PROSTHETICS

Touching reality: Bridging the user-researcher divide in upper-limb prosthetics

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Realistically improving upper-limb prostheses is only possible if we listen to users' actual technological needs.

There have been considerable advances in the technology for upper-limb prostheses during the past five decades. Beginning in the 1970s, researchers developed the concept of extended physiological proprioception (EPP), demonstrating improvements in dexterous control when sensory perception can extend to the distal end of the prosthesis terminal device (*1*, *2*). This seminal work paved the path toward the use of noninvasive haptic feedback to provide the missing sensory information (*3*). At the same time, surgical advancements led to the development of targeted sensory reinnervation (*4*) and peripheral and cortical neural interfaces (*5*).

Still, there remains a substantial gap between the needs of users and the technologies that are available. Roughly half of upper extremity prosthesis users eventually abandon their powered prosthesis in favor of simpler body-powered devices, passive cosmeses, or no device at all (*6*, *7*). It has recently been demonstrated that, despite our best intentions, we lack an understanding of how prosthesis users prefer to use their prosthesis (*9*). Moreover, we are only beginning to understand how prostheses are represented in the brain (*10*). Although we envision robotic limbs that are indistinguishable from natural limbs, what we have are complicated and delicate pieces of engineered metal and plastic that work best in the lab environments in which they are developed.

Engineers and scientists too often leave prosthesis users out of the innovation process, limiting their involvement to user studies in lab-controlled conditions that, while important, lack ecological validity. Although some of the full-time research authors of this manuscript are guilty of all the above, we feel that there is a better path forward. This path must involve bringing prosthesis users into the early brainstorming phase to truly understand their needs and desires for prosthesis utility and function.

To that end, we report on the findings from a workshop held at the 2023 IEEE World Haptics Conference focused on understanding the needs of prosthesis users in the context of touch sensation. The workshop featured a panel discussion composed of prosthesis users, who were asked to complete a pre-workshop survey (survey 1; Supplementary Materials) regarding their experience using their prothesis and their desire for improved sensory utility from their prosthesis. During the workshop, the outcomes of this survey were used as prompts for conversation. Panelists then completed a post-workshop survey (survey 2; Supplementary Materials) that asked the same set of improved sensory utility questions to evaluate any changes after the workshop conversation.

Responses from the pre-workshop survey highlighted the heterogeneity among our panelists regarding their daily usage of their prosthesis ranging from less than 2 hours to more than 10 hours a day (table S1). Panelists who spent less time using their prosthesis highlighted weight, comfort, and limited functionality as the main causes (table S2). Panelists also reported using their prosthesis in a limited fashion or not at all for many of their daily living activities (table S3). This is consistent with previous results (*8*, *9*).

Responses from the pre-workshop survey also highlighted that, overall, the panelists considered functionality, reliability, and comfort as the three most important aspects of an upper-limb prosthesis (table S4). Specific features that they also considered important were grip force feedback, notification of impending prosthesis damage, feedback on prosthesis hand pose, and the ability to manipulate unseen objects (table S5 and fig. S1). Other features, such as temperature and texture feedback, were generally perceived as less important (table S5 and fig. S1). Interestingly, the ranking of desired features remained essentially unchanged between the pre- and post-workshop surveys, with only the top four features changing order, indicating that the panelists were fairly set in their opinion of which features are most important. Last, panelists indicated a general preference for haptic and auditory feedback to receive information on grip force, slip, damage, and level of hand opening. The results were similar post-workshop, with fewer "not sure" responses and more in favor of haptic feedback, perhaps as a consequence of information obtained during the workshop.

For comprehensive understanding of each panelists' views regarding their workshop participation, we refer readers to statements authored by each panelist in the Supplementary Materials. Here, we summarize the main themes. Overall, what emerged most strongly was that needs and preferences can vary widely across each prosthesis user. For example, there were panelists that expressed frustration with the available level of technology and reported using their prosthesis very little. In contrast, some of the panelists reported being very satisfied with the level of technology

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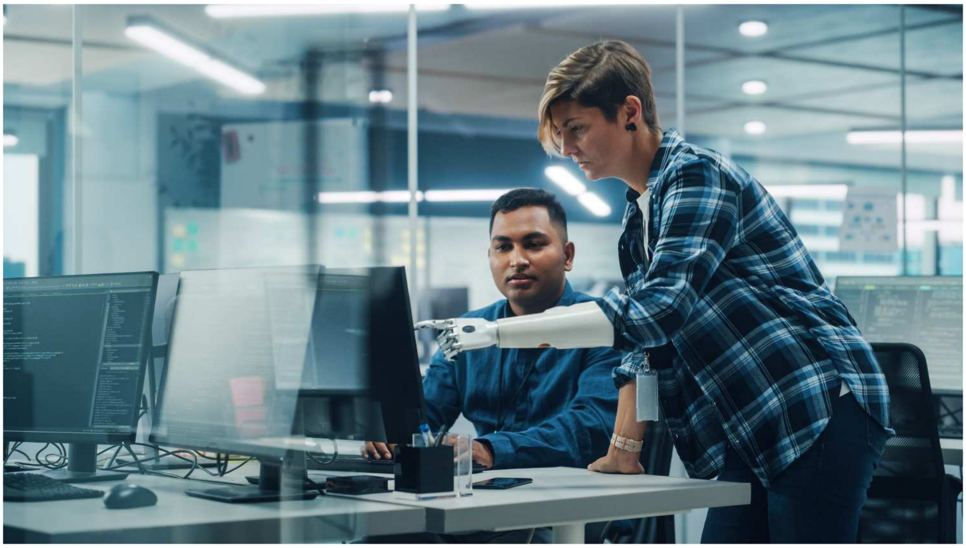

in their prosthesis, expressing desire for better reliability and easier access. Similarly, most panelists expressed at least some interest in richer haptic feedback features, although there was concern regarding the impact of more features on prosthesis reliability. This sentiment was not universally shared, however: Some of the panelists expressed no interest at all in the addition of haptic feedback and instead had a strong preference for simpler prostheses that were more inconspicuous and comfortable. We refer to the text from authors A.P. and S.E. in the Supplementary Materials for more on these different perspectives.

Another aspect that was offered was that the needs of underserved individuals are not likely to be addressed with current prosthesis technology. Individuals with limb loss who lack financial means or health care coverage are unlikely to receive high-end technological prostheses, and user studies are likely to be overrepresented by individuals who have the economic ability to acquire cutting-edge prosthesis technology. Without intervention, the scientific community is in danger of focusing only on the needs of individuals from certain socioeconomic levels. Similarly, some panelists lamented the fact that high-end prostheses can be feature rich, but ultimately these features were determined by the scientific community rather than the users themselves. We refer to the text from authors E. S. and G.L. in the Supplementary Materials for more on these different perspectives.

Overall, the outcomes of this workshop indicate a pressing need for more nuanced analyses of the true needs of prosthetic users. Given the difference in opinions that emerged from the panelists who participated in the workshop, it is evident that no "one-size-fits-all" approach will enable enhanced quality of life for all individuals with limb loss. In addition, the composition of the panel itself (with more than half of the panelists being PhD holders) and the thoughts shared by the panelists highlighted the need for a more inclusive model for user study recruitment that does not alienate groups of end users purely out of convenience. To realize impactful prosthesis technology, scientists, engineers, and technologists need to intentionally seek to understand the concrete needs of users by talking to them directly and developing unique prosthesis innovations designed to address those needs. This article, which includes authors as the panelists themselves, serves as a step toward articulating user needs and expectations and seeks to motivate researchers to engage users early in the prosthesis design process.

Supplementary Materials

This PDF file includes:
Supplementary Text
Figs. S1 and S2
Tables S1 to S5

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Supplementary Materials for

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Workshop Information

A full-day workshop, entitled "Improving the Utility of Haptic Feedback in Upper-Limb Prosthesis Control: establishing user centric guidelines for engineering innovation," was held at the 2023 IEEE World Haptics Conference in Delft, the Netherlands, on July 10, 2023. This full day workshop was organized by authors J. D. B., PhD, E. B., PhD, M. O., PhD, and K. Z., PhD. The workshop featured: 1) presentations from invited researchers; 2) a prosthesis user panel discussion; 3) a student poster session; and 4) a consensus round table discussion.

The workshop included invited research presentations given by Adam Spiers, PhD, Tamar Makin, PhD, Sliman Bensmaia, PhD, research poster presentations by graduate researchers, and a panel of upper limb prosthesis users. The prosthesis users who participated in the workshop were authors A. P, PhD, E. S., G. L. MS, M. F., PhD, and S. E., PhD. Four of the five prosthesis users participated in person, while S.E. participated over video conference.

https://sites.google.com/gcloud.utah.edu/2023-whc-workshop/home

Direct Input from panelists.

Amy Parks.

About the workshop: I have been a prosthesis user for over 50 years. In all that time, I've never had the opportunity to connect with the engineers at the vanguard of this field. It was really exciting to hear about the work they are doing, and to get a glimpse of the future of prosthetics. Some of their innovations may not suit me as a user, but they will surely broaden the options for others going forward. I also really enjoyed the chance to meet other amputees – some who wear prostheses and some who don't. Our varying perspectives yielded no easy, singular answers for those developing prosthetics, but provided a rich context for understanding our needs, for the engineers and users alike. The whole experience was wonderful, and I feel honored to have been a part of the conversation.

About my experience as a prosthesis user: I am a unilateral below-elbow amputee, and I wear my myoelectric prosthesis all day, every day. I am less interested in technological advances than I am in a prosthesis that is comfortable, reliable, durable, and natural-looking. I am fortunate to have insurance coverage for my prosthesis, but at the same time, this need has limited some of my life choices (e.g. where I live or work). I consider my prosthesis to be a part of me, and I'm uncomfortable without it. I rely on its functionality for nearly every manual task, so I feel hindered when I'm not wearing it. My biggest challenges are comfort and durability. I wish my prosthesis was more user-serviceable, so every minor issue didn't require a visit to my provider.

Elizabeth Skinner.

Participants at the Delft workshop impressed me as genuinely interested in user input at all stages of development and design. This openness did not surprise me - I've had many positive experiences collaborating with researchers in biomedical engineering labs at my local university. I realize, though, that not all users have these opportunities. Factors like location, work schedules, family obligations and transportation act as constraints. Similarly, access to prostheses may be limited by insurance coverage or an amputee's economic resources.

The Delft workshop gave me a chance to see a world larger than my own individual experience. I gained the insight that prosthetic researchers, designers, and users all tend to possess similar class and education levels. The reasons that I don't use my myoelectric device (convenience, comfort) may be very different than someone else's (cost of repair, fear of breaking). Addressing the gap might mean taking research to the users (at VA centers, health care providers or via teleconference) in addition to bringing users to the research lab. Cooperation benefits users, researchers, and the end-product so I hope that more users from different backgrounds will have opportunities to participate.

Susannah Engdahl.

As a bilateral myoelectric prosthesis user from a young age, I have extensive experience learning to interpret the sensory cues that are natively available in my prostheses. I can maintain an accurate understanding of the state of my prostheses based on external visual cues, sounds from the motors, vibrations and pressures transmitted through the socket from the motors or from contacting an object, and the duration and intensity of my residual limb muscle contractions to move the hand. In most cases, this information is sufficient for meeting my functional needs. As such, I have little interest in using prostheses with additional haptic cues, especially if those cues are conspicuous and would be noticeable by people around me. I do not use my prostheses for everything, but a need for sensory feedback is rarely the primary reason why I would remove a prosthesis before doing a task. For example, I prepare food while wearing a prosthesis only on my dominant arm. It is much easier to use my nondominant residual limb for stabilizing objects (e.g., while cutting) because mechanical limitations in the prosthetic hand require my arm to maintain postures that are uncomfortable for my neck and shoulders. The decision not to wear a prosthesis is related to comfort, rather than a need to have sensory feedback from my residual limb.

Gyorgy Levay

I lost my left arm at the transhumeral level and my right hand at the metacarpal over 12 years ago. Shortly after the amputations I received my first prosthesis which included a body powered elbow with a motorized wrist and hand with direct control. Although I was highly motivated and technically savvy (my education and career are centered around development of upper limb control strategies), I was never able to achieve a level of functionality that offset the discomfort of wearing the device. Over the past 12 years I upgraded both my prosthetic components to all-motorized and my control strategy to pattern recognition, but these changes still did not bring enough benefit to warrant daily use. Regarding sensory feedback, I think the most important work that can be done is work that gets us closer to understanding and simulating proprioception. All other modalities might have limited and compartmentalized benefits, but until users can continuously incorporate their prostheses into their minds map of the body, advances will be incremental. I think R&D in the field is scattered and resources are limited. The lack of shared objectives based in small part on user needs, and in larger part a consensus of priorities among those working in the field is a significant issue.

Survey

Part A (filled only before the workshop).

Q1: How often do you use your prosthesis on a daily basis?

Table s1: Use of the prosthesis

Time	*Choice count*
Less than 2 hours	*2*
2-4.9 hours	*1*
5-7.9 hours	*1*
8-11.9 hours	*0*
10+ hours	*1*

Q2: What prevents you from wearing your prosthesis all day? Check all that apply.

Table s2: Factors preventing prosthesis use

Field	*Choice count*
It's too heavy	*4*
It's painful to wear	*2*
It's too difficult to use	*2*
It's not useful as I can do most things with my other limb(s)	*4*
It doesn't look good	*0*
It is unreliable	*1*
It breaks too often	*0*
Other (please specify)	*3*

Q3: How do you complete the following tasks? (Using...) Your intact limb is defined as your non-prosthetic arm

Table s3: Daily living activities

Activity	*Only my intact/residual limb(s)*	*My prosthesis with support from my intact limb*	*Only my prosthe sis*	*My intact limb with support from my prosthesis*	*Both my intact and my prosthesis equally*
Any of your usual work, housework, or school activities	*2*	*0*	*0*	*2*	*1*
Your usual hobbies, recreational or sporting activities	*2*	*0*	*0*	*1*	*2*
Lifting a bag of groceries to waist level	*3*	*0*	*1*	*0*	*1*
Grooming your hair	*4*	*0*	*0*	*0*	*1*
Pushing up on your hands (e.g. from a chair or bathtub)	*2*	*0*	*0*	*0*	*2*
Preparing food (e.g.cutting, peeling)	*3*	*1*	*0*	*1*	*0*
Driving	*1*	*0*	*1*	*3*	*0*
Vacuuming, sweeping, or raking	*2*	*1*	*0*	*2*	*0*
Dressing	*5*	*0*	*0*	*0*	*0*
Doing up buttons	*4*	*0*	*0*	*0*	*1*
Using tools or appliances	*2*	*1*	*0*	*1*	*1*
Opening doors	*4*	*0*	*1*	*0*	*0*
Cleaning	*3*	*1*	*0*	*1*	*0*
Tying or lacing shoes	*2*	*0*	*1*	*2*	*0*
Sleeping	*5*	*0*	*0*	*0*	*0*
Laundering clothes (e.g. washing, ironing, folding)	*4*	*0*	*0*	*1*	*0*
Opening a jar	*3*	*0*	*1*	*1*	*0*
Carrying a small suitcase with your affected limb	*3*	*1*	*1*	*0*	*0*

Part B (two rounds, one before and one after the workshop).

Q4: Please list the most desirable features of a prosthetic hand in your opinion, in order of importance.

Table s4: Desirable prosthesis features

Pre-Workshop	*Post-Workshop*
Functionality, comfort, lightweight, appearance, low noise level, durability, reliability, user-serviceable	*Functionality, comfort, aesthetics*
Functionality, socket comfort, lightness, appearance	*Durability, speed, cosmetic appearance, noise, weight*
Durability, reliability, speed, low noise, life-like appearance	*Comfort, function, appearance, reliability, durability, user serviceable*
Light weight (important for long wear), intuitive (not requiring intense focus), reliable (consistently produces same motion), versatile (does more than grip a thing in a single position), affordable (using it doesn't risk breaking something that costs tens of thousands of dollars)	*Reliable (consistently makes same gesture), Flexible (helps me perform multiple tasks), Comfortable (light weight, easy to wear for hours)*
Comfort, reliability, ease of use	*Comfort, ease of use, functional in everyday situations, provides proprioceptive feedback, provides tactile feedback*

Q5: Please rate the importance of the following (Not at all important, Slightly important, Moderately important, Very important, Extremely important):

1. Knowing how hard I squeeze an object with my prosthesis;
2. The ability of my prosthesis to automatically adjust the grasp force depending on the type of object;
3. The ability of my prosthesis to automatically prevent objects from slipping from my grasp;
4. Knowing when an object is starting to slip (even if the prosthesis automatically prevents slip);
5. Feeling the temperature of an object I hold with the prosthesis;
6. Feeling textures with my prosthesis (soft, hard, rough, smooth, etc.);
7. Recognizing shapes with my prosthesis;
8. Knowing when I might accidentally damage my prosthesis (such as with sharp objects, extreme temperatures, etc.);
9. Knowing how open/closed my prosthesis is;
10. Manipulating objects without needing to look at them;
11. Feeling social gestures on my prosthesis (hand holding, someone stroking your arm, the temperature of someone's hand, etc.)

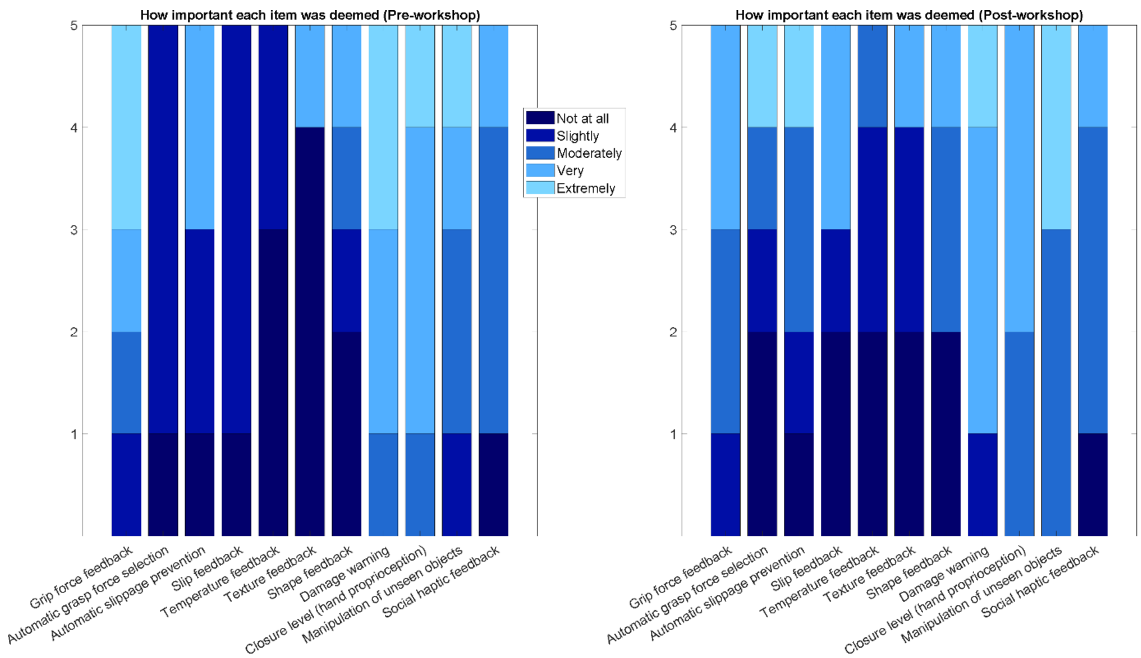

Figure s1: Perceived importance of features

Table s5: Importance ranking for desirable features in a prosthetic hand. Desirability scores were obtained from the Likert-style question 5 by assigning values 0 (not desirable) to 4 (highly desirable) to each choice and calculating the mean across participants.

Pre-Workshop		**Post-Workshop**	
Feature	**Desirability score**	**Feature**	**Desirability score**
Temperature feedback	0.4	Temperature feedback	0.8
Texture feedback	0.6	Texture feedback	1
Automatic grasp force selection	0.8	Automatic grasp force selection	1.4
Slip feedback	0.8	Slip feedback	1.4
Shape feedback	1.2	Shape feedback	1.4
Automatic slippage prevention	1.6	Automatic slippage prevention	1.8
Social haptic feedback	1.8	Social haptic feedback	1.8
Manipulation of unseen objects	2.4	Force feedback	2.2
Grip Force feedback	2.8	Closure level (hand proprioception)	2.6
Closure level (hand proprioception)	3	Damage warning	2.8
Damage warning	3.2	Manipulation of unseen objects	2.8

Q6a: I would like to know how hard I squeeze an object that I am holding with my prosthesis by receiving... (check all that interest you)
Q6b: I would like to know when an object I am holding with my prosthesis is starting to slip by receiving... (check all that interest you)
Q6c: I would like to know when I might damage my prosthesis by receiving... (check all that interest you)
Q6d: I would like to know how open or closed my prosthesis is by receiving...(check all that interest you)

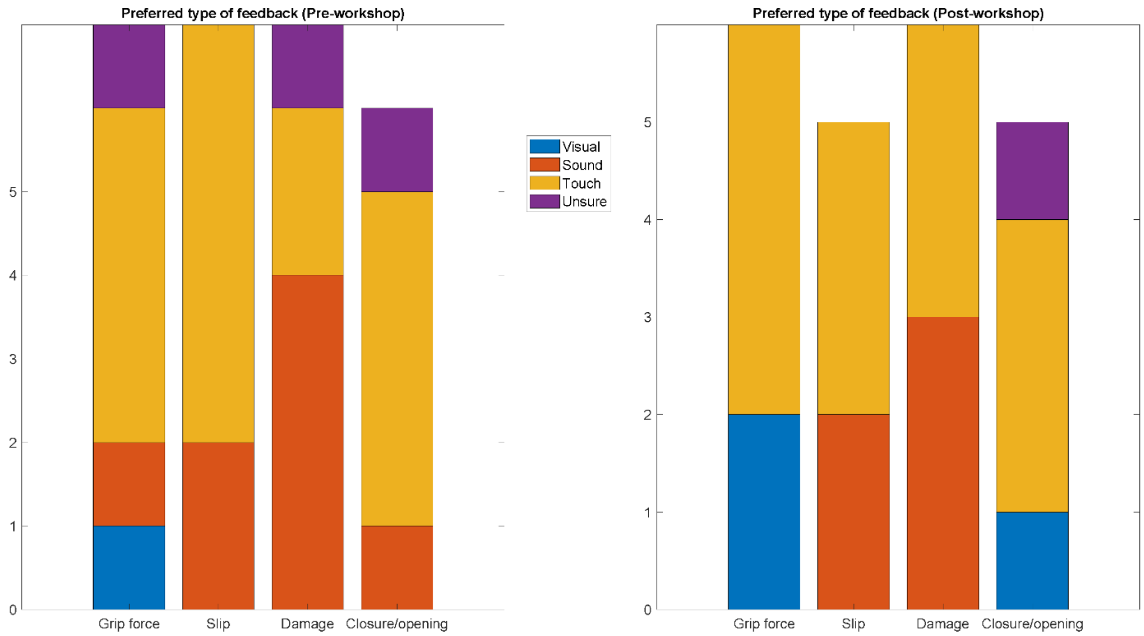

Figure s2: Preferred type of feedback