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Review

SENSORY FEEDBACK IN UPPER LIMB PROSTHESES

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Loss of an arm is a devastating condition that can cross all socioeconomic groups. A major step forward in rehabilitation of amputees has been the development of myoelectric prostheses. Current robotic arms allow voluntary movements by using residual muscle contraction. However, a significant issue is lack of movement control and sensory feedback. These factors play an important role in integration and embodiment of a robotic arm. Without feedback, users rely on visual cues and experience overwhelming cognitive demand that results in poorer use of a prosthesis. The complexity of the afferent system presents a great challenge of creating a closed-loop hand prosthesis. Several groups have shown progress providing sensory feedback for upper limb amputees using robotic arms. Feedback, although still limited, is achieved through direct implantation of intraneural electrodes as well as through non-invasive methods. Moreover, evidence shows that over time some amputees develop a phantom sensation of the missing limb on their stump. This phenomenon can occur spontaneously as well as after non-invasive nerve stimulation, suggesting the possibility of recreating a sensory homunculus of the hand on the stump. Furthermore, virtual reality simulation in combination with mechanical stimulation of skin could augment the sensation phenomenon, leading to better interface between human and robotic arms.

Key words: *sensory feedback, robotic arm, myoelectrical prosthesis, closed-loop prosthesis, virtual reality simulation.*

INTRODUCTION

The function of upper extremities is to perform our daily living activities and guarantee our independence. Any loss of extremity results in profound and devastating disability. Hand amputation incidence is estimated at 1.5 of 1000 people, approximately 3 million people worldwide (LeBlanc, 2008), and the numbers are predicted to rise every year (Ziegler-Graham *et al.,* 2008). Amputees are faced with a great challenge to regain their functionality and independence. Effective prosthesis plays a major role in the battle towards improved quality of life. Moreover, recently another category of patients has increased the demand for high functioning prostheses. Carefully selected patients with global brachial plexus injuries undergo psychological assessment followed by amputation (Hruby *et al.,* 2017; 2018). In cases where all salvage and reconstructive options are exhausted and biological restoration of function can no longer be achieved, amputation with subsequent hand replacement with a bionic limb has proven to be beneficial (Aszmann *et al.,* 2016).

Nowadays, the development of science and technology has led to invention of robotic prostheses that provide voluntary movements using human-robot interfaces. These intention-controlled prostheses are a great achievement in improving the quality of life for amputees. Modern myoelectric hands use electromyographic signals from residual muscles in the stump. These signals are then read and translated to the robotic arm resulting in intentional movement of the prosthesis (Geethanjali *et al.,* 2016). The need for a better interface has changed the surgical techniques in amputation, adding rewiring of nerves to different muscles. Targeted muscle reinnervation is now a routine procedure aiming to improve

intention-controlled myoelectric signal transmission to artificial arm, thus facilitating information exchange and improving voluntary movement (Kuiken *et al.,* 2007; 2009; Cheesborough *et al.,* 2015; Gart *et al.,* 2015; Kuiken *et al.,* 2017; Zuo *et al.,* 2018).

Despite recent advances, current myoelectrical prostheses mostly provide just motor function. Satisfactory long-term sensory feedback has not yet been achieved. Nevertheless, the increased use of myoelectric prostheses has led to a better understanding of amputees' needs. According to surveys, the lack of sensation leads to an approximately 40% prosthesis rejection rate (Biddiss *et al.,* 2007). The additional information from vision does not allow sufficiently correct and adjusted movement (Johansson *et al.,* 2009). Prosthetic users admit the necessity to reduce the reliance on visual cues to perform basic daily activities (Atkins *et al.*, 1996). Moreover, sensory feedback provides the sense of embodiment (D'Alonzo *et al.*, 2015), and reduces phantom limb pain (Dietrich *et al.,* 2012). That would allow the use of prosthesis more regularly, with a significantly decreased cognitive load. Other user concerns address the heavy weight of a prosthesis that leads to fatigue, high power consumption, and difficulty in performing precise and meticulous tasks (Benz *et al.*, 2016; Cipriani *et al.*, 2016). In fact, a survey developed by Peerdeman *et al.* (2011) has shown user feedback priorities, in hierarchical importance: (i) continuous and proportional feedback on grasping force, (ii) position feedback, (iii) easy and intuitive interpretation of stimulation used for feedback, (iv) unobtrusive feedback to user and others, and (v) adjustable feedback (Peerdeman *et al.,* 2011).

A closed-loop robotic arm that takes care of voluntary motor function at the same time providing a sensory feedback is still a major challenge to overcome. Due to the complexity and multimodality of the afferent system a singular solution is not sufficient. The sensory system provides information about the physical properties of the object — shape, size, weight, texture, and temperature (Johansson *et al.,* 2009). Our hand perceives various different types of stimuli through skin and translates them into afferent information. In fact, there are over 17 000 sensors in the human hand, ensuring continuous perception of the external environment and dexterous handling of surrounding objects (Ahmad and Chappell, 2009). There are seven major sensory receptors: pain receptor, cold receptor, warm receptor, and four mechanoreceptor types. Each receptor type measures forces on different time scales and with different receptive field sizes. This biological feedback travels through the peripheral nervous system as action potentials and carries information to the central nervous system. At any given time, a large variety of different afferent impulses are transmitted through nerves at once (Chortos *et al.,* 2016). In turn, the sensory cortex processes information and adjusts the intentional movement, thus providing control over any motor action (Jenmalm *et al.,* 2003). Amputees do not receive this vital information, even when using a myoelectrical prosthesis, leading to inability to plan, tailor and execute precise and adaptive movement. In these cases, vision provides indirect information, however, not sufficient for satisfactory performance (Johansson *et al.,* 2009).

Human skin possesses unique properties that does not yet exist in conventional electronics. Hardships involve not only designing multiple different sensors densely covering small areas of robotic hand, but also developing signal encoders and transmitters that could convey unambiguous and close to real sensations (Hammock *et al.,* 2013; Chortos *et al.,* 2016). This aspect raises a question about the man-machine interface. Not only engineering of applicable sensors used in prosthesis is still a challenge, but also linking the gap between artificial and biological impulse is not yet resolved.

Multiple studies have shown some promising results using invasive and non-invasive approaches to restore sensory feedback. However, they are mostly limited to laboratory settings, presenting case reports or small cohorts. Moreover, a great majority of papers report non-invasive techniques to be used on healthy and abled individuals. (Kaczmarek *et al.,* 1991; Raspopovic *et al.,* 2014; Chai *et al.,* 2015; Clemente *et al.,* 2016; Davis *et al.,* 2016; Oddo *et al.,* 2016; D'Anna *et al.,* 2017; Valle *et al.,* 2018). Although, the invasive techniques are investigated on amputees, usually trials are brief and conducted with few participants (Bark *et al.,* 2008; Antfolk *et al.,* 2013; D'Alonzo *et al.,* 2014; Leonardis *et al.,* 2015; Reza Motamedi *et al.,* 2017; Meli *et al.,* 2018).

Researchers have described a phenomenon of referred sensation, a phantom hand map on the residual stump (Ramachandran and Hirstein, 1998; Ramachandran and Rogers-Ramachandran 2000). For every individual the map is unique. The localisation can vary from tip of the stump to more proximal areas. The phantom hand map can represent either a complete hand with all fingers or only some parts of the lost extremity. Reasons for this phenomenon are still unclear, but local nerve regeneration and cerebral reorganisation could be contributing factors. Changes in primary somatosensory cortex and thalamus ventroposterior nucleus after amputation have already been recognised (Chen *et al.,* 2002; Wall *et al.,* 2002), and functional magnetic resonance images demonstrates that primary somatosensory cortex perceives referred sensation in a way that is consistent with normal sensory homunculus (Bjorkman *et al.,* 2012; Kikkert *et al.,* 2016). The same group analysed sensory qualities of a phantom hand map. The capacity to detect cutaneous stimulus in a phantom map was shown to be the same as in the contralateral side, though discrimination was much higher, suggestive of adaptation in brain function (Bjorkman *et al.,* 2016). This phenomenon could therefore be used to localise the area for application of targeted stimulation, augment man-machine interface and provide a better sensory feedback.

Therefore, in this article an overview of different sensory feedback mechanisms found in scientific literature is provided.

INVASIVE METHODS

There are three major invasive sensory feedback approaches — targeted sensory reinnervation, peripheral nervous system direct stimulation, and central nervous system stimulation. It is noted that direct stimulation of the peripheral nerve is better understood and translated in somatosensory cortex, providing with more natural sensation (Saal and Bensmaia, 2015). However, it is also possible to evoke close to natural sensation and ownership of prosthesis by direct central nervous system stimulation (Collins *et al.,* 2017).

Targeted sensory reinnervation. Targeted reinnervation is a surgical technique where nerves of an amputated hand are transferred to more proximal nerves innervating muscles. Myoelectrical signals from these muscles are then used to power voluntary movement of a robotic arm. Researchers have demonstrated that transposed nerves also innervate the skin overlying targeted muscles, giving various sensation properties of a missing hand (Herbert *et al.,* 2016), thus enabling to use this skin area for interface. The same group has shown advantage of more precise surgical intervention — targeted sensory reinnervation (TSR), where the nerve sensory fascicles are transferred to more proximal sensory nerves unaffected by amputation. Redirected sensory nerves innervate the skin on the remaining arm providing more detailed and widespread sensation of the lost hand areas. Case reports have shown the possibility of peripheral nerve bidirectional flow of information and improvement in myoelectric prosthesis control (Herbert *et al.,* 2014). The advantages demonstrated are: (i) no foreign bodies, (ii) more natural sensation compared to that evoked by artificial electrical stimulation, and (iii) long-term stability. However, the restrictions of this approach are: (i) somatotopical representation of hand map is unorganised, (ii) the ability to evoke transmission of sensation lays on a tactor array that is responsible to produce a wide range of sensation, (iii) unpredictability of skin reinnervation pattern, and (iv) no proprioceptive feedback (Sall and Bensmaia, 2015).

Direct peripheral nerve stimulation. Various electrodes have been developed to directly interface with peripheral nerves. Electrodes are implanted by surgical intervention around or within the nerve and current, carrying information, is applied to the nerve. This approach allows direct machine-made sensory impulses to be transmitted through nerves evoking sensation feedback. Depending on invasiveness, three main types of electrodes are known: extraneural, intraneural, and regenerative (Svensson *et al.,* 2017). With the increase of invasiveness, lower intensity of signal is necessary as well as higher selectivity of stimulated nerve fibres can be reached (Navarro *et al.,* 2005). However, often with more selectivity, stability of the electrode interacting with an identical fibre population decreases (Saal and Bensmaia, 2015).

Extra-neural electrodes. Extra-neural electrodes, such as cuff and epineural electrodes (Walker *et al.,* 1977), encircle the nerve and provide notable contact area around the cuff, allowing to stimulate considerable number of largely myelinated axons close to the surface of the nerve (Del Valle and Navarro, 2013). Another version of an external electrode is a flat interface nerve electrode (FINE), which yields a higher number of active surfaces throughout the cuff, thus granting better contact and more selective activation of fibres (Tyler and Durand, 2002). Although this type of electrode causes less damage to the nerve, higher stimulation of current is required to evoke sensation (Grinberg *et al.,* 2008). Moreover, higher current activates a larger number of fascicles diminishing the selectivity and limiting the accuracy and precision of the evoked sensation (Leventhal and Durand, 2003). In fact, an increased number of synchronously activated fascicles can lead to unnatural sensation and paraesthesia (Tan *et al.,* 2014).

Intraneural electrodes. Various intraneural electrodes have been developed. Major differences lay in electrode density and layout. Some of the more known interfaces are longitudinal intra-fascicular electrode (LIFE), where contacts are placed parallel to the nerve (Dhillon *et al.,* 2004), transversal intra-fascicular multichannel electrode (TIME), where contacts are places perpendicular to the nerve (Boretius *et al.,* 2010), and the Utah slanted electrode array (USEA), where multiple parallel contact arrays are perpendicularly penetrate nerves in different depths (Ledbetter *et al.,* 2013). Intra-fascicular interfaces are inserted directly into the nerve, allowing access to different fascicle groups across the nerve. The electrode has closer contact to nerve fibres and threshold to evoke potential is reduced, and lower stimulation current is necessary, allowing to activate different fascicles more selectively (Branner *et al.,* 2001, Badia *et al.,* 2011). Higher selectivity results in more natural and more precise feedback. A disadvantage, however, is the invasiveness of the procedure that can lead to a higher degree of nerve damage. Another issue is long-term stability that is compromised due to disruption of contacts between the electrode and the nerve fibres. Finally, both extra- and intra-neural electrodes can evoke motor nerve fibres. This can lead to uncomfortable and confusing muscle twitches that can decrease the level of prosthesis control (Saal and Bensmaia, 2015).

Regenerative electrodes. Regenerative electrodes are implanted in between two nerve ends, similar to a nerve graft. However, instead of using a biological graft, an artificial material sieve is used to close the gap between nerve ends. The sieve has a large number of holes through which the transacted nerve fibres regenerate, creating small bundles and thus maximising contact area with separate fascicle groups. The mechanism allows then to stimulate axons highly selectively (Kovacs *et al.,* 1992). This approach increases the feeling of natural sensation. Moreover, decreasing the size and increasing the number of holes can achieve even higher resolution. In addition, introducing specific growth factors that target exact neural populations, like tactile or proprioceptive, fibres potentially could be guided to reach designated electrodes (Lotfi *et al.,* 2011). However, research conducted on animals and long-term human results

have yet to be shown. This procedure is the most invasive one leading to nerve damage and possible degradation in the long-term. Furthermore, early results of a successful outcome require several months to be observed due to the re-growth of nerves through the sieve (Lago *et al.,* 2005). In fact, the re-growth pattern is disorganised allowing smaller less myelinated axons to grow faster more centrally and largely myelinated axons to remain more superficially. This can prevent proper contact with the electrode as well as can complicate the transmission (Castro *et al*., 2008).

Central nervous system stimulation. Brain-machine interfaces are used to transmit cortical neuron activity to external devices, like prosthetic arms. O'Doherty and colleagues have studied primates with installed brain-machine-brain interfaces, where information about tactile sensation is transferred from brain-controlled virtual reality arm to sensory cortex (O'Doherty *et al.,* 2011).

Direct somatosensory cortex stimulation via implanted electrodes can also provide the sense of ownership of the artificial limb. It was shown on a human, when touches applied to a rubber hand were synchronised with cortical stimulation, resulting in a sense of touch and embodiment of the set hand (Colins *et al.,* 2017). The authors also showed that this illusion was not induced if stimulus was delivered asynchronously or to a cortical area other than hand. This implies that vision gives input to adjust the received information of direct stimulation. Similar studies have been done with patients after complete spinal cord injuries. Microelectrodes were implanted in somatosensory cortex, and upon stimulation conveyed information about touch and pressure in respective hand areas (Flesher *et al.,* 2016).

Although the high invasiveness of these procedures carries great surgical risks, direct somatosensory cortex stimulation shows that the peripheral nervous system can be bypassed. These studies suggest that intracortical microelectrode arrays could be used for neuroprosthesis feedback to increase fine motor control and object manipulation (O'Doherty *et al.,* 2011; Klaes *et al.,* 2014). However, implants are possibly short lived (Svennson *et al.,* 2017) and can malfunction if detached or shifted from cortex.

NON-INVASIVE METHODS

There are several non-invasive sensory feedback methods that are being explored — mechanotactile, vibrotactile, electrotactile, and thermal feedback. Another method that can be classified as non-invasive is augmented reality simulation. These methods have been shown to produce sensory feedback to certain degree, (Antfolk *et al.,* 2013; Chai *et al.,* 2013; 2015; Liu *et al.,* 2015; Zhang *et al.,* 2015; Clemente *et al.,* 2017), especially when used on phantom hand maps (Li *et al.,* 2018). Each of these methods provides only partial afferent information, and so far, a multimodality system and somatotopical matching has still been a challenge.

Mechanotactile stimulation. Mechanotactile stimulation is a feedback mechanism that uses pressure or skin stretch to convey tactile information. Most often an inflatable plastic or silicon bulbs are used to imitate pressure that is translated from robotic hand sensors when an object is grasped or touched. Another technique is to use a belt- or cuff-like devices to stretch the skin. Depending on applied pressure forces on any area of skin, sensation of touch and object qualities, like hard, medium or soft, can be evoked (Casini *et al.,* 2015). The contact pressure can be discriminated in up to three different positions (Culjat *et al.,* 2010). Also, a different level of strength can be recognised (Antfolk *et al.,* 2012), and grasping force captivated and modulated (Godfrey *et al.,* 2016; Morita *et al.,* 2016). However, a similar study by Godfrey and colleagues showed that the changes in grasping objects were not statistically significant when compared to visual feedback. It has been proposed to apply mechanic force directly to a phantom hand map to improve somatotopical feedback (Antfolk *et al.,* 2013).

Use of linear skin stretch was shown to increase grasp recognition for healthy subjects (Akhtar *et al.,* 2016). Also, rotational skin stretch shows benefits in determining position of a myoelectric hand, but it is only suitable for one degree of freedom prosthesis (Bark *et al.,* 2010). Nevertheless, other researchers found that rotational skin stretch decreases target error and visual demand (Wheeler *et al.,* 2010), and conveys proprioceptive information in an easily understandable way (Battaglia *et al.,* 2017). These devices, however, are mostly large, bulky, and have a high noise level and high power consumption (Antfolk *et al.,* 2013).

Vibrotactile stimulation. The vibrotactile technique is one of the most often used sensory feedback systems in studies (Svensson *et al.,* 2017). The tactile, pressure force or position information is usually transmitted from sensors in the prosthesis to a vibrating device placed on the participants skin. The modalities of signals are mismatched; however, studies showed that the vibration is understandable, and beneficial when proper training is done (Stepp *et al.,* 2012). Some researchers provided evidence that more than one vibration force, represented by pulse frequencies and strength, can be distinguished (Rosenbau-Chau *et al.,* 2016). However, they also suspected that more than three (low, medium, high) could confuse the user, thus tampering with the received feedback information. Also, they discovered that series of vibration pulses have higher success rate than continuous vibration.

Vibrotactile feedback could be used to provide information about grasping force, point of contact, hand velocity, proprioception and texture of an object (Hasson and Manczurowsky, 2015; Witteveen *et al.,* 2015; Hanif *et al.,* 2016; Nabeel *et al.,* 2016). However, all of these senses cannot be translated to vibration at once. This is due to the fact that with training the user learns to identify vibration at site of applied device as only one modality of sensation. Vibrotactile stimulation has been investigated as a means for proprioception (Hasson *et al.,* 2015). Nonetheless, the study was applied on healthy individuals and did not show posi-

tive outcome when visual feedback was removed and only vibration was left as feedback for movement control.

In contrast, another group demonstrated that changing amplitude and frequency of vibration in association to grasping force and using constant frequency with varying amplitude for velocity of the closing hand, were sufficient to allow to successfully pick up objects (Ninu *et al.,* 2014). These vibration modalities were shown to convey hand velocity, point of contact and grasping force, of which hand velocity was deemed the most important for the users. Furthermore, intermittent vibration with changes in pulse modalities could be translated as different surface texture (Hanif *et al.,* 2016).

Researchers find that applying vibrotactile feedback mostly reduced cognitive load (Yamada *et al.,* 2016) and increased sense of embodiment (Ehrsson *et al.,* 2008). In addition, vibrotactile systems are cheap, light weighted, and preferred over electrostimulation (Witteveen *et al.,* 2012). However, they are still limited by excessive training (Raven *et al.,* 2018), narrow modality of sensation feedback, feedback delay (Cipriani *et al.,* 2012), perception of vibration dependence on tightness of attached vibrator (Cohen *et al.,* 2005), and feedback perception variability between different users (Yamada *et al.,* 2016), thus, making it hard to standardise the method.

Electrotactile stimulation. Electrotactile stimulation provides sensory feedback by delivering electrical current through skin, also referred as transcutaneous electrical nerve stimulation (TENS). Electrical stimulation is used to evoke pressure, grip force and slip sensation (Xu *et al.,* 2016). Researchers have shown that electrotactile feedback allows the user to analyse grip force (Jorgovanovic *et al.,* 2014; Isakovic *et al.,* 2016), thus, improving myoelectrical prosthesis control. The subjects preferred using electrical stimulation in addition to visual feedback (Schweisfurth *et al.,* 2016). Moreover, electrotactile feedback allows to better choose the necessary grasping force when dealing with light and heavy object lifting (Shi and Shen, 2015).

However, electrical stimulation feedback system demonstrates quite many shortcomings that need to be addressed. First of all, the minimum sensation threshold and pain threshold, as response to electrical stimulation, varies from person to person, and also differs when an electrode is placed in a different position (Antfolk *et al.,* 2013). The slightest movement of the electrode on skin, or quality of skin, can influence transmission of a feedback signal. Moreover, a recalibration of thresholds is required every time when a new electrode is placed (Dosen *et al.,* 2014; Jiang *et al.,* 2014; Xu *et al.,* 2016). While some studies have shown that varying frequency, intensity and pulse width of electrical stimulation can portray different sensation forces (Jotgovanovic *et al.,* 2014; Shi and Shen, 2016; Strabac *et al.,* 2016), these three parameters would still need to be readjusted each time when an electrode is used to achieve the same perception (Jiang *et al.,* 2014; Xu *et al.,* 2016). Furthermore, electrical stimulation can interfere with electromyographic readings that are used for processing the movement of robotic arm. Some groups, however, have demonstrated possible solutions, like application of time-division multiplexing and blanking (Dosen *et al.,* 2014; Hartmann *et al.,* 2016).

Thermal stimulation. Temperature provides us with information about surrounding objects and warns us about potential danger of extreme heat or cold. For amputees, the thermal feedback, although important information, is not the priority (Peerdeman *et al.,* 2011). Some studies have shown that thermal sensors from a robotic arm can convey information to the amputee via a wireless Peltier element on the opposite hand (Cho *et al.,* 2007). The subject could discriminate between high, warm and cold temperature. Another modification of the technique was used to decrease response time by using a prediction algorithm that improved results (Udea and Ishii, 2017). However, the main issue about using a Peltier element is delayed response and the prolonged time that is required to change from hot to cold state (Stephens-Fripp *et al.,* 2018). Nevertheless, some new developments have been made by introducing Thermotactil Multimodal Display that allows to sense high temperature variations (Gallo *et al.,* 2014).

Virtual reality simulation. Virtual reality simulation has mostly been used to treat phantom limb pain for amputees as a modern alternative to a mirror box therapy. In this simulation, 3-dimensional goggles are usually used to portray an image of the lost limb to a patient. Virtual reality software allows an amputee to see the movements of the missing body part. Coincidentally, the visual cortex is stimulated, and the brain is tricked into believing an alternative reality. The mechanism is not fully understood, but the method provides necessary stimulus for neuroplasticity processes to take place. The technology allows using augmented reality in combination with a myoelectric hand and a haptic feedback system, resulting in decries of phantom pain (Chau *et al.,* 2017; Snow *et al.,* 2017; Osumi *et al.,* 2019). However, other advances, with some success, have been made in attempt to communicate feedback such as aperture angle, grasping force and grip closure via virtual reality (Clemente *et al.,* 2017; Markovic *et al.,* 2017). Although the speed and accuracy of gripping could be improved, the long-term benefit of this mean of feedback is not yet determined.

POTENTIAL FOR DEVELOPING SENSORY FEEDBACK INTERFACE

The major goal for amputees' rehabilitation nowadays is to create a prosthesis that resembles a human limb with its bidirectional information transmission. Rapid development of technology has significantly increased the possibilities over the past decade and closed-loop systems are being created and tested. As the use of myoelectrical hands has expanded, so has the demand for even more intelligible prosthesis functioning in both ways — afferent and efferent. Not only are the possibility of motion, many degrees of free-

dom, and strength of the artificial arm important, but also a high level of dexterity, precision, and nuanced movement are expected. The latter is provided and adjusted by sensory feedback, thus, augmenting the necessity for sensory control. Moreover, afferent feedback also increases the sense of embodiment and diminishes cognitive load.

Research is predominantly focused on the advancements of technology. However, even with the new technologies that provide complex multimodal sensors on the robotic hand, machine-human interface, the actual transmission of ascending information, is still a challenge. It is evident that there are quite many obstacles to guarantee unambiguous and intuitive sensory feedback. The variables that need to be taken into account are not only mechanical, but also biopsychological. From machinery point of view, there is no clear answer which kind of stimulation is superior to others — mechanotactile, electrotactile, or vibrotactile. All of above mentioned techniques have been shown to transmit a certain amount of sensation. Nonetheless, all of these techniques entail drawbacks, some of them being — lack of multimodality and somatotopical precision, necessity to adjusts threshold levels, pulse width, frequency and other parameters, interference with electromyographic readings, and no long-term evidence of consistency. Another debate about the level of invasiveness has not been concluded. In fact, the risks of long-term invasive feedback techniques outside controlled laboratory environment are yet to be ascertained. Even more, individual prosthesis users often have different expectations, needs and capabilities, and that will further determine the course of their learning and training process, as well as their compliance, acceptance and adaptation to robotic prosthesis.

So far, only a few case studies have assessed the effect of using myoelectric arm with sensory feedback long-term in a natural environment at home (Clemente *et al.,* 2016; Graczyk *et al.,* 2018). The majority, however, are carried out in controlled laboratory environments, thus making it difficult to draw comprehensive conclusions about which sensory feedback method is more superior. In fact, it is not yet possible to determine which factors could affect the use of any of previously mentioned feedback systems in the home environment. Hence, more studies in a natural habitat should be attempted.

Engineering is a major part of bionic prosthesis development. However, the biological component, which in this case is the peripheral and central nervous system of an amputee, should not be overlooked as less relevant. The processes of cortical reorganisation and natural peripheral nerve adaption to amputation are not yet fully understood. At the same time, there is feasible evidence in the literature suggesting neuroplasticity taking place after amputation (Di Iorio *et al.,* 2018), and after targeted motor and sensory reinnervation (Serino *et al.,* 2017). There is some evidence about the same happening after sensory feedback stimulation as well (Van Der Heiligenberg *et al.,* 2018). Moreover, it has been demonstrated that due to changes in cortex, and possibly disconnected peripheral nerve regrowth after amputation, a spontaneous cortical representation of a lost hand, referred to as phantom hand map, can be found on an amputees' stump (Bjorkman *et al.,* 2012).

Furthermore, this spontaneous phantom hand phenomenon unlocks potential possibilities to enhance machine-human non-invasive interface, facilitating the process of receiving and transmitting mechanical impulses. Also, the phantom hand map could heighten somatotopical characteristics of sensory feedback. Therefore, this phenomenon should be the focus of future research.

In addition, as previously discussed, virtual reality simulation has already proven to be extremely beneficial to reduce phantom limb pain. However, the research should not be limited only to this aspect. As vision already serves as feedback system for amputees, the use of available virtual reality technology should be incorporated more to explore the spontaneous phantom hand map phenomenon. It has been already established that sensory feedback performance can be improved with training. Thus, possible future investigation should entail assessment of augmented reality's impact on either reinforcement of a spontaneous phantom hand map, or on creation of a cortical representation map of the missing hand on the stump. The continuing research would allow to better understand and use the phenomenon, and possibly aid in developing training protocols using virtual reality techniques.

CONCLUSION

The major goal in managing upper extremity amputees is to help them regain as much hand function as possible. Current robotic prostheses offer a great deal of motor function, however, sensory feedback and movement control are still challenges. Different types of invasive and non-invasive techniques of sensory feedback have been developed and studied. Nevertheless, it is difficult to draw wide-range conclusions due to the fact that most studies are short-term, undertaken in controlled laboratory settings and quite a lot are done on healthy individuals. Invasive techniques show some promising results. However, not all users are willing to undergo surgery; even more, long-term effects are still unknown. Non-invasive techniques seem to be a reasonable alternative, yet, the level of feedback is not satisfactory enough. In future research more emphasis should be placed on investigating how technology could be used to enhance natural coping phenomenon like a phantom hand map in order to facilitate the machine-human interface.

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SENSORĀ ATPAKAĻSAITE PACIENTIEM AR AUGŠĒJĀS EKSTREMITĀTES PROTĒZI

Augšējo ekstremitāšu amputācija ir nozīmīga problēma dažādās sociālekonomiskajās cilvēku grupās. Ievērojams solis uz priekšu šo indivīdu rehabilitēšanā ir mioelektrisko protēžu izveidošana. Komerciāli pieejamās robota rokas protēzes atļauj veikt voluntāras kustības, izmantojot amputācijas stumbra reziduālo muskuļu kontrakcijas. Taču, nozīmīgs trūkums ir kustību kontroles un sensorās atpakaļsaites neesamība. Bez sensorās atpakaļsaites protēžu lietotāji lielākoties paļaujas uz redzi, kas rada kognitīvu pārslodzi un sekojošu atteikšanos lietot protēzi. Sensorie receptori un aferentā perifērās nervu sistēmas daļa ir sarežģīta un multimodāla, tādēļ slēgtas "turp–atpakaļ" sistēmas izveidošana ir liels izaicinājums. Zinātnieku līdz šim izveidotās sensorās atpakaļsaites sistēmas ir limitētas. Daļu no jušanas informācijas ir iespējams pārvadīt, izmantojot invazīvas metodes — elektrodu implantāciju tieši nervā. Taču arī neinvazīvas metodes pētījumos sniedz pozitīvus rezultātus. Nozīmīgi ir pieminēt, ka daļai indivīdu uz amputācijas stumbra ādas izveidojas zaudētās ekstremitātes fantoma jušanas karte. Šis fenomens var rasties gan spontāni, gan pēc neinvazīvas transkutānas nervu stimulācijas. Tas liek domāt par šī fenomena tālāku izpēti un iespējām šo karti izmantot neinvazīvas sensoras atpakaļsaites radīšanai. Fantoma karti, jādomā, ir iespējams izveidot, izmantojot mehānisku stimulāciju un virtuālās realitātes simulāciju, kas jau pašreiz tiek plaši pielietota fantoma sāpju mazināšanai un modulēšanai. Izveidotā fantoma karte, iespējams, varētu kalpot kā sensorās informācijas apmaiņas panelis, uzlabojot informācijas pārvadi no robota rokas uz cilvēka perifēro nervu sistēmu.