Sensory Feedback for Upper-Limb Prostheses: Opportunities and Barriers

Leen Jabban, *Graduate Student Member, IEEE*, Sigrid Dupan, Dingguo Zhang, *Senior Member, IEEE*, Ben Ainsworth, Kianoush Nazarpour, *Senior Member, IEEE*, and Benjamin W. Metcalfe, *Member, IEEE*

***Abstract*—The addition of sensory feedback to upper-limb prostheses has been shown to improve control, increase embodiment, and reduce phantom limb pain. However, most commercial prostheses do not incorporate sensory feedback due to several factors. This paper focuses on the major challenges of a lack of deep understanding of user needs, the unavailability of tailored, realistic outcome measures and the segregation between research on control and sensory feedback. The use of methods such as the Person-Based Approach and co-creation can improve the design and testing process. Stronger collaboration between researchers can integrate different prostheses research areas to accelerate the translation process.**

***Index Terms*—Control, embodiment, phantom limb pain, prostheses, sensory feedback, translation, user needs.**

I. Introduction

TOUCH delivers the first sensory input to humans before birth and remains one of the most important means of communication with the world throughout our lives [1]. The sense of touch is delivered through mechanoreceptors dispersed across the skin at varying depths. Spatial and temporal information from those receptors is processed in the somatosensory cortex based on their location on the body [2]. Tactile signals from the fingertips encode a multitude of information enabling dexterous manipulation as part of the Activities of Daily Living (ADL) [3]. The high reliance of humans on hands for manipulation, expression and communication makes their loss an injury with dramatic consequences on both body image and quality of life [4]. Despite recent developments, the mismatch between the wishes of people with limb difference and what prostheses offer reduces the likelihood of long-term device adoption [4].

Manuscript received August 31, 2021; revised December 17, 2021 and February 11, 2022; accepted March 10, 2022. Date of publication March 15, 2022; date of current version March 24, 2022. The work of Leen Jabban was supported in part by the Dr. Brian Nicholson Scholarship, in part by the Antony Best Scholarship, in part by the Esther Parkin Trust Scholarship, and in part by the University of Bath under the University Research Studentship Award (URSA). The work of Kianoush Nazarpour was supported by the Engineering and Physical Sciences Research Council (EPSRC), U.K., under Grant EP/R004242/2. *(Corresponding author: Benjamin W. Metcalfe.)*

Leen Jabban, Dingguo Zhang, and Benjamin W. Metcalfe are with the Department of Electronic and Electrical Engineering, University of Bath, Bath BA2 7AY, U.K. (e-mail: lj386@bath.ac.uk; dz492@bath.ac.uk; bwm23@bath.ac.uk).

Sigrid Dupan and Kianoush Nazarpour are with the School of Informatics, The University of Edinburgh, Edinburgh EH8 9AB, U.K. (e-mail: sigrid.dupan@ed.ac.uk; kianoush.nazarpour@ed.ac.uk).

Ben Ainsworth is with the Department of Psychology, University of Bath, Bath BA2 7AY, U.K. (e-mail: ba548@bath.ac.uk).

This article has supplementary downloadable material available at https://doi.org/10.1109/TNSRE.2022.3159186, provided by the authors.

Digital Object Identifier 10.1109/TNSRE.2022.3159186

Sensory feedback is a broad term used to describe any sensation delivered to an upper-limb prosthesis user (rather than to the internal control system, e.g. [5]) to relay information about the prosthesis' current state. This feedback is added to supplement other sensory cues such as vision and sound. Sensory feedback has been implemented using both invasive and non-invasive interfaces (fig.1) and has been shown to improve control, increase embodiment and reduce phantom limb pain [6]. Despite these benefits, sensory feedback is only incorporated in a limited number of high-end myoelectric prostheses through vibrotactile and electrotactile interfaces [7].

There have been recent reviews that focus on the technological advances in sensory feedback systems (implanted devices in particular) [6], [8] and the impact of sensory feedback on control [9]. Thus, this paper aims to highlight specific barriers and opportunities drawn from the literature concerning the *impactful* incorporation of sensory feedback in upper-limb prostheses. We define impactful implementation of sensory feedback as one that ultimately leads to an improved quality of life. This can be achieved through increased user satisfaction and prosthesis use and, thus, reduced abandonment rates and overuse injuries. The paper will start with presenting the literature on user needs (section II), followed by a brief overview of the clinical results obtained with the different feedback methods, with a focus on conflicting or unclear results (section III). Section IV will then discuss the challenges and opportunities associated with producing translatable sensory feedback research that matches the user needs and results in effective clinical implementation.

II. User Needs

Many recent surveys have focussed on trying to understand the needs of individuals with upper-limb difference, many of which focused on device abandonment, and while reported rates vary there is broad agreement that current prostheses need improvement. The reported abandonment rates of passive, body-powered and myoelectric prostheses range between 6 and 100%, 80 and 87% and 0 and 75%, respectively. The variation in the reported rates can be linked to the different recruitment methods and the intrinsic differences among the population [10], [11].

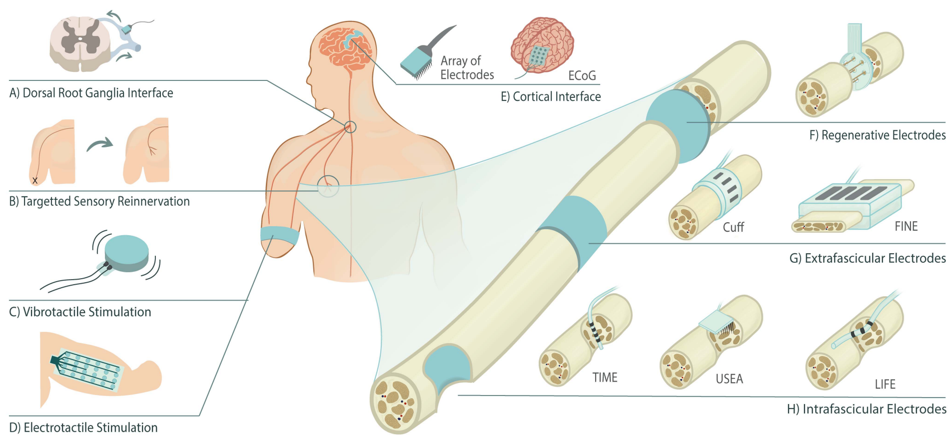

Fig. 1. Interfaces used to deliver sensory feedback. An illustration of the different sensory feedback interfaces showing both invasive and non-invasive approaches. A) DRG interfaces limit stimulation to sensory pathways. B) Targeted Sensory Reinnervation is the process of attaching nerve endings to muscles close to the amputation site, such as the chest. C) Vibrotactile stimulation uses vibration motors to map sensations from the hand. D) Electrotactile stimulation follows the same concept of vibrotactile stimulation but uses transcutaneous electrical stimulation. E) Cortical stimulation. Implanted nerve interfaces include: F) Regenerative electrodes G) Extrafascicular electrodes: cuff and flat interface nerve electrode (FINE) H) Intrafascicular electrodes: transversal intrafascicular multichannel electrode (TIME), Utah slanted electrode array (USEA) and longitudinal intra-fascicular electrode (LIFE).

The Atkins survey reported in 1996 is one of the largest conducted, representing the views of 1,575 participants. The survey summarises the problems faced by the users of both body-powered and electric-powered prosthesis, and defines the areas of improvement, split into near-term and long-term. The near-term were focused on improving reliability and comfort, with the cables and harness being key for body-powered prostheses and batteries and electrodes for electric-powered. Glove material was also a common concern. The proposed future work was similar for both, focusing on wrist movement and reduced visual attention [10].

Twenty-five years later and the challenges facing prostheses users do not seem to have changed; comfort and function are still considered innovation priorities. The reasons for abandonment are linked to those priorities and include temperature, weight, pain, poor fit, difficulty of control, slow response speed, lack of durability and functionality as well as lack of sensory feedback [11]. What is particularly surprising is that glove durability and reliability of electrodes, what Atkins *et al.* described as "near-term considerations," remain a source of frustration among upper-limb prosthesis users [11]–[19].

A. The Need for Sensory Feedback

Varying survey methodologies and demographics have led to conflicting results about the importance of sensory feedback. The need for sensory feedback is often considered more important for myoelectric than body powered prostheses. The Atkins survey showed that sensory feedback (described as reduction in visual attention required) was given an average priority of 3rd and 5th out of 10 by myoelectric and body-powered prostheses users, respectively, with a lower number indicating greater preference [10]. Similarly, Biddis *et al.* showed that, out of 10 options, sensory feedback was ranked as the 4th most important by myoelectric users, but only 8th by body-powered users [12]. This difference in perceived importance can be linked to the ability of the mechanical nature of body-powered prostheses to provide some level of sensory feedback which improves the control of the device.

Biddis *et al.* also observed that sensory feedback is considered more important by rejectors than wearers, with 85% of rejectors and 44% of wearers ranking it as a significantly important feature [14]. Whereas this could be a result of many different factors, surveys have showed that users who spend more time learning to use their prostheses are less likely to reject it [20]. This could suggest that the users have learnt to compensate for the loss of sensory feedback through methods such as pressure on the stump or the sound of the motor [21]. The survey by Pylatiuk *et al.* found the highest rate of support for sensory feedback at over 90% [22].

Surveys that use open-ended questions surrounding imagined sensory feedback often report participants finding it difficult to imagine. Having not tried any form of sensory feedback, they tend to answer with "*not really sure*" or "*literally have no clue*" [16]. However, more guided questions such as those proposed by Lewis *et al.* enabled the most important sensations to be identified by asking the respondents to rate their importance. Grip force was identified as the most important, followed by movement, position, first contact, end of contact and touch. In another question, the participants were asked about the preferred feedback modality. This was done after prompting the respondents to self-assess the sensitivity of their stump to pressure, vibration, and temperature. Surprisingly, their preferred modality was chosen to be temperature, even though the average sensitivity score for temperature was the lowest. Vibration, electric and pressure were the next preferred modalities with the acceptability of visual and acoustic feedback being markedly lower. No details were provided on how each of the modalities were described to explain why an "electric" feeling was chosen over a seemingly more natural sensation of pressure [23]. This presents the limitation of relying on surveys to understand user needs, particularly when using speculative questions. Moreover, surveys provide a limited insight into why participants selected their specific answers. For example, Lewis *et al.* showed that grip force is the most important sensation amongst the options given. However, participants did not express if that is important to enable dexterous manipulation or simply to hold objects without dropping them. Further engagement with users through interviews will enable researchers to understand *how* sensory feedback is useful in a practical sense and thus where to focus research and development to maximise impact.

B. Acceptance of Invasive Approaches

With many of the sensory feedback approaches depending on invasive devices (i.e., surgical implants), it is important to understand potential user acceptance. Engdahl *et al.* found that participants were most interested in myoelectric control, followed by peripheral nerve interfaces (PNI) and targeted muscle innervation (TMR) and least interested in cortical interfaces (CI). Engdahl *et al.* also reported the comments received on each of the different methods which showed that, based on prior negative experience of reliability, users are hesitant to try new technology, especially if some of the parts that may need repair are implanted. Furthermore, most of the respondents prefer not to undergo surgery again and are more interested in having reliable basic features than advanced ones [24].

III. Overview of Results to Date

Section II has demonstrated that there is limited literature on the need and efficacy of sensory feedback. Improvement in control of the prosthesis is a primary metric used to assess sensory feedback, using both existing and bespoke outcome measures (see Table I). Other metrics include the naturalness of the sensation (in terms of being somatotopic and homologous), as well as the effect on embodiment and phantom limb pain. Emotional benefits, from direct quotes, may also be considered if available. This section will highlight the range of outcome measures available, identify if results are conflicting or in agreement, and identify challenges and opportunities. The reader can refer to recent review papers for more details on different systems' design and functionality [6], [8], [9] and to [25] for a historical perspective.

Starting with recent review papers and branching out to cover new and related research within the period 2010- 2020, the approaches with consistent or increasing interest in the literature were identified, as shown in fig 1. Vibrotactile and electrotactile feedback are common non-invasive methods that rely on stimulating the mechanoreceptors and afferent nerve endings in the skin to relay different pressures and/or hand positions through spatial, frequency or intensity mapping [26]. Invasive techniques include electrical stimulation of the peripheral nerves using implanted electrodes to elicit action potentials (mimicking those generated by mechanoreceptors), and thus referred sensation. Interfaces at the Dorsal Root Ganglia (DRG) ensure that only afferent fibres are excited [27], whereas CI enable the selection of the stimulation location based on the architecture of the somatosensory cortex [28]. Both DRG interfaces and CI are still in their early development phase, with a limited number of clinical trials, and will not be covered in this review [29]. Extended Physiological Perception (EPP), first proposed in 1974, is an alternative feedback approach that utilises the body's inherent proprioceptive abilities by creating a mechanical link between the prostheses joint and body joint. The physiological appropriateness of EPP is thought to enhance its intuitiveness, as subconscious pathways are used to process the feedback [30]. EPP has been recently extended in an approach that suggests replacing the mechanical link to the prosthesis with implanted devices connected to the muscles to apply the appropriate forces [31].

A. Improving Control of Prostheses

Research on sensory feedback for upper-limb prostheses gained momentum after the commercialisation of powered prostheses [33]. Unlike their body-powered counterparts, powered (myoelectric) prostheses are controlled using electromyographic (EMG) signals, reducing the user's ability to assess the force applied. This, combined with the inherent uncertainty of measured EMG signals, are the main drivers for implementing sensory feedback as it allows the user to adjust prediction errors, thus facilitating learning and ultimately improving control [34], [35].

Humans rely on sensory inputs to perform even the simplest actions. Consider drinking water from a cup as an example; the brain uses vision, tactile inputs from the fingers and proprioception to enable us to drink without dropping the cup or spilling. The brain weighs those inputs and noisy and delayed sensory signals tend to receive lower weightings as they are considered less trustworthy [9], [36]. Over time, the brain builds an internal model that enables more efficient use of the different sensory inputs. Considering the availability of rapid implicit feedback (such as vision, the sound of motors or actuators and pressure on the socket), sensory feedback must operate with high reliability and minimal latency if the brain is to integrate the additional sensory inputs into the internal model [9]. Moreover, the uncertainty of the controller also influences the measured improvement; ideal controllers (only available in virtual environments) might underestimate the importance of feedback as the user can rely on pure feedforward control with practice. The presence of uncertainty increases the reliance on sensory feedback [35], [37]. However, highly uncertain controllers (e.g., high forces using EMG control) reduce the benefit from feedback as adjustments of the control signal do not always translate into adjustments in the resulting action [38], [39].

It is also important to consider the type of tasks used to measure improvement, they should represent ADL and capture the benefit of sensory feedback. Simple tasks (e.g. level reaching) can underestimate the benefit, as participants are more likely to depend on feedforward control, and complex tasks may overestimate the benefit during ADLs (e.g. picking a cherry stem) because, until a sufficiently reliable and dexterous prosthesis is developed, the user is likely to handle the more delicate part of the task using the intact limb. Fig. 2 shows results obtained using different sensory feedback systems split based on the type of tasks assessed (Supplementary material, Table I) and the availability of other sensory cues. The figure shows that most studies confirm that sensory feedback improves control. However, those representing more realistic assessments tend to show little or no improvement. While this does not necessarily mean that sensory feedback does not improve control, it does highlight room for improvement in

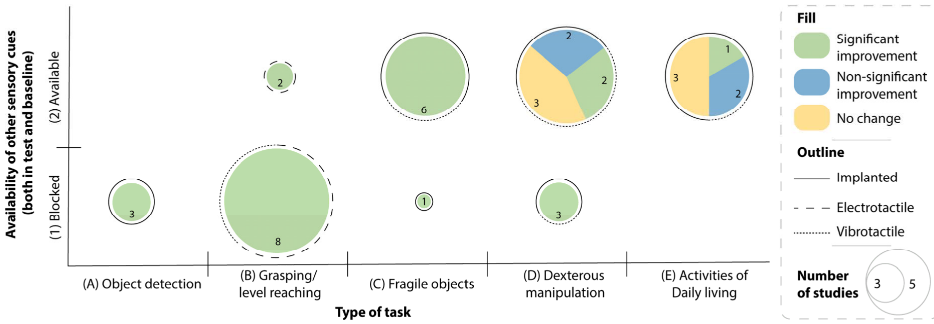

Fig. 2. Overview of effect of feedback on control. The plot compares the results obtained using different types of tasks (x-axis) when carried out with and without other sensory (vision and/or auditory) cues being available to the participant (y-axis). The radius of the bubbles represents the number of studies, the colour represents the results of those studies, and the outline represents the type of sensory feedback used. Tactile and proprioception feedback were not differentiated in the classification. The results were classified based on the best outcome (e.g., increased accuracy at the expense of time and improved performance limited to lower force levels were considered an improvement). The studies included in each of the bubbles are as follows. A1: [71], [80], [120], C1: [63] C2: [58], [64], [69], [121]–[123], D1: [35], [80], [120], D2: [35], [121], [123], [124], E2: [71], [120], [121], [124], [125]. Note: Multiple experiments within one paper are represented as different studies. This is an overview of the results to highlight the variation in results obtained, for a more comprehensive analysis the reader can refer to [9].

the type of assessment used. This will be discussed further in the challenges and opportunities section.

B. Providing Somatotopic and Homologous Feedback

Producing homologous (of the same type as the original) and somatotopic (in the same location) sensation would serve to increase the intuitiveness of a sensory feedback system [40].

The deafferented cortex, initially connected to the arm, can be activated through two pathways: hand maps and the original nerve structure. Those pathways can be utilised to elicit sensations that are referred to the phantom hand. Hand maps are skin areas where tactile stimulation is perceived as originating from the phantom limb. They are highly variable between participants and are usually found on the stump and face [41]. Although time-consuming to locate, hand-maps can enable perception of specific fingers with reduced stimulation thresholds [42]–[44]. The evoked sensations are stable in terms of stimulation threshold and location for at least 11 months [45].

Stimulation of the peripheral nerves (Ulnar, Median and Radial) using implanted electrodes has been shown to, in most cases, produce referred sensations matching the innervation areas even 20 years post-amputation. The stability of innervation areas confirms that the original somatosensory pathways remain intact following amputation, despite the apparent reorganisation present as hand maps [46], [47]. Congenital amputees do not report phantom sensations as the required somatosensory pathways have never developed [48].

It is also possible to elicit referred sensation non-invasively via transcutaneous stimulation of the peripheral nerves [40], [49]–[51]. However, a disadvantage of this non-invasive approach is the poor stability of the somatotopic sensation with limb movement and persistent sensation under the electrodes [50]. Methods to reduce the sensation under the electrodes include interferential stimulation and channel-hopping [52], [53]. Moreover, this concept does not seem to work for digital amputees due to the stump's different cortical representation [54].

Studies have shown that delivering more natural and pleasant (not painful or uncomfortable) sensations during electrical stimulation results in stronger embodiment, although a natural sense of touch has yet to be achieved [55], [56]. Experiments performed in the 1970s using implanted electrodes resulted in unnatural sensations such as paraesthesia and throbbing [57]. Since then, new encoding methods have enabled more natural sensations to be achieved using peripheral nerve interfaces. Fig. 3 compares the studies that describe the type of evoked sensation and indicates the invasiveness of the electrodes (x-axis) and the chosen encoding method (colour). Tactile sensing is encoded through spatial and temporal activation of afferent fibres. Therefore, the high-order processing of the different sensory inputs controls the sensory modality experienced [58]. The low selectivity of transcutaneous stimulation limits its ability to elicit natural sensation with sensations of paraesthesia or vibration reported [59]–[61]. In fact, vibrotactile stimulation appears to be to be more comfortable [62]. Implanted electrodes enable higher selectivity and, therefore, the stimulation waveform parameters affect the sensory modality experienced [63]. Thus the fine-tuning of the waveforms through biomimetic approaches can produce the most natural sensations [56], [64]–[67]. Duration of use also influences the naturalness of the elicited sensation, with prolonged use being associated with improved quality of sensation [68]–[71].

C. Increasing Embodiment

Embodiment relates to the feeling that the prosthesis is an extension of the body rather than a tool. It is usually measured subjectively through questionnaires that are based on the rubber hand illusion [72] and objectively through measuring the temperature of the residual limb [73] or using the phantom hand location [74]. Communicative Hand Gestures have also been suggested as an implicit measure of embodiment [75]. Experiments that consider the effect of sensory feedback on embodiment tend to report an improvement [73], [76], [77] even with modality mismatched feedback [78]. However, this increased embodiment is higher when natural sensations are delivered (biomimetic feedback) [64]. The definition of embodiment is inconsistent between reports, particularly concerning whether or not agency is intrinsic within embodiment. Middleton and Ortiz-Catalan warn against relying on lab tests for an assessment of embodiment: "*We must be careful not to extrapolate a sense of ownership and agency (or both) that*

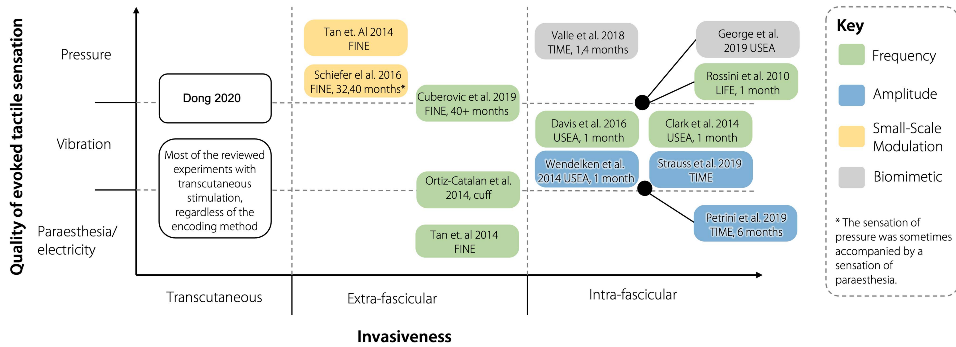

Fig. 3. Quality of Sensation elicited through electrical stimulation A comparison of the naturalness of the evoked sensation against the electrodes' invasiveness. Invasive approaches tend to elicit a range of sensation qualities and this figure focuses more of the best quality elicited. The colour coding indicates the different encoding methods [63], [64], [68], [69], [71], [85], [121], [126]–[130]. Small-scale modulation uses a slow sinusoidal envelope to modulate the pulse width of a 100Hz square pulse train. The lower limit of the pulse width is limited to ensure some activation of the neuronal population at all times (see [63] for details).

occurs in a cultivated moment or instant to an irreversible, sustained phenomenon" [79].

Home use studies provide an avenue for a more complete assessment of the benefit of sensory feedback on embodiment, and user experience as a whole. Studies with both implanted and TSR feedback methods have shown that home use increases the measured benefits of the feedback. Graczyk *et al.* reported that while in-lab functional tests did show increased embodiment, only home use resulted in significant improvement that was most evident in the first month and stabilised afterwards [71], [80]. Schofield *et al.* showed that embodiment became more specific to certain conditions after home use. Participants that reported increased embodiment with time-delayed and non-somatotopic feedback at the start of the experiment only reported increased embodiment with timely somatotopic feedback by the last trial [81].

D. Reducing Phantom Limb Pain

Most adults with acquired amputation report phantom sensations, of which 80% are painful. When persistent, phantom limb pain has a negative effect on the quality of life and adaptation to amputation [82]. Sensory feedback has a demonstrable positive effect on phantom limb pain, as has been demonstrated using methods including the Visual Analogue scale [69], [83]–[85], the McGill pain questionnaire [85], the Trinity amputation and prosthesis experience scale [63], the present pain intensity scale [85], the neuropathic pain symptom inventory [69] and verbal scoring [86]. The reduction in phantom pain is usually linked to a change in the pain sensation to pressure/vibration sensation elicited by the stimulation [74]. However, this reduction in pain was not evident once feedback was removed (at the three-month follow-up) [85]. The reduction in phantom limb pain was sometimes described as the hand "opening up" [63], [74]. Additionally, the phantom sensation change was shown as an increase in the length of the phantom limb to align with the prostheses [68], [71], [80], [87].

E. Emotional Benefit

Sensory feedback is primarily discussed in relation to increased performance of the prosthetic, with less focus given to the emotional benefits (perceived or observed) despite their importance for psychological adjustment [88]. Given the increased rates of depressive symptomatology amongst individuals with acquired upper-limb loss [89], promoting positive coping mechanisms that elevate their self-worth and minimise their sense of isolation is vital for improving quality of life [88]. This suggests that the need for more systematic methods of assessing the emotional benefits of sensory feedback. Participants of experiments on sensory feedback tend to report such emotional benefits. One described it as

"*I felt what I was doing, do you understand, it was exactly as it was my own fingers. What a feeling!.*"

Further, sensory feedback is often linked to benefits with interactions with children and loved ones.

"I hope for some sort of sensory feedback for the grip function, when you touch things. When I use my hands for touching I want to avoid pinching my children by mistake."

This emotional benefit seemed less relevant to individuals with congenital limb deficiencies who have never experienced the sense of touch through the missing hand [21].

IV. Challenges and Opportunities

Despite the development of a wide range of technologies for sensory feedback, and their promising results, clinical translation is poor. The following subsections reflect on the challenges hindering translation and highlight the key opportunities to overcome them. The specific challenges associated with translation of neurostimulation technologies within the associated ethical and regulatory environments are outside the scope of this manuscript, and have been addressed in recent reviews [90]–[92].

A. Gaining a Deep Understanding of User Needs

While surveys are highly valuable and do highlight common problems, they often fail to communicate the underpinning behaviours and needs, leading to a mismatch between user expectations and reality and, potentially, device abandonment [93]. Fortunately, the challenges associated with understanding user needs in the context of healthcare and rehabilitation are well known, and many qualitative research tools (such as interviews and focus groups) can be used to provide richer data. In the context of sensory feedback, such data might involve what participants expect sensory feedback to feel like, what sensor locations they think are most useful, and what tasks they expect sensory feedback to help with. While these questions can be asked via a survey, using qualitative methods enables a more in-depth explorations of such participant expectations and motivations, providing an understanding of how sensory feedback will fit into the users' life beyond responses to pre-existing questions defined by the researcher. It is this in-depth insight into the user's behaviours (i.e., how they interact with the environment and intervention) that enables the design of acceptable and engaging interventions that 'fit' into the user's life, subsequently increasing uptake and ultimately effectiveness. Indeed several qualitative studies have been conducted in relation to upper-limb difference (see [94] for meta-synthesis). There have been a few qualitative studies evaluating the benefit of sensory feedback systems but they are more *summative* in nature, focusing on how the developed sensory feedback systems affected the participants' lives [70], [79].

We propose using the Person Based Approach (PBA), which provides a systematic method to integrate *formative* qualitative studies, using guiding principles that are then modified throughout the planning, design, development and evaluation stages [95]. *Formative* studies, as opposed to *summative*, focus on understanding user needs in a broader manner rather than evaluating the performance of the developed system. The PBA relies on detailed evidence synthesis and iterative qualitative research to develop an in-depth understanding of the behaviours and lives of potential users in order to understand how they engage with the intervention [95]. It values autonomy and empathetic understanding, which are particularly important for personal devices, such as prostheses [96], [97]. This approach, with early integration of qualitative studies, captures the users' lived experience and their expectations of sensory feedback, emphasizing this without being limited by the constraints of an already-developed system. Removing these constraints ensures that the in-depth understanding of user needs remain at the heart of the process throughout the stages of intervention planning, development, optimisation, and evaluation. Furthermore, once the initial intervention has been developed, the iterative nature of the process means that the guiding principles and design features are regularly refined to reflect the users' experience trying the intervention – thus ensuring that the intervention remains as acceptable and effective as possible. The reader can refer to [98] for an overview of how the structured and systematic PBA can be applied by research teams at each research stage. A summary of this process can be found in Fig.1 of the supplementary material).

B. Meaningful Assessment Measures

The measures used to assess prostheses technology are critical to the translation of research and the derivation of demonstrable impact; it provides the evidence required to convince both investors and users of its benefit. It has been shown in the literature considered in Section 3A that sensory feedback improves control. However, tests that attempt to *quantify* this improvement in representative use cases tend to show insignificant improvement, if any (fig. 2). The one case that showed improved performance was a subjective measure where the participants reported the improved performance in the tasks that they found most difficult [71]. While it is possible that this assessment reflected increased confidence rather than improved control, it resonates with Schaffalitzky *et al.*'s recommendations to consider functional improvements from the user's perspective rather than physical functioning *per se* [99]. Moreover, it highlights the importance of developing tailored ADL tests. Given that prostheses users are constantly evaluating the benefit of using a prosthesis against its problems [4], the assessment measures should aim to align to the users' personal metrics. This has significant potential implications on predicting prostheses usage, as current lab measures show no significant correlation to prostheses usage [100]. (See [101] for more information on outcome measures for upper-limb prosthesis). The influence the user input has on outcome measures can be illustrated by using the cups relocation task as an example. This task tests the user's ability to handle fragile objects (disposable cups). If user engagement highlighted that holding a cup while walking is the trickiest scenario in day-to-day life, the assessment could, therefore, incorporate a walking activity. This will enable the feedback system to be tested to ensure reliability while walking while also evaluating how effective sensory feedback is in such situations.

Qualitative research approaches, such as the PBA, can be the first step in developing meaningful measures as they enable researchers to capture the behaviours and unmet needs of the population of people with upper-limb difference [97]. Further involvement of a subset of participants in the design process, through co-creation, can ensure that the qualitative data collected is interpreted and utilised appropriately. Co-creation design frameworks have been used to rapidly ensure health interventions are accepted and useful for users by making stakeholders (such as the users, clinicians, industry and policymakers) part of the design process [102]. Each stakeholder provides input at various stages of the work [103]. When designing outcome measures, users and clinicians can provide valuable insight into what has worked in the past and what has not to guide the ideation process. Industry partners have more technical experience and can spot potential failures during home use, ensuring that the chosen designs are robust. Finally, including policymakers ensures that the chosen assessment measures can provide sufficient evidence of value and impact, and paves the way for them to be translated into clinical assessments.

If the assessment measures are developed alongside the sensory feedback system, then there is the potential to collect detailed and tailored usage data. This data should aim to capture the different factors discussed in section III. Comparisons between the home-use and lab-use measures could provide valuable insight into differing use patterns and could guide modifications to maximise at-home benefit. Such longitudinal home-use data would also support future clinical decision making.

C. Integrating Forward Control and Feedback

The interaction between the feedforward (control) and feedback systems is often not considered, despite it affecting both basic functionality and overall performance.

Electrical stimulation used to elicit sensation poses challenges arising from stimulation artefacts if recordings are made at the same level for the purposes of control, with the risk that control could be lost during stimulation [104]. Current closed-loop experiments using implanted interfaces rely on surface EMG recordings, rather than recordings from the implanted interface, to control the prostheses [105], [106]. This approach reduces the effect of stimulation artefacts due to both the spatial separation of the interfaces and the reduced stimulation magnitude required for direct nerve interfaces. Experiments involving surface stimulation (transcutaneous) and recording have been designed by placing the stimulating and recording electrodes on different arms [107], [108]. However, this is thought to reduce the system's intuitiveness, making it unsuitable for use outside the lab environment [107]. Several methods exist to overcome the interference between stimulating and recording electrodes, including using concentric electrodes [109], blanking [110], [111] and time-division multiplexing [112], [113].

The design of current sensory feedback systems aims to enhance the performance obtained with standard myoelectric control. However, several new decoding algorithms are being developed on an invasive and non-invasive level [114]. With a few of those methods reaching maturity and clinical trials, it would be interesting to test how sensory feedback integration differs with such methods as well as data acquisition [115]. The current home tests being planned for different control methods can provide an opportunity for concurrent testing with sensory feedback. The resulting increased complexity of experimental design will pay off in the long run, as the two systems will be expected to work synergistically. The recent work of Marasco *et al.* provides a key step towards the integration of feedforward and feedback through the development of metrics that assess the contribution of each of the parts of the interface on the overall performance [116].

V. Importance of Interdisciplinary Collaborations

The theme arising in the previous three sections is the need for an interdisciplinary, integrated qualitative and quantitative, and long-term research approach to the design of sensory feedback systems. Established research groups may have the capabilities and expertise required to perform this integrated interdisciplinary research but it may become more difficult to maintain this capability as more advanced technologies near translation. Indeed, the breadth of expertise required may prove to be a significant barrier to many research groups, or worse still may negate any potential clinical impact due to a lack of expertise in one or more areas. The existing regulations in place to reach participants and conduct (both invasive and non-invasive) experiments are rightly robust but are themselves often a significant barrier for smaller research groups.

The shift to more interdisciplinary research necessitates the development of new means of collaboration to improve research efficiency. An optimal collaboration structure would be supported by national centres of excellence supported and funded by government. The role of such a centre would be: to define outcome measures and develop strategies for implementation, to manage the engagement with device user groups and stakeholders, to shape policy and regulation, to maintain registers of expertise, and ultimately to enable interdisciplinary collaborations and co-creation for the design of long-term studies. Co-design requires goodwill and engagement from user groups, and thus must be effectively managed at a national level to ensure that the maximum benefit can be derived.

While the ultimate aim may be to produce prostheses that are as functional as the human arm, a national centre would enable the identification of grand challenges that solve existing problems faced by users while paving the path towards the ultimate aim. Those challenges can be used to guide research efforts. This centre can also facilitate the development of a shared platform for participants to register interest in different research activities outlining their background and preferences to allow for both convenience and purposive sampling.

Surveys and interviews will be designed based on input from multiple stakeholders to ensure similar areas of investigation are grouped, reducing repetition while increasing the engagement per study. Research on specific technical advancements will continue independently by different groups, with scheduled meetings providing an opportunity for the exchange of ideas and suggestions. Long term experiments, however, can and should be done collaboratively to enable different technologies and theories to be demonstrated. The development of assessment measures must be synergistic with the technologies being developed, and tools such as the PBA can be used to strengthen the links between quantitative and qualitative research.

Moreover, the collaboration of different research groups to develop shared libraries of commonly required resources eliminates the time spent replicating them and increases their reliability. This collaborative library can include software used to collect sensation information (such as [117]), the design of home use tracking devices (critical for assessment measures) as well as a shared list of lessons learnt, to name a few. A collaborative network is one route forwards, although there are well known challenges associated with highly interdisciplinary research [118]. However, the relatively small scale of research on sensory feedback for upper-limb prostheses means that the development of this framework can provide an interesting case study that can be adapted to other areas of research.

VI. Conclusion

This paper has highlighted the available literature on the sensory feedback needs of individuals with upper-limb difference and the outcome measures used to assess the developed feedback systems in terms of improving control, naturalness, embodiment and reducing phantom limb pain. This has shown that developing user-focused outcome measures is a potential area of improvement, particularly in relation to control and emotional benefits. Sensory feedback is progressing to include cutting-edge technology such as cortical stimulation and Dorsal Root Ganglia interfaces. However, only the simplest form of sensory feedback is found in a few high-end commercial prostheses [119]. This shows the inherent lag in the commercialisation of the research. Establishing stronger interdisciplinary collaborations will accelerate translation by

1) enabling user needs and experiences to be better captured through co-creation and person-based approaches, 2) ensuring the assessment measures used are meaningful for those who use them, and 3) testing the integration sensory feedback and control. This shift in the way research on upper-limb prostheses is conducted is expected to enable the basic user needs, that have been mostly consistent for 25 years, to be finally met.

References

[1] T. Field, *Touch*. Cambridge, MA, USA: MIT Press, 2001.

[2] B. P. Delhaye, K. H. Long, and S. J. Bensmaia, "Neural basis of touch and proprioception in primate cortex," *Comprehensive Physiol.*, vol. 8, no. 4, pp. 1575–1602, Sep. 2018.

[3] R. S. Johansson and J. R. Flanagan, "Coding and use of tactile signals from the fingertips in object manipulation tasks," *Nature Rev. Neurosci.*, vol. 10, no. 5, pp. 345–359, 2009.

[4] A. Saradjian, A. R. Thompson, and D. Datta, "The experience of men using an upper limb prosthesis following amputation: Positive coping and minimizing feeling different," *Disability Rehabil.*, vol. 30, no. 11, pp. 871–883, Jan. 2008.

[5] L. L. Salisbury and A. B. Colman, "A mechanical hand with automatic proportional control of prehension," *Med. Biol. Eng.*, vol. 5, no. 5, pp. 505–511, Sep. 1967.

[6] S. J. Bensmaia, D. J. Tyler, and S. Micera, "Restoration of sensory information via bionic hands," *Nature Biomed. Eng.*, to be published.

[7] W. Williams, *Sensory Feedback for Bionic Hands | Bionics For Everyone*, BionicsForEveryone.Com, 2021. [Online]. Available: https://bionicsforeveryone.com/sensory-feedback-bionic-hands/

[8] S. Raspopovic, G. Valle, and F. M. Petrini, "Sensory feedback for limb prostheses in amputees," *Nature Mater.*, vol. 20, no. 7, pp. 925–939, Apr. 2021.

[9] J. W. Sensinger and S. Dosen, "A review of sensory feedback in upper-limb prostheses from the perspective of human motor control," *Frontiers Neurosci.*, vol. 14, p. 345, Jun. 2020.

[10] D. J. Atkins, D. C. Y. Heard, and W. H. Donovan, "Epidemiologic overview of individuals with upper-limb loss and their reported research priorities," *J. Prosthetics Orthotics*, vol. 8, no. 1, pp. 2–11, 1996.

[11] L. C. Smail, C. Neal, C. Wilkins, and T. L. Packham, "Comfort and function remain key factors in upper limb prosthetic abandonment: Findings of a scoping review," *Disab. Rehabil., Assistive Technol.*, vol. 16, no. 8, pp. 821–830, 2020.

[12] E. Biddiss, D. Beaton, and T. Chau, "Consumer design priorities for upper limb prosthetics," *Disab. Rehabil., Assistive Technol.*, vol. 2, no. 5, pp. 346–357, 2007.

[13] P. J. Kyberd and W. Hill, "Survey of upper limb prosthesis users in Sweden, the United Kingdom and Canada," *Prosthetics Orthotics Int.*, vol. 35, no. 2, pp. 234–241, 2011.

[14] E. Biddiss and T. Chau, "Upper-limb prosthetics: Critical factors in device abandonment," *Amer. J. Phys. Med. Rehabil.*, vol. 86, no. 12, pp. 977–987, 2007.

[15] B. Peerdeman, "Myoelectric forearm prostheses: State of the art from a user-centered perspective," *J. Rehabil. Res. Dev.*, vol. 48, no. 6, pp. 719–738, 2011.

[16] B. Stephens-Fripp, M. Jean Walker, E. Goddard, and G. Alici, "A survey on what Australians with upper limb difference want in a prosthesis: Justification for using soft robotics and additive manufacturing for customized prosthetic hands," *Disab. Rehabil., Assistive Technol.*, vol. 15, no. 3, pp. 342–349, 2020.

[17] F. Cordella *et al.*, "Literature review on needs of upper limb prosthesis users," *Frontiers Neurosci.*, vol. 10, p. 209, May 2016.

[18] K. Østlie, I. M. Lesjø, R. J. Franklin, B. Garfelt, O. H. Skjeldal, and P. Magnus, "Prosthesis rejection in acquired major upper-limb amputees: A population-based survey," *Disab. Rehabil., Assistive Technol.*, vol. 7, no. 4, pp. 294–303, 2012.

[19] H. L. Benz *et al.*, "Upper extremity prosthesis user perspectives on unmet needs and innovative technology," in *Proc. 38th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Aug. 2016, pp. 287–290.

[20] K. Østlie, I. M. Lesjø, R. J. Franklin, B. Garfelt, O. H. Skjeldal, and P. Magnus, "Prosthesis use in adult acquired major upper-limb amputees: Patterns of wear, prosthetic skills and the actual use of prostheses in activities of daily life," *Disab. Rehabil., Assistive Technol.*, vol. 7, no. 6, pp. 479–493, Nov. 2012.

[21] U. Wijk and I. Carlsson, "Forearm amputees' views of prosthesis use and sensory feedback," *J. Hand Therapy*, vol. 28, no. 3, pp. 269–278, Jul. 2015.

[22] C. Pylatiuk, S. Schulz, and L. Döderlein, "Results of an internet survey of myoelectric prosthetic hand users," *Prosthetics Orthotics Int.*, vol. 31, no. 4, pp. 362–370, Dec. 2007.

[23] S. Lewis, M. F. Russold, H. Dietl, and E. Kaniusas, "User demands for sensory feedback in upper extremity prostheses," in *Proc. IEEE Int. Symp. Med. Meas. Appl.*, May 2012, pp. 188–191.

[24] S. M. Engdahl, B. P. Christie, B. Kelly, A. Davis, C. A. Chestek, and D. H. Gates, "Surveying the interest of individuals with upper limb loss in novel prosthetic control techniques," *J. Neuroeng. Rehabil.*, vol. 12, no. 1, p. 53, Jun. 2015.

[25] D. S. Childress, "Closed-loop control in prosthetic systems: Historical perspective," *Ann. Biomed. Eng.*, vol. 8, nos. 4–6, pp. 293–303, Jul. 1980.

[26] B. Stephens-Fripp, G. Alici, and R. Mutlu, "A review of non-invasive sensory feedback methods for transradial prosthetic hands," *IEEE Access*, vol. 6, pp. 6878–6899, 2018.

[27] H. P. Saal and S. J. Bensmaia, "Biomimetic approaches to bionic touch through a peripheral nerve interface," *Neuropsychologia*, vol. 79, pp. 344–353, Dec. 2015.

[28] A. E. Schultz and T. A. Kuiken, "Neural interfaces for control of upper limb prostheses: The state of the art and future possibilities," *PM&R*, vol. 3, no. 1, pp. 55–67, 2011.

[29] S. N. Flesher *et al.*, "A brain-computer interface that evokes tactile sensations improves robotic arm control," *Science*, vol. 372, no. 6544, pp. 831–836, May 2021.

[30] T. R. Farrell, R. F. Weir, C. W. Heckathorne, and D. S. Childress, "The effects of static friction and backlash on extended physiological proprioception control of a powered prosthesis," *J. Rehabil. Res. Develop.*, vol. 42, no. 3, pp. 327–342, 2005.

[31] S. Kontogiannopoulos, G. A. Bertos, and E. Papadopoulos, "A 'biomechatronic EPP' upper-limb prosthesis control configuration and its performance comparison to other control configurations," *IEEE Trans. Med. Robot. Bionics*, vol. 2, no. 2, pp. 282–291, May 2020.

[32] T. R. Clites *et al.*, "Proprioception from a neurally controlled lower-extremity prosthesis," *Sci. Transl. Med.*, vol. 10, no. 443, p. 8373, May 2018.

[33] D. S. Childress, "Historical aspects of powered limb prostheses," *Clin. Prosthetics Orthotics*, vol. 9, no. 1, pp. 2–13, 1985.

[34] R. Ackerley and A. Kavounoudias, "The role of tactile afference in shaping motor behaviour and implications for prosthetic innovation," *Neuropsychologia*, vol. 79, pp. 192–205, Dec. 2015.

[35] I. Saunders and S. Vijayakumar, "The role of feed-forward and feedback processes for closed-loop prosthesis control," *J. Neuroeng. Rehabil.*, vol. 8, no. 1, p. 60, 2011.

[36] D. Blana *et al.*, "Model-based control of individual finger movements for prosthetic hand function," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 28, no. 3, pp. 612–620, Mar. 2020.

[37] S. Dosen *et al.*, "Multichannel electrotactile feedback with spatial and mixed coding for closed-loop control of grasping force in hand prostheses," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 3, pp. 183–195, Mar. 2017.

[38] S. Dosen *et al.*, "Building an internal model of a myoelectric prosthesis via closed-loop control for consistent and routine grasping," *Exp. Brain Res.*, vol. 233, no. 6, pp. 1855–1865, Jun. 2015.

[39] A. Ninu, S. Dosen, S. Muceli, F. Rattay, H. Dietl, and D. Farina, "Closed-loop control of grasping with a myoelectric hand prosthesis: Which are the relevant feedback variables for force control?" *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 22, no. 5, pp. 1041–1052, Sep. 2014.

[40] E. D'Anna *et al.*, "A somatotopic bidirectional hand prosthesis with transcutaneous electrical nerve stimulation based sensory feedback," *Sci. Rep.*, vol. 7, no. 1, pp. 1–15, Dec. 2017.

[41] A. Björkman *et al.*, "Phantom digit somatotopy: A functional magnetic resonance imaging study in forearm amputees," *Eur. J. Neurosci.*, vol. 36, no. 1, pp. 2098–2106, Jul. 2012.

[42] X. X. Liu, G. H. Chai, H. E. Qu, and N. Lan, "A sensory feedback system for prosthetic hand based on evoked tactile sensation," in *Proc. 37th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Aug. 2015, pp. 2493–2496.

[43] D. Zhang, H. Xu, P. B. Shull, J. Liu, and X. Zhu, "Somatotopical feedback versus non-somatotopical feedback for phantom digit sensation on amputees using electrotactile stimulation," *J. Neuroeng. Rehabil.*, vol. 12, no. 1, pp. 1–11, Dec. 2015.

[44] M. Hao *et al.*, "Restoring finger-specific sensory feedback for transradial amputees via non-invasive evoked tactile sensation," *IEEE Open J. Eng. Med. Biol.*, vol. 1, pp. 98–107, 2020.

[45] G. Chai, X. Sui, S. Li, L. He, and N. Lan, "Characterization of evoked tactile sensation in forearm amputees with transcutaneous electrical nerve stimulation," *J. Neural Eng.*, vol. 12, no. 6, Dec. 2015, Art. no. 066002.

[46] T. R. Makin and S. J. Bensmaia, "Stability of sensory topographies in adult cortex," *Trends Cognit. Sci.*, vol. 21, no. 3, pp. 195–204, 2017.

[47] T. Makin and L. P. Lab, "Phantom limbs and brain plasticity in amputees," in *Oxford Research Encyclopedia of Neuroscience*. Oxford, U.K.: Oxford Univ. Press, 2020.

[48] P. Montoya *et al.*, "The cortical somatotopic map and phantom phenomena in subjects with congenital limb atrophy and traumatic amputees with phantom limb pain," *Eur. J. Neurosci.*, vol. 10, no. 3, pp. 1095–1102, Mar. 1998.

[49] L. Vargas, H. Shin, H. Huang, Y. Zhu, and X. Hu, "Object stiffness recognition using haptic feedback delivered through transcutaneous proximal nerve stimulation," *J. Neural Eng.*, vol. 17, no. 1, Dec. 2019, Art. no. 016002.

[50] H. Shin, Z. Watkins, H. Huang, Y. Zhu, and X. Hu, "Evoked haptic sensations in the hand via non-invasive proximal nerve stimulation," *J. Neural Eng.*, vol. 15, no. 4, May 2018, Art. no. 046005.

[51] L. E. Osborn *et al.*, "Sensory stimulation enhances phantom limb perception and movement decoding," *J. Neural Eng.*, vol. 17, no. 5, Oct. 2020, Art. no. 056006.

[52] L. Jabban, D. Zhang, and B. W. Metcalfe, "Interferential current stimulation for non-invasive somatotopic sensory feedback for upper-limb prosthesis: Simulation results using a computable human phantom," in *Proc. 10th Int. IEEE/EMBS Conf. Neural Eng. (NER)*, May 2021, pp. 765–768.

[53] A. E. Pena, J. J. Abbas, and R. Jung, "Channel-hopping during surface electrical neurostimulation elicits selective, comfortable, distally referred sensations," *J. Neural Eng.*, vol. 18, no. 5, Oct. 2021, Art. no. 055004.

[54] M. D. Alonzo, L. F. Engels, M. Controzzi, and C. Cipriani, "Electrocutaneous stimulation on the palm elicits referred sensations on intact but not on amputated digits," *J. Neural Eng.*, vol. 15, no. 1, Feb. 2018, Art. no. 016003.

[55] H. E. van Stralen, M. J. E. van Zandvoort, S. S. Hoppenbrouwers, L. M. G. Vissers, L. J. Kappelle, and H. C. Dijkerman, "Affective touch modulates the rubber hand illusion," *Cognition*, vol. 131, no. 1, pp. 147–158, Apr. 2014.

[56] C. M. Oddo *et al.*, "Intraneural stimulation elicits discrimination of textural features by artificial fingertip in intact and amputee humans," *eLife*, vol. 5, pp. 1–27, Mar. 2016.

[57] A. Anani and L. Körner, "Discrimination of phantom hand sensations elicited by afferent electrical nerve stimulation in below-elbow amputees," *Med. Prog. Through Technol.*, vol. 6, no. 3, pp. 131–135, 1979.

[58] D. W. Tan, M. A. Schiefer, M. W. Keith, J. R. Anderson, J. Tyler, and D. J. Tyler, "A neural interface provides long-term stable natural touch perception," *Sci. Transl. Med.*, vol. 6, no. 257, Oct. 2014.

[59] M. Perovic *et al.*, "Electrical stimulation of the forearm: A method for transmitting sensory signals from the artificial hand to the brain," *J. Autom. Control*, vol. 21, no. 1, pp. 13–18, 2013.

[60] L. Seminara *et al.*, "Dual-parameter modulation improves stimulus localization in multichannel electrotactile stimulation," *IEEE Trans. Haptics*, vol. 13, no. 2, pp. 393–403, Apr./Jun. 2020.

[61] L. P. Paredes, S. Dosen, F. Rattay, B. Graimann, and D. Farina, "The impact of the stimulation frequency on closed-loop control with electrotactile feedback," *J. Neuroeng. Rehabil.*, vol. 12, no. 1, pp. 1–16, Dec. 2015.

[62] H. J. B. Witteveen, E. A. Droog, J. S. Rietman, and P. H. Veltink, "Vibro- and electrotactile user feedback on hand opening for myoelectric forearm prostheses," *IEEE Trans. Biomed. Eng.*, vol. 59, no. 8, pp. 2219–2226, Aug. 2012.

[63] D. W. Tan, M. A. Schiefer, M. W. Keith, J. R. Anderson, J. Tyler, and D. J. Tyler, "A neural interface provides long-term stable natural touch perception," *Sci. Transl. Med.*, vol. 6, no. 257, Oct. 2014.

[64] G. Valle *et al.*, "Biomimetic intraneural sensory feedback enhances sensation naturalness, tactile sensitivity, and manual dexterity in a bidirectional prosthesis," *Neuron*, vol. 100, no. 1, pp. 37–45, Oct. 2018.

[65] J. A. George, M. R. Brinton, C. C. Duncan, D. T. Hutchinson, and G. A. Clark, "Improved training paradigms and motor-decode algorithms: Results from intact individuals and a recent transradial amputee with prior complex regional pain syndrome," in *Proc. 40th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Jul. 2018, pp. 3782–3787.

[66] E. Formento, E. D'Anna, S. Gribi, S. P. Lacour, and S. Micera, "A biomimetic electrical stimulation strategy to induce asynchronous stochastic neural activity," *J. Neural Eng.*, vol. 17, no. 4, Aug. 2020, Art. no. 046019.

[67] E. V. Okorokova, Q. He, and S. J. Bensmaia, "Biomimetic encoding model for restoring touch in bionic hands through a nerve interface," *J. Neural Eng.*, vol. 15, no. 6, Dec. 2018, Art. no. 066033.

[68] K. Horch, S. Meek, T. G. Taylor, and D. T. Hutchinson, "Object discrimination with an artificial hand using electrical stimulation of peripheral tactile and proprioceptive pathways with intrafascicular electrodes," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 19, no. 5, pp. 483–489, Oct. 2011.

[69] F. M. Petrini *et al.*, "Six-month assessment of a hand prosthesis with intraneural tactile feedback," *Ann. Neurol.*, vol. 85, no. 1, pp. 137–154, 2019.

[70] E. L. Graczyk, A. Gill, D. J. Tyler, and L. J. Resnik, "The benefits of sensation on the experience of a hand: A qualitative case series," *PLoS ONE*, vol. 14, no. 1, pp. 1–29, 2019.

[71] I. Cuberovic, A. Gill, L. J. Resnik, D. J. Tyler, and E. L. Graczyk, "Learning of artificial sensation through long-term home use of a sensory-enabled prosthesis," *Frontiers Neurosci.*, vol. 13, pp. 1–24, Aug. 2019.

[72] M. Botvinick and J. D. Cohen, "Rubber hands 'feel' touch that eyes see," *Nature*, vol. 391, p. 756, Feb. 1998.

[73] P. D. Marasco, K. Kim, J. E. Colgate, M. A. Peshkin, and T. A. Kuiken, "Robotic touch shifts perception of embodiment to a prosthesis in targeted reinnervation amputees," *Brain*, vol. 134, no. 3, pp. 747–758, Mar. 2011.

[74] D. M. Page *et al.*, "Motor control and sensory feedback enhance prosthesis embodiment and reduce phantom pain after long-term hand amputation," *Frontiers Hum. Neurosci.*, vol. 12, p. 352, Sep. 2018.

[75] R. O. Maimon-Mor *et al.*, "Talking with your (Artificial) hands: Communicative hand gestures as an implicit measure of embodiment," *iScience*, vol. 23, no. 11, Nov. 2020, Art. no. 101650.

[76] M. R. Mulvey, H. J. Fawkner, H. Radford, and M. I. Johnson, "The use of transcutaneous electrical nerve stimulation (TENS) to aid perceptual embodiment of prosthetic limbs," *Med. Hypotheses*, vol. 72, no. 2, pp. 140–142, Feb. 2009.

[77] M. Schiefer, D. Tan, S. M. Sidek, and D. J. Tyler, "Sensory feedback by peripheral nerve stimulation improves task performance in individuals with upper limb loss using a myoelectric prosthesis," *J. Neural Eng.*, vol. 13, no. 1, 2015, Art. no. 016001.

[78] M. Markovic, M. A. Schweisfurth, L. F. Engels, D. Farina, and S. Dosen, "Myocontrol is closed-loop control: Incidental feedback is sufficient for scaling the prosthesis force in routine grasping," *J. Neuroeng. Rehabil.*, vol. 15, no. 1, pp. 1–11, Dec. 2018.

[79] A. Middleton and M. Ortiz-Catalan, "Neuromusculoskeletal arm prostheses: Personal and social implications of living with an intimately integrated bionic arm," *Frontiers Neurorobot.*, vol. 14, pp. 1–18, Jul. 2020.

[80] E. L. Graczyk, L. Resnik, M. A. Schiefer, M. S. Schmitt, and D. J. Tyler, "Home use of a neural-connected sensory prosthesis provides the functional and psychosocial experience of having a hand again," *Sci. Rep.*, vol. 8, no. 1, p. 9866, Dec. 2018.

[81] J. S. Schofield, C. E. Shell, D. T. Beckler, Z. C. Thumser, and P. D. Marasco, "Long-term home-use of sensory-motor-integrated bidirectional bionic prosthetic arms promotes functional, perceptual, and cognitive changes," *Frontiers Neurosci.*, vol. 14, pp. 1–20, Feb. 2020.

[82] B. Lenggenhager, C. A. Arnold, and M. J. Giummarra, "Phantom limbs: Pain, embodiment, and scientific advances in integrative therapies," *Wiley Interdiscipl. Rev., Cognit. Sci.*, vol. 5, no. 2, pp. 221–231, Mar. 2014.

[83] C. Dietrich *et al.*, "Sensory feedback prosthesis reduces phantom limb pain: Proof of a principle," *Neurosci. Lett.*, vol. 507, no. 2, pp. 97–100, Jan. 2012.

[84] S. Preißler, D. Thielemann, C. Dietrich, G. O. Hofmann, W. H. R. Miltner, and T. Weiss, "Preliminary evidence for training-induced changes of morphology and phantom limb pain," *Frontiers Hum. Neurosci.*, vol. 11, pp. 1–12, Jun. 2017.

[85] P. M. Rossini *et al.*, "Double nerve intraneural interface implant on a human amputee for robotic hand control," *Clin. Neurophysiol.*, vol. 121, no. 5, pp. 777–783, 2010.

[86] D. M. Page, S. M. Wendelken, and T. Davis, "Discriminability of multiple cutaneous and proprioceptive hand percepts evoked by intraneural stimulation with Utah slanted electrode arrays in human amputees," *J. Neuroeng. Rehabil.*, vol. 18, no. 1, Jan. 2021, Art. no. 12.

[87] Å. B. Vallbo, "Microneurography: How it started and how it works," *J. Neurophysiol.*, vol. 120, no. 3, pp. 1415–1427, Sep. 2018.

[88] C. D. Murray and M. J. Forshaw, "The experience of amputation and prosthesis use for adults: A metasynthesis," *Disability Rehabil.*, vol. 35, no. 14, pp. 1133–1142, Jul. 2013.

[89] D. M. Desmond, “Coping, affective distress, and psychosocial adjustment among people with traumatic upper limb amputations,” *J. Psychosomatic Res.*, vol. 62, no. 1, pp. 15–21, Jan. 2007.
[90] R. K. Shepherd, J. Villalobos, O. Burns, and D. A. X. Nayagam, “The development of neural stimulators: A review of preclinical safety and efficacy studies,” *J. Neural Eng.*, vol. 15, no. 4, Jun. 2018, Art. no. 041004.
[91] H. Charkhkar, B. P. Christie, G. J. Pinault, D. J. Tyler, and R. J. Triolo, “A translational framework for peripheral nerve stimulating electrodes: Reviewing the journey from concept to clinic,” *J. Neurosci. Methods*, vol. 328, Dec. 2019, Art. no. 108414.
[92] D. A. Borton, H. E. Dawes, G. A. Worrell, P. A. Starr, and T. J. Denison, “Developing collaborative platforms to advance neurotechnology and its translation,” *Neuron*, vol. 108, no. 2, pp. 286–301, Oct. 2020.
[93] A. T. Sugawara, V. D. Ramos, F. M. Alfieri, and L. R. Battistella, “Abandonment of assistive products: Assessing abandonment levels and factors that impact on it,” *Disab. Rehabil., Assistive Technol.*, vol. 13, no. 7, pp. 716–723, Oct. 2018.
[94] N. Kerver, S. van Twillert, B. Maas, and C. K. van der Sluis, “User-relevant factors determining prosthesis choice in persons with major unilateral upper limb defects: A meta-synthesis of qualitative literature and focus group results,” *PLoS ONE*, vol. 15, no. 6, Jun. 2020, Art. no. e0234342.
[95] L. Yardley, B. Ainsworth, E. Arden-Close, and I. Müller, “The person-based approach to enhancing the acceptability and feasibility of interventions,” *Pilot Feasibility Stud.*, vol. 1, no. 1, pp. 1–7, 2015.
[96] L. Yardley, L. Morrison, K. Bradbury, and I. Müller, “The person-based approach to intervention development: Application to digital health-related behavior change interventions,” *J. Med. Internet Res.*, vol. 17, no. 1, p. e30, Jan. 2015.
[97] C. L. McDonald, C. L. Bennett, D. K. Rosner, and K. M. Steele, “Perceptions of ability among adults with upper limb absence: Impacts of learning, identity, and community,” *Disab. Rehabil.*, vol. 42, no. 3, pp. 3306–3315, Apr. 2019.
[98] L. Morrison, I. Müller, L. Yardley, and K. Bradbury, “The person-based approach to planning, optimising, evaluating and implementing behavioural health interventions,” *Eur. Heal. Psychol.*, vol. 20, no. 3, pp. 464–469, 2018.
[99] E. Schaffalitzky, P. Gallagher, M. Maclachlan, and N. Ryall, “Understanding the benefits of prosthetic prescription: Exploring the experiences of practitioners and lower limb prosthetic users,” *Disab. Rehabil.*, vol. 33, nos. 15–16, pp. 1314–1323, Jan. 2011.
[100] A. Chadwell *et al.*, “Upper limb activity in myoelectric prosthesis users is biased towards the intact limb and appears unrelated to goal-directed task performance,” *Sci. Rep.*, vol. 8, no. 1, p. 11084, Dec. 2018.
[101] P. J. Kyberd, “Outcome measures,” in *Bionic Limb Reconstruction*. San Francisco, CA, USA: Public Library of Science, 2021, pp. 57–74.
[102] A. van Dijk-de Vries, A. Stevens, T. van der Weijden, and A. J. H. M. Beurskens, “How to support a co-creative research approach in order to foster impact. The development of a co-creation impact compass for healthcare researchers,” *PLoS ONE*, vol. 15, no. 10, Oct. 2020, Art. no. e0240543.
[103] H. Jones *et al.*, “Co-creation facilitates translational research on upper limb prosthetics,” *Prosthesis*, vol. 3, no. 2, pp. 110–118, Apr. 2021.
[104] F. T. Sun and M. J. Morrell, “Closed-loop neurostimulation: The clinical experience,” *Neurotherapeutics*, vol. 11, no. 3, pp. 553–563, 2014.
[105] S. Wendelken *et al.*, “Restoration of motor control and proprioceptive and cutaneous sensation in humans with prior upper-limb amputation via multiple Utah slanted electrode arrays (USEAs) implanted in residual peripheral arm nerves,” *J. Neuroeng. Rehabil.*, vol. 14, no. 1, pp. 1–17, Dec. 2017.
[106] S. Raspopovic *et al.*, “Restoring natural sensory feedback in real-time bidirectional hand prostheses,” *Sci. Transl. Med.*, vol. 6, no. 222, 2014, Art. no. 222ra19.
[107] G. K. Patel, S. Dosen, C. Castellini, and D. Farina, “Multichannel electrotactile feedback for simultaneous and proportional myoelectric control,” *J. Neural Eng.*, vol. 13, no. 5, 2016, Art. no. 056015.
[108] M. Isaković *et al.*, “Electrotactile feedback improves performance and facilitates learning in the routine grasping task,” *Eur. J. Transl. Myol.*, vol. 26, no. 3, pp. 197–202, Jun. 2016.
[109] R. N. Scott, R. H. Brittain, R. R. Caldwell, A. B. Cameron, and V. A. Dunfield, “Sensory-feedback system compatible with myoelectric control,” *Med. Biol. Eng. Comput.*, vol. 18, no. 1, pp. 65–69, Jan. 1980.
[110] Z.-Y. Bi *et al.*, “A hybrid method for real-time stimulation artefact removal during functional electrical stimulation with time-variant parameters,” *J. Neural Eng.*, vol. 18, no. 4, Aug. 2021, Art. no. 046028.
[111] C. Hartmann, S. Došen, S. Amsuess, and D. Farina, “Closed-loop control of myoelectric prostheses with electrotactile feedback: Influence of stimulation artifact and blanking,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 23, no. 5, pp. 807–816, Sep. 2015.
[112] S. Dosen, M.-C. Schaeffer, and D. Farina, “Time-division multiplexing for myoelectric closed-loop control using electrotactile feedback,” *J. Neuroeng. Rehabil.*, vol. 11, no. 1, pp. 1–10, Dec. 2014.
[113] B. C. Johnson *et al.*, “An implantable 700μW 64-channel neuromodulation IC for simultaneous recording and stimulation with rapid artifact recovery,” in *Proc. Symp. VLSI Circuits*, Jun. 2017, pp. C48–C49.
[114] V. Mendez, F. Iberite, S. Shokur, and S. Micera, “Current solutions and future trends for robotic prosthetic hands,” *Annu. Rev. Control, Robot., Auton. Syst.*, vol. 4, no. 1, pp. 595–627, May 2021.
[115] A. Gigli, D. Brusamento, R. Meattini, C. Melchiorri, and C. Castellini, “Feedback-aided data acquisition improves myoelectric control of a prosthetic hand,” *J. Neural Eng.*, vol. 17, no. 5, Oct. 2020, Art. no. 056047.
[116] P. D. Marasco *et al.*, “Neurorobotic fusion of prosthetic touch, kinesthesia, and movement in bionic upper limbs promotes intrinsic brain behaviors,” *Sci. Robot.*, vol. 6, no. 58, p. 3368, Sep. 2021.
[117] G. Valle *et al.*, “A psychometric platform to collect somatosensory sensations for neuroprosthetic use,” *Frontiers Med. Technol.*, vol. 3, Mar. 2021, Art. no. 619280.
[118] E. C. Pischke *et al.*, “Barriers and solutions to conducting large international, interdisciplinary research projects,” *Environ. Manage.*, vol. 60, no. 6, pp. 1011–1021, Dec. 2017.
[119] W. Williams, “A complete guide to bionic arms & hands,” BionicsForEveryone.Com, Tech. Rep., 2021. [Online]. Available: https://bionicsforeveryone.com/bionic-arms-hands/
[120] M. Schiefer, D. Tan, S. M. Sidek, and D. J. Tyler, “Sensory feedback by peripheral nerve stimulation improves task performance in individuals with upper limb loss using a myoelectric prosthesis,” *J. Neural Eng.*, vol. 13, no. 1, Feb. 2016, Art. no. 016001.
[121] J. A. George *et al.*, “Biomimetic sensory feedback through peripheral nerve stimulation improves dexterous use of a bionic hand,” *Sci. Robot.*, vol. 4, no. 32, Jul. 2019, Art. no. eaax2352.
[122] F. Clemente, M. D’Alonzo, M. Controzzi, B. B. Edin, and C. Cipriani, “Non-invasive, temporally discrete feedback of object contact and release improves grasp control of closed-loop myoelectric transradial prostheses,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 24, no. 12, pp. 1314–1322, Dec. 2015.
[123] M. Markovic *et al.*, “The clinical relevance of advanced artificial feedback in the control of a multi-functional myoelectric prosthesis,” *J. Neuroeng. Rehabil.*, vol. 15, no. 1, pp. 1–15, Mar. 2018.
[124] E. L. Graczyk, B. P. Delhaye, M. A. Schiefer, S. J. Bensmaia, and D. J. Tyler, “Sensory adaptation to electrical stimulation of the somatosensory nerves,” *J. Neural Eng.*, vol. 15, no. 4, Aug. 2018, Art. no. 046002.
[125] T. R. Chou, W. Daly, R. Austin, P. Chaubey, and D. Boone, “Development and real world use of a vibratory haptic feedback system for upper-limb prosthetic users,” *J. Prosthetics Orthotics*, vol. 28, no. 4, pp. 136–144, 2016.
[126] G. A. Clark *et al.*, “Using multiple high-count electrode arrays in human median and ulnar nerves to restore sensorimotor function after previous transradial amputation of the hand,” in *Proc. 36th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Aug. 2014, pp. 1977–1980.
[127] I. Strauss *et al.*, “Characterization of multi-channel intraneural stimulation in transradial amputees,” *Sci. Rep.*, vol. 9, no. 1, pp. 1–11, Dec. 2019.
[128] J. Dong, E. N. Kamavuako, S. Dosen, W. Jensen, and B. Geng, “The short-term repeatability of subdermal electrical stimulation for sensory feedback,” *IEEE Access*, vol. 8, pp. 63983–63992, 2020.
[129] M. Ortiz-Catalan, B. Håkansson, and R. Brånemark, “An osseointegrated human-machine gateway for long-term sensory feedback and motor control of artificial limbs,” *Sci. Transl. Med.*, vol. 6, no. 257, Oct. 2014.
[130] T. S. Davis *et al.*, “Restoring motor control and sensory feedback in people with upper extremity amputations using arrays of 96 microelectrodes implanted in the median and ulnar nerves,” *J. Neural Eng.*, vol. 13, no. 3, Jun. 2016, Art. no. 036001.