in a thin latex sleeve in order to prevent the somewhat sticky outer soft rubber layer from damaging the foam. This FSR demonstrated a much higher resolution due to the proximity and size of the electrodes — affording the user more control over the signal.

Electronics

Keppi's electronic core (in both V1 and V2) consists of three main components: analogue signal conditioning, a microprocessor, and Bluetooth Low Energy (BLE) (see Figure 4). For the signal conditioning circuit, we made use of a transimpedance (current to voltage) op-amp design using the Texas Instruments TLV2772 op-amp. We used a combined microprocessor/BLE chip (RFD22301) to read the signal with its onboard 10-bit Analog to Digital Convertor (ADC) and transmit it to a mobile device via BLE (see Figure 5).

The circuit also has a 3V, 0.25mA voltage regulator, breakout cable for USB programming, and connects directly to a 110mAh Polymer Lithium Ion Battery, which we attached to a micro-USB charging circuit (see Figure 6). All of these components fit in an acrylic housing on the device, in which they connect directly to the FSR. In order to manage voltage irregularity in the ADC, a signal is sent directly from the voltage regulator to another ADC, which can then be used as a coefficient to eliminate noise on the signal.

Casing

A key consideration when creating technologies that utilize force-sensitive resistive materials is the design of the enclosure, especially when dealing with materials that are constantly being handled. In our case, it was particularly important to balance physical constraints with a user's ability to exert pressure in a meaningful way. Based on complaints about V1's too-stiff cotton cover, the solution we arrived at in V2 was to use a

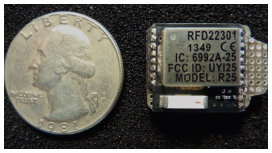

Figure 5. BLE and microprocessing unit (RFD22301)

Figure 6. Electronics outside the housing connected to the FSR

flexible, thin latex that was firm enough to hold everything together while also allowing the sensor to return to a normal state rapidly, even after elongated periods of intense manipulation. Only the top of the device therefore demonstrates physical constraint, in order to prevent the sensor from being pulled off or the electrodes from being damaged.

Making it Squishy

We explored many different materials in order the find the optimal balance between providing a squishy, stress ball-like texture and affording users control over the input pressure. Ultimately, we selected a soft, polyurethane rubber (Durometer 40A) that we used in both V1 and V2. This material combined with the soft, compressible conductive foam underneath provided a good balance in tactile sensation and control. It also demonstrated rapid recovery so that the sensor could easily normalize, and it was extremely resilient to tearing or misshaping.

Making It Wearable

Prior research has found that when given the choice between a mobile application and a wearable device for self-reporting pain, over 2/3 of people prefer the wearable option [55]. Such findings together with feedback from our user evaluations of V1 and V2 led us to finally create a wearable Keppi (V3). We settled on the designs shown in Figure 7, a coin shaped disk and a small cylinder. We fabricated both as a necklace and as a keychain, though they could be modified to take on many form factors. To issue a self-report, either device can be squeezed between the thumb and the side of the index finger or by gripping the device in the palm of the hand.

The primary difference between V3 and the previous versions (beside size and shape) is the electrode design, type of foam used in the FSR, and casing. V3's electrode design, as seen in Figure 8, was changed to better balance how the distribution of pressure affected output. We used several different materials, including various rubbers and foams, mixed with piezo-resistive foams and films to achieve a level of compression preferred by users, and we covered V3 in an elastic cloth that is commonly used as a medical wrap. In addition, considering V3's move to a smaller size, we made modifications to the electronics that would maintain resolution within a small change in resistance. Specifically, we used a Wheatstone bridge amplification circuit, as seen in Figure 9, instead of the transimpedance amplifier circuit for signal conditioning used in V1 and V2. We also moved the electronics in such a way to suit the new size and design of the FSR, connecting them with silicon wire that additionally served as a chain for the device.

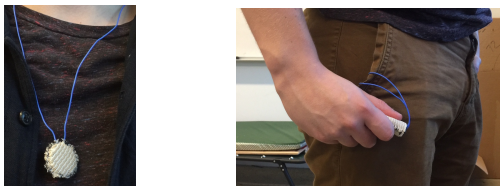

Figure 7. Keppi V3 worn as a necklace (left) and as a keychain (right)

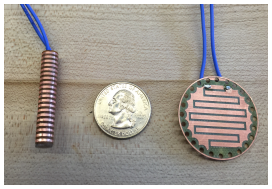

Figure 8. Electrodes for two variations of Keppi V3

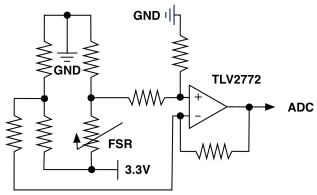

Figure 9. Schematic for Keppi V3

User Studies

V1 & V2 Evaluation

To evaluate the feasibility and usability of our first two versions of Keppi, we conducted in-lab studies with 28 participants (10 females, 18 males ranging from 19–38 years old, with an average age of 25) recruited via email, in-person intercept, and snowball sampling. 10 participants were experiencing some form of chronic pain (e.g., injury-related ankle or neck pain, frequent migraines, lower back pain). Compensation was $10, and the Cornell IRB approved all procedures.

We tested two key assumptions to verify Keppi's feasibility: (i) can users make sense of and use the device to map intended pain level to squeeze intensity and (ii) can this input technique achieve sufficient reporting resolution to capture the four pain levels (no/low/medium/high) the literature indicates is necessary for assessment. This sort of evaluation was best suited to a lab study, which also allowed us to observe and question participants as part of qualitatively appraising reactions and deriving design implications.

Participants were given V1 or V2 to hold and asked for their initial impressions of the device and how it might be used to report a value such as pain intensity. After confirming or explaining Keppi's mapping from pressure to pain, participants familiarized themselves with this mapping by squeezing the device while receiving real-time visual feedback of squeeze intensity on a slider widget (no numbers were displayed). Once familiarized, participants completed three tasks while receiving visual feedback of the pressure they were applying:

1. Report the highest possible value (hardest squeeze).
2. Report a medium value and release, a high value and release, a low value and release.
3. Watch an animation of a red circle tracing a series of sinusoidal curves and a step function (see Figure 10), and use Keppi to continuously report the values traced.

Participants then repeated these three tasks, this time without visual feedback of their applied pressure. To conclude the study session, we interviewed participants about their overall experience with Keppi.

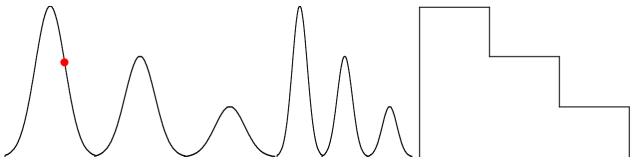

Figure 10. Sinusoidal and step function curves for continuous tracking tasks

The first 10 participants (P1–P10) used V1 and were provided visual feedback on a smartphone, with Keppi transmitting data via Bluetooth LE. The next 18 participants (P11–P28) used V2, which had been constructed by that time, and were provided visual feedback on a laptop screen, with Keppi transmitting data via a serial port. Given the previously described improvements of Keppi V2 over V1, we report quantitative results only from the 18 participants using V2, though qualitative findings come from all participants who used V1, V2, or V3.

V3 Evaluation

To assess receptivity and other qualitative reactions toward V3, we conducted in-person 30–60 minute semi-structured interviews with 7 additional participants (P29–P35) recruited through email and snowball sampling. All were older adults (5 females, 2 males ranging from 58–72 years old, with an average age of 65) with various types of chronic pain (e.g., arthritis, rotator cuff injury, knee replacement surgery). Compensation was $20, and the Cornell IRB approved all procedures.

All interviews from the evaluations of V1, V2, and V3 were audio-recorded, transcribed verbatim, and edited to remove identifiers and other references that might identify the participants and anyone they mentioned. We analyzed this data using thematic analysis [10] whereby we collaboratively and iteratively refined themes.

RESULTS

Quantitative Findings

For quantitative analysis, we separated out our data from the low/medium/high reporting task from the data from the continuous tracking task. For each participant, we have data from the condition where visual feedback was provided (VF) and the condition where no visual feedback was provided (noVF).

As shown in Figure 11, in the low/medium/high reporting task, we find via a one-way ANOVA that the means of none/low/medium/high reporting levels are significantly different in both the VF ($p < 0.0001, F = 144.12, DoF = 2$) and noVF ($p < 0.0001, F = 61.73, DoF = 2$) conditions, as well as when we ignore the visual condition and average them together ($p < 0.0001, F = 132.46, DoF = 2$). A two-way ANOVA between the VF and noVF conditions overall shows no significant difference ($p = 0.78, F = 0.25, DoF = 2$), indicating that participants were able to report these varying intensities both with and without visual feedback.

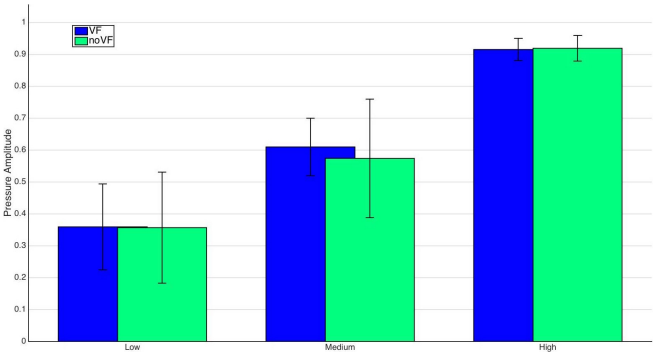

Figure 11. Participants were able to report low, medium, and high levels of pain intensity (no pain is 0) with visual feedback (VF) or no visual feedback (noVF)

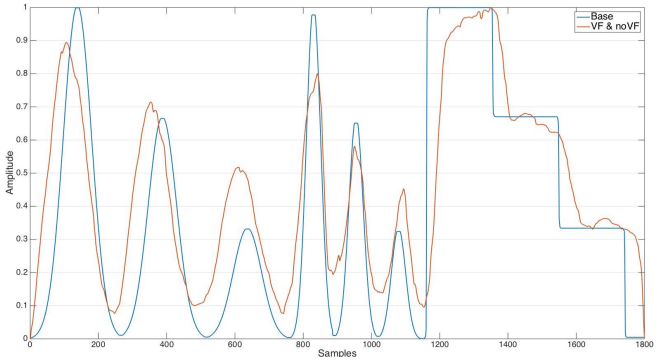

Figure 12. Visual comparison of the baseline curve (blue) and normalized and averaged continuous tracking data, over all data (orange)

To analyze the continuous tracking task, we prepared the data by normalizing both the baseline curve and the user-tracking data, to account for individual differences in squeeze pressure; we converted to 0-1 using min/max normalization according to the squeeze range exerted by each participant (though it would be possible to translate to any range — e.g., the anchors of a standard instrument). It was not necessary to normalize or fit the data in the x dimension, as it was equally spaced 1D data at the same sampling resolutions. We then examined how well participants were able to track the baseline curve using Keppi. A visual inspection of the data (see Figure 12) indicated that participants on average tracked the baseline curve very well. Performing a cross-correlation of baseline and VF, baseline and noVF, and VF and noVF (see Figure 13) confirmed that each of these series were pairwise highly cross-correlated (0.98 w/lag = -0.044 sec, 0.93 w/lag = 0.1556 sec, and 0.92 w/lag = -0.0667 sec). Cross-correlation is a measure of the similarity of two series as a function of the lag of one relative to the other; in our data, we neither anticipated nor found a lag (participants tracked the baseline curve in real-time), so the peak in the cross-correlation plot is at lag=0. Similar to the visual inspection, this result shows that participants were able to very closely track the baseline curve in the continuous tracking task, both with and without visual feedback.

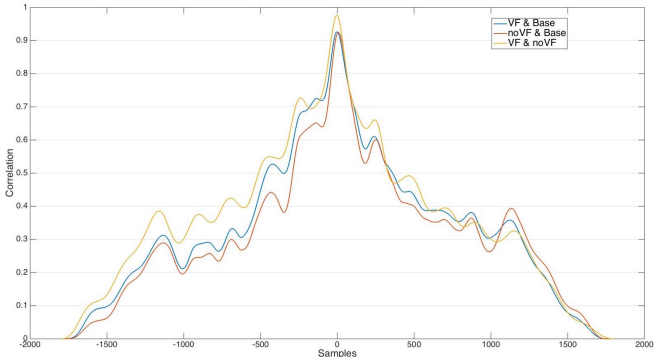

Figure 13. Cross-correlation of Keppi continuous tracking task data: VF vs baseline (blue), noVF vs baseline (red), and VF vs noVF (yellow). The series are all highly correlated

Qualitative Findings

Reactions and Assumptions

When initially handed Keppi V1 or V2 and asked how they might use it to report pain levels, many respondents (correctly) assumed squeezing to be the interaction modality. The squishy stick form factor invites such a grip. Our design inspirations may also have been evident given multiple participants suggested Keppi was like a stress ball. Two thought it might be a microphone, and one thought Keppi might *"test my physiological status while holding it"* (P9) — perhaps thinking of the handles on exercise machines that infer heart rate when held.

After interacting with V1/V2 for some time, we invited participants to describe the device in three words. Many reacted positively, viewing Keppi as "convenient", "useful", "intuitive", and "easy-to-use", though reactions regarding portability, texture, and overall appeal were sometimes mixed. Some perceived V1/V2 as "compact", "light", and "mobile", while others found it "bulky" and "heavy". Most regarded the device as "fun", "squishy", and to "feel good to hold", but a few thought the texture felt "strange". And while Keppi was seen as "advanced", "innovative", and "technological", it came across as "medical", "confusing", and "weird" in some cases.

Regarding V3, while two participants thought it resembled a treatment apparatus that would administer some sort of drug or electrical pulse to the area where it was applied, all participants quickly warmed to the idea of using V3 to self-report pain.

Intuitions and Reservations

Participants on the whole thought the mapping from squeeze intensity to pain level made sense for all Keppi versions — e.g., *"It is pretty intuitive, I naturally relate pain to more squeezing"* (P5). The majority thought squeezing was a natural interaction, associating higher levels of pain with harder squeezes — e.g., *"If it's a small pain that I want to record, probably a quick squeeze would mean a low amount of pain. If it was longer and harder, it would mean more pain"* (P29). Keppi was also seen as a potential outlet for pain, with squeezing as a way to release and externalize negative pain perceptions.

Two participants, however, thought pressure was too subjective and found it more intuitive to map pain level to the number of squeezes or the length of a squeeze rather than the intensity of a squeeze — e.g., *"I think squeezing it 1–5 seconds. 1 second for a quick, sharp pain; 5 seconds if it's really, really intense. Holding onto it 5 seconds is not too long... Or, you could press it 5 times. That'd be better - the number of touches instead of the length of them. That's my preference"* (P34).

Entering input in such ways might help mitigate reservations expressed by other participants regarding scenarios in which squeezing to report pain would be less suitable — e.g., *"If I have a headache, I don't want to do anything to force more pressure"* (P7). Another participant (P35) similarly pointed out that any sort of squeezing might be problematic given her arthritic hand pain and suggested a dial or knob instead. Two other participants likewise suggested incorporating buttons onto the device (P32), not unlike an electronic car key fob (P33), in order to remove some of the ambiguity and potential inconsistency they associated with pressure-based input.

Other participants were concerned about the likelihood of unintentional logging, given that a device like Keppi, especially the smaller V3, could easily be sat on, pressed against, or otherwise triggered accidentally. They thought specific, customizable patterns of touch, as opposed to raw pressure alone, might be helpful in avoiding such misreports. P6 suggested that getting some form of feedback from Keppi after logging a pain episode would be helpful in reducing his worry about accidental or failed recording.

Reporting Confirmation and Feedback

We heard mixed responses when we probed participants' thoughts about these sorts of feedback signals, which could indicate that an interaction was detected, provide confirmation that a report had been received, or signify the input value captured. Just under half of participants expressed interest in either a light-based or vibration-based indicator of a self-report being received. The remainder of participants, however, felt that additional feedback either was not necessary or at least not all the time, namely because the tactile sensation of squeezing Keppi itself provided such cues.

Such perspectives from participants who interacted with V1 motivated us to remove its cloth cover and make V2 easier to squeeze, as V1 was widely considered not squishy enough — e.g., *"I would like it be more elastic because when I want to squeeze with more strength, I feel too much resistance with this"* (P2). This issue of squishiness was one of both hedonics as well as perceived reporting range and resolution — with a squishier Keppi, participants believed it would be easier to report more values more accurately.

Portability and Ubiquity

In daily life, most participants imagined carrying Keppi V1/V2 in trouser pockets, jacket pockets, and bags — e.g., *"in the side pocket of my backpack; it's the exact same size as my mace which I keep there too"* (P6). P10, who engaged with V1, reported wanting to wear Keppi around the neck; however, some perceived a bulkiness or heaviness problem with V1 and V2 that could impact portability.

In contrast, none of the participants who engaged with V3 found it to be bulky or heavy, and most preferred the flat, coin-shaped form factor over the cylindrical shape akin to a miniature V1/V2. They envisioned wearing the device as a necklace or on one's wrist, belt, or keychain. However, not all participants shared the same viewpoint when it came to wearability. For example, two participants (one female, one male) wanted to wear Keppi V3 around the neck (e.g., because it fit with one participant's aesthetic sense and fondness for necklaces); while other participants were adamantly opposed to that idea because it would be *"obnoxious"* (P29), *"too obvious and not fashionable enough"* (P33), or would exacerbate pre-existing neck pain (P35).

Although we did not ask about the use of Keppi in a clinical environment, several participants observed that the device could be integrated into such settings too. For example, P7 observed, *"If I am having my teeth removed, I cannot communicate with the doctor. This device could be used to gauge pain scales to the doctor based on the force I use on the device."*

Accessible and Inconspicuous

Regardless of the specific look-and-feel of the device, two qualities were most important to participants: they wanted a device to be handy and discreet. First, participants explained that it was important to have the device easily accessible throughout the day (including while sleeping for P6), which did make a body-worn Keppi more appealing. Most participants believed a wristband might be more accessible and less likely to be lost compared to, for instance, a keychain, which at least two participants mentioned often not carrying with them.

The second feature participants strongly valued in a logging device like Keppi was for it to be inconspicuous and unlikely to draw attention. It was important that Keppi could be easily concealed (for instance by slipping it under a shirt) or that it could be passed off as a common fitness device — e.g., *"I tend to be more private about my pain. I don't want to talk to people about it. Don't want them to know I'm in pain. I don't want them coming up and saying to me, 'What is that little thing that you're squeezing?'"* (P29). One participant pointed out that an aesthetic external casing could help: *"If it had different covers, multicolored, that you could slip on, slip off, be interchangeable, then it becomes fashion instead of just a medical device"* (P34). Several participants emphasized that this was not because they were ashamed of their pain or wanted to hide the fact that they had a pain condition (which some explained was evident anyway, given that they carried canes, had noticeable trouble walking, or frequently massaged a painful body part). Rather, those individuals explained that they just *"don't want to make a big deal out of it"* (P35).

While participants appreciated the ability of the more modest V3 to be discreet and privacy-sensitive, participants described social benefits that could stem from more overt use as well. For example, one participant noted that if his family witnessed him trying to log pain with Keppi, they would be comforted that he was taking proactive steps to manage his condition; and another participant said she would like to use the collected data to "prove" she was experiencing severe pain in order to gain empathy from her spouse. Logs of pain data could similarly supply credibility when discussing treatments with doctors, as participants explained Keppi could help them substantiate intuitions about how their pain fluctuates with self-tracked evidence or help overcome the limitations of retrospective recall they normally face when trying to convey their recent pain experiences during clinical visits. Some participants were also interested in seeing their own data to learn about patterns in their pain and its links with specific behaviors and contexts.

DISCUSSION

To address the serious public health issue of chronic pain and the main limitations of existing pain assessment approaches (namely, poor usability for users with cognitive or visual impairments or low digital skills, time-consuming reporting that is limited to the point-of-care, and privacy concerns), all of which can impact accuracy and adherence, this research has explored the iterative, user-centered development of novel tangible interfaces that support in-situ, momentary, reliable self-assessment in an intuitive and discreet manner. Specifically, all versions of our Keppi device support natural interactions via touch as well as private reporting given the device can be placed in a pocket or purse and used inconspicuously, with V3 especially able to blend in and counteract potential stigma. Keppi also provides accurate measurement, with V2 delivering a more stable pressure sensor. Additionally, the portability of all Keppi versions enables ecological momentary assessment; plus frequent, quick use is promoted, as a squeeze issues a self-report in seconds, with the wearable, more lightweight V3 further enhancing integration with daily activities.

This problem space posed a number of significant technical and user oriented challenges. By detailing our design process and proposed solutions to encountered constraints (e.g., from ideas on constructing casings, to selecting appropriate materials, to creating a stable pressure sensor that does not skew over time and affords sufficient resolution), we aimed to provide guidance that will be useful for others creating similar hardware for use in the domain of pain or other application areas. Altogether, our approaches balanced issues and goals related to physical constraints, durability, input control and sensitivity, tactile sensation and comfort, and user experience. Our work made use of a custom sensor for detecting physical pressure, covered in a soft rubber, and was the first systematic test of a two-sided, grip-style interface designed to support pain reporting through squeezing.

While there is a precedent in the older adult population for dedicated health devices (e.g., emergency alert systems worn as necklaces or bracelets) and a history of dedicated self-report devices in the behavioral literature (e.g., wrist-worn bands [44]), there is a lack of work into dedicated TUIs for the EMA-style self-report of chronic pain. Overall, our studies indicate that an unobtrusive, portable TUI like Keppi would be positively received by a diverse set of individuals experiencing chronic pain, including older adults. At the same time, our findings illustrate the importance of understanding and accommodating personal preferences and nuances in various physical and aesthetic design choices — for instance by allowing a user to manipulate the device in one of several ways to report pain (e.g., using pressure, duration, or number of touches) or by providing ways to customize the device's appearance.

Going forward, we see a number of areas of compelling opportunity to pursue further, both to address limitations of our current work and to continue advancing the development of tangible user interfaces for health assessment.

Thinking Outside the Smartphone Box

Keppi indicates the strong potential for novel devices and wearables to support more naturalistic self-report. There are many contexts in which using a phone for self-report is impossible, impractical, or socially inappropriate — but within those same situations, tremendous benefit could be gained from meaningful self-report data. We imagine Keppi being worn on the body or kept in a pocket and being used unobtrusively, potentially without even removing it from that pocket. A similar pressure-based sensor could be wrapped around a car's steering wheel or embedded within the arms of a dentist chair. During group therapy, using Keppi to privately collect continuous or momentary self-reports from patients about comfort or specific feelings could be extremely valuable information for

the therapist, both during the session and as part of ongoing skill building. During athletic activities, grasping Keppi to capture moments of interest for later review or to record subjective performance indices could be highly informative. As fitness bands, smartwatches, and other commercial wearables become increasingly available, it will make sense to leverage them as part of scalable research that explores such scenarios and use cases where TUIs may be particularly worthwhile.

Pressure Perceptions and Feedback

While we were able to quantitatively distinguish between different values in applied squeeze pressure, participants did report a perception of less pressure control at lower pressure levels. There is some evidence from prior research that there may indeed be less pressure control at lower pressure levels [53], although other work has found no such association [61]. In the case of Keppi, the squeezable material wrapped around the device does not deform linearly; rather, it deforms more easily at lower pressures when it is relatively less dense — which may contribute to the perception of less control. This perception of differential control warrants further investigation, both in order to refine the user experience and to rule out its impact as a possible reporting bias.

One strategy for improving a user's understanding of and perceptual confidence in a tangible report is by providing feedback about the captured input. For instance, some prior work indicates visual feedback is necessary to ensure accurate pressure-based input [59, 63]. Our findings suggest, however, that visual feedback may not be necessary for accurate reporting at four levels of pain intensity — at least after training, as we observed participants apparently learning to calibrate self-reporting quite quickly. Given one intended use case for Keppi is an EMA-style day-to-day report, we imagine this repeated use would serve as a sort of continued training and familiarization with the input interaction and how to fine-tune one's reporting accuracy. Nevertheless, it is important to confirm that individuals can continue to accurately report using a TUI day after day and over long periods of time, and it would be similarly desirable to explore the incorporation of feedback, which might similarly adapt over time based on a user's experience level with the system.

Specifically, it is necessary to investigate the impact of on-device feedback that is provided mid-squeeze during the reporting action, post-squeeze to indicate that a report has been captured, or at both times. Our intuition is that, like a button, squeezing Keppi would provide sufficient haptic feedback that a report is taking place. It is also possible that as the user becomes familiar with Keppi and can see accumulated reports or end-of-day summaries of their collected data, post-squeeze feedback would become less useful. Still, some vibration on-device or a notification of some sort on a connected smartphone may be helpful. Alternative feedback formats could be supplied as well, such as audio, which previous research has suggested can be highly useful to improve pressure accuracy [71]. However, over time or in more public settings, such feedback might become intrusive or a privacy concern. For example, several participants noted that using LEDs and sound to provide feedback could particularly compromise discreetness, preferring a more subtle vibration. Exploring such trade-offs is a valuable next step.

Multimodal TUIs

Though diminished strength or grip ability is not terribly problematic since input sensitivity can be calibrated to each individual (e.g., by having a user complete tasks like those from our study as part of device setup), it is still the case that Keppi's squeeze-based reporting is not intended for use by individuals experiencing some form of hand or wrist pain or movement limitation. It has also become clear through our studies that for some conditions such as migraines, pressure-based reporting is less appropriate, as this can increase a sense of tension and pain. Participants suggested a number of alternative forms of tangible reporting, including squeezing the device a particular number of times or grasping the device for a particular length of time, rather than with a particular pressure. A desirable strategy would be to create a multimodal interface that can recognize any of those forms of tangible input, giving users the flexibility to report via whichever modality is best suited to their current abilities or preferences.

A related issue is that at higher pressure levels and for longer reporting tasks, pressure-based input may result in muscle fatigue [31, 50]. Empirically, the only participants to report fatigue when using Keppi were those seeking to achieve the high pressure value (i.e., to make the feedback slider widget go all the way to the top), and three participants experienced some fatigue after the continuous tracking task (which lasted 48 seconds and was performed twice). We believe user fatigue can be ameliorated in three ways: first, by increasing the squishiness of the device such that reporting across all pressure levels requires less exertion; second, by tailoring the reporting range to the individual, such that for any strength capability, reporting a high value requires, say, only 70% of a maximal squeeze; and third, by recognizing that in EMA-style reporting, there will rarely be reporting tasks that last longer than a few seconds, and in a clinical continuous-reporting setting, health care professionals can invite subjects to report a low baseline level of pain and then indicate only spikes in pain using Keppi, as appropriate.

Designing Around Discreetness

Individuals with chronic pain often feel that pain is associated with negative interpersonal perceptions. Prior research shows that the stigma associated with chronic pain influences individuals to want to further conceal their pain when they are experiencing it, consequently affecting social interactions [68] as well as their use of medical technologies [51]. To reduce the negative consequences of stigma, our V3 design considered these social elements of chronic pain by focusing on modest sizes, shapes, and understated aesthetics that were also flexible in terms of wearability to suit a user's preferred level of discretion (e.g., an in-pocket keychain versus a more prominent necklace). Participants who engaged with this version reported that they wanted and preferred a discreet device as they valued the ability to report pain without drawing unwanted attention, highlighting the importance of identifying and designing around the specific needs of chronic pain patients. Taken together, to help individuals with chronic pain

decrease their perception of stigma, decrease negative impacts of pain on wellness, and increase frequency of logging and in turn improve condition management, we believe it is important to continue developing and testing more compact and inconspicuous medical devices for pain reporting. Still, it may ultimately be necessary to produce versions that come in multiple sizes, including some on the larger side, so that individuals of different hand sizes can choose the version that fits and is the most comfortable for them.

Another idea that would both support unobtrusive self-reporting as well as eliminate the need to carry and reach for a separate device is embedding Keppi's sensors into everyday items, whereby the technology could measure pain while a person holds onto something as they naturally would. This may be particularly well-suited to populations for whom it is difficult to precisely capture self-perceptions; for instance, placing our pressure sensors in toy-based form factors, such as a squeezable stuffed animal, could help address well-known challenges of collecting self-assessments in the pediatric context. Squeezable input devices could be also valuable for tasks other than capturing pain (e.g., grip style interfaces like that of Keppi V1/V2 could have a number of potential applications in domains such as gaming and controllers).

At the same time, although discreet usage was a high priority for participants, some individuals did express that using Keppi publicly could be socially beneficial, by showing family members that patients were proactively managing their pain or helping participants gain empathy from others. Extant studies show that these types of positive interpersonal interactions with family members, friends, and perceived support from other social networks are linked to better pain-related outcomes [27, 28]. Such findings reinforce the need for medical devices like Keppi to be designed in personalized ways that suit individuals' social needs. In particular, it is important to keep in mind that for some users, unobtrusive designs may not be ideal. More generally, we also see a delicate design tension, wherein promoting more unobtrusive designs can potentially have negative effects by sending the implicit message that a pain condition *should* remain hidden, which could unintentionally contribute to a sense of stigma that the device was originally designed to reduce.

Limitations and Future Work

Lastly, we would like to point out some limitations to our current approach and the space these leave for future work.

First, even though recruitment in pain research is a known challenge, especially for already underserved groups including older adults [11], we did manage to engage with diverse samples that were well balanced in terms of age, gender, and type of pain (e.g., various congenital, injury-, surgery-, and age-related conditions). Still, chronic pain is multi-faceted, and it is imperative for future research to design for and investigate the effectiveness of devices like Keppi across more diverse groups, in order to better understand the specific mechanisms of the condition and the validity of self-reported pain data, the types of personalization that are necessary, and to help close health disparities and gaps in adequate care.

A related necessary next step is conducting field trials of devices in order to evaluate efficacy and usage in ecologically valid contexts, including in comparison to alternative assessment approaches (e.g., standard surveys delivered via EMA). In exploring a novel reporting medium, this paper's scope was to lay the groundwork for TUI-based pain assessment, while shedding light on user concerns. We therefore focused on open HCI questions around design, technical, and usability issues, with our study evaluating the basic building blocks of device interaction that are required for reliable pain measurement (a prerequisite before comparisons against standard instruments are meaningful). This was served well by lab studies, and most work to date on pressure-based interactions has been similarly conducted inside controlled laboratory settings. Going forward, it would therefore be highly valuable to pursue research aimed at addressing a number of real-world challenges, such as developing a high fidelity device that meets user needs we identified (aesthetics, customizability) and satisfies practical engineering problems (battery, storage/transmission/processing of collected data), with deployment studies undertaken to investigate real-world validity over time with populations of targeted abilities. Such in-situ, longitudinal data could also enhance our basic scientific understanding of the patterns of pain throughout everyday life as well as pain's relationship with various contributing factors.

Finally, in this research we focused on pain measurement, but an ultimate goal is for our work to go hand-in-hand with pain treatment. In particular, we see a compelling opportunity to use devices like Keppi in combination with intervention technologies (e.g., to deliver therapeutic suggestions that are tailored based on the results of a user's recent pain reports and/or holistic personal patterns). We believe this will be especially valuable for older adults with chronic pain, many of whom tend not to fully rate their pain or take other steps to effectively manage it, as they often times view their pain as part of the normal aging process.

CONCLUSION

This paper reports on the development of Keppi, a novel pressure-based user input device for self-reporting scalar values — in this case, of pain intensity. Constructing three versions of Keppi to meet a variety of identified design considerations, hardware constraints, and user preferences, we illustrated the feasibility, reliability, and usability of our approach to support the momentary self-assessment of pain levels through an unobtrusive and natural tangible interaction. In doing so, we additionally identified a range of factors (e.g., from a user's hand strength and pain type to general aesthetic and ergonomic issues) that can help guide others working in this space or on similar problems. Overall, our findings provide a number of implications for the continued development and evaluation of such self-assessment tools.

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