EXPERT REVIEWS

Applications of sensory feedback in motorized upper extremity prosthesis: a review

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Dexterous hand movement is possible due to closed loop control dependent on efferent motor output and afferent sensory feedback. This control strategy is significantly altered in those with upper limb amputation as sensations of touch and movement are inherently lost. For upper limb prosthetic users, the absence of sensory feedback impedes efficient use of the prosthesis and is highlighted as a major factor contributing to user rejection of myoelectric prostheses. Numerous sensory feedback systems have been proposed in literature to address this gap in prosthetic control; however, these systems have yet to be implemented for long term use. Methodologies for communicating prosthetic grasp and touch information are reviewed, including discussion of selected designs and test results. With a focus on clinical and translational challenges, this review highlights and compares techniques employed to provide amputees with sensory feedback. Additionally, promising future directions are discussed and highlighted.

Keywords: grasp and touch • kinesthesia and proprioception • modality matching • motorized prostheses • prosthetics • sensory feedback • sensory substitution • somatotopic matching • translational capabilities • upper-limb

In 2005, there were an estimated 1.6 million people living in the USA with the loss of a limb, 34% of which were upper limb [1]. Upper limb loss is one of the most difficult challenges for prosthetic replacement, given the complexity of fine sensory input and dexterous function of a hand. The loss of a hand and arm can significantly reduce quality of life, leaving an individual feeling less capable and more dependent [2]. Prosthetic arms are designed with the goal of restoring function to those with upper limb loss.

Upper limb prosthetic functionality is ultimately dependent on the user's ability to efficiently manipulate and interface with their prosthesis. It follows that having intuitive control would increase the utility of the device. Yet, closely mimicking the performance of a human hand and arm is technically challenging. A normal hand is capable of coordinating movements with 27 degrees of freedom to perform strength-based grasping functioning as well as highly coordinated precision movements [3]. Recently, there have been extensive advances in motorized, multiarticulated prosthetic arms that are capable of a wide range of grasps and movement [4]. These prostheses are controlled using surface electromyogram (EMG) signals generated by the muscles. While extensive technical developments are being made in myoelectric (EMG-controlled) prostheses, significant barriers remain which prevent them from being as widely accepted as traditional body powered hook-and-pulley systems [5].

Execution of dexterous hand movements is highly dependent on both efferent motor control and afferent sensory feedback. Sensory feedback mechanisms relay on exteroceptive and proprioceptive information to higher control centers in the brain [6] and are responsible for detecting grip force and hand position, as well as object shape, compliance and textures, among others [7]. Therefore, the basis of hand movement is closed-loop motor control comprised of a dynamic interplay between motor output and sensory input [6,8,9]. The loss of an upper extremity significantly alters this closed-loop control strategy as sensations of touch and movement are inherently lost. Those with upper limb loss become dependent on their prosthesis to restore lost motor function;

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Table 1. Methods of sensory feedback discussed in this review.

Sensory feedback		
Somatotopically matched	**Modality matched**	**Substitution**
Neural stimulation	Mechanotactile	Vibrotactile
Phantom mapping	Other methods	Electrotactile
Targeted reinnervation		Auditory
Kinesthetic illusion		Other methods

however, most myoelectric prostheses are open-loop devices and are thus unable to communicate external stimulus acting on the prosthesis to the user. The absence of exteroceptive and proprioceptive sensibility impedes efficient use of the prosthesis. About 29–39% of upper limb amputees will discontinue usage of their prosthesis [10] with lack of sensory feedback often being highlighted as a major contributing factor [2,6,11,12]. Typically, prosthetic users adopt a system of strategies to compensate for this lack of sensory information; they rely heavily on visual feedback as well as on indirect feedback mechanisms such as the sound of the motors, vibrations and changes in pressure on the residual limb [6]. Consequently, the cognitive demand placed on the user is greatly increased as operation of the prosthesis requires high and continuous conscious attention [13,14].

A recent review by Antfolk *et al.* highlighted the need to interface prosthetic limbs with sensory feedback and reported on numerous strategies to address prosthetic sensibility [15]. These systems have yet to be incorporated in prostheses for long-term use or convincingly proven usable outside of a laboratory. Furthermore, no commercially available myoelectric prosthesis provides conscious sensory feedback to the user [15]. Therefore, a gap currently exists between research prototypes and devices with clinical translational capabilities.

The objectives of this review are to highlight and compare methods for providing amputees with prosthetic sensibility, which have been detailed in research-based literature. Methodologies for communicating prosthetic grasp and touch information will be discussed including selected designs and test results within each research area. An overview of future directions including promising methods for grasp and touch feedback, approaches for establishing proprioceptive or kinesthetic feedback, as well as clinical and translational challenges is also provided.

Search methods

Scopus was used as the primary literature database and cross-referenced with PubMed. The following key words were used in the search for literature: *prosthetic sensory feedback*, *haptic prosthetic feedback*, *prosthetic sensory substitution*, *targeted reinnervation* and *prosthetic tactile display*. Literature discussed in this review has been published prior to 1 December 2013. This paper mainly focuses on *methods* for providing sensory feedback to upper limb amputees; it is not meant to be an exhaustive review of individual feedback devices.

Grasp & touch sensory feedback

Sensory *feedback systems* employ instrumentation (or *sensors*) at the prosthetic level to detect an external stimulus. This instrumentation in turn drives the output of a haptic feedback device (also termed *tactor*) that conveys information about the external stimulus to the prosthetic user. Various types of tactors have been reported in the literature, relying on methods such as vibration, pushing or shear force to communicate the external stimulus to the user. The method used to communicate information through the tactor to the user is defined as the *feedback signal*. This paper categorizes feedback systems in terms of how the user experiences the feedback signal. The sensory feedback systems reviewed in this paper have been divided into three categories: substitution, modality-matched and somatotopically matched methods (Table 1).

Sensory substitution categorizes a group of feedback systems that apply a feedback signal that is not matched in modality to the stimulus occurring at the prosthesis. Furthermore, the feedback signal is presented to a location that, physiologically, will not be perceived to the user as in the same corresponding location on their missing limb. Modality matching refers to a feedback signal that is congruent to the external stimulus detected by the prosthetic sensor; however, the feedback signal may not be presented to a location physiologically representative of the hand or limb. Somatotopic matching refers to methods in which the feedback signal is perceived as being anatomically matched in location to where the stimulus is being applied to the prosthesis. To achieve feedback that is intuitive and perceived as physiologically *natural* to the user, the sensory feedback system ideally meets both these conditions: modality matching and somatotopic matching [7].

Substitution feedback

Sensory substitution methods communicate the state of the prosthesis to the user through sensory feedback not physiologically representative of what the missing hand or arm would experience. Typically, these techniques are the most technically straightforward approaches [7,16] as they do not consider modality or somatotopic matching. The success of the approach depends on the user's ability to interpret the type and location of the stimulus and associate it with the prosthesis. The most common methodology has been to translate tactile information from the prosthesis to the amputee using vibration, electrocutaneous or auditory stimuli.

Vibrotactile feedback

Most commonly reported in prosthetic literature, vibrotactile feedback involves communicating sensory information from the prosthesis to the user through the application of mechanical vibration to a strategic area of the user's skin (Figure 1) [17]. Mechanical vibration, when introduced to the skin, has been shown to activate numerous cutaneous mechanoreceptors with the response of individual receptor types being a function of vibration frequency, amplitude and duration of vibration [18].

Vibrotactile sensory substitution is most often applied to communicate tactile information during grasping tasks. A tactor will apply continuous vibration or pulses of vibration are provided when the prosthetic prehensor comes into contact with an object [19–21]. Able-bodied participants are often used to evaluate the efficacy of vibrotactile systems by manipulating vibration parameters such as amplitude [21] and pulse rate [20,21] to convey grasping force. In three studies, vibratory feedback has been shown to increase confidence and success rates in performing grasping tasks and compliment visual feedback [17,22,23]. Conversely, one study has shown that while vibrotactile feedback improved grasp success using complex control strategies, in simplistic control strategies, it did not enhance control when visual feedback was already being used [24]. In amputee studies, amplitude and frequency of vibration have been used to communicate grasping forces present in a prosthetic prehensor. This work concluded that vibrotactile feedback may reduce excess prehensor force in experienced users, but negatively influenced those with little previous myoelectric prosthetic experience [19].

As a mechanism for providing sensory feedback, vibration is often a baseline standard to which other feedback methods are compared [21,23,25–28]. Vibrotactile tactors are advantageous in that they are relatively inexpensive, with small size and weight; important factors for prosthetic applications. However, prior to successful implementation, it must be demonstrated that the vibration induced into the residual limb tissues does not contaminate the motor control signals. Furthermore, analysis is warranted as to whether the vibration will affect socket movement or cause separation of tissue from the EMG electrodes.

Electrotactile feedback

Electrotactile feedback communicates sensory information to the prosthetic user via electrodes placed on the user's skin (Figure 2). Sensory communication is most often achieved through modulation of the electrical current parameters: amplitude, frequency and pulse rate to single or multiple electrode sites [15,25,29–33]. These parameters are mapped such that a touch or force stimulus introduced to the prosthesis corresponds to a specific electrical signal presented to the user's skin.

Electrocutaneous stimulation can evoke a range of sensations that have been qualitatively described by participants as a tingling, itch, vibration, buzz, touch, pressure, pinch and sharp or burning pain [34]. One study reports participants describing the sensation as similar to small bubbles bursting on the skin [25]. Some studies do not report the specific sensations experienced by the participants as a result of the electrocutaneous feedback; rather, they identify the range between initial sensation and pain [35,36]. Despite the mismatched modality, testing in able-bodied participants has shown that electrotactile feedback may improve participants' ability to reach and maintain specific grasp force values [35], while requiring similar amounts of time to integrate both electrocutaneous and visual information to the use of visual feedback alone [31]. In testing with amputee populations, improvements in user confidence, control and grasp force discrimination have also been demonstrated with electrotactile feedback [29,32,33].

A benefit to electrocutaneous systems is that they often require less power than mechanical systems (e.g., vibrotactile devices). Yet, overall, electrotactile feedback is less accepted than vibrotactile feedback by populations using myoelectric devices [25,34]. Perhaps, a reason for these lower acceptance rates lies in the limitations of electrotactile feedback. Elicited

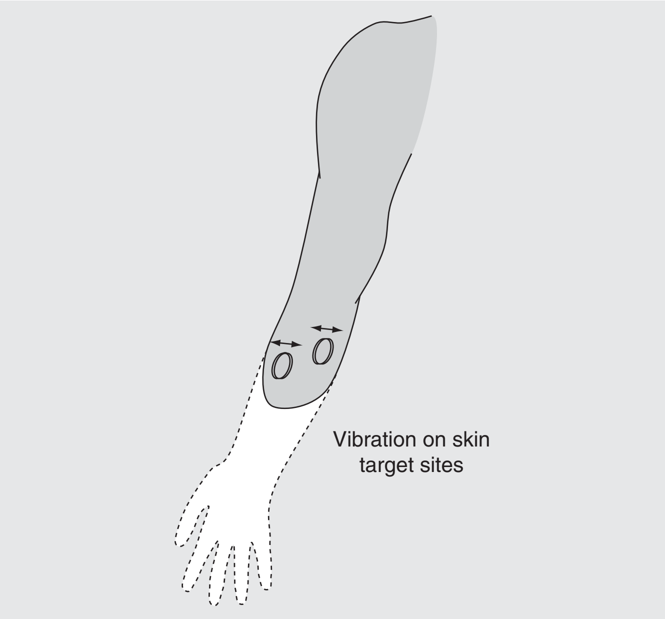

Figure 1. Vibrotactile feedback, where vibration is applied to the skin.

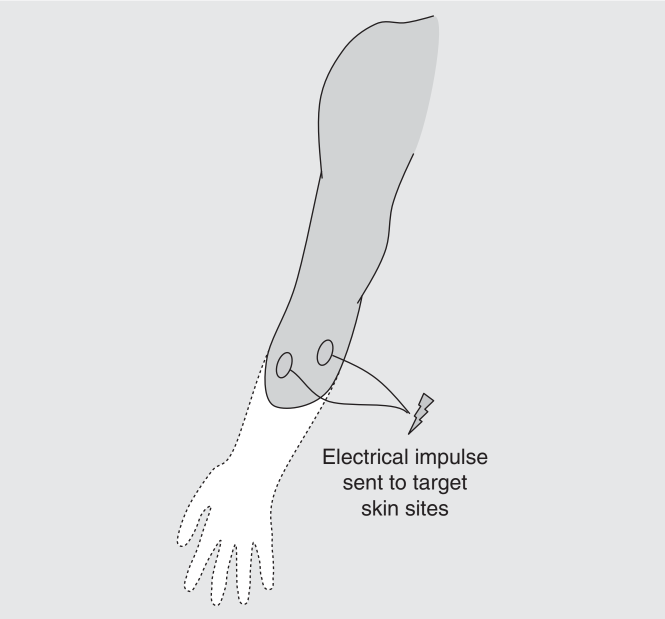

Figure 2. Electrotactile feedback, where electrodes are placed over the skin.

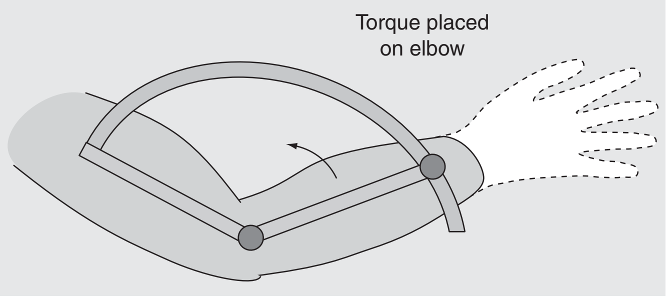

Figure 3. Applied elbow torque, where torque is proportional to grip force.

sensations have been shown to be dependent on many stimulation parameters such as voltage, current, wave form, electrode size, material and contact force, as well as physiological factors such as skin location, thickness and electrochemistry [34]. Therefore, the ability to repeatedly isolate and elicit a specific sensation becomes an involved task. In a prosthetics context, sensory feedback devices should have long-term stability and consistency of the prosthetic-to-user communication channel. Without stability in the elicited sensations, the user may face substantial challenges in learning to interpret feedback. To further complicate these issues, participants often demonstrate adaptation to electrocutaneous stimulation over time. Research to minimize adaptation for use in a prosthetic environment is ongoing [36]. Finally, incorporating electrocutaneous feedback in to a myoelectric prosthesis may require spatial consideration, as electrical signals from the sensory feedback system should not contaminate the myoelectric motor control signals to the prosthesis.

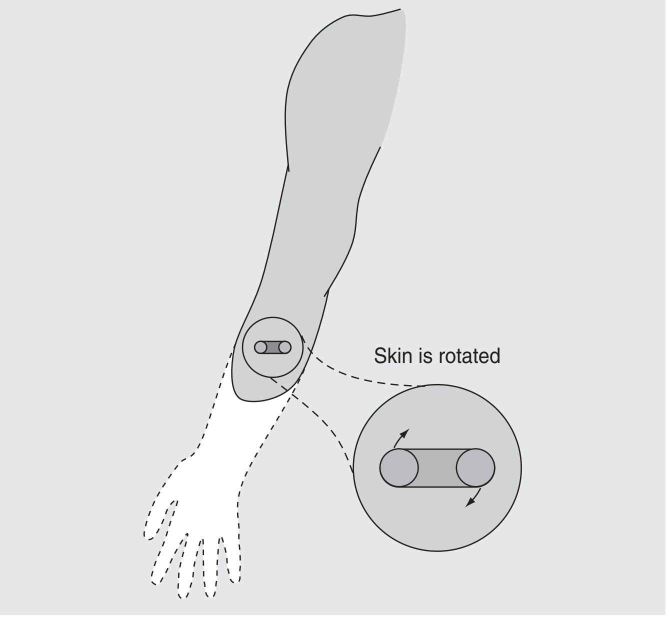

Figure 4. Rotational skin stretch, where tactor ends are attached to the skin using adhesive and then rotated proportional to grip force.

Auditory feedback

Auditory feedback has been demonstrated as a technique to convey contact of a robotic hand to an object [37] as well as the position of the hand's digits and intended grasping pattern [14,38,39]. Methods of auditory feedback provide information on the state of a robotic or prosthetic hand through varying frequencies of tones or sounds. For example, Gonzalez *et al.* conducted able-bodied testing with an auditory scheme that utilized the sounds of a cello to signify thumb movement and a violin for index finger movement. During the grasping task, these two instruments would play a specific starting note and a final note to signify successful completion of the task. Errors in finger trajectory were signified by a separate unique note for each finger to inform the user of the need to correct the movement [14,38,39]. Compared with the absence of auditory feedback (strictly visual feedback), participants demonstrated improved grasping task performance and reduced cognitive burden during the operation of a robotic hand [14,38,39]. One amputee study indicated that auditory feedback could be useful for identifying which prosthetic fingers are being touched at any given time [37].

Audio-based sensory substitution systems inherently require training for effective use. The user must learn to interpret auditory stimulation as tactile stimulation and associate these audio cues with specific prosthetic limb states. Although with training an amputee may be able to utilize this feedback system, the substitutive challenge may create excessive cognitive burden and a significant barrier to effective use.

Other substitution methods

Other methods have been investigated to achieve sensory substitution. One such method involves using a motorized elbow brace to apply extension torques to the elbow proportional to grasp force (Figure 3) [28,40]. This method has been tested on able-bodied and trans-radial amputee participants. In able-bodied users, the use of elbow torques was found to be equivalent to using vibration feedback to adapt to unpredicted weight change [28], and showed improvement in the ability to identify different object stiffness or weights compared with visual feedback only [28,40]. Amputee participants have shown similar results regarding coordination, task performance and adaption [28]. However, as this technique relies on intact function of the elbow joint, it would only be useful for amputation below the elbow.

Rotational skin stretch has also been investigated in which a feedback mechanism is attached to the skin with adhesive and then rotated to stretch the skin proportional to grasp strength (Figure 4). Tested with able-bodied participants in a virtual environment, this method decreased the number of errors and amount of visual attention required compared with visual feedback alone [41]. However, the temporary nature of this adhesive may be a drawback as its effectiveness has yet to be evaluated beyond 2 h of usage [41], and consistency in reapplication may be an important consideration prior to incorporation in prostheses.

Many of these nontraditional feedback methods have yet to be studied extensively with amputee participants; to justify their use, further research is required. In particular, results must be compared with different methods including vibrational and mechanotactile feedback in order to understand their potential as sensory feedback mechanisms. Additionally, comparisons regarding cost, weight, size and longevity should be considered.

Modality-matched feedback

In modality-matched methods, the information communicated to the user is matched in sensation, for example touch to the prosthesis is felt as touch to the skin, although mismatched in location. As a result, the user must still dedicate conscience attention to interpret the feedback signal. In some applications, modality-matched feedback may be preferable to sensory substitution. These systems potentially require a lower cognitive demand as the modality of the feedback signal does not require interpretation by the user. Most often, modality-matched feedback methods communicate tactile information to the amputee using force or pressure applied perpendicular to the skin although other methods being investigated include tangential forces and thermal devices.

Mechanotactile feedback

Mechanotactile feedback is commonly used to communicate conditions of touch and grasp occurring at the prosthetic prehensor to the user. Most systems will translate touch or grasp force information from the prehensor as a perpendicular force or pressure applied to a strategic location on the amputee's residual limb or body [15]. To achieve this task, numerous tactor designs are present in literature, utilizing pneumatics [23,27,42,43], servomotors [26,44–46], and voice coils [13] to generate force (Figure 5).

Studies conducted in able-bodied populations have demonstrated participants being able to incorporate these types of feedback signals into their control strategy of a robotic [13,27] or virtual hand [23,47], as well as reduce error in replicating grasping pressure to a consistent value [27]. In amputee studies, incorporation of mechanotactile feedback has been shown to improve performance during object manipulation tasks [44]. Additionally, as a feedback signal, mechanotactile tactors can provide graduated levels of force (or pressure) and typically enable the user to discriminate between various levels [43,47]. These systems have demonstrated improved multisite force and spatial discrimination over vibration [26,43].

Compared with other feedback systems, mechanotactile systems typically consume more power and are often larger and heavier than vibrotactile or electrotactile devices; development into minimizing these drawbacks is ongoing [48,49].

Other modality-matched methods

Although perpendicular force is presently the most common form of mechanotactile feedback, advances in tactile systems have led to a broad range of mechanical feedback modalities.

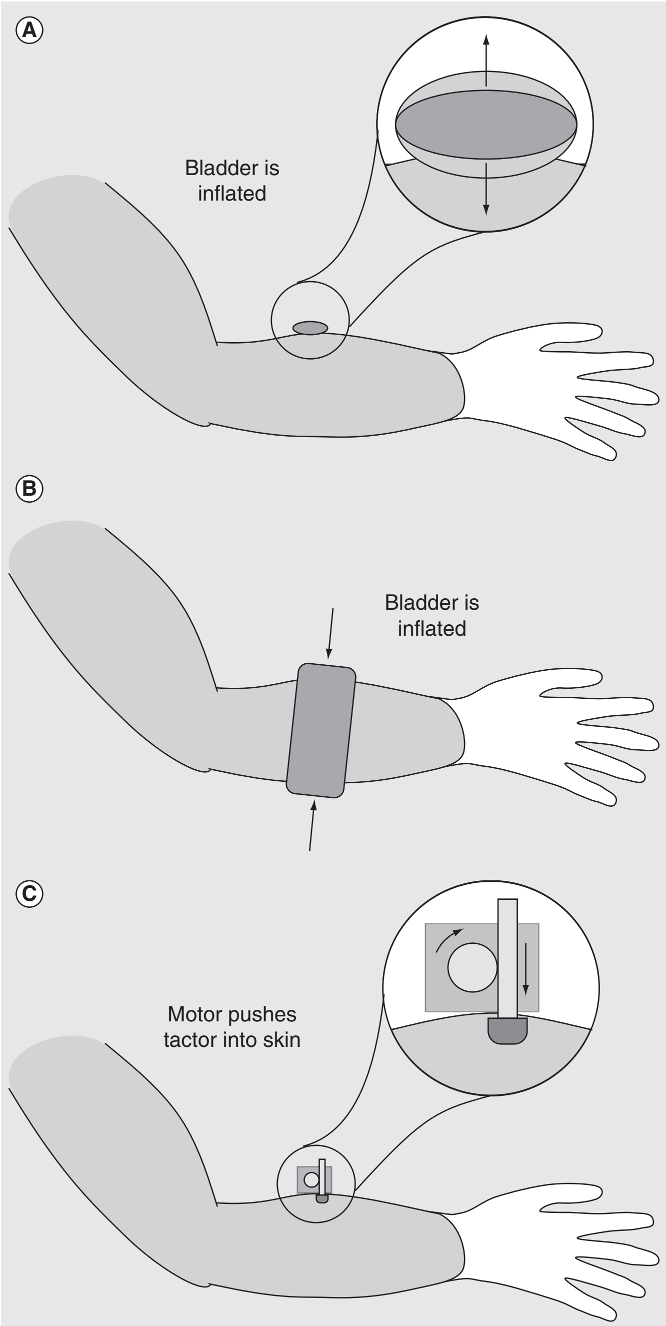

Figure 5. Mechanotactile feedback. (A) Pneumatic bladder; **(B)** pneumatic pressure cuff and **(C)** servomotor or voice coil.

Two separate multimodal tactors have been described, capable of providing perpendicular force, tangential force, vibration and temperature [7,48,50,51]. Armiger *et al.* further described a system to incorporate a multimodal device into a prosthetic socket [48]; a condition crucial to clinical implementation.

Although multimodal tactors have the ability to deliver significantly more information than a traditional single-mode feedback device, the utility of providing additional signals needs to be further evaluated. Investigation must be conducted on the ability of the participants to effectively utilize multiple

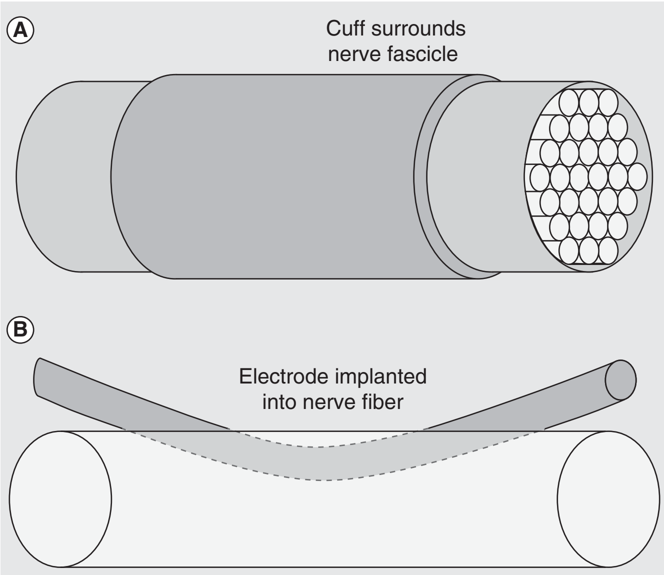

Figure 6. Peripheral nerve electrodes. (A) Nerve cuff and **(B)** longitudinal intrafascicular.

feedback modalities as it has been demonstrated in two amputee participants that provide multiple kinds of feedback simultaneously, actually degrades grip force control [51]. This may result from a greater degree of conscious attention being required to interpret multiple sensory signals applied to a single location. Although these devices represent technological strides in design challenges inherent to feedback devices, demonstration of clinical practicality will be needed to validate their effectiveness.

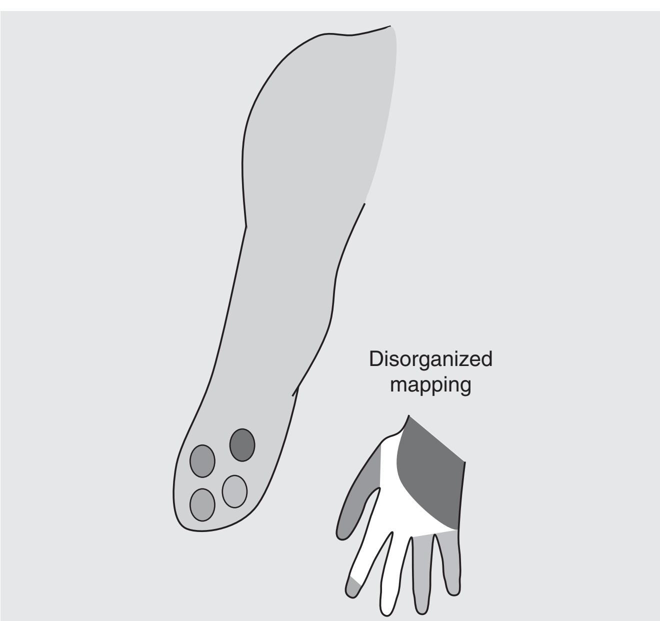

Figure 7. Hypothetical corresponding regions between location of pressure on residual limb and sensation on phantom hand.

Somatotopically matched feedback

Somatotopically matched methods deliver feedback such that an amputee senses the stimulus as though it were applied to the same corresponding location of their missing limb. Compared with substitution or modality-matching methods, somatotopically matched feedback may reduce the cognitive burden placed on the user as the stimulus applied to the prosthetic sensor will be perceived as occurring at a physiologically matched location in the user's missing limb. As a result, the user may require less training and conscience attention to interpret feedback signals. Somatotopic-matching techniques have been investigated with direct neural stimulation; by exploiting the effects of nerve remapping that occurs following amputation; and by purposefully rerouting sensory nerves using targeted reinnervation (TR).

Peripheral nerve stimulation

As the nervous system functions on electrical voltage potentials, perhaps, the most obvious solution is to electrically stimulate physiological channels to simulate sensory feedback. Peripheral nerve stimulation relies on the principle that, following upper limb amputation, the original afferent neural pathways are preserved proximally and can be exploited for interfacing with prostheses [52]. This principle suggests that *natural* physiological feedback can be restored through strategic electrical stimulation of nerve afferents using invasive neural electrodes. To date, peripheral nerve stimulation has been investigated in amputees using two styles of electrodes: nerve cuff electrodes, where the electrode wraps around the exterior of the fascicle [53]; and longitudinal intrafascicular electrodes, where electrodes are placed in the nerves longitudinally (Figure 6) [54–58]. Amputee participants have been reported to experience tactile sensation such as touch and pressure, as well as proprioceptive sensations such as position sense and movement [52,58] in their missing limb. Through manipulation of the electrical frequency and current, investigators are able to influence the location, magnitude and modality of these elicited sensations [56,58].

As a technique for sensory feedback, peripheral nerve stimulation holds inherent technological limitations. Ultimately, the success of eliciting a particular sensation in a certain location is dependent on the system's ability to selectively stimulate specific sensory afferents in a particular fascicle. Current electrodes lack this selectivity and as a result, spatial resolutions of referred sensations are often large, encompassing entire fingers or areas as large as the palm [59,60]. Beyond spatial discrimination, this lack of selectivity often results in a loss of *naturalness* in elicited sensations. Although participants do report tactile or proprioceptive sensations, they are frequently accompanied by foreign sensations resembling vibration, taping or fluttering on the skin [15,59]. Furthermore, the long-term stability of intrafascicular electrode stimulation in human participants has yet to be comprehensively studied [52,61]. Therefore, whether the body acclimates to the stimuli or if the system requires adjustments of the stimulus parameters over time remains unknown. For this method to move forward, the longevity, and ultimately feasibility, of using peripheral nerve stimulation in clinical or long-term prosthetic applications must be proven.

Phantom mapping

Phantom sensation is defined as occurring when an amputee feels sensation of their missing limb. Phantom mapping relies on the ability to intentionally elicit these phantom sensations as a result of stimulation of the residual limb. This feedback technique requires the identification of areas on an amputee's residual limb that consistently elicit sensations referring to the missing hand (Figure 7). Tactors that elicit this illusion are positioned in the locations where the sensations are experienced and are mapped to the input from the prosthetic digits. When activated, the tactors provide somatotopically matched sensations experienced in the amputees missing digits. Thus far, mechanotactile [26,62] or vibrotactile [62] systems have been studied with transradial amputee participants.

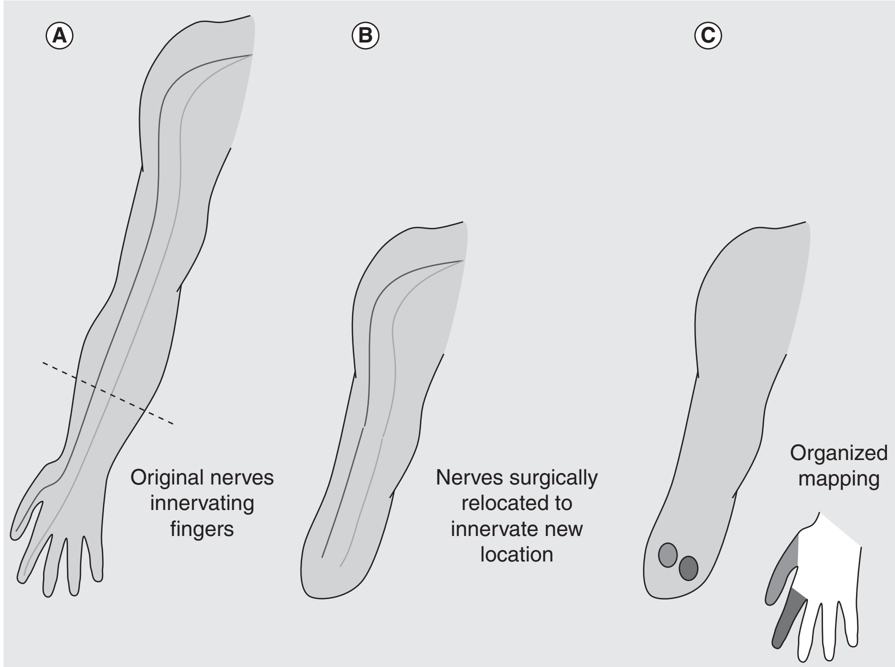

Figure 8. Overview of targeted reinnervation procedure. (A) Original nerves innervating the fingers; **(B)** the transfer of the nerves to new sites and **(C)** the ideal resultant final mapping.

As a mechanism for sensory feedback to multiple sites on an amputee's residual limb, phantom mapping has been shown to improve feedback site discrimination beyond the capabilities of able-bodied participants [26]. Additionally, when comparing vibrotactile to mechanotactile devices, participants demonstrated better discrimination results using mechanotactile devices [26]. Although literature has only reported use of mechanotactile and vibrotactile devices for somatotopic matching, there may be potential to apply other feedback methods such as electrotactile or skin stretch. Investigation is warranted to further identify feedback signals that effectively exploit phantom-mapping techniques.

Although phantom mapping enables the possibility of both somatotopic and modality matching, it relies exclusively on participants having a consistent phantom representation of their digits. However, phantom mapping is not experienced by all upper extremity amputees and often dissipates with time following the amputation surgery [63]. Furthermore, elicited phantom sensations may range from a *natural* feeling of touch to *unnatural* itching, tingling or pain. These sensations will vary from individual to individual as well as over time. Phantom mapping has the potential to provide somatotopically matched feedback to amputees; however is limited by the reliability and level of sensations experienced in the individual's phantom map. As a result, phantom-mapping techniques may only be an option for a limited population of prosthetic users.

Targeted reinnervation

TR is a surgical procedure that moves the motor and sensory nerves that previously innervated the amputated limb to muscle and skin target sites (Figure 8) [64]. This surgery was initially performed to increase the number of motor control sites for myoelectric prostheses and to allow for intuitive control [64–66]. However, it was found that the redirected sensory afferents also reinnervate overlying skin. This reinnervation creates an expression of the hand map such that when touched, the patients feel as if they are being touched on the missing limb [67–69]. Cutaneous sensations such as vibration, temperature and skin stretch have been introduced to participants' reinnervation sites and experienced as a referred sensation in their missing hand although one participant has described paresthetic sensations [67]. Unlike phantom mapping, TR allows the reinnervated sites to be selectively placed [66]. The experienced sensations have also been shown to be repeatable and discrete. In other words, participants may develop an organized, detailed and consistent hand map capable of receiving stimuli in multiple modalities [67].

Consequently, patients who have undergone TR surgery may have the ability to receive prosthetic feedback that is intuitive, feels *natural* and utilizes the same physiological channels that were lost with their missing limb. While using somatotopically and modality-matched sensory feedback systems, TR amputees have shown an enhanced ability to detect force gradation [70] and improved grip force control in a virtual environment [51]. Furthermore, a TR participant demonstrated the ability to distinguish object stiffness [71] and discriminate between two spatially separated tactors while using motor control sites to operate a robotic hand [66]. Another participant improved simple task completion speed using a new prosthesis developed to read signals from her reinnervated chest muscle [68]. Clinical translation of

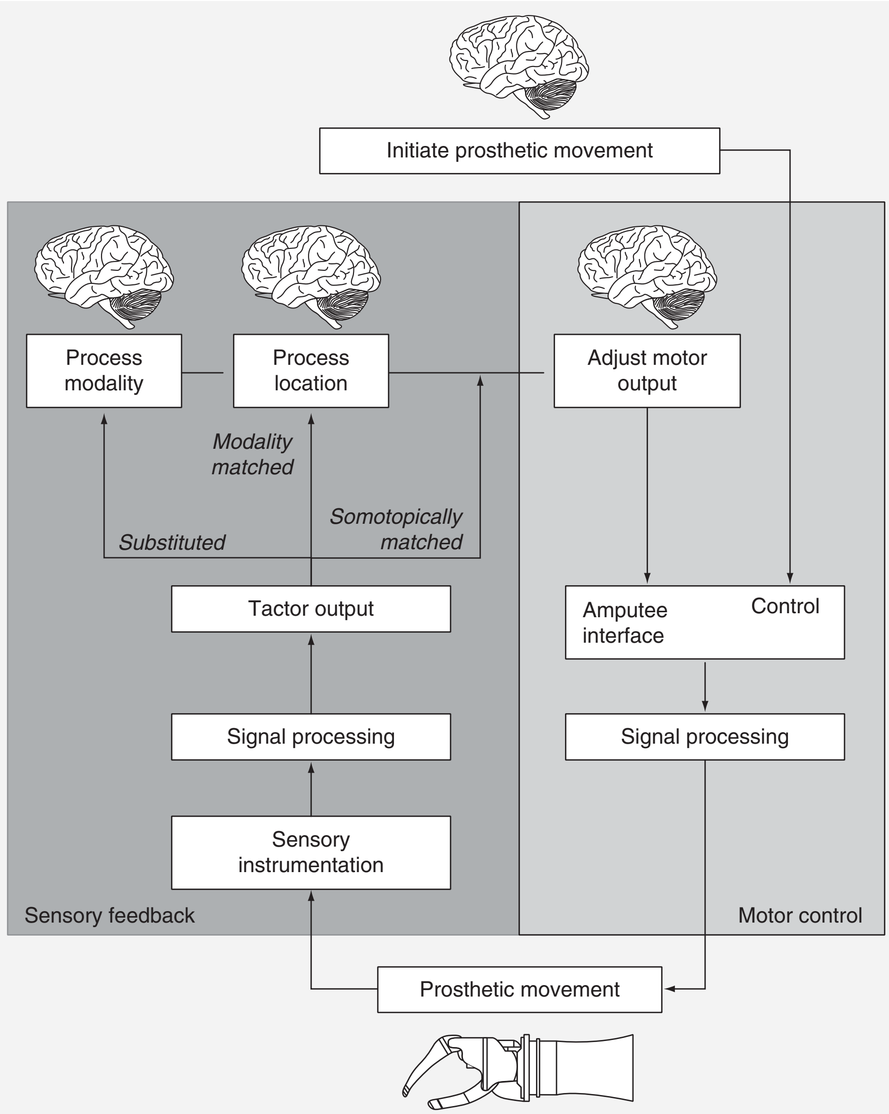

Figure 9. Schematic of the process used to control a myoelectric prosthetic with sensory feedback.

these finding to a prosthetic device might be achieved by linking the sensors from the prosthetic hand to strategically positioned tactors on the residual limb to stimulate the relevant area of the hand map. This might allow the participant to experience sensations matched in modality and somatotopy simultaneous to a stimulus occurring at the prosthetic device.

Although promising, TR feedback techniques, first published in 2004, are in their relative infancy compared with other feedback methods [64,69]. Research is still ongoing to develop means of effectively utilizing the reinnervated skin sites. A further limitation lies in the need for surgery to utilize TR feedback techniques. There are a limited number of institutions performing TR surgeries and as of 2013, just over 40 patients have received TR surgery [72]. Regardless, TR may provide a rich platform on which to build natural physiologically based feedback systems.

Expert commentary

Grasp & touch sensation

In moving toward sensory systems capable of being implemented for long-term use, a number of factors must be considered. The concept of providing 'natural, physiological feedback' should be considered. Neither substitution nor modality-matched methods provide input through the original sensory pathways of the amputee [55]. Thus, the corresponding sensory information may be perceived as *unnatural* and may require additional time, training and attention to effectively exploit [73,74]. The ideal system would combine the benefits of modality and somatotopic-matching systems to allow the participant to feel a relevant stimulus at the correct location on their missing limb [69,75].

Another consideration is that methods of evaluating feedback systems have occurred in controlled laboratory environments where participants are asked to perform relatively simple object grasping and manipulating tasks. As the complexity of the task is often low, most of the participant's concentration can be dedicated to interpreting the feedback signals provided. In reality, day-to-day activities incorporate varying levels of complexity with corresponding concentration required of the user. Feedback signals requiring high levels of concentration to decode will ultimately increase the cognitive burden of the users or be perceived as extraneous and distracting from the given task. Many systems proposed in literature require training and sensory adaptation to interpret a nonphysiological signal as exteroceptive or proprioceptive information [34]. This additional processing of information increases the cognitive burden and has the potential to negate one of the largest benefits of sensory feedback: reduced conscious attention (Figure 9). Therefore, an effective feedback signal must first input the correct stimulus, and secondly ensure that the feedback signal is received as natural and not as a distraction. In the future, it will be important for researchers to develop better measures for evaluating the usability of sensory feedback systems in day-to-day life, such as reporting on the naturalness of measured sensations as well as the amount of cognitive burden required. Furthermore, to sufficiently address a feedback systems efficacy, the device must be integrated in to a prosthetic socket and functional tasks beyond grip force or simple object manipulation must be performed. Participant testing should occur over multiple sessions to enable evaluation of the training and time required for the feedback system to imporve prosthetic use.

Five-year view

While systems providing cutaneous sensation have been studied extensively, providing the user with a sense of joint position and movement has been less studied. However, allowing an individual to sense the position of their prosthesis in space without requiring visual attention has the potential to greatly improve dynamic prosthetic control.

Vibrotactile feedback has been implemented to establish proprioceptive communication between the user and prosthesis through substitution [62,76]. In a case study, Mann *et al.* introduced vibratory tactors to the residual limb of a single participant with above elbow amputation. The amplitude of vibration was manipulated to provide the user with information on the state of elbow flexion and extension in the prosthesis. The participant demonstrated improvements in positional control of the prosthesis during reaching tasks [76]. Although this area has not been studied extensively, there is potential for vibrotactile sensory substitution (or other substitution methods) to be implemented to communicate the positional state of prosthetic joints or the prehensor.

An alternative possibility to providing kinesthetic sensibility would be to exploit vibration-induced movement illusions. Also termed the *kinesthetic illusion*, this unique physiological phenomenon possesses the ability to provide somatotopically matched kinesthetic feedback. In able-bodied individuals, vibration introduced to musculotendinous regions of a limb can induce sensations that the limb is moving [77,78]. It is believed that the vibratory stimulus induces muscle spindle activity [79]; consequently, the direction of illusionary movement will be experienced as though the stimulated muscle group is being stretched (Figure 10). However, the kinesthetic illusion has yet to be tested with amputee participants or implemented as a method of prosthetic sensory feedback. As a potential unique solution to kinesthetic sensibility, it warrants further investigation.

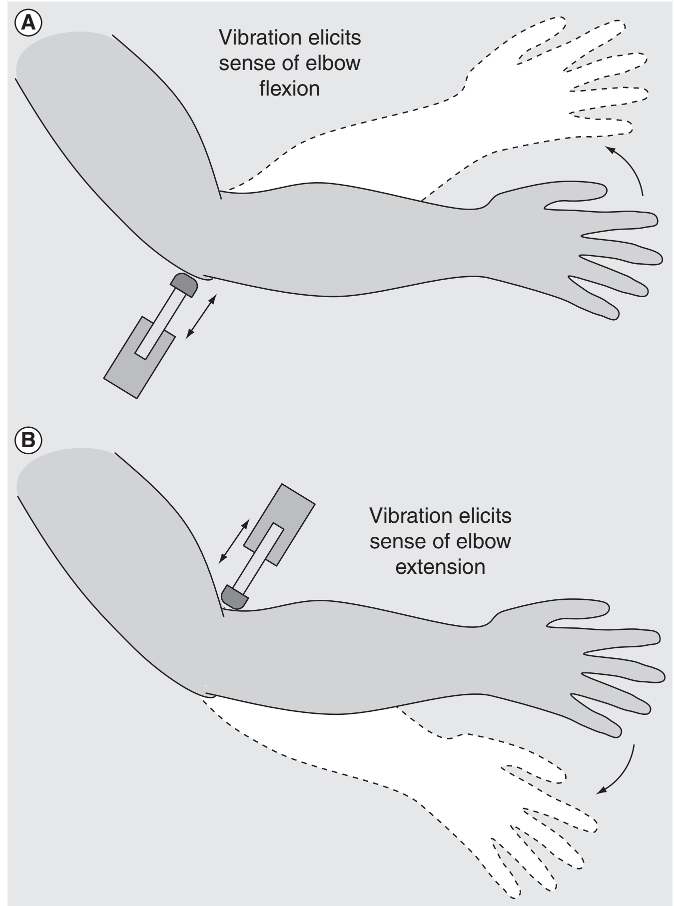

Figure 10. Overview of kinesthetic illusion showing. (A) Elbow flexion and **(B)** elbow extension.

Translational capabilities

In moving toward clinical or commercial use, it is important to consider several future directions related to sensory feedback methods, socket integration challenges and overall system usability.

One current challenge involves integrating these feedback systems into the prosthetic socket. Sockets are used to attach the prosthesis to the residual limb, and different designs may include combinations of roll-on suction suspension liners, flexible materials and an anatomically contoured casing [2,80]. Suction attachments are typical in myoelectric arms [81]; and therefore, it is imperative that implementing a sensory feedback system does not compromise this suction seal. Currently, electrodes are connected to the body by embedding them into a fabric liner that fits between the socket and the body [82] or embedding the electrodes directly into the socket wall for a skin suction fit. Most literature concerning current tactor designs do not address the socket integration issue, instead tactors are simply placed directly on the skin for testing without regards to the vacuum seal that must be maintained for prosthetic use. One exception is the work by Armiger *et al.* in which a tactor has been mounted in the interface between the user and the prosthetic device within the socket [48]. However, the vacuum seal issue is not directly addressed, and specific details of the integration are not provided. Therefore, it will be important to address this subject in future research.

Another potential difficulty facing amputees is misalignment of tactors during the donning process, when they attach the prosthesis over their residual limb. It is hypothesized that misalignment of tactors could result in feedback that is neither intuitive nor useful (similar to misalignment of myoelectric sensors used to record muscle signals [83]). For this reason, it will be important to consider methods and designs to consistently align the tactors.

Other general aims in the design of sensory feedback systems are to make the system robust enough to reliably provide feedback over extended periods of time, have a small enough profile to allow freedom of movement, ensure a reduced footprint to allow ample spacing for sensors and other features and consume low enough amounts of power to ensure function throughout an entire day. It will be important to continue to investigate different feedback methods as it is possible that a better method for communication between a person and their prosthesis has yet to be comprehensively tested. As is the nature of prosthetic limb replacement, each intervention is unique and tailored to the individual user. Individual patients may want varying degrees of sensory feedback, with specific modalities and somatotopy dependent on preference and application; therefore, patient specificity will ultimately drive an individual's ideal solution.

Conclusion

The state of upper limb prostheses can be characterized by rapid technological advancements limited by an inability to provide a reliable sensory interface with the amputee. State-of-the-art prostheses are capable of mimicking the multiple degrees of freedom possessed by the human hand and arm, and can be equipped with instrumentation to measure position, temperature and grasping forces [48]. For decades, the lack of sensory feedback from prosthetic to user has been highlighted as a major barrier hampering upper limb prosthetic utility. Today, this issue has become even more significant due to the rapid developments in multifunction prostheses. Various sensory feedback systems have been proposed, and most have shown that a user can improve their ability to manipulate the prostheses with feedback. However, a sensory feedback system has yet to be proven effective for long-term use outside of a research setting [15]. This paradox can perhaps be attributed to two factors crucial to a feedback systems success: the ability to provide relevant feedback that does not detract attention from the user (and therefore be rejected), and the ability to incorporate the system into prostheses without compromising fit or function. If a feedback device is to be successfully incorporated into prostheses for clinical use, then these two issues will be pivotal in the device's success.

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Key issues

- The basis of hand movement is closed-loop motor control comprised a dynamic interplay between motor output and sensory input. The loss of an upper extremity significantly alters this closed-loop control strategy as sensations of touch and movement are inherently lost.
- The lack of sensory feedback in prostheses increases the cognitive demand placed on the user as operation of the prosthesis requires continuous conscious attention.
- Sensory *feedback systems* employ instrumentation (or *sensors)* at the prosthetic level to detect an external stimulus. This instrumentation in turn drives the output of a haptic feedback device (also termed *tactor*) that conveys information about the external stimulus to the prosthetic user.
- Grasp and touch sensory feedback systems can be divided into three categories: substitution, modality matched and somatotopically matched methods.
- Sensory substitution categorizes a group of feedback systems that apply a feedback signal that is not matched in modality to the stimulus occurring at the prosthesis and includes vibrational, electrotactile, auditory and other less common feedback types.
- Modality matching refers to a feedback signal that is congruent to the external stimulus detected by the prosthetic sensor and includes mechanotactile feedback and other multimodal feedback types.
- Somatotopic matching refers to methods in which the feedback signal is perceived as being anatomically matched in location to where the stimulus is being applied to the prosthesis and includes peripheral nerve stimulation, natural phantom mapping and targeted reinnervation.
- The ideal feedback system would combine the benefits of modality and somatotopic-matching systems to allow the participant to feel a relevant stimulus at the correct location on their missing limb.
- In future clinical trials, it will be important to integrate feedback devices in to a prosthetic socket and perform functional tasks beyond grip force discrimination and simple object manipulation to comprehensively evaluate a feedback system's efficacy.

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