proCover: Sensory Augmentation of Prosthetic Limbs Using Smart Textile Covers

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Figure 1. With proCover, we present a novel concept for prosthetic-sensing wearables (1) based on smart textiles that allows amputees to "feel" again (2). In our studies, participants had less difficulties while performing the tasks with proCover (3). A mobile app enables user-driven creation and mapping of sensing regions (4). Finally, the sensor can also be used for tracking bodily positions (5).

ABSTRACT

Today's commercially available prosthetic limbs lack tactile sensation and feedback. Recent research in this domain focuses on sensor technologies designed to be directly embedded into future prostheses. We present a novel concept and prototype of a prosthetic-sensing wearable that offers a non-invasive, self-applicable and customizable approach for the sensory augmentation of present-day and future low to mid-range priced lower-limb prosthetics. From consultation with eight lower-limb amputees, we investigated the design space for prosthetic sensing wearables and developed novel interaction methods for dynamic, user-driven creation and mapping of sensing regions on the foot to wearable haptic feedback actuators. Based on a pilot-study with amputees, we assessed the utility of our design in scenarios brought up by the amputees and we summarize our findings to establish future directions for research into using smart textiles for the sensory enhancement of prosthetic limbs.

Author Keywords

Assistive technology; disability; smart textiles; prosthetic limbs; customization.

ACM Classification Keywords

K.4.2. [Computers and Society]: Social Issues – assistive technologies for persons with disabilities.

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INTRODUCTION

The design and construction of prostheses that can emulate a natural sense of touch is of growing research interest. Over the last few decades, a number of solutions have been developed for the detection of pressure, slip, heat and texture [20]. Many of these are centered upon embedded sensor technologies, with the objective of restoring sensing capabilities for people who have lost a limb and must therefore rely on a prosthesis.

However, many of the exciting innovations in this field will likely remain out of reach for most people, due to a multitude of factors pertaining to cost, accessibility, health status, and personal attitudes towards elective surgery. In fact, while there are already advanced prosthetics available on the market today, only a few people can leverage these high-end solutions. Rather, prosthetic limbs currently in use span from high-end EMG-controlled options to low-end options with basic mechanisms such as levers and straps. Ultimately, each prosthetic leg is a very individualized piece that depends heavily on factors such as one's level of amputation, activities, health conditions and expectations regarding functionality, as well as – very prominently – the monetary cost. The cost of a new prosthetic leg can be prohibitively expensive with costs ranging from 5,000 to 50,000 USD [28], which is not a onetime investment, as prosthetics have to be replaced every couple of years.

The range of research directions being taken in the domain of prosthetics is similarly broad. On one end, there is a demand for more low-cost and accessible solutions that has given rise to the popularity of 3D printed, or do-it-yourself (DIY) type prosthetics [7,8]. On the other end, there is a push towards developing advanced, high-end embeddable sensors and circuitry [11,23]. Our vision is to introduce a low-cost sensing wearable that can be applied retroactively to prosthetics to address this gap. The main contributions of this paper are:

- A *novel concept and prototype* of a textile wearable that can be self-applied and retroactively used to augment a wide range of lower-limb prosthetics with customized sensing capabilities, and which offers coverage beyond the plantar region of a prosthetic foot.
- *Novel interaction techniques* that allow for the customization of the sensing capabilities for prosthetic limbs. This includes the ability to both *dynamically* create distinct sensing regions from a high-resolution matrix of sensors and map them to feedback actuators.
- *Outline of the design space* for prosthetic sensing socks through extensive questionnaires and discussion with eight lower-limb amputees.
- An *early assessment* of the design of sensing textile wearables and their applicability to real users in different scenarios in a final pilot-study conducted with four lower-limb amputees.

In this paper, we present a prototype of a sensing sock that can be worn over a lower-limb prosthetic. We then explore the real-world potential of this concept in consultation with eight lower-limb amputees. Based on feedback gathered from them through questionnaires and discussion, we refine our prototype and incorporate features to address their concerns. Finally, we conduct an in-lab pilot-study with four of the previous eight study participants where they try on the sock and a knee-guard to assess their utility in the context of different scenarios that they had brought up in our first study.

RELATED WORK

'Feeling' in Biomechatronic Prosthetic Limbs

Recent advancements have made it possible to enable amputees to regain near-natural physical sensations through the use of artificial limbs that either directly or indirectly stimulate nerve endings. The use of electrodes, which encircle or pierce nerve bundles have facilitated real-time grasp perception as well as near-natural touch perception in prosthetic hands [17,22]. Artificial fingertips enabling wearers to discriminate between different textures have also been made possible with the use of an electrode inserted into a nerve in the arm [13]. However, in our work, we omit the use of invasive surgical procedures and implants, for which the process may be complex and for which the long-term effects are still being carefully studied [22] . Instead, we focus on wearable systems with haptic feedback mechanisms, which provide a less invasive and cost-effective alternative for sensory feedback for prosthetic legs.

Non-Invasive Sensory Feedback for Prosthetics

Many systems were designed to improve balance and gait. Fan et al. [4] created a haptic feedback system comprising of four piezoresistive force sensors mounted on a leather insole and corresponding pneumatic balloon actuators mounted on a cuff worn on the middle thigh. Sabolich et al. [18] used pressure sensors adhered to the plantar surface of the prosthetic foot to relay pressure information via transcutaneous electrical stimulation. Crea et al. [2] as well as ORPYX® Medical Technology [34] have also explored the use of vibration feedback on the thigh and back respectively, driven by pressure-information from sensorized shoe insoles. Employing a similar technique with vibration motors embedded in the prosthetic socket and driven by discrete force sensitive resistors (FSRs) mounted on a shoe insole, Egger [25] discovered that even near-natural sensations could be elicited when the motors were applied to a patch of skin with regrown nerves on the patient's stump. However, these works have taken a generalized approach to introduce sensing into lower-limb prosthetics, since they have been designed to offer the same sensor configuration for each user. Additionally, they appear "sole-focused" – positioning discrete, hardware-based pressure sensors located exclusively along the sole (plantar side of the foot). In contrast, our work seeks to explore the utility of sensing applied to the whole surface of the foot, including the edges and dorsal side of the foot, and investigates the possibility for user-driven sensor configurations.

Electronic Skin and Smart Textiles

Tactile sensing technologies such as electronic skin (e-skin), artificial skin with human-like sensory capabilities [6], have applications in a breadth of disciplines ranging from medicine to aerospace [24]. While non-textile based approaches exist to creating electronic skin, many of which are promising in the field of prosthetics [11,23,26], we choose to focus on a textile-based approach. The reason for this is that non-textile based approaches require that they are embedded or adhered to prosthetic limbs. In contrast, textile-based sensors can be worn over prosthetics like ordinary clothing, allowing for a more accessible means for sensing that can be easily applied to a broad spectrum of prosthetic limbs.

Flexible, stretchable piezoresistive fabric is available for a wide variety of pressure-sensing applications, ranging from e-skin for robotic limbs [15] to smart casts capable of detecting a good fit [3]. Such fabric also has applications in more traditional wearables. While Büscher et al. created a dataglove [1], Sensoria Fitness [29] developed commercially available smart socks with three embedded textile-based pressure sensors in the sole of each sock to monitor running. Pressure-sensitive socks have also been developed by Perrier et al. [16] to help prevent pressure foot ulcers in diabetic patients, while embroidered sensing socks were developed by Alphafit GmbH to manufacture custom fit shoes for people with diabetic foot syndrome [30,31,33]. The broad applicability of piezoresistive fabrics was demonstrated in FlexTiles [14], where the authors showed its applications in automobiles and furniture in addition to wearables. Yet none of these works considered using fabric to augment prosthetics, which in itself is a challenging problem since prosthetics take on various shapes and sizes.

Customization in Prosthetics

Prosthetics need to be highly customized to ensure a good physical fit for the wearer. However, more precedent is now being given not only to custom fits, but custom functionality and style. Hofmann et al. [7] explored how a design process can engage users to create assistive technology that better meets their own unique needs, and Torres [21] created a prosthetic arm which enables children to construct an arm from

LEGO®. In this paper, however, we will explore customization concerning sensing needs.

PROCOVER - SENSING SOCK PROTOTYPE

Design Considerations

On a high-level, we observe the creation of touch-sensitive prosthetics as having two main sides: sensing and feedback. Sensing involves the detection and measurement of a multitude of different sensations such as pressure, slip, temperature, and proprioception [20], while feedback refers to the means in which the system interacts with the human body to relay information. As shown in Figure 2, a mapping between these two aspects is necessary to transform data collected from sensors into signals, which the user can then interpret.

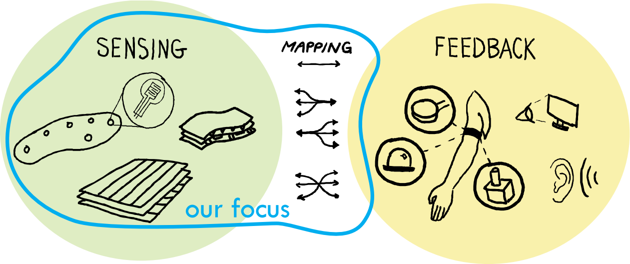

Figure 2. The problem domain can be viewed as having a sensor aspect mapped to a feedback aspect. In this work, our primary focus is on the sensing and mapping aspect.

While there are a multitude of feedback possibilities, in this work we focus on the sensing and mapping aspects of the problem. While it is recognized that users benefit from custom-fitting legs and ones that are programmable or specifically designed for different types of physical activities (e.g. walking, biking, running, climbing), we noticed that the approach taken to develop sensing solutions for prosthetic legs has been in contrast, inflexible. To our knowledge, no previous research has been conducted into using stretchy, high-resolution pressure-sensitive fabrics to create a wearable-sensing layer for prosthetics. However, we see potential for smart fabrics to provide novel, dynamic, customizable sensing solutions when combined with innovative mapping strategies. Using high-resolution pressure-sensitive fabrics would allow us to have enough pressure points at hand to change the mapping accordingly to the need of the different users and their custom-fitted legs as well as the different physical activities they engage in.

Implementation

proCover, pictured in Figure 1, consists of a textile-based sensor sock, electronics (wiring, and microcontrollers connected to a PC), and a vibrotactile band.

Textile-Based Sensor Construction

The sock consists of three fabric layers that are worn over one another (see Figure 3). The top and bottom layers are made of Narrow Stripe Zebra Fabric distributed by HITEK, characterized by alternating strips of conductive and non-conductive fabric. The strips are 8.125 mm and 9 mm wide respectively. A piezoresistive, stretchable knitted EeonTex LG-SLPA fabric is used as the middle layer. The zebra-fabric layers aligned orthogonally to one another and sandwiching the piezoresitive layer create a deformable and stretchable pressure-sensing matrix, which can be used to envelop complex 3D geometries such as that of a prosthetic foot. Each layer was sewn by machine with regular cotton thread using zigzag stitches to make them robust under stretch. Non-conductive fabric was sewn in to prevent column lines that travel down the length of the foot from shorting one another. This resulted in sock prototype containing 192 sensor intersections (16 rows × 12 columns), providing a resolution of 1.6 sensors/inch^2 to fit a foot with the approx. female shoe size of 8.5 US.

Figure 3. Prototype of the textile-based sensing sock

Mechanical force applied to a sensor changes its resistivity. A single sensor tested from 25 to 1,000 g shows a high dynamic resistance change (6 kΩ to 0.42 Ω, *SD* = 0.28). While it cannot be used as a scale due to the data loss between single sensors cells, it shows a good force distribution.

Reading from Sensor Matrix

The measurement electronics consists of multiplexers (74HC4051) and shift registers (74HC595) driven by a microcontroller (SAM3X8E) with an internal analog-to-digital converter. Sensors in the matrix are measured sequentially. Changes in resistivity are measured via the voltage change of a reference resistor connected in series.

Haptic Feedback

Six vibration motors (Pico Vibe™ 10mm vibration motors) are controlled by an Arduino Micro board to create a haptic feedback system. These motors are mountable with Velcro onto different lengths of elastic band that can then be worn around different parts of the body (e.g. arm, leg, torso, etc.).

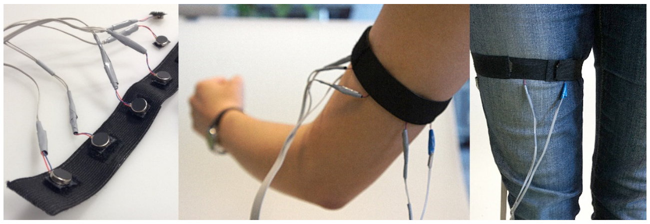

Figure 4. Array of vibration motors used for haptic feedback. The motors can be attached to different bands, which can be worn on different body parts like the upper arm or thigh.

Sensor data from the sensing sock is used to drive these motors. While many forms of feedback (e.g. nerve-interfacing electrodes, pneumatic actuators, etc.) are possible for use with prosthetics (see Figure 2), we chose to use robust, low-power, low-cost vibration motors as in [12,19,25], to affix to various parts of the body (see Figure 4). As we focus on sensors and sensor-feedback mapping in this work, we plan to explore a wider range of actuator technologies in the future.

Mapping Sensors to Feedback

While a high-resolution pressure map was achieved, we note that one-to-one mappings between sensors and haptic actuators is unsuitable due to limitations in human tactile perception. Two-Point-Discrimination thresholds (TPDT) are a measure of spatial tactile acuity, defined as the minimum spatial distance needed for a person to distinguish between two simultaneous stimuli from a single stimulus [10]. While it is influenced by a multitude of factors including bodily location and stimulus-type, previous research suggests that the TPDT for the fingertip and back for a static touch is 3 mm and 39 mm respectively [27]. Thus, there is clearly a limitation to the number of actuators that can be placed on a part of the body to represent sensor information. This is even more crucial for vibration-based stimuli, since vibrations are conducted readily through the body.

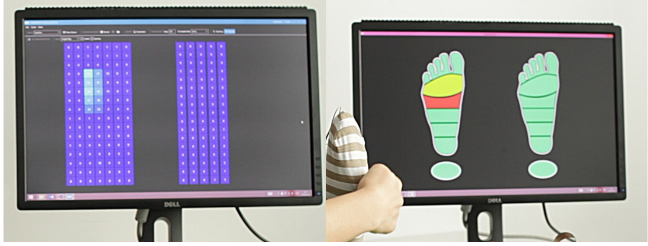

Figure 5. Mapping sensors to haptic feedback. Individual sensing intersections from sock (left). Sensors split into distinct sensing regions along the bottom and top of the foot and ankle (right). Warmer colours indicate higher pressure readings.

For our prototype, we map sensors to actuators by subdividing the 192 sensor intersections into discrete sensing regions along the plantar and dorsal regions of the foot, as pictured in Figure 5. As a default, we map each of the 6 sensing regions on the bottom of the foot to one motor on the vibration armband. Furthermore, we use the peak pressure applied to each sensor region to determine the vibration intensity of the corresponding motor. Vibration motors time out after 3 seconds of activation to avoid constant stimulation in situations such as when the wearer stands still. Motors reactivate when the pressure drops low and then peaks again.

UNDERSTANDING SENSING NEEDS

In order to design a sensing wearable that would suit the needs of those with prosthetics, we decided to investigate more deeply what people's sensing needs would be, including possible associated factors such as their amputation-type, attitudes and activities.

Method

In consultation with the eight lower-limb amputees, we investigated *(a) the implications and potential of having pressure sensing on all surfaces of the foot*, *(b) the acceptability of a textile form factor for a sensing solution*, *(c) customization and personalization in the context of sensing for prosthetics*, and *(d) possible factors that influence users' sensing needs*. We presented the participants with a demo of proCover and collected data in the form of a questionnaire. Overall, participants took 20 to 60 minutes to complete the questionnaire.

Demographics

8 lower-limb prosthesis-users (3 female) answered the questionnaire. 7 of them had one lower-limb amputation. 3 participants had a transtibial (below-knee) amputation. 4 participants had a transfemoral (above-knee) amputation. 1 participant had a double amputation (right: ankle disarticulation, left: below-knee). The participants ranged from 37 to 74 years of age (M = 60.13 years, SD = 13.81). While 7 out of 8 participants were retired, examples of their professions were baker, bank teller, farmer, and hunter. The time for which they used a prosthetic leg ranged from 3 months to 50 years (M = 12.16 years, SD = 15.42).

RESULTS

Opinions on Sensory Feedback for the Foot

Having seen the prototype of the sensing sock prior to completing the questionnaire, participants were asked to rate (1 = strongly disagree, 4 = strongly agree) the degree to which they believe that they would be able to do their activities more easily if their prosthetic foot/feet could detect when it is touching something. 5 out of 8 participants strongly agreed (62.5%), 1 agreed (12.5%), and 2 had no opinion (25%). The fact that most potential users believed this technology could help them in better performing their activities was very encouraging.

Socks and Footwear

Asked about their current use of socks, 7 of the 8 participants reported wearing socks over their prosthetic foot. 3 reported changing their socks on a daily basis, 2 on a weekly basis, and 1 reported wearing socks only when needed (1 sock-wearer did not answer this question). Participants were also asked to indicate the types of shoes they wear. They responded with a spectrum of different shoe types. Running shoes were the most popular, followed by specialized shoes for prosthetics, sandals, hiking shoes, sneakers and dress shoes. Only one participant reported wearing strappy-sandals, and crocs. No one selected options such as flip-flops, boots, ballerina flats/loafers, or high-heels. The results shown in Figure 6 suggest that participants favour footwear that is flat, and can be fixed to the prosthetic foot securely. 6 of the 8 participants (with 4 up to 50 years of experience using their prosthetic limb) reported wearing 3 or more different types of shoes. The other two participants with the least amount of experience using a prosthetic limb (3 months and 2 years of experience respectively) reported wearing only running shoes.

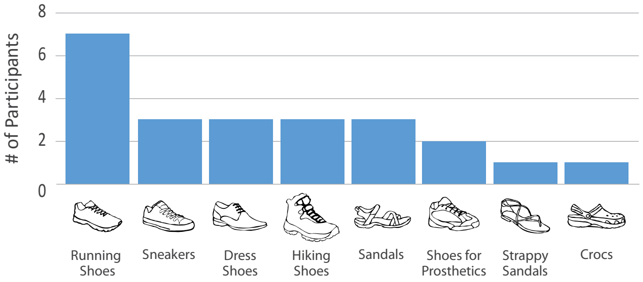

Figure 6. Shoes worn by participants. Participants were asked to report all the types of shoes that they wear.

The majority of the prosthesis users are accustomed to wearing socks on a regular basis, and primarily wear footwear that is compatible and designed to be worn with socks, meaning that a sensing layer in the form of a sock would be minimally disruptive to their normal routines.

Activities

Lower-limb amputees are often assigned a mobility grade when they are fitted for a prosthetic leg. While slightly different systems exist, they generally contain grades ranging from 0-4. Grade 0 implies a patient does not have the ability to transfer or ambulate safely with or without assistance, and a prosthesis does not enhance their quality of life. Grade 1 implies the patient has the potential to use a prosthesis for transfers or ambulation on level surfaces. Grade 2 implies the patient has the potential to overcome small obstacles such as curbs. Grade 3 patients can move over wild terrain so long as not too much stress is put on the leg. Grade 4 patients would place high impact or stress on the leg, with distance and time capabilities similar to healthy individuals [32].

The mobility grades amongst the participants varied (Grade 1: 3, Grade 2: 4 and Grade 4: 1), as can be seen in Figure 7, top. Participants self-reported partaking in a diverse range of physical activities. These included sports-related activities such as hiking, biking, wheelchair basketball, qi gong and Bavarian curling but also other activities, such as walking, climbing up and down stairs, shopping, and household chores including ironing, gardening, and even farm work (milking cows).

Confidence Levels

Each person was also asked to report their confidence (1 = very insecure, 5 = very confident) in performing different activities (bicycling, car driving, ladder-climbing, stair-climbing). The results are depicted in Figure 7, middle. While most of them felt confident climbing stairs, but insecure climbing ladders. Of the participants who could drive, all felt okay or better. We noted that all drivers owned automatic vehicles, but occasionally used manual cars from friends or family. Two needed a left-foot throttle modification since they had amputations on their right-leg. Only 3 participants reported on bike-riding, each with a different level of confidence.

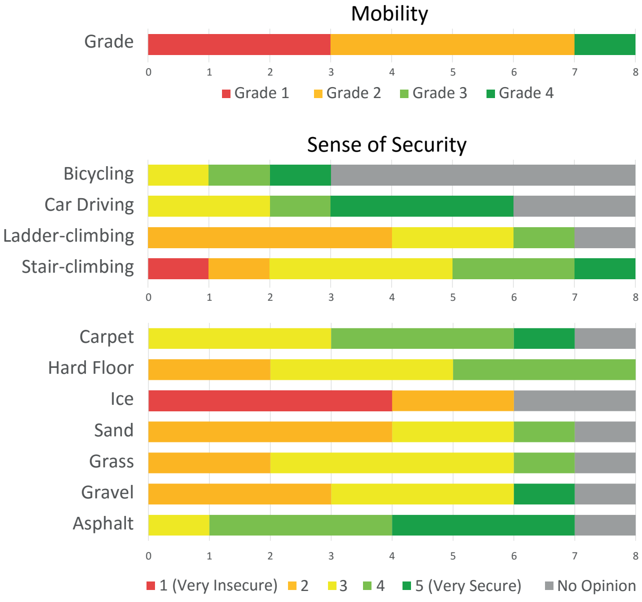

Figure 7. The mobility grade of the participants (top); how secure the participants feel practicing different activities (middle); how secure participants move on different surfaces (bottom).

The participants were also asked to report their level of confidence (1 = very insecure, 5 = very confident) traversing different types of surfaces (see Figure 7). In general, they felt confident on firm, textured surfaces such as asphalt/concrete and carpet, but insecure on sand or ice. One participant also reported feeling 'insecure' descending slopes.

Importance of Sensing Regions

Participants were then asked to perform a colouring activity, where they shaded parts of the foot using different colours depending on how important it would be for them to sense in those regions (either 'important', or 'very important'). The shape of the foot was presented in three views (the sole, and two complementary three-quarter perspectives) for them to colour. 7 of the 8 participants performed the activity. Figure 8 shows their individual responses (top) and a compilation of all the coloured responses (bottom). No two people provided the same response for the colouring activity; their responses illustrate that each participant had a different mental concept of what regions on the foot should have sensing.

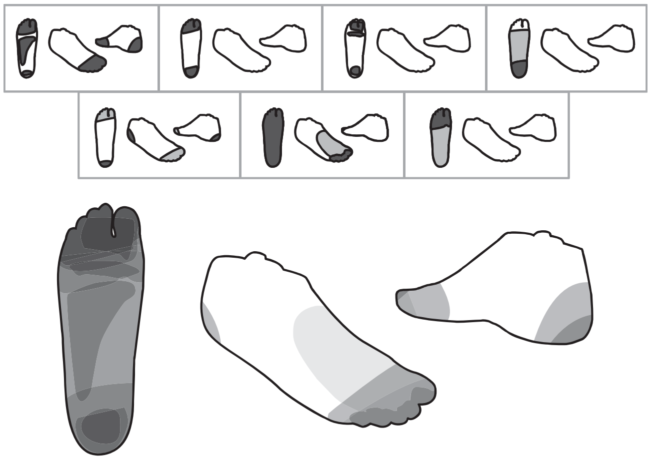

Figure 8. Seven colouring responses expressing different sensing needs, with light and dark grey signifying 'important' and 'very important' respectively (top). Compiled responses with left and right feet responses superimposed over one another; darker regions signify that more participants coloured there (bottom).

DISCUSSION: DESIRED SENSING ON THE FOOT

Interestingly, answers received from the questionnaire and also in discussions following the completion of the questionnaire illustrated that sensing needs can vary from person to person. In general, all participants considered sensing on the sole, by the toes and by the heel, as 'very important'. This preference is visible in Figure 8. However, their responses appeared to differ according to their amputation type and types of activities.

Impact of Amputation Type on Sensing Needs

The range of responses differed between above and below knee amputees, as seen in Figure 9. The four above-knee amputees put precedence on the region under the heel (**Sole-Heel**) and below the toes (**Sole-Toes**), but also identified the **Sole-Ball** and **Back-Edge** areas as 'very important'. In contrast, the three below-knee amputees had a much wider range of desired sensing regions; they identified the whole bottom of the foot (**Sole-***), the **Front-Edge**, and the top and side of the toes (**Toes-Top, Toes-Side**) as being 'very important'.

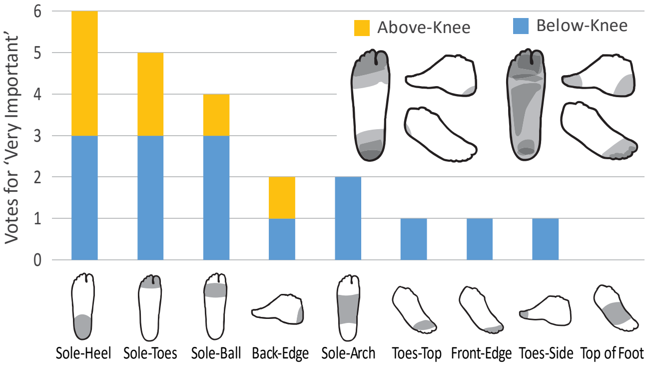

Figure 9. Regions marked as 'very important' for sensing by above and below-knee amputees. Above-knee amputees desired a narrower range of sensory regions than below-knee amputees.

Discussions with participants also indicated that the amputation type (either above-knee or below-knee) highly influences a person's sensing needs on the foot. Some of them also unveiled different and fairly specific issues.

One above-knee amputee with Grade 2 mobility stated *"I want to know if I stand on my heel, and if the knee is locked securely."* He explained that his leg could only fully support his weight when fully extended. When bent, the knee would simply hinge under his weight, which could cause him serious injury if he accidentally puts pressure on the leg. At present, he regularly visually inspects his leg. However, he expressed the belief that a textile sensor on his heel could help him identify more easily whether his leg is fully extended and improve his sense of safety and security when ambulating.

One woman with a below-knee amputation with Grade 2 mobility explained that she would like sensing along the front of the toes, stating *"If I could feel if my forefoot [is caught on something], it would reduce the danger of tripping."* As her current leg does not have any sensory capabilities, she cannot feel if her prosthetic foot catches on low-lying obstacles. The introduction of sensing on the front of the toes could therefore improve her safety, as it would give her the chance to fix its position before moving forward.

Impact of Activities on Sensing Needs

Participants expressed desire for sensing on certain regions of the foot based on their different scenarios and activities.

Figure 10 illustrates how activities influenced the location and priority of sensing regions on the foot, and is based off an aggregation of quotes from the participants.

Concerning walking, one participant recognized that her sensing needs were motivated by the types of walking surfaces she encounters. "*Walking on hard-floor is very slippery. I think the area [in the middle] is of additional value for the sense of balance and better stability when walking on different surface such as a wet street, or when climbing stairs, etc.,"* and added *"When walking on gravel I could feel the pits better."* Differences in the texture and levelness of terrain contributed to participants' wishes to have sensing that was more widespread around the foot, that included **Sole-Toes**, **Sole-Heel**, **Sole-Arch**, **Front-Edge**, **Toes-Side**, and **Back-Edge**.

In contrast, participants expressed that while biking, the important sensing regions are more isolated to the **Sole-Ball** and **Sole-Toes** regions of the foot. This is easy to comprehend, as the ball ideally remains in firm, constant contact with the pedal while riding for maximal feeling of control.

Interestingly, the topic of crouching was also a scenario of concern for the participants. They would assume this position for instance, when gardening. As one participant explained, *"When bending down, the stability would be better…when crouching, the toes are up in the air a bit and the point of gravity is on the heel."* Assuming, maintaining, and exiting this position requires shifts in one's center of gravity. As such, participants felt that the ability to feel the degree to which their weight is distributed towards the front versus towards the back would help them to maintain their balance, and gave emphasis to **Sole-Toes**, **Sole-Heel** and **Back-Edge**.

Figure 10. Importance of different regions of foot for different physical activities. Left to right: walking, biking, crouching. Darker regions signify higher agreement.

Driving was considered by two participants as an activity during which sensing would be very helpful. One above-knee amputee with Grade 3 mobility explained that at times he is not aware if his prosthetic foot is in contact with pedals in the car. He explained that there was one incident where he did not realize his foot was against the gas pedal, pressed it down, and accelerated which resulted in a rear-end collision. The ability to better feel if his foot is against the pedal could help him to have better control over his car. Another lady with a below-knee amputation with Grade 2 mobility stated *"When driving, I could react better with the clutch."* (*P1, P4*)

Summary: Sensing Socks for Lower-Limb Prosthetics

In summary, the results from the questionnaire provide the following takeaways regarding a pressure-sensing layer for lower-limb prosthetics:

- Participants generally have a positive outlook on having sensory feedback for their prosthetic legs, and believe such technology can improve their performance in activities.

- A sock form factor for the sensing layer is likely to be minimally disruptive to prosthetic-user routines, which can help with user acceptance and adoption. The majority of participants wear socks regularly, and the majority of the footwear worn by participants can be worn with socks, making this form factor more versatile than a sensing insole or shoe.
- Customization is valuable in sensing. It is beneficial for sock sensing regions to be variable in shape, size, location, and number to account for different user preferences.
- Activities have a large influence on which sensing regions on the foot are important. However, the sole of the foot, particularly by the heel and by the toes, are generally important to prosthesis-users. Most concerns relate to maintaining one's balance while standing and walking.

FURTHER DEVELOPMENTS

We created another prototype of proCover (men's shoe size 13 US) with 221 sensors (17 rows × 13 columns), to fit the foot sizes of our participants, added an offset function that could be triggered to remove default pressure readings as a calibration step once it is put on, and included new features into the sensing system, motivated by issues raised in the pre-study.

User-Configuration Tool: Mapping Sensing Regions to Haptic Feedback Stimuli

Our pre-study results revealed that prosthesis-users have different opinions about sensing locations on the foot and their relative priority, and that each user typically engages in multiple different activities that demand unique sets of sensing regions. As such, a dynamic, user-configurable sensory substitution system, rather than one with a single, designer-prescribed and static configuration of sensors to feedback actuators, would be better able to handle these variations.

Therefore, we expanded upon our initial implementation of proCover by integrating a mobile app-based user configuration tool. In contrast to our initial implementation (that featured one-to-one mappings between sensing regions and single motors), our refined system allows a flexible number of sensors and motors to be mapped non-exclusively at any time during run time. The system thereby empowers users to control and optimize the system's sensing behavior for themselves.

The tool supports a two-step process for creating sensing regions and mapping them to actuators (shown in Figure 11 left and middle). First, while wearing the sock, the user can press 'Record' and touch sensors on the sock to select them to add into a new sensing region. Second, the user can select in the app which motors will vibrate when the sensing region is touched. This allows for one-to-one, one-to-many, many-to-one, and many-to-many type mappings to be created between sensing intersections and actuators. The system can furthermore store multiple different mappings, which can be activated or deactivated as desired.

Figure 11. Customization allows for mapping custom regions dynamically to actuators via a mobile app (left, middle). The knee guard detects the degree of bending of a knee-joint (right).

Sensing Knee-Guards: From Pressure and Touch to Bending and Proprioception (Joint Position)

The concerns of the above-knee amputee with a hinged-knee from our pre-study inspired us to investigate the potential in using the textile to not only detect pressure, but to also detect bending. We envisioned that a solution in the form of a knee guard or a longer stocking could be worn over a prosthetic knee-joint to provide for proprioception (i.e. position-sense).

We constructed two different prototypes for this concept. One version was a full cylindrical sleeve that would surround the limb. The other had a broad half-sleeve design (see Figure 13, right) which contained 112 sensors (14 rows × 8 columns), and could be strapped over knee-joints to account for possible variations in the diameter of prosthetic legs. While our prototypes provided visual feedback for bend-states, we considered that other modalities such as audio or haptic feedback could be used in future to accommodate different users' specific needs.

Two approaches were developed to detect the degree of bending using these sensing sleeves. One was a naïve approach, which used the pressure reading from a single sensor situated at the apex of the joint to determine the degree of bending. The other was a Support Vector Machine (SVM) approach implemented using the LIBSVM[1] open source library. For this approach, 24 training samples must be captured per bend state (*no bend, slight bend* and *high bend*), per user to train the system. For the second prototype, each sample contains 112 features, corresponding to each sensor intersection in the sleeve.

PILOT STUDY

After one month, participants from the first study were invited to the lab to test our revised textile-based sensing solutions. Four participants (two females, two males, aged 37, 42, 50, 74) came. Two were above-knee amputees (*P3*, *P4*), one had a below-knee amputation (*P2*), and another had double below-knee amputations (*P1*). They used their prostheses for a different number of years (7, 10, 20 and 50). Each participant was using a different type of prosthetic leg, pictured in Figure 12.

Figure 12. The participants' prosthetic legs.

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[1] https://www.csie.ntu.edu.tw/~cjlin/libsvm/

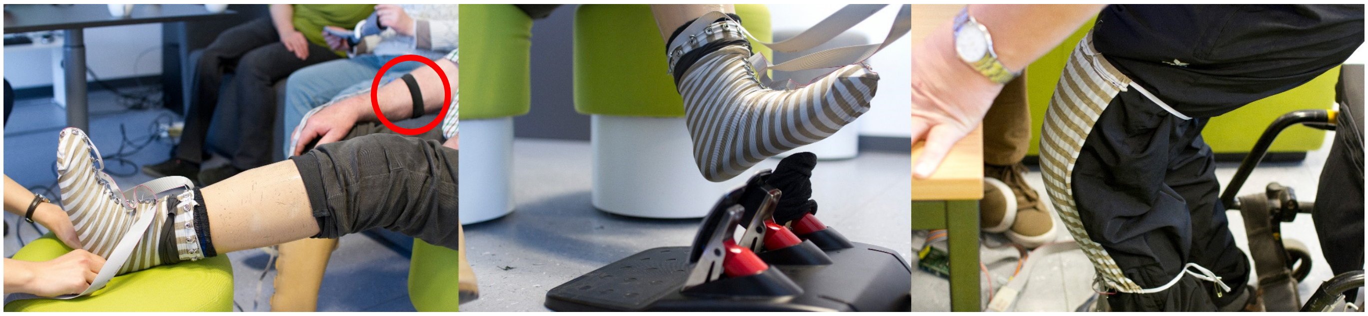

Figure 13. In a pilot-study, lower-limb amputees tried proCover in three different tasks involving sensing region touch discrimination, pressure variation and bending. These tasks were inspired by their concerns that were expressed in the pre-study.

The pilot study consisted of three different tasks with the overall goal to assess the validity of the textile-based sensing concept for the sensory augmentation of real-world prosthetics and to collect experience with applying these prototypes to real potential users. Overall, the study took approximately two hours to complete with all four participants.

Task 1 – Touch-Position Discrimination

The goal of this exercise was to assess whether sensing regions could be dynamically created on the sock for each prosthesis despite their differences in geometry and material stiffness (see Figure 12). With their eyes closed, participants were asked to state which region of their foot was being touched, for a random alternating sequence of presses (applied by hand) against the ball and heel of the foot. The task was conducted under two conditions (*with-sock* and *without-sock)*, as we suspected that participants may have some sensation through their residual limb. In the *with-sock* condition, each participant donned the sock over his or her prosthesis, and wore the vibration armband on either the upper or lower arm for a snug fit. In dialog with the participants, we used the configuration app to dynamically create sensing regions and map them to actuators in the armband. The same 'perceivable mapping' was created for participants; sensing regions created on the ball and heel of the foot were mapped to motors facing upwards towards the ceiling and downwards towards the floor respectively. Different hardware mappings were created in this process since the fit and orientation of the wearables always changed for each person. The mean of the upper-quartile of pressure sensor readings from each sensing region was linearly mapped and scaled to the vibration intensity of the corresponding motors. In total, each participant completed 12 trials (2 regions × 3 trials per region × 2 conditions). The number of correctly identified touches was logged, and participants were asked to comment on the experience afterwards.

Results

All four participants performed this task. The sensing sock was successfully applied to each prosthesis allowing for dynamically created personalized sensing regions. In the *without-sock* condition, participants on average had a 75% error rate ($SD = 0.083$). In the *with-sock* condition, all participants identified which region of their foot was being pressed without error. Without the sock, *P2-P4* were observed to simply guess which region was being touched. For *P1*, although he reported feeling confident that he could correctly identify the touches based on the force he felt through his stump, he misidentified the touches 5 out of 6 times without the sock. This was most likely due to misinterpreting the torque he felt on his residual limb with his heel raised instead of resting on firm ground.

Participants were asked to rate how challenging it was to use the sensing sock system (1 = very hard, 5 = very easy). All participants rated the system as 5, or 'very easy' to use. Users were also asked to rate how easy it was to remember the mapping on the same scale. All participants rated the mapping between sensor and actuators as 'very easy' to remember, as there were only two regions. However, *P4* commented that he felt the task was more mentally demanding with the sock on, since he had to interpret the vibration feedback that corresponded with the pressing of different regions.

When asked if they could imagine using this system in the future, the responses were encouraging. One below-knee amputee (*P2*) who had also tried the setup in a standing position and had shifted her weight forwards and backwards announced she could 'feel' how her foot contacted the ground through the vibration feedback on her arm, and expressed that she would like to use the system when walking (particularly when on uneven terrain such as gravel). An above-knee amputee (*P4*) stressed that he would like to use the system to feel his toes and heel while walking. *P1*, a double below-knee amputee, felt that his current legs gave him sufficient feedback through straps that led from his legs to a belt around his torso; however, he believed that people who are new to using a prosthetic limb would benefit from having this system.

Discussion

The results of Task 1 demonstrated the sensing sock in combination with the vibration armband provides a clear improvement over the sensory feedback that a user otherwise relies on through his or her stump. Furthermore, the task confirmed that distinct sensing regions on the sock can be both created and mapped *dynamically* to haptic feedback actuators that users can quickly learn, memorize and interpret. In fact, the mapping was so memorable that in the second task (described below), one participant (*P2*) exclaimed that she could feel her heel when she pressed the pedal, which she thought was a mistake. However, we had simply mapped the region that was touching the pedal (in her case the ball of the foot) to a motor that had happened to correspond with her heel in the first task.

Task 2 – Applying Pressure to a Car Pedal

The goal of this exercise was to assess the feasibility and value of using the sensing sock to detect varying amounts of pressure and drive haptic feedback of variable intensity in situations such as operating the pedals of a car. For this task, participants wore the sock and armband like in Task 1. Using the configuration tool, one region was created on the sock, and was mapped to two vibration motors on the armband. The mean of the upper-quartile of pressure sensor readings from the region was mapped and scaled linearly to the input voltage range of the two motors. Using a set of Logitech G27 foot pedals, participants were instructed to depress a pedal to three different levels (*shallow*, *medium* and *full*) with their eyes closed under two conditions (*with-sock and without-sock).* Left-leg amputees were asked to control the clutch pedal, while right-leg amputees were asked to control the gas pedal. Participants completed three trials per pressure level, for a total of 9 trials per condition, and 18 trials in total (3 pressure levels × 3 repetitions × 2 conditions). The number of errors (incorrectly performed presses) were logged. At the conclusion of this exercise, participants were asked to comment on the experience under the two conditions, and whether they could imagine using the sensing system in the context of driving in the future. In addition, they were invited to test the system in a standing position for comparison against the feedback they received from operating the pedals.

Results

All four participants attempted this task. Participants demonstrated fairly high proficiency in this task without any sensory feedback, and had an average error rate of 11.1% (*SD* = .079). However, the sensing system led to a minor improvement, lowering the average error rate to 8.3% (*SD* = .048).

All participants reported that they could feel different degrees of pressure, and could clearly sense an increasing and decreasing stimulus when depressing and releasing the pedal. However, participants expressed some difficulty in interpreting the relative intensity of the vibrotactile feedback; they explained that it was easier to distinguish between no and some pressure, than to distinguish between mid and high pressure levels. We observed that when participants operated the pedals, a smaller range of pressures was induced in the sock than when participants assumed a standing position and tried shifting their weight. Furthermore, all the participants were observed to hover with their prosthetic foot rather than rest the heel of their foot on the ground while operating the pedals. This is likely because their ankles were inflexible and incapable of dorsal and plantar flexion (i.e. they could not alter the angle of their prosthetic feet).

When asked about the concept of using pressure sensing when operating pedals, the responses were mixed. *P2* expressed that she would want to feel the pressure so she could better operate the clutch. Two others expressed that they did not need such a system; *P1* felt confident that he could apply the correct amount of pressure without the system, while *P3* felt her good-leg was sufficient for the job. *P4* expressed that he would see more value in being able to determine which pedal his leg was in contact with, rather than being able to feel the amount of pressure he was applying to a particular pedal.

Discussion

The results of Task 2 highlight that the range of applied force on the sensors generated from interacting with pedals is on a different level as the forces applied to the sensors when users stand. Therefore, we learned that the mapping between pressure and vibration intensity should be adaptable, such that the feedback can correspond well with the expected range of pressures for different activities (e.g. driving versus walking), and can be optimized to maximize users' abilities to perceive differences in pressure levels in the different scenarios.

Furthermore, based on our observations of their driving style, we learned that careful consideration is needed when creating sensing regions for a particular activity. We observed that people hovered their foot over the pedal, and displayed some inconsistency regarding which parts of their foot they used to depress the pedal. For example, they sometimes shifted their foot forward, pressing the pedal with the arch of their foot, while at other times they shifted their foot backward, pressing the pedal more with the ball of their foot. Therefore, it would be important that created sensing regions are made to account for such variations.

Lastly, the results for Task 2 are that some prosthesis-users are of the opinion that they do not need much additional pressure sensing support in the context of driving, while others would appreciate the additional feedback (especially when driving non-specially adapted cars). Beyond this, it would be interesting to explore other scenarios in which variable pressure and feedback would then be helpful.

Task 3 – Knee-Bend Detection

The goal of this task was to assess the feasibility of using our textile-based sensing solution to detect the degree of bending in prosthetic legs. For this task, participants with an above-knee amputation had the broad sensing pad prototype affixed to their pants over their prosthetic knee-joint (see Figure 13, right). We refrained from asking participants to remove their clothing for the study and instead fitted the sensing prototype over their clothing.

The SVM approach was used and trained for each user as explained under the Further Developments section. Participants were asked to bend their legs in a random alternating sequence of bend-states, and the number of times the system correctly identified the true bend-state of the leg was logged for a total of 9 test trials (3 states × 3 trials). The number of test trials was limited due to the physical strain on the participants. At the conclusion of this exercise, participants were asked to comment on both their experience and on how they could envision the system being used in the context of their daily lives.

Results

Two above-knee amputees performed this task. In general, it was difficult to affix the sensor securely over their pants. As such, we observed that the sensor tended to shift while they moved, reducing the accuracy of the classification. Despite these conditions, the system correctly classified 6 out of 9 test trials for the participant wearing very loose jogging pants *(P4)*, and 8 out of 9 trials for the participant wearing jeans *(P3)*.

When asked about this sensing solution, participants stressed that bend detection is of utmost importance for improving safety from falling. For the participant with the simple hinged knee (*P4*), the detection of a slight bend versus no bend was of particular importance, as his leg must be perfectly straight in order to support his weight. Furthermore, both participants explained that preference would be given to using this information to trigger automatic responses in the leg, rather than generating feedback that would be relayed to the wearer.

Discussion

Task 3 demonstrated the potential for our textile-based approach to be used to detect the bending of a knee joint. However, it is clear that it is crucial for the final sensing solution to fit very snugly around the prosthetic knee for optimal classification results. As we were not fully satisfied with the classification results for *P4*, we created a third knee guard prototype (see Figure 1, right and Figure 11, right) designed to fit snugly and directly over his leg. It had slimmer profile with 6 sensors (1 row× 6 columns) and a button sewn into the fabric to simulate a kneecap. These changes stabilized the readings and allowed us to extract the angle of the joint with higher precision.

Of course, while other types of bend-sensors can be used, our results from this test demonstrate the potential for a long sensing stocking to serve a dual purpose for augmenting sensory capabilities for the foot as well as monitoring the position of the prosthetic leg.

DISCUSSION & LIMITATIONS

Overall, we learned that customization is a valuable and necessary aspect to consider in the provision of non-invasive sensing solutions for prosthesis-users, as lower-limb amputees have different concepts for what their sensing needs are. While amputation type is a contributing factor, individuals' sensing needs change even when switching between their own physical activities. Thus, we highlight that the value of high-resolution sensing is not necessarily only in driving high-resolution feedback, but is also in providing a necessary degree of flexibility to accurately capture users' unique desires for sensing regions, which can vary in location, size and number.

Through the development and application of our prototypes on real prostheses, we showed the potential for wearables to be leveraged for the purposes of pressure and bend perception for a broad array of prosthetics, and showed the potential user-driven customization has to enhance the utility of such wearables. To extend this work, certain technical limitations would need to be addressed in order for the system to be portable and usable by amputees in practice. The components should be made smaller, wireless, and runnable on an external power supply. Better connectors than the currently used snap-fasteners would reduce the time needed to put on the sock. Additionally, the durability of the textile should be examined, as participants noted that prosthetic feet tend to put socks under greater physical stress. From an evaluation standpoint, we note that the pilot-study was short in duration, and users had little time to familiarize themselves with the vibration feedback. Longer-term studies could reveal the potential impact learning effects may have on the overall utility of the system for users.

Furthermore, sensory substitution systems are a 'package-deal.' Their effectiveness in practice is determined by the quality of both the sensing and output. As such, our results should be interpreted in light of our choice of vibration feedback, which we worked with as a first step in exploring the potential for flexible mappings to improve the utility of such systems. Using vibration motors introduces a time delay (40 ms lag), which should be carefully considered, particularly when designing a system to be used in time-sensitive scenarios. The use of more elaborate pressure mapping functions, tactile phenomena (e.g. sensory saltation [5] as in Tactile Brush [9]), and/or different feedback modalities (e.g. pressure feedback via pneumatic actuators, auditory and visual cues, or combinations of them) may offer improvements to the feedback and should therefore be a subject of future work.

CONCLUSION & FUTURE WORK

In this paper, we presented a novel wearable sensing sock that can be self-applied for the purposes of introducing sensory capabilities into a wide range of lower-limb prosthetics. We created a working prototype, and investigated the design space for the concept in consultation with a diverse group of eight lower-limb amputees. Based on our insights from this process, we introduced novel customization capabilities into our solution to make it user-modifiable and capable of adapting to users' unique and dynamic sets of needs (that change in accordance to different physical activities). The validity of the concept was confirmed in a pilot-study, where the sensing sock was successfully applied to a diverse set of prosthetic limbs to dynamically create and map sensing regions to actuators – thereby enabling participants to distinguish between touches on different locations and at different levels of applied pressure. Furthermore, we demonstrated the potential for the same fabric approach to be used for bend-detection for prosthetic limbs with a working prototype of a sensing knee guard.

Besides the minimization of hardware, we are currently reducing the three layers into a single sensing layer. This will help maintain a consistent alignment of the sensor grid over the foot when the sock is taken off and put back on, eliminating the need to remap regions in each session. It would also allow for greater flexibility to accommodate wider ranges of motion. Moreover, in addition to exploring other feedback modalities, we see a benefit and potential in using this approach to make sensing gloves for upper-limb prostheses.

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