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INVITED PAPER

A Review of Non-Invasive Sensory Feedback Methods for Transradial Prosthetic Hands

BENJAMIN STEPHENS-FRIPP, GURSEL ALICI, AND RAHIM MUTLU
Intelligent Nano-Tera Systems Research Laboratory, University of Wollongong, Wollongong, NSW 2522, Australia
School of Mechanical, Materials, Mechatronic, and Biomedical Engineering, University of Wollongong, Wollongong, NSW 2522, Australia
ARC Centre of Excellence for Electromaterials Science, University of Wollongong, Wollongong, NSW 2522, Australia

Corresponding Author: Gursel Alici (gursel@uow.edu.au)

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ABSTRACT Any implant or prosthesis replacing a function or functions of an organ or group of organs should be biologically and sensorily integrated with the human body in order to increase their acceptance with their user. If this replacement is for a human hand, which is an important interface between humans and their environment, the acceptance issue and developing sensory-motor embodiment will be more challenging. Despite progress in prosthesis technologies, 50-60% of hand amputees wear a prosthetic device. One primary reason for the rejection of the prosthetic hands is that there is no or negligibly small feedback or tactile sensation from the hand to the user, making the hands less functional. In fact, the loss of a hand means interrupting the closed-loop sensory feedback between the brain (motor control) and the hand (sensory feedback through the nerves). The lack of feedback requires significant cognitive efforts from the user in order to do basic gestures and daily activities. To this aim, recently, there has been significant development in the provision of sensory feedback from transradial prosthetic hands, to enable the user take part in the control loop and improve user embodiment. Sensory feedback to the hand users can be provided via invasive and non-invasive methods. The latter includes the use of temperature, vibration, mechanical pressure and skin stretching, electrotactile stimulation, phantom limb stimulation, audio feedback, and augmented reality. This paper provides a comprehensive review of the non-invasive methods, performs their critical evaluation, and presents challenges and opportunities associated with the non-invasive sensory feedback methods.

INDEX TERMS Sensory feedback, prosthetics, non-invasive, electrotactile stimulation, mechanotactile stimulation, vibrotactile stimulation.

I. INTRODUCTION

Tactile information is required for correction and control of object grasps and manipulations as vision alone does not provide enough of the information required [1]. Prosthetic users have also shown a strong desire to decrease the need for visual attention to perform functions [2]. Prosthetic hand rejection rates are estimated to be as high as 40% [3], with some of user's reasons for rejection and not wearing a prosthetic device being that they believe it is more functional and easier to receive sensory feedback through their stump without using the prosthetic hand [4]. Sensory feedback is also important for prosthetic devices as it can provide users with a sense of embodiment in their prosthesis [5]–[7].

Body-powered prosthetic limbs can transmit a limited amount of sensory feedback through cable tension. However, with myoelectric prosthetic devices, this indirect feedback pathway no longer exists [8]. This problem was identified early on in the Boston Arm prosthetic [9] where the authors introduced vibration feedback to give the user position information on the elbow joint of an EMG controlled prosthetic resulting in a performance comparable to that of the cable driven prosthetic. Sensory feedback from the nerves within our hands provides feedback on our grasp, contact surface and its roughness and shape, and grasp stability [1]. Biological skin detects these features through four different types of mechanoreceptors in our skin [10], as shown in Figure 1. In a simplified overview of a biological feedback system, action potentials are then sent through our Peripheral Nervous System to transmit this information to our Central Nervous System (CNS) for decision making. However, as shown in Figure 2, the feedback loop for a prosthetic device differs from our own biological feedback system. A combination of

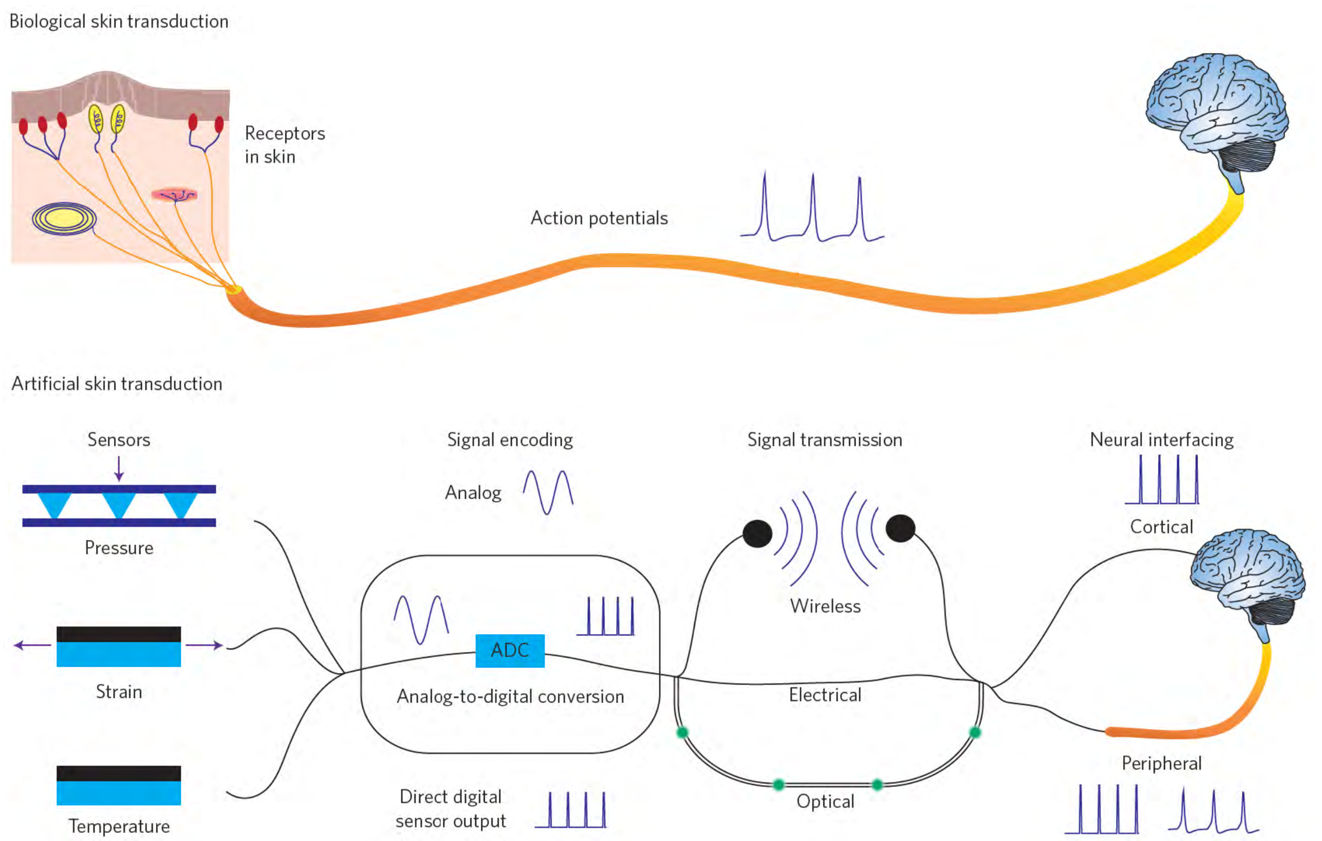

FIGURE 1. Sensory feedback in biological skin vs artificial skin [10] ©2016 Springer. Reprinted, with Permission, from "Pursuing prosthetic electronic skin" by Chortos *et al.* in Nature Materials 2016.

sensors is required in prosthetic devices to match the range of signals detected by our mechanoreceptors in our skin. The signals from these sensors require signal processing to encode them into a form that the user can understand. This encoded information is then sent to the CNS, either by direct stimulation of the PNS [11], [12] or CNS [13], [14] using electrode arrays as shown in Figure 1, or via activation of the mechanoreceptors at a location somewhere on the body.

Sensory feedback for prosthetic devices can be provided by applying a sensation to a different area of the body to represent the stimuli detected by the hand. This, however, requires the user to associate this sensation with the stimuli being detected. Having the feedback somatotopically and modality matched makes the feedback feel more natural and potentially easier to understand. In modality matched feedback, the stimulus is perceived as the same method of stimulation. For example, a pressing force on the finger is perceived by a feeling of pressure [15], [16]. An example of a non-modality matched feedback is using vibration on the skin to represent the detected pressure on a finger. Modality matching in non-invasive feedback can be achieved through mechanotactile feedback for grasping force, temperature feedback for temperature and vibrotactile feedback to communicate surface vibrations, as presented in Figure 3. In addition, electrotactile feedback can be used to create modality matched sensations by varying the stimulation waveform properties to create the feeling of either vibration, tapping and/or pressure/touch. In Somatotopical feedback, the stimulus is perceived to be in the same location that the stimulus is acting on. For example, when the prosthetic pointer finger detects pressure, the communicated sensation is detected by the brain at the pointer finger. Although the invasive methods of targeted reinnervation [17] and nerve electrode interfaces [11], [12] communicate through somatotopical feedback, non-invasive methods can also apply mechanotactile, electrotactile, vibrotactile or temperature feedback to phantom hand maps [18]–[23] to produce somatotopical feedback.

In a recent review conducted by Benz [24], prosthetic users felt a strong need for their prosthetic devices to be lightweight, as the weight of their current prosthetic hand leads to fatigue in the arm, shoulder and back. Users also raised concerns about their limited functionality and difficulty in performing precise tasks. In addition to the requirement of low weight, Cipriani *et al.* [25] have also suggested that transradial prosthetic devices need to be low in their power consumption so they can be used all day, and have a low cost. Peerdeman *et al.* [26] developed a survey, which examined the requirements for feedback (and control) from a combination of interviews with professionals who regularly interacted with users (occupational therapists,

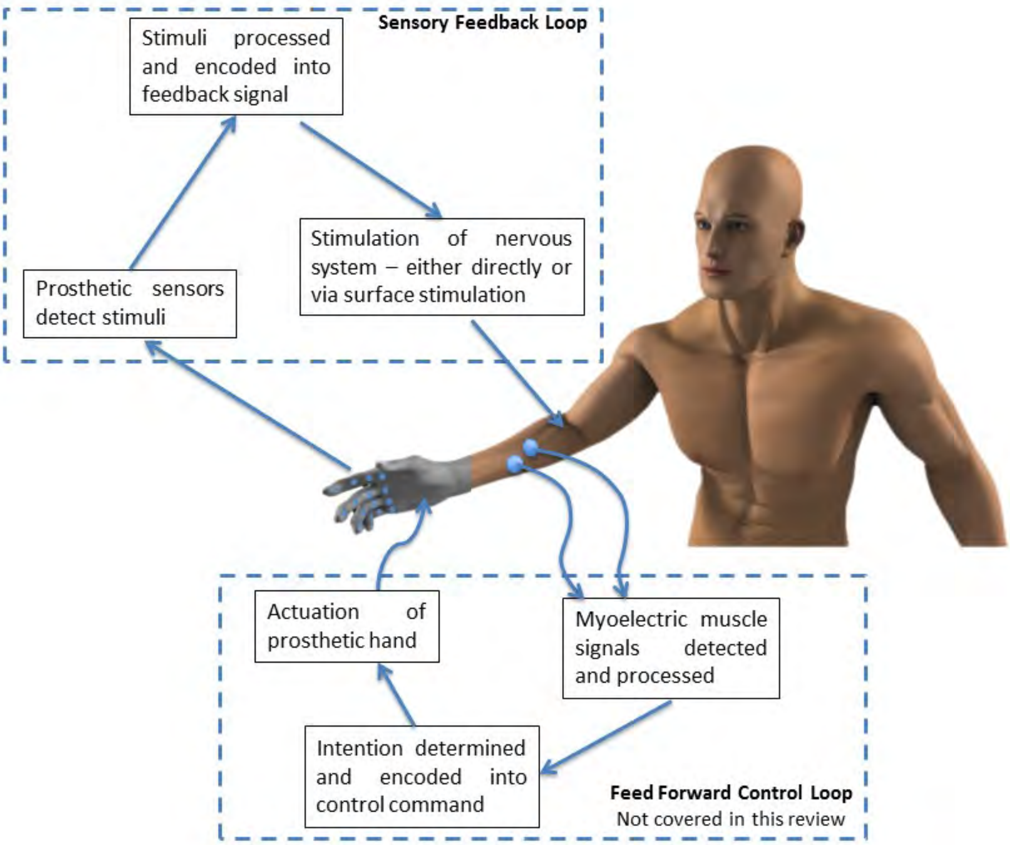

FIGURE 2. **Sensory feedback and feed forward control loops.**

physio etc.) and existing literature surveys. As a result, they produced the following feedback priorities, in hierarchical importance

1) Continuous and proportional feedback on grasping force should be provided
2) Position feedback should be provided to user
3) Interpretation of stimulation used for feedback should be easy and intuitive
4) Feedback should be unobtrusive to user and others
5) Feedback should be adjustable

These user priorities are considered in this review when assessing non-invasive sensory methods that have been presented within literature.

Within literature, there are currently survey papers that have reviewed the methods deployed in sensory feedback, which have various degrees of invasiveness. A few surveys have examined the role of implants into the CNS [13], [14]. These methods, however, require a high level of invasiveness as subjects are required to undergo brain surgery to place the appropriate implant. Recent developments have also been made with direct nerve stimulation, which relies upon implants within the PNS. Normann and Fernandez's review paper [27] focussed on the variety of nerve arrays available and their use within control and feedback in prosthetic hands. Nghiem *et al.* [28] also provided a comprehensive overview of current types of feedback methods and prosthetic hands on market, with a large focus on direct nerve stimulation through the PNS. Although the work involving PNS electrodes has shown some good early results [11], [12], [29], [30], it is still in an early stage of development with limited numbers of test subjects in the laboratory testing that has been undertaken, hence it is not ready for real-life application. In addition, at present there remains a reluctance within prosthetic users to undergo surgery [24].

The focus of this review is, therefore, on non-invasive methods (those not requiring surgery), and will therefore not discuss recent advances in sensory feedback that require surgery. Even though sensory perception can be communicated via non-invasive methods once a patient has undergone targeted reinnervation [17], these approaches will be not discussed as part of this review as patients are still required to undergo surgery in preparation.

Svensson *et al.* [31] provided a brief overview of sensors used to detect stimuli, as well as some of the invasive and non-invasive methods used to provide sensory feedback. Because of the broad nature of this review, only an introduction to a few of the stimulation techniques used in sensory feedback was provided. In this paper, in addition to providing a deeper and more comparative look at the techniques used, we shall also describe the use of temperature feedback, augmented reality and phantom hand map stimulation, which were not included in their review.

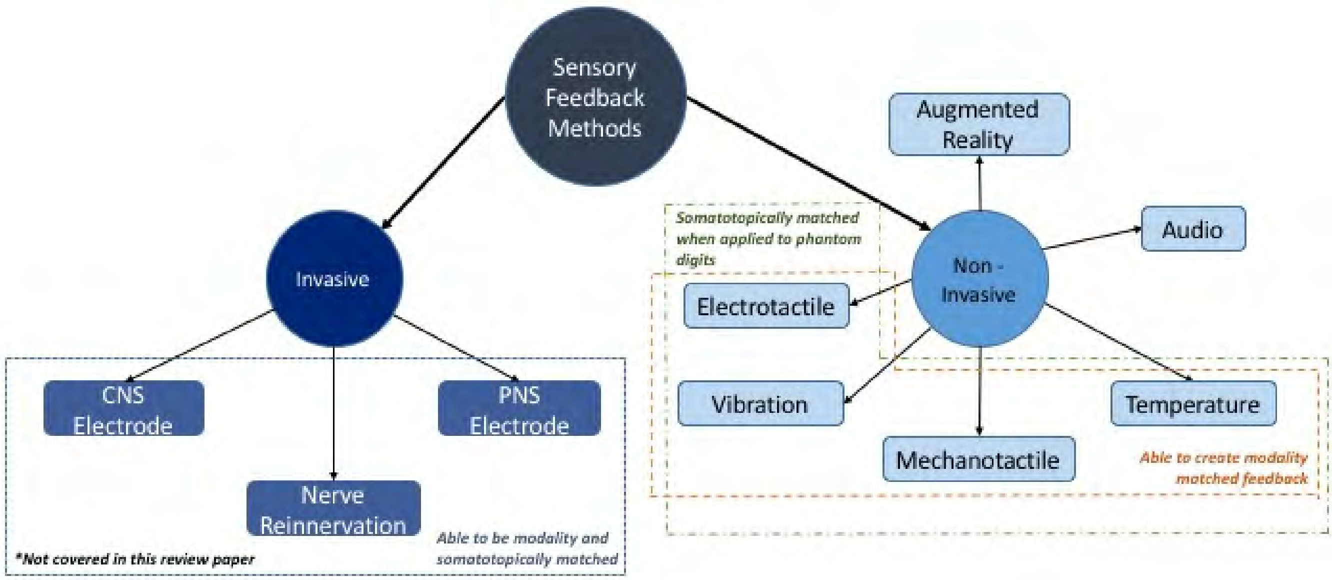

FIGURE 3. Mind map for feedback methods.

Saudabayev and Varol [32] also provided an overview of the development of sensors for feedback in prosthetic hands. They examined the development during the period of 2000-2015, but had a focus on the sensors that provide the feedback, as opposed to the feedback methods. Schofield *et al.* [33] presented the most recent review that had a major focus on non-invasive feedback methods for prosthetic hands in 2014, which discussed literature up until December 2013. Similarly, Antfolk *et al.* [34] published a review on sensory feedback in upper limb prosthetics in 2013. However, there has been significant progress in the field of research since then, presenting a need for an updated comprehensive review. This paper is differentiated from existing reviews by presenting a comprehensive overview of the different methods deployed in providing non-invasive sensory feedback for transradial prosthetic hands and the recent developments that exist within current literature, and challenges and opportunities associated with the non-invasive sensory feedback methods.

When conducting a systematic search of the literature, the following restrictions were, therefore, placed on studies to be included in this review;

- Focus on full hand prosthetic devices, not partial amputees, with the emphasis being on transradial amputees (amputation through the forearm). One study showed that out of 427 upper limb amputees interviewed, 63% of them had either a forearm or wrist amputation [35].

- Focus on feedback methods to the user, not the sensors used to detect information within the prosthetic hand.

- Feedback to include the user as part of the feedback loop. Will not include studies where the hand creates its own feedback loop without involving the user (such as camera to automatically recognise appropriate grip [36], or automatically adjusting grip when slip occurs [37], [38]).

- Focus on non-invasive methods, i.e. those not requiring surgery, such as [11], [12], [17], [29], and [30].

II. STIMULATION TECHNIQUES

There are a variety of feedback methods that currently have been deployed within literature including the use of temperature [39], [40], vibration [41]–[51], mechanical pressure and skin stretching [15], [16], [52]–[57], electrotactile stimulation [58]–[71], audio feedback [72]–[74], and augmented reality [75], [76]. A mind map of the different feedback methods is shown in Figure 3. Some of these stimulation techniques have been explored being deployed together [77]–[82]; whereas electrotactile, vibration and mechanical pressure have also been applied to phantom limb stimulation [18]–[23]. Each of these methods are discussed separately, with an assessment of the methodologies used and any challenges and opportunities that are involved in each technique. Studies with limited subjects and/or a lack of performance metrics have still been included to give an insight into the different approaches currently being explored within this area.

A. VIBRATIONAL FEEDBACK

Vibrational feedback typically uses small commercially available vibrators, which are applied to the skin surface and activate the Pacinian corpuscle mechanoreceptors in the skin. These are usually small and light weight, as shown in Figure 4. The user learns to associate the vibration at that site with one of the senses from their prosthetic hand.

A comparison of the studies using vibrotactile feedback is shown in Table 1. Vibration has typically been used to communicate grasping force, however, a few studies have examined its role in communicating proprioceptive information [42], [50], [83], and some hybrid systems have

TABLE 1. Comparison of vibrotactile studies.

Reference	Type of Hand	Location	Number of subjects/ Number of amputees	No of feedback channels and Sensor	Range and number of feedback levels	Performance
Yamada et al. [41] 2016	Myoelectrically controlled 1-DOF robotic hand gripper	3 on bicep – one for each level	5 / 0	1 - Single force sensor for grasping force OR Potentiometer for aperture angle	PWM range matched to strength of grasping force PWM range matched to aperture angle	3 Subjects demonstrated 10% lower cognitive load from vibrotactile feedback on grasping force 4 Subjects demonstrated a lower cognitive load (10-40%) from vibrotactile feedback on aperture angle
Ninu et al. [42] 2014	Myoelectrically controlled Gripper	1 on forearm	13 / 2	2 - Single Force Sensor and Velocity sensor	Varied Amplitude to match closing velocity Varied Frequency and amplitude simultaneously proportionally to grasping force	Performance in achieving desired grasping force for Low and High Force levels: Visual Hand feedback – 76% & 52% Velocity and Contact Vibration feedback (No visual) – 74% & 33% Velocity, Force &Contact Vibration Feedback (No visual) – 84% & 53% No visual or Vibration Feedback – 19% & 22%
Nabeel [43] 2016	Body powered prosthetic hand	2 on the forearm	7 / 1	1 - Single Force sensor	PWM range corresponding to sensor values 0-255	94% of able bodied subjects could use feedback to determine whether bottle was half or completely full of water
Rosenbau-Chau et al. [44] 2016	Myoelectrically controlled Robotic Hand (opens and closes)	2 on the forearm below the elbow	6 / 6	1 - Single force sensor on thumb	Varying Pulse Pulse rate and Frequency to induce Light, Medium and Strong.	Vibrational feedback improved grip force accuracy by 129% for light grip force, 21% for medium grip force. No statistical improvement for strong grip force
Chaubey et al [45] 2014	Myoelectrically controlled Robotic Hand (opens and closes)	12 locations on biceps (one activated at a time	7 / 7	1 - Pressure sensor on target object	Linearly mapped PW to pressure signal input	Vibrational feedback significantly improved grasping force error at 60% maximum force but not at 80% maximum force
Clemente et al. [46] 2016	Myoelectrically controlled Robotic Hand (opens and closes)	2 within a cuff on bicep	5 / 5	1 - Pressure sensor on thumb and index finger	60ms length vibration when hand made or broke contact with object	Less blocks were broken with vibrotactile feedback on compared to no vibrotactile feedback ($p<0.001$)
Hanif and Cranny [47] 2016	N/A - Computer Simulation	N/A -Computer simulation	0 / 0	1 - 1 piezoelectric sensor at fingertip	Changed length of on and off pulses to represent roughness	N/A – No performance measures listed
Li et al. [48] 2016	N/A – simulated sensations for perception test	5 Vibrators, one on the back of each finger of the opposite hand mounted in a sports glove	5 / 0	5 (one each finger) – simulated sensations for perception test of forces on individual fingers	3 Values for each finger – Strong Medium and Weak	N/A – No performance measures listed
Raveh et al. [49] 2017	Myoelectrically controlled artificial hand	8 Vibrators wrapped around the forearm	43 / 0	1 - 2 Force Sensors to determine force	Full strength to indicate contact pressure above predefined threshold, otherwise off	No statistical difference in visual demand when using vibrotactile feedback to communicate contact of object
Hasson and Manczurowsky [50]	Virtual Arm, EMG controlled angle	1 Vibrator on Forearm	9 / 0 (9 in each of the 3 groups, 27 total)	1 – Calculated position of Arm OR Calculated velocity of arm	Amplitude modulated to Velocity OR Amplitude modulated to Position	No significant improvement resulting from velocity based vibrotactile feedback or position based vibrotactile feedback in achieving desired arm position
Walker et al. 2015 [51]	Simulation of holding an object, controlled by a stylus	1 vibrator on bicep	23 / 0	2 – Force Feedback on stylus and objects slipping acceleration through vibration	Vibration mapped to objects acceleration due to slip	Recovery of slipping objects - Visual feedback only 90% - No feedback 42% - Vibrotactile feedback 80%
Witteveen et al. 2015[83]	Computer simulated hand controlled through mouse scrolling	An array of 8 vibrators for aperture 1 Vibrator on forearm for force	10 / 10	1 – Hand Aperture OR Grasping Force	Position of tactor activated representing hand opening / 8 different levels of intensity represent grasping forces	No significant differences between performance in grasping objects when using either Hand Aperture Feedback OR Grasping Force Feedback

FIGURE 4. Examples of vibrators used in vibrotactile feedback. (a) Spatially Changed Vibrators [41] ©2016 IEEE. Reprinted, with permission, from "Investigation of a cognitive strain on hand grasping induced by sensory feedback for myoelectric hand" by Yamada et al, in 20016 IEEE International Conference on Robotics and Automation (ICRA). (b) Coin Vibration Motors [43] ©2016 IEEE. Reprinted, with permission, from "Vibrotactile stimulation for 3D printed prosthetic hand" in 2nd International Conference on Robotics and Artificial Intelligence (ICRAI).

used vibration to provide modality matched feedback on texture information [80], [84]. These studies only contain preliminary testing and further investigation into this form of modality matched feedback is required. Using vibration as a source of force feedback has been demonstrated to have improvements over using vision alone as a feedback tool [41], [44], [46], but some literature suggests that this benefit is only visible during inadequate feedforward control [85]. However, the drawbacks of using vibration include: an extra delay of approx. 400ms to begin generating vibration and a limited bandwidth being available [86]. In addition, it has also been suggested that perception of vibrational frequency can be affected by how tightly a vibration motor is attached [87], which raises difficulties in predictive and reliable sensory feedback.

The use of three vibration feedback devices to communicate grasping force and grasping angle (separately) from a prosthetic hand to its user was examined by Yamada *et al.* [41]. They concluded that by incorporating vibration feedback, there was a reduction in cognitive load required to pick up objects compared to using visual feedback alone, however, this was not consistent across all the subjects. Deploying vibrotactile stimulation has also been shown to provide an amputee with a higher sense of embodiment in their prosthetic [5] when undertaking simulations modelled after the rubber hand experiment. However, vibrational feedback requires users to undergo training in order to develop the full benefit [88]. Ninu *et al.* [42] examined the performance of vibrational feedback on the forearm to help improve grips for picking up objects. This study examined 13 subjects (11 able-bodied subjects and two amputees), using a commercially available myoelectrically controlled prosthetic arm. The authors used a constant frequency with varying amplitude to communicate velocity of the closing hand, and simultaneously modulated the amplitude and frequency of vibrations to the grasping force. The researchers demonstrated that using vibrotactile feedback to communicate hand velocity, point of contact and grasping force without visual feedback was enough information for the subjects to pick up objects. However, they also noted that the hand velocity was the most important feature and the addition of grasping force feedback had a minimal effect. Other studies have also demonstrated that the use of vibrotactile feedback results in an improvement in grasping objects [89]–[91]. Nabeel [43] developed a pressure sensor that could be applied to the finger tip of any prosthesis and implemented a vibration feedback system to the forearm of the user. Their test was only conducted on one amputee, who, however, recognised the improvements as a result. The authors also suggested that performance increases would require more training.

Rosenbau-Chau *et al.* [44] demonstrated that recognition of grip force could be improved by using vibrotactile feedback, however, the impact was large for some users and not for others. The feedback system had three stages of force; low, medium and high; represented by differing pulse frequencies and strengths. They proposed that by incorporating more than three stages of feedback, the system could become more unreliable. The effectiveness of sinusoidal, sawtooth and square vibrational waves on amputees with upper limb prosthetic devices was examined and sinusoidal waveform performed the best. The bicep region was determined to be the most comfortable by the subjects and achieved the highest accuracy. Desensitisation occurred after 66 seconds and the authors proposed to instead use a series of pulses, rather than continuous vibrations, to achieve a higher success rate and reduce desensitisation. They also concluded that training increased the success of vibrotactile feedback. This research group also examined the effect of varying pulse frequency in vibrotactile feedback to communicate grasping force [45]. In their home testing, the subjects' batteries lasted a period ranging from one day to three days. The six subjects overall had positive responses to the use of vibrational feedback, with one subject commenting that he enjoyed shaking his five-year-old granddaughter's hand knowing that he was not squeezing too tight.

Clemente *et al.* [46] also demonstrated a practical method of using vibrational feedback to control grasping force. The researchers placed pressure sensor thimbles on an existing prosthetic and used a cuff on the upper arm to provide vibrotactile feedback to the subjects for a period of 60ms when the hand either made or broke contact with an object. Their data showed that the subjects using vibrotactile feedback achieved a higher success rate picking up blocks without breaking than those only using visual feedback. The subjects maintained this performance whilst using this prosthetic hand with vibration feedback at home over a period of 4 weeks. Hanif and Cranny [47] demonstrated the use of intermittent vibrational pulses as a possible method to communicate different surface textures. The feedback system detected different surface textures using a piezoelectric sensor at the fingertip and sent vibrational frequencies corresponding with each of the four surfaces. They only demonstrated the production of differing frequencies visually, as the method was not tested on any subjects and their perception of these varying vibrational frequencies.

Li *et al.* [48] examined the use of vibrators on a sports glove on the remaining hand to provide force feedback from the prosthetic. This enabled the user to identify the level of force on the back of the corresponding finger on the remaining hand quickly. Each vibrator had three different intensities to represent either a soft, medium or a hard level of force being applied to the prosthetic. Their results showed that users quickly learnt how to interpret the vibrations and their performance in picking up objects improved as a result. However, it may be not as effective outside of the laboratory when two hands are required to complete tasks.

Raveh *et al.* [49] examined the effect of vibrotactile feedback on the visual attention required in performing tasks with a prosthetic. Subjects drove a simulated car whilst performing basic tasks with their myoelectric controlled hand. Their data showed no improvement in the required visual attention to complete basic tasks. However, their subjects were new to myoelectric control, received minimal training on vibrotactile feedback and the system only used vibration feedback to communicate contact. The authors hypothesised that the subjects may not have had enough time to begin to trust the feedback and, therefore, still felt they needed to rely on visual cues.

Hasson and Manczurowsky [50] examined the effect of vibrational feedback on providing position and velocity proprioception information. They only tested moving a virtual arm to a target position, not in grasping objects. However, their results showed no improvement from vibration feedback.

Witteveen *et al.* [83] also compared using vibrotactile feedback to communicate grasping force to communicating grasping aperture. Both forms of vibration feedback improved performance in grasping objects, however, there was no significant difference between the two different approaches.

Vibrational feedback offers a cheap and lightweight system of feedback that users prefer the sensation over electrotactile feedback [92]. One limitation, however, is the delay in stimulation and since the feedback delay can decrease embodiment [93], [94], this may attribute towards some of the negative results.

B. ELECTROTACTILE FEEDBACK

Electrotactile stimulation contains no moving parts and has an efficient power consumption. Multiple features can be easily and reliably controlled including the intensity, pulse width, frequency and location of stimulation (with multiple electrodes), which leads to a higher bandwidth being available [95]. The electrodes are slim and lightweight, shown in Figure 5, and electrotactile stimulation is safe and comfortable to use. However, each person's minimum sensation threshold and pain threshold is different and the perception of electrotactile information changes with the placement of the electrodes [63], with movements as small as 1mm having an influence [96]. In addition, skin conditions can also influence the comfort and dynamic range of electrotactile stimulation [96].

Not only does this mean that re-calibration of thresholds are required every time electrodes are placed on the user; but that the pulse width, frequency and amplitude may need readjusting to achieve the same perception each time. In addition, potential problems arise from interference between myoelectric sensors for control and electrotactile stimulation, however, this has begun to be addressed within literature [69]–[71].

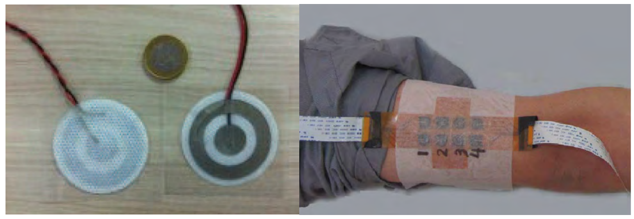

FIGURE 5. Examples of electrotactile electrodes. (a) Concentric Electrodes [58] "Virtual grasping: closed-loop force control using electrotactile feedback" by Jorgovanovic *et al.* in Computational and Mathematical Methods in Medicine 2014, licensed under CC BY. (b) Four pairs of electrodes [62] ©2016 IEEE. Reprinted, with permission, from "Effects of different tactile feedback on myoelectric closed-loop control for grasping based on electrotactile stimulation" by Xu *et al.* in IEEE transactions on Neural Systems and Rehabilitation Engineering 2016.

Electrotactile stimulation induces a sensation by directly stimulating the primary myelinated afferent nerves in the dermis [97]. Concentric electrodes limit the current spread and can increase localisation and discernibility of the induced sensation [95], [97] and can reduce the resulting noise on the EMG used for myoelectric control [70]. Despite their advantages, only approximately half of the electrotactile feedback systems examined use them [60], [64], [66], [68]–[71], which may impact upon their performance. A comparison of the studies using electrotactile feedback is shown in Table 2.

A few studies have demonstrated the benefit of using electrotactile feedback, such as [58]. The authors used a constant 100Hz frequency and 3mA intensity sent to electrodes on the dorsal side of the forearm to communicate the force applied to a joystick controlled robotic hand. The Pulse Width (PW), however, was varied from 20% above their sensation threshold to 20% below their pain threshold to communicate the force level detected on the robotic hand by a pressure sensor. Their research indicated that training with electrotactile feedback helped improve the user's recognition of grip strength when picking up a variety of objects. Isakovic *et al.* [59] also demonstrated that using electrotactile feedback helped users learn to regulate myoelectric control of grasping force quicker. Schweisfurth *et al.* [60] showed that using electrotactile stimulations to feedback the EMG control signals outperformed force feedback in achieving a target initial grasping force. In EMG feedback, the processed myoelectric control signal was sent to the subject via electrotactile stimulation from beginning of trial to 0.35 seconds after contact with the object. In force feedback, the system detected the grasping force by a pressure sensor on the prosthetic finger, and then sent an electrotactile signal corresponding to this level of pressure from contact until 0.35 seconds after contact. The range of pressures was matched to a varying amplitude and PW of the stimulation current, up to 90% of the pain value.

TABLE 2. Comparison of electrotactile feedback studies.

Reference	Type of Hand	Location	Number of subjects/ Number of amputees	No of feedback channels & Sensor	Range and number of feedback levels	Performance
Jorgovanovic et al. [58] 2014	Joystick controlled 1-DOF gripping simulation	Two bipolar electrodes on dorsal side of forearm	10 / 0	1 - Simulated force	PWM to correspond to grasping force, increments of 50µ from 20% above minimum sensation to 20% below pain threshold	Success picking up objects: - 72% wih feedback - 40% without feedback
Isakovic et al. [59] 2016	Myoelectrically controlled 2-DOF prosthetic hand	Electrode array – 16 cathodes and one anode	3 / 3	1 - Grasping force	Six discrete Force levels represented by different combinations of electrodes being activated	94% accuracy in recognition of 6 discrete force levels Reduction of error from 24.4% to 15.6% when using feedback
Schweisfurth et al. [60] 2016	Myoelectrically controlled 2-DOF prosthetic hand, but only one movement was used	Four electrodes on forearm	11 / 1	1 - Grasping force	Eight, four electrodes each with two frequency options	EMG feedback resulted in 21% lower error than force feedback
Shi and Shen [61] 2015	N/A – just rating feelings from feedback method	One stimulation electrode on wrist	1 / 0	1 - No sensor – testing sensations	Intensity ranging from 0-3mA, .1ma increment; Frequency ranging 1Hz-100HZ, 5HZ increment; Pulse width 1ms – 50ms, 1ms increment	No quantitative measurement - Increasing electrotactile sensation can be brought on by increasing amplitude, frequency or pulse width
Xu et al. [62] 2016	Simulated Hand	Four pairs of electrodes on bicep. One pair used at a time	12 / 6	2 - Slip sensor and/or Grasping force	Pressure feedback: PWM 0µs to 500µs Slip feedback: Time between switching pairs of electrodes used 20ms-500ms	Pressure, Slip, Pressure +Slip feedback outperformed no feedback ($p<0.05$) in achieving desired grasping force and grasping time. However, Visual Feedback outperformed all tactile feedback methods in achieving desired grasping force and outperformed pressure as well as slip feedback in time of grasping force ($P<0.05$)
Choi et al. [63] 2016	N/A – simulated sensations for perception test	Two pairs of electrodes, one stimulating electrode on either side of upper arm between bicep and tricep	10 / 0	3 - simulated sensations for perception test	Four different levels on two channels – resulting in 15 different stimuli across the two channels. An additional on/off state was communicated for the thumb through offset pulses	Two channel stimulation resulted in recognition accuracy of 52.9% for simultaneous stimulation and 73.8% for intermittent stimulation
Patel et al. [64] 2016	Myoelectrically controlled simulated prosthetic hand with 4-DOF and Myoelectrically controlled Robotic hand with 4-DOF	Four concentric electrodes on forearm	9 / 0 (Virtual Finger) 8 / 0 (Virtual Grasp) 11 / 0 (Robotic Finger)	4 - Simulated thumb flexion, thumb opposition, index flexion and middle/ring/litter finger flexion	Linearly mapped frequency from 3 to 30Hz to represent flexion level	Finger flexion recognition – 94% Grasp pattern recognition – 79%
Pamungkas and Ward [65] 2015	Data glove controlled humanoid robotic hand	Six electrodes on forearm	1 / 0	6 - Pressure force on each of the five fingers and on the palm	Four intensity ranges (Zero, light, light, medium, high) corresponding to change in intensity	No Measurements listed
Strbac et al. [66] 2016	N/A – simulated sensations for perception test	16 electrodes on flexible cuff placed on forearm	16 / 6	8 different patteren used as channels - simulated sensations for perception test	Tested 3,4,5,& 6 different frequency intervals	The concentric electrode pattern had a recognition rate of 99%, 95%, 80% and 74% for 3,4,5&6 different frequency levels respectively
Franceschi [67] 2015	N/A – simulated sensations for perception test	32 channel electrode array placed on forearm	5 / 0	10 different movement patterns on sensors - Array of 60 pressure sensors	10 different movement patterns – on/off no in between	Direction recognition ~ 90% Orientation recognition ~70% Position recognition ~ 60% (Measurements approximated from graph)

The participants achieved closer to a target force when receiving electrotactile feedback based on EMG control signals than electrotactile feedback based on grasping force.

Shi and Shen [61] demonstrated the effect of varying intensity, frequency, PW on electrical stimulation and the effect on subject's perception. The authors individually varied the

TABLE 2. *(continued.)* **Comparison of electrotactile feedback studies.**

Hartmann et al. [68] 2014	N/A – simulated sensations for perception test	8 electrodes placed on the forearm	2 / 0	8 different locations - Array of 60 pressure sensors	Intensity of stimulation used to help provide location	Subjects could recognise each of the eight locations with 92% accuracy
Dosen et al. [69] 2014	Myoelectrically controlled simulation	1 concentric electrode on the forearm	9 / 0	1 - Simulation error	Intensity proportional to error amplitude	RMS tracking error increases from ~13% for normal feedback to ~21% with a 100ms delay. Overshoot increased from ~13% for normal feedback to ~27% feedback with 100ms delay. (Measurements approximated from graph)
Jiang et al. [70] 2014	6 EMG electrodes to detect noise	1 stimulated electrode on upper arm	1 / 0	1 - Constant Simulation current	On and off value, compared noise from 6 different types of EMG electrodes	Filtering increases Signal to Noise ratio from 15dB to 43dB
Xu et al. [71] 2016	Myoelectrically controlled virtual arm to move elbow joint	2 electrodes on bicep	1 / 0	1 - Position of simulated elbow joint	1 pressure sensor - Intensity of stimulation proportional to gripping force OR Virtual Arm angle mapped to varying intensity of 2 electrodes	No measurements given

PW, frequency and amplitude, and applied these stimulation currents through 9mm diameter electrodes to the subject's arm. The data showed that pulse width could be varied from 0.2-20ms; intensity from 0.2mA-3mA; and frequency from 45-70Hz. These ranges delivered an appropriate level of feeling in the subject and proportionally increased grades of intensities felt by the subject.

The work by Xu *et al.* [62] compared communication of pressure, slip, and pressure with slip information through electrotactile stimulation, with visual feedback of lights representing the sensors information, and no feedback. They tested 12 subjects, with six of them being amputees, using a simulated environment gripping and picking up objects. Four pairs of electrodes placed on the forearm, shown in Figure 5b, was used to deliver the electrotactile feedback. The frequency was set to a constant value of 100Hz, and the PW was regulated from $0\mu s$ to $500\mu s$ to communicate any detected changes in grasping force. To communicate slip, the authors sent the electrotactile stimulation through a sequence of the four available pairs of electrodes (1-2-3-4-1 etc.), where the time interval between changing electrode pairs represented the amount of measured slip in the hand grasp, ranging from 20ms to 500ms. The data showed that pressure + slip feedback through electrotactile feedback performed the best out of sensory feedback methods, however, visual feedback outperformed all of them in grasping failure rate and ability to keep the grasping force as constant as possible. The authors also identified a performance difference between amputees and able-bodied test subjects, but they also recognised that their able-bodied subjects used their dominant hand and were younger than their amputee subjects.

Although there has been success in incorporating one feedback channel with electrotactile communication for one grasp, prosthetic devices often control more than one grasp. Therefore, more than one feedback channel is beneficial when closing the loop in feedback control with the user. Choi *et al.* [63] demonstrated that subjects could distinguish two channels of electrotactile feedback on their biceps. However, they did not connect the system to any sensors but instead showed that users could distinguish between the two channels. They also demonstrated that better recognition was achieved when using intermittent stimulation on both channels (switching between the two), rather than both channels being on at the same time, resulted in better recognition.

Patel *et al.* [64] used four electrotactile feedback sensors to map the configurations of a 4-DOF prosthetic hand. They maintained a constant PW and intensity but varied the frequency. Four channels of feedback were used on the subjects to help them either control individual finger flexion, or different hand grasps, with myoelectric control. However, tests were only conducted on able-bodied patients, with feedback being on the opposite arm to the myoelectric sensing. Patel *et al.* used multiple electrotactile channels to communicate position whereas Pamungkas and Ward [65] demonstrated the potential of using six electrotactile feedback channels for force feedback. Six electrotactile locations were used to communicate information from pressure sensors contained on a glove controlled robotic hand. Five of the locations were used to communicate force acting on the prosthetic fingers, and the other location was used to communicate the force acting on the palm. For each finger, three frequencies (100Hz, 60Hz and 30Hz) were used to represent the force on each phalange, and 20Hz was used for the palm. Only the highest pressure value from each finger was sent to the fingers' corresponding electrode to avoid confusion from multiple frequency signals. Their data showed that the subject learnt how to use the feedback appropriately to pick up a range of objects, as they had more success when alternating between picking up heavy and light objects. Their subject also stated that they preferred electrotactile feedback to only using visual feedback when operating the robotic hand.

Strbac *et al.* [66] demonstrated a different electrode design that enabled users to distinguish up to 16 stimulation locations, with up to five different frequencies at once, to provide multiple levels of feedback. Test results from a small number of able-bodied and amputee subjects demonstrated that six electrodes with four different frequency signals could be identified with more than 90% accuracy by the subjects after minimal training. The highest number of channels recognised was from one able-bodied subject identifying all 16 pads after two hours of reinforced learning. Six amputees also recognised eight different stimulation patterns that corresponded to different movements, with an average accuracy of 86%. The authors stated that their next development was to integrate this approach into the prosthetic socket connection with an automatic calibration (minimum amplitude set at just above recognition and maximum just below maximum pain threshold), but this is yet to appear in any published literature. They also noticed that there was a large difference between individual user's performances, indicating that this approach could work well for some but not others. Although this study only used simulated signal patterns instead of feedback from sensors, it demonstrated the potential of using a multichannel electrotactile feedback as a potential interface for prosthetic hands.

A human hand does not contain pressure sensors, which communicate isolated forces back to the user, rather, nerves are embedded throughout the whole skin and each translates a different feeling to the brain. Franceschi *et al.*[67] investigated possibilities of communicating information from artificial skin by translating information from 64 pressure sensors into 32 electrotactile electrodes on the subject's arm. They only conducted tests on able-bodied subjects and the users could detect movement directions easily, but had trouble determining individual positions. Hartmann *et al.* [68] also demonstrated that the recognition of simple movement patterns using electrotactile arrays could be learnt by able bodied subjects through training. This opens future possibilities to be explored that could provide the prosthetic user with richer sensory feedback.

Surface electrodes are predominantly used for myoelectric control of prosthetic devices. One problem that arises is the interaction of the electrotactile stimulation with the myoelectric surface electrodes. In experiments, by using myoelectric control on the opposite arm to the one being stimulated, this effect is sometimes avoided, but in practical applications interference needs to be addressed. One approach undertaken is time-division multiplexing for myoelectric control and electrotactile stimulation [69]. The system constantly switches between myoelectric control and electrotactile stimulation so that the two are never occurring at the same time, with a minimal reduction in performance. Other studies have reduced noise interference through redesigned electrodes. Jiang *et al.* [70] demonstrated a special designed electrode for electrotactile stimulation that, in combination with signal processing and optimisation of the stimulation waveform, limited the noise interference from electrotactile stimulation feedback with the myoelectric control. Xu *et al.* [71] produced a new flexible electrode design that incorporated stimulation and EMG recording at the one site simultaneously without interference. Their redesigned electrodes were used to control the robotic hand and transmit electrotactile stimulation feedback. The electrotactile stimulations were proportional to grasping force and they resulted in a lower error rate when picking up a plastic bottle. Xu *et al.* also demonstrated the use of tactile funnelling illusion in position feedback, whereby stimulation was perceived at a location between two electrodes, depending upon the intensity of each of the corresponding electrode. The higher the ratio of intensity of one electrode in the pair, the closer the perceived stimulation will be towards that electrode.

Electrotactile feedback shows potential for a quick and easily controllable method of feedback that users can identify multiple sites of feedback at once. However, currently this sensation is often referred to as a tingling feeling and occasional feeling of touch. Further research is required to be undertaken on the particular waveform characteristics to improve the induced sensation to the subject to achieve a more natural feeling of pressure, as has been demonstrated in direct nerve stimulation [98]. Additional care and analysis is also required to ensure that minimal interference occurs with the EMG interface used for myoelectric control, so it does not significantly impact the control of the prosthetic device.

C. MECHANOTACTILE PRESSURE

Preliminary tests conducted by Aziziaghdam and Samur [52] showed that an object could be identified as either hard or soft from the acceleration response obtained whilst tapping an object. Pressure feedback on the clavicle bone could then be used to communicate this acceleration profile to the user. Some other studies have examined the role of wearable haptic devices on feedback. Morita *et al.* [53] used a winding belt motor on the upper arm to communicate grasping force feedback of a myoelectric controlled prosthetic hand. The speed of winding also gave the user an indication of the hardness of the object. Casini *et al.* [54] demonstrated the application of distributed haptic force to help a user determine an object as hard, medium or soft. A combination of pressure and skin stretch on the bicep was used as the feedback mechanism for the subject. Godfrey *et al.* [15] also examined the use of a feedback band around the arm to provide information to users on grasping force. However, although a trend was observed in grasping force modulation, this was not statistically significant compared to visual feedback. Also, as can be seen in Figure 6, all these haptic feedback devices were quite large and provided unnecessary bulk to prosthetic devices.

Antfolk *et al.* [16] demonstrated the use of five servo controlled mechanical pressure devices, shown in Figure 7a. This allowed the user to recognise touch within individual digits

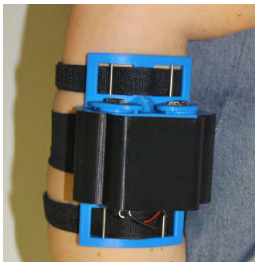

FIGURE 6. **Pressure feedback cuff [54] ©2015 IEEE. Reprinted, with permission, from "Design and realization of the CUFF- clenching upper-limb force feedback wearable device for distributed mechanotactile stimulation of normal and tangential skin forces", by Casini *et al.* in 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).**

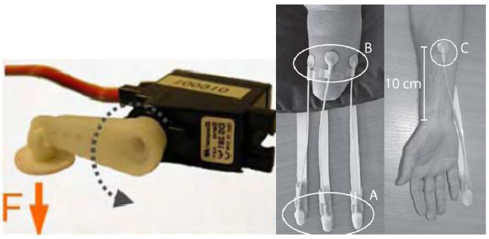

FIGURE 7. **(a) Mechanical Pressure Feedback device [18] ˙ 2013 IEEE. E/Reprinted, with permission from "Artificial redirection of sensation from prosthetic fingers to the phantom hand map on transradial amputees: Vibrotactile versus mechanotactile sensory feedback" by Antfolk *et al.* in IEEE Transactions on Neural Systems and Rehabilitation Engineering 2013. (b) Silicon Bulb Mechanical Feedback [55] from "Sensory feedback from a prosthetic hand based on air-mediated pressure from the hand to the forearm skin" by Antfolk *et al.* in journal of rehabilitation medicine, licensed under CC BY-NC.**

and three levels of pressure feedback. The authors noticed, however, that it was not helpful for improving grip recognition, but they suggested more training was necessary to overcome confusion between neighbouring areas. Antfolk *et al.* also suggested the use of improved actuators and placing them on the phantom hand map to further improve results. The use of silicon bulbs, shown in Figure 7b, has been shown as a novel way to apply mechanotactile feedback [55] to communicate touch and levels of grasping pressure. Three silicon bulbs were attached to the user's forearm and they recognised three distinct zones and up to two levels of force. The authors, however, recognised that the ideal location for the bulbs was within the phantom digit zones and they had positive feedback from a pilot test on one amputee with distinct phantom digit locations.

Akhtar *et al.* [56] explored the use of linear skin stretch on the forearm to provide feedback on the position of fingers. As one of the three motors for thumb, index, remaining three fingers, respectively, drives the tendon in the corresponding finger, it pulls a contact pad attached to the forearm to increase the skin tension. Participants described this as comfortable over the whole experiment and the data indicated an improved grasp recognition whilst using the feedback. However, testing was only conducted on unimpaired subjects and the contacts pad required tape or adhesive glue to attach to the skin.

Bark *et al.* [100] examined the use of rotational skin stretch for position feedback. Although subjects had trouble with using absolute position sensing, the authors concluded that rotational skin stretch had some benefit for position feedback when controlling movement, for an EMG controlled prosthetic. This would, however, only be for suitable for feedback for 1-DOF. Wheeler *et al.* [57] then investigated its application to position feedback of an elbow of a myoelectric transhumeral prosthesis. The authors found that the use of the rotation skin feedback resulted in a lower target error and visual demand.

Battaglia *et al.* [99] used skin stretch from a rotating mechanical rocker on the bicep of the arm to communicate proprioception information for a 1-DOF hand. Using this feedback, eighteen healthy subjects were able to discriminate between different spherical sizes with an average accuracy of 73.3%. A comparison of the studies using mechanotactile feedback is shown in Table 3.

D. TEMPERATURE FEEDBACK

Temperature feedback has only been deployed to communicate identify force of their grip and the position of their fingers [26]. Temperature, however, provides users with extra information about their environment, and potential dangers or warnings that involve heat. Producing heat on the upper arm to correspond with temperature detected at the prosthetic hand was the only method of temperature feedback found within literature. A comparison of the studies using temperature feedback is shown in Table 4. Cho *et al.* [39] used a disguised temperature sensor in a prosthetic hand to sense temperature and wirelessly transmit the measured temperature range. The corresponding temperature was then communicated to the subject via a Peltier element on their opposite hand. The subjects distinguished between high, warm and cold temperature setting with reasonable accuracy, however, it drew upon a large amount of power. Ueda and Ishii [40] also examined the use of temperature feedback via a Peltier element. However, they developed a prediction algorithm based upon initial measurements to speed up their response times. This resulted in a quicker response time when providing temperature information to the subject. Although these results are positive, with the desire for minimal weight and power consumption in prosthetic devices, and a higher need for other sensations sent to the user, this feedback method may not be deeply investigated until further advances are made with force and position feedback. A potential focus of research would be to incorporate temperature feedback with another feedback method so that they occur simultaneously, since it is not a priority to occur by itself.

E. AUDIO FEEDBACK

Wilson and Dirven [72] demonstrated the potential of deploying audio to communicate sensory feedback from a prosthesis. They examined the test subject's ability to inter-

TABLE 3. Comparison of mechanotactile feedback.

Reference	Type of Hand	Location	Number of subjects/ Number of amputees	No of feedback channels & Sensor	Range and number of feedback levels	Performance
Aziziaghdam et al. [52] 2014	N/A Simulated sensations from tapping mechanism for perception test	Mechanical Actuator on Clavicle Bone	1 / 0	1 - Acceleration on tapping mechanism to simulate tapping finger on object	3 - one for hard, semi hard and soft	No performance measurement
Morita et al. [53] 2014	Myoelectrically controlled prosthetic hand with thumb and only one finger	Mechanically winding belt on bicep	5 / 0	1 - Pressure and displacement of finger to calculate hardness	Speed of winding corresponds to hardness	Hardness sensitivity of 0.59N/mm
Casini et al. [54] 2015	Robotic hand – SoftHand Pro	Pressure and skin stretch cuff worn on bicep	1 / 0	1 - difference in current to close hand compared to look up table	3 levels of hardness	100% accuracy in distinguishing between three levels of hardness
Godfrey et al. [15] 2016	Robotic Hand – SoftHand Pro	Pressure and skin stretch cuff worn on bicep	6 / 0	1 - Estimation on force based on current drawn	5 levels of tightness mapped to grasping force	Measurements only displayed in graphical form
Antfolk et al. [16] 2013	N/A only tested recognition of sensations	5 servo motor controlled actuators on forearm	10 / 5	Up to five - Pressure sensor from prosthetic hand	Up to 3 levels of pressure	(Amputee and Able Bodied) Localisation: 75.2% & 89.6%; Pressure level: 91.7% & 98.1%; Grip recognition: 58.7 & 68.0%
Antfolk et al. [55] 2012	N/A only tested recognition of sensations	Bulbs attached to the forearm	32 / 12	Up to 3 - simulated sensations for perception test	2 levels of pressure	Pressure: 90% & 80%; Localisation: 96%
Akhtar et al. [56] 2014	Myoelectrically controlled prosthetic hand	Contact pads on forearm	5 / 0	3 - Driven by motors that drive thumb, index and middle fingers	Range of 13mm of movement to represent fingers range of motion	Single Finger identification error: NF – 17.75%, VT – 8.58%, Skin stretch – 9.79%
Wheeler et al. [57] 2010	Myoelectrically controlled virtual arm	Rotational Skin Stretch on back of tricep	15 / 0	1 – rotational angle of elbow	±60° of elbow range corresponds to ±45° skin rotation	Error rate only displayed in graphical form; 23% reduction in visual demand using skin stretch device
Battaglia et al. [99] 2017	Myoelecrically controlld SoftHand	Rocker on the bicep	18/0	1 – aperture of hand grip	Hand opening linearly mapped to 0-60° rocker rotation	Discrimination of different sized spheres with an accuracy of 73.3%

TABLE 4. Comparison of temperature feedback.

Reference	Type of Hand	Location	Number of subjects / Number of amputees	No of feedback channels & Sensor	Range and number of feedback levels	Performance
Cho et al. [39] 2007	Externally driven prosthetic hand (Myoelectric controls bypassed)	Peltier element placed on users left hand	6 / 0	1 - Temperature Sensor on prosthetic finger	3 Temperature values – Hot, Mild and Cold	Temperature recognition of three temperature ranges with an accuracy of 96.7%
Ueda and Ishii [40] 2016	Myoelectrically controlled prosthetic hand with thumb and only one finger	Peltier element placed on users bicep	10 / 0	1 - Temperature Sensor on prosthetic finger	5 Temperature values - Hot, Lukewarm, not much, a little cold, cold	Temperature recognition of five temperature ranges with an accuracy of 88%

pret modulation of two audio channels to control a computer simulation. Their data showed that the subject could interpret two channels, but there was a 602ms delay and the audio feedback resulted in a high cognitive load. The subjects accurately completed the simulation and their success improved with training, although they rated two frequencies playing simultaneously as difficult to interpret. Gibson and Artemiadis [73] showed that a subject could use auditory feedback alone to pick up objects with a robotic hand. Within their study, the variance in volume represented the level of grasping force and the varying frequency corresponded with the location of two different regions of the hand. After training, subjects incorporated feedback to pick up and identify objects. In another approach, Gonzalez *et al.* [74] utilised triads to communicate the movement of a robotic hand. The sound of cello corresponded to the force on the thumb and a piano sound represented the force on index finger. The subjects were also able to use the audio feedback to help improve their movements and control when grasping objects. Each of these audio feedback experiments was conducted within the

TABLE 5. Comparison of audio feedback.

Reference	Type of Hand	Location	Number of subjects / Number of amputees	No of feedback channels & Sensor	Range and number of feedback levels	Performance
Wilson and Diren [72] 2016	N/A – Sensations simulated for perception test	Headphones	8 / 0	2 - Sensations simulated for perception test	Range of Frequency from 300-3400Hz, Amplitude from 50-65dB and beat frequency 0-15Hz	Frequency and beat modulation resulted in a mean squared error of 0.0406 and delay of 522ms for frequency, and a mean squared error of 0.0658 and a delay of 602ms for the beat frequency channel
Gibson and Artemiadis [73] 2014	5 Fingered Myoelectrically controlled prosethesis	Headphones	12 / 0	2 - Pressure Sensor on prosthetic fingers and position of robotic hands	Amplitude corresponded to grasping force, 2 different frequencies used to represent two different hand locations	Three groups of four subjects with their own individual mappings of frequencies to hand locations. They identified objects with and accuracy of 83%, 87% and 100% respectively.
Gonzalez et al. [74] 2012	Tendon driven robot hand	Headphones	8 / 0	3 - Pressure Sensor on prosthetic fingers and position of robotic hands	8 different piano triads to recognise different hand configurations. Amplitude corresponded to grasping force	Subjects achieved a lower duration completing tasks with audio feedback (37.52s vs 43.67s) and used a lower grip force (0.17V vs 0.25V)

TABLE 6. Summary of augmented reality feedback.

Reference	Type of Hand	Location	Number of subjects / Number of amputees	No of feedback channels & Sensor	Range and number of feedback levels	Performance
Markovic et al. [75] 2017	Myoelectrically controlled prosthetic hand	Graphical feedback displayed in Google glasses	20 / 0	4 - Aperture angle, Pressure sensor (contact), Pressure Sensor (Grasping Force), EMG sensors	Hand aperture on a linear scale, Contact with object displayed as on/off, Grasping force and EMG force on a linear scale	The improvement in speed and accuracy of grasping from using augmented reality feedback compared to no augmented reality was statistically significant.
Clemente et al. [76] 2017	Myoelectrically controlled prosthetic hand	Feedback in ellipse form displayed in Google glasses	8 / 0	2 – Pressure sensor (force), potentiometer (angle)	Horizontal axis of ellipse representing grip closure Vertical axis of ellipse representing grasping force	Smaller variability in initial grip force with feedback provided. Significantly larger duration in picking up the object with feedback provided

laboratory, and given their high cognitive load required, further investigation is required to determine their effectiveness whilst background noise is occurring. A comparison of the studies using audio feedback is shown in Table 5.

F. AUGMENTED REALITY

Markovic *et al.* [75] used Google glasses to communicate the aperture angle, contact time, grasping force and EMG strength for sensory feedback of a prosthetic hand to its user. Subjects used the visual feedback to improve their task performance when moving objects that required various strengths without breaking them. The subjects noted, however, that they typically only glanced at the information and did not use EMG strength signals.

Clemente *et al.* [76] also examined the use of augmented reality for sensory feedback for prosthetic devices. They communicated information through an ellipse, with the axis lengths corresponding to grasping force and angle of grasp closure. The authors changed the proportions of the grip force and grip closure feedback and examined if the users changed their movements accordingly. The data indicated that the subjects relied on the force feedback but not the closure feedback, however, in the tasks they were constantly looking at the objects so the grip closure information was redundant. The grasp angle feedback may only become important when doing tasks without looking at the hand as closely. Although there was a lower variability in initial grip force using the feedback, there was a significant increase in the duration of time required to pick up the object. This suggests that although performance repeatability can be increased with augmented feedback, it increases the cognitive load required from the user. A comparison of the studies using augmented reality is shown in Table 6.

III. STIMULATION OF PHANTOM HAND

Amputees can not only experience phantom limb pain, but also experience phantom limb sensations as explored in [101]. Amputees can have locations known as phantom digits that, when touched, trigger a sensation that corresponds in their brain to touching their missing finger. Phantom digits

TABLE 7. Comparison of phantom limb stimulation.

Reference	Type of Hand	Location	Number of subjects / Number of amputees	No of feedback channels & Sensor	Range and number of feedback levels	Performance
Antfolk et al. [18] 2013	N/A – simulated sensations for perception test	On the forearm, up to 5 vibrotactile or 5 mechanotactile	8 / 8	5 – simulated sensations for perception test	Only on and off values were used	Complete Phantom Map: Mechanotactile – 100%, Vibrotactile – 91% Partial Hand Map: Mechanotactile – 61%, Vibrotactile – 49%
Zhang et al. [19] 2015	N/A – simulated sensations for perception test	Up to 5 electrodes On Phantom digits for SF and Upper arm for NF stimulations	7 / 7	1,3, and 5 channels tested – simulated sensations for perception test	Changed frequency from 1-75Hz	Position: SF 97%, NF 90% Strength: SF 86%, NF 80%
Chai et al. [20] 2013	N/A – simulated sensations for perception test	1 Stimulation electrode on user's phantom digits	2 / 2	5 (only 1 tested at a time) – simulated sensations for perception test	Current: 0 to Upper limit (UL), .125mA increment, PW: 20μs to UL, 10μs increment Frequency: 1Hz to UL, 10Hz increment	Measurements displayed in graphical form
Liu et al. [21] 2015	N/A – simulated sensations for perception test	1 Stimulation electrode On user's phantom digits	2 / 2	5 (only 1 tested at a time) - Pressure sensors to detect force on prosthetic finger	Current varied proportional to pressure, from 0mA to 25mA	Measurements displayed in graphical form
Chai et al. [22] 2015	N/A – simulated sensations for perception test	1 stimulation electrode On user's phantom digits	19 / 11	5 (only 1 tested at a time) – simulated sensations for perception test	Current: 0 to Upper limit (UL), .125mA increment, PW: 20μs to UL, 10μs increment Frequency: 1Hz to UL, 10Hz increment	Measurements displayed in graphical form
Li et al. [23] 2015	N/A – simulated sensations for perception test	2 electrodes placed on PTP area	6 / 6	2 – simulated sensations for perception test	On and off value	(electrode size – discrimination distance) Parallel electrode: 12mm–39.0mm, 9mm-36.1, 7mm-31.3mm, 5mm-27.2mm Perpendicular electrode: 12mm-36.1mm, 9mm-33.5mm, 7mm-29.1mm, 5mm-26.5mm

provide a pathway for a natural and efficient communication for a variety of sensations that would not require any training. However, these phantom digit locations are not located in all amputees and their location and size can vary amongst individuals, as shown in Figure 8. Wang *et al.* [102] suggested that the distribution of phantom digits is located along the stump nerves. This approach, therefore, cannot be applied uniformly to all patients, as it is unsuitable for those without phantom digits. It will also require individual customisation for those who possess them, however, prosthetic sockets are customised to each individual and mapping stimulators to phantom digits could potentially be part of this process. Alonzo *et al.* [5] were able to demonstrate that by stimulating phantom digit locations during a rubber hand experiment, they were able to promote a sense of self attribution with the rubber hand. A comparison of the studies using phantom limb stimulation is shown in Table 7.

Ehrsson *et al.* [6] examined 18 amputees, out of which 12 had a phantom hand map. These 12 subjects underwent a human rubber hand illusion test whilst their phantom digit locations were stimulated. Their experimental data showed that stimulating these sites induced a sense of ownership with the prosthetic. In addition, another study [7] examined two amputees undergoing a functional MRI scan whilst completing the rubber hand illusion test. The MRI scans showed that stimulating these phantom locations activated the corresponding finger location within the brain.

Antfolk *et al.* [18] examined multi-site stimulation through vibrotactile and mechanotactile feedback with amputees that

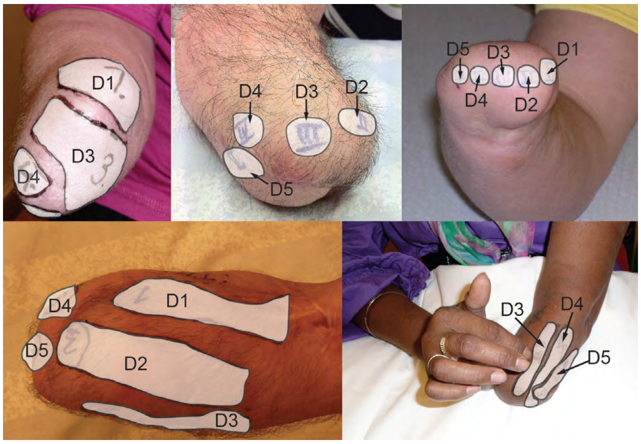

FIGURE 8. Examples of Phantom Hand Maps and their corresponding Phantom digit locations [101] from "Sensory qualities of the phantom hand map in the residual forearm of amputees" by Bjorkman *et al.* in Journal of Rehabilitation Medicine 2016. Licensed under CC BY-NC.

had complete phantom hand maps. They found that those with a complete phantom hand map recognised multiple sites of feedback with a higher success rate than those who had an incomplete or no phantom hand map. Zhang *et al.* [19] demonstrated that using Somatotopical (phantom digits) Feedback (SF) outperformed Non-Somatotopical feedback (NF) on the upper arm in electrotactile stimulation feedback. The SF was faster in response time (600ms), had a lower cognitive workload and achieved a higher recognition rate. One channel of feedback resulted in similar recognition rates for NF and SF; however, three channel SF performed as effectively as one channel of NF. Five feedback channels in SF performed marginally lower and was equivalent to the three channels of NF; although the authors suggested that interference and crossovers with the different electrodes due to their size may have affected the performance of the five channel SF feedback. Zhang *et al.* also recommended to combine SF and NF for those who do not have complete mapping and/or have limited stump size to place the electrodes.

Transcutaneous Electrical Nerve Stimulation (TENS) can induce sensations in these phantom digit locations for all fingers [20]. This study demonstrated the effect of varying pulse width, frequency and current density, and their corresponding sensation induced. The feelings of pressure, pressure + vibration, vibration, tingling and numbness in the corresponding finger location were induced through TENS applied to the phantom digit location. Liu *et al.* [21] further expanded on this work by showing that these signals could be induced by pressing on a tactile sensor on each prosthetic finger. Chai *et al.* [22] went on to demonstrate that these sensations were stable for an 11-month period for nine amputees. Testing was only conducted using one electrode and further investigation is required on simultaneous stimulation of multiple electrodes. Furthermore, a thorough investigation into creating sensations that correspond to varying levels of grasping force has not yet been reported in published literature.

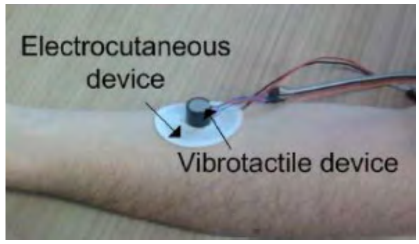

FIGURE 9. Combination of electrotactile and vibrotactile feedback [77] ©2014 IEEE. Reprinted, with permission, from "HyVe: hybrid vibro-electrotactile stimulation for sensory feedback and substitution in rehabilitation" IEEE Transactions on Neural Systems and Rehabilitaiton Engineering 2014.

Although initial data suggests that variations in the TENS PW, amplitude and frequency ranges, could induce varying intensity of sensations [20].

Li *et al.* [23] examined the effect of electrode size and spacing on stimulating a phantom hand map with TENS. They demonstrated that the bigger electrode, the wider range of sensations produced. However, a higher current is then required and further space between electrodes is needed. They concluded that having an electrode sizing of 5-7mm was a good compromise based on their preliminary investigations.

IV. COMBINING MODALITIES: HYBRID TACTILE FEEDBACK METHODS

The literature discussed thus far has only communicated one type of sensation at a time, this can often lead to an ability to only communicate one sensation at a time. A few studies have examined the potential of using multiple feedback methods simulataneously. This may be to improve the recognition rates and/or range of one type of stimuli, or create the ability to communicate two different stimuli simultaneously. A comparison of the studies using hybrid tactile feedback methods is shown in Table 8.

D'Alonzo *et al.* [77] demonstrated that subjects could identify nine levels of stimulation through a hybrid feedback of electrotactile or vibrotactile stimulation, shown in Figure 9, compared with either mode in isolation. These same authors also went on to show that subjects could identify patterns from four stimulation devices, that used a combination of electrotactile and vibrotactile stimulation, with a higher accuracy than similar sized vibrotactile devices [78]. However, testing was only conducted on able-bodied subjects. D'Alonzo *et al.* suggested that their results were limited by the size of electrodes and the performance may improve if their size was reduced. Combining mechanical pressure and vibration has also been explored [79], but only an experimental prototype was built, without any testing performed on subjects. The device also appears very bulky.

Jimenez and Fishel [80] examined a prosthetic finger with a temperature, vibration and force sensor incorporated for sensory feedback. The weight of an object was translated into squeezing pressure on the arm, the temperature was produced on the bicep of the arm and surface textures were communicated through vibration feedback. The subject accurately

TABLE 8. Comparison of hybrid stimulation techniques.

Reference	Type of Hand	Location	Number of subjects / Number of amputees	No of feedback channels & Sensor	Range and number of feedback levels	Performance
D'Alonzo et al. [77] 2014	N/A – Sensations simulated for perception test	1 Electrotactile/Vibrotactile combination stimulator on the Forearm	10 / 0	1 – Sensations simulated for perception test	9 levels of intensity	Recognition of 9 levels using hybrid setup – 56% & 72%, vibrotactile only – 29%, electrotactile only 44%
D'alonzo et al. [78] 2014	N/A – Sensations simulated for perception test	A combination of 3 electrotactile stimulators and 2 vibrotactile stimulators spread across three locations on the forearm	10 / 0	1– Sensations simulated for perception test	5 different single channels (representing each finger), 5 different grasp patterns	Single Finger: Hybrid – 98%, Electrotactile-94%, Vibrotactile 1 – 89%, Vibrotactile 2 – 73% Pattern: Hybrid – 77%, Electrotactile-79%, Vibrotactile 1 – 77%, Vibrotactile 2 – 69%
Clemente et al. [79] 2014	No Testing conducted – just prototype built			2 - Contact made/break & grasping force	5 levels of pressure Vibration frequency range from 5Hz to 200Hz	No performance measurement as no testing undertaken
Jimenez and Fishel [80] 2014	Robotic Gripper	Force Tactor, Vibration Tactor and Temperature Tactor - all on bicep	1 / 1	3, only one tested at a time: Temperature, Force and Vibration sensor	Temperature range +- 3C Vibration varied amplitude Pressure 0-200kpA of air muscle pressure	Measurements only displayed in graphical form
Li et al. [81] 2016	No Testing conducted – just prototype built			2 channels of 15 actuators - No Testing, just prototype built	Max Vibration 240Hz, Max Pressure 4.4N	No performance measurement as no testing undertaken
Motamedi et al. [82] 2017	N/A – Sensations simulated for perception test	Applied to forearm. Normal stress and Vibration applied at same location OR 6cm away from each other	14 / 0	1 channel of feedback	Three values of normal stress, three values of vibration feedback	Measurements only displayed in graphical form

perceived the mass, temperature and roughness of the objects but each modality was only tested one at a time. The subject also suggested that the vibrational feedback mechanism was too distracting. Li *et al.* [81] also presented a new design for a feedback mechanism that combined vibrational feedback with mechanical pressure into a small, lightweight and power efficient module that can be used as part of arrays. However, at the time of preparation of this review, there was no literature on the testing of this system on a person.

Motamedi *et al.* [82] examined the perception of pressure and vibration feedback at the same time. They found that pressure by itself was perceived with the highest accuracy, followed by pressure and vibration at the same location, pressure and vibration at different locations and lastly vibration by itself performed the weakest.

Hybrid tactile feedback systems are still in an early stage of development, with half of the studies examined only displaying a prototype without undertaking any experimentation. Further testing is therefore, not only required to be undertaken to determine a person's ability to recognise two different feedback systems simultaneously, but to also examine the effect on the cognitive load. More experimental data on recognition rates and cognitive load could help determine if hybrid tactile feedback systems can be successfully incorporated into a feedback loop to improve the user's control and embodiment with their prosthetic hand.

V. CONCLUSION AND FUTURE PERSPECTIVES

Each of the different methods of sensory feedback have been shown to be successful in providing extra information to the prosthetic user, often enabling them to make better decisions in the control and use of their prosthetic hand. Although some studies included subjects' reflections on their use of the prosthetic device with sensory feedback at home [46], [55], the majority of testing, however, has been completed under laboratory conditions, often involving an external computer. During simulated sensation testing, all concentration is on perception of the sensation. However, during everyday tasks, perception requires detection and understanding whilst undertaking other tasks, thus minimisation of cognitive load becomes more important. To use these feedback methods within a real-life context, thorough home testing is required to examine success rates with the normal background noise and distractions that occurs within every day environments. For example, will audio feedback be able to be heard as easily with background noise, or will vibrational feedback be able to be felt whilst undertaking everyday tasks?

A large amount of testing was completed on the dominant arm of able-bodied participants. However, when this same feedback is fed to the forearm of an amputee, the perception, sensitisation and response could be different.

Both electrotactile stimulation and vibrotactile stimulation suffer from the disadvantage that perception can not only vary between people, but also by the location of applied contact. This may affect the practicality of systems for use day after day. There has also been no examination on whether repeated application produces the same results. Vibrotactile feedback is dependent upon the pressure of the tactor against the skin, and the tactor reapplication by the user therefore may not result in consistent sensations. In addition, when using multiple vibration tactors or electrotactile electrodes, electrode locations may affect their repeatability. Recalibration may be required each time the user places it on, and moving locations may impact the cognitive load required in using the device. Further research into these areas is required.

Another challenge that exists is communicating the location of the feedback. Within current literature, most studies only communicate the force that represents one location on the digit. When grasping an object, however, subjects may want to feel the difference between force on the fingertip and force on the inside of the finger. Vibrotactile and electrotactile arrays appear to be one potential solution to this problem.

There is a large amount of different approaches to test sensory feedback methods. Some studies have only tested simulations to ensure correct perception, whilst others have incorporated a myoelectric controlled prosthetic hand. There are also variances within the number of degrees of freedom employed, the number of channels and levels of feedback, as well as the type of sensation being communicated. These differences can make a performance comparison between studies difficult. However, in addition, it also appears that different approaches may be required for different prosthetic users [66] and for different prosthetic hands. For example, if a prosthetic hand only contains a simple grasping motion, then using a pressure cuff or single vibration motor could be well suited. Although current pressure cuffs are quite bulky, the winding belt mechanisms provide a simple and easy to learn feedback device for single DOF devices. However, if feedback is required for all five fingers, then an approach of using phantom digits or electrotactile stimulation could be better suited. Commercial prosthetic hands are further developing in their dexterity and degrees of freedom [103] and will therefore require multiple channels of feedback. Initial results for vibrotactile and electrotactile arrays have shown some successes as users have been able to identify locations and movements, however, more research should be undertaken to connect them with a prosthetic hand through sensory feedback.

Comparative testing is required to compare the effectiveness in improving control and user comfort when using the various methods. This testing would be required to be specific for each type of prosthetic hand. For example, one set of experiments on feedback mechanisms for a 1-DOF hand and then another series of tests for a 3-DOF hand, as they may not produce the same result. These would need to not only incorporate grasping performance, but also measures from the subjects on areas such as: comfort, ease of use and cognitive load.

Electrotactile stimulation of the phantom hand [19]–[23] has shown some potential for sensory feedback in a multiple DOF system. Current literature suggests that by stimulating the phantom digits, it can provide up to five separate somatotopicaly matched feedback pathways that feel natural to the user. By using electrotactile stimulation, it provides a lightweight, low-power, larger bandwidth mechanism that can be easily controlled. However, phantom hand maps are not located on every amputee, and their location and number of digits appear to be unique to each person. Initial testing has only stimulated one site at a time, and no testing has been reported on stimulating multiple phantom digits at once. Graczyk *et al.* [12] has reported a predictable linear relationship between perceived intensity, amplitude, frequency and pulse rate in intraneural stimulation. Further testing is required to determine if this same relationship exists within phantom digit stimulation.

As previously discussed, the top two feedback priorities for prosthetic hand users are force and position feedback. Initial research on proprioceptive feedback has had mixed results. Hasson and Manczurowsky [50] concluded that providing position information through vibrotactile feedback did not result in any improvement. Blank *et al.* [104] concluded from their data that proprioceptive feedback alone improved the performance of a 1-DOF grasping task when no visual cues were available. When visual cues were available, however, the feedback only improved tasks with a moderate level of difficulty. The authors suggested that for precise tasks, other tactile cues are required as well. Pistohl *et al.* [105] also examined the role of proprioceptive feedback. Subjects controlled a cursor with EMG on one arm and fed proprioceptive information to the other user's arm using a robotic manipulator. The proprioceptive information was beneficial to the user when no visual information was available, but did not benefit the user when visual information was available. However, both Bark *et al.* [100] and Wheeler *et al.* [57] concluded that rotational skin stretch had some benefit in providing position feedback, but only for 1-DOF actuator such as an elbow joint. Similarly [99] also demonstrated success in providing position information for a 1-DOF hand. Further research is therefore required to provide proprioceptive information for hands with multiple degrees of actuation in the fingers.

At present, the majority of literature has focussed on using feedback to send one sensation at a time. Using a single method to communicate more than one sensation may be difficult for the user to understand or result in a high cognitive load for the user. An effective approach could be to use multiple feedback methods to communicate combinations, with each feedback method communicating a different sensation, either simultaneously or by constantly switching between the two modalities running concurrently. There have been some contradicting results on a person's ability to understand multiple sensory feedback cues. Ajoudani *et al.* [84] demonstrated multiple cues being used successfully, with mechanical pressure cuff to communicate pressure forces and vibrational feedback to communicate texture information. However, in a study undertaken by Kim and Colgate [17], their subject showed a lower performance picking up a virtual object when receiving shear forces through vibrations at the same time as receiving pressure feedback on grasping force, although this experiment was only performed with one subject with five sets of trials. Other multimodal feedback systems [12], [19]–[23], [77]–[81] have shown capability, with initial testing demonstrating that users could distinguish multiple channels of information sent simultaneously. This could provide a method that allows for multiple channels of information to be provided back to the user to make informed controlling decisions on their prosthetic hand.

Both electrotactile stimulation of the phantom hand and multimodal sensory feedback are only at initial stages of testing, with only simulated perception being examined. Further testing is required to determine whether these feedback mechanisms improve the user's ability to take part in the control loop.

Examination of effectiveness of sensory feedback techniques needs to progress away from being done in isolation from the control system. In the case of electrotactile sensory feedback, interference may occur and compromises may need to be made in the feedback or control system's performance to enable then to work together at the same time, as reported in [69]. In addition, as shown in Figure 10, it may be optimal for two sensory feedback loops to exist, one to the controller and one to the user. This is because currently there are limited pathways to effectively transmit all stimulations back to the user. Too much information may cognitively overload them or incorporate too long of a delay. Instead when minor alterations are required, such as during an object slipping, a higher performance may result from the prosthetic controller regulating the constant grasp rather than incorporating the user. However, further testing in this area is required to ensure the correct balance is achieved for improving grasping performance, user comfort, cognitive load and embodiment.

Although there are a few longitudinal studies that examine the use of sensory feedback over a longer period [46], [88], [107], these mainly repeat the testing regularly over a few days or weeks. However, further analysis should be done on whether performance is maintained when consistently using the sensory feedback throughout the day over a few weeks, similarly to the work done by Clemente *et al.* [46]. Potentially, over time, the nervous system could become desensitised to the stimulation site, resulting in a higher cognitive load required to focus on the stimulations. If such a problem exists, stimulation sites may need to be moved up and down the arm to reduce the chance of desensitisation. Longitudinal studies are also required to examine the impact of the training and adaptation to using sensory feedback. Chai *et al.* [108] demonstrated that subjects were able to improve their recognition rate of electrotactile feedback on non-phantom digit

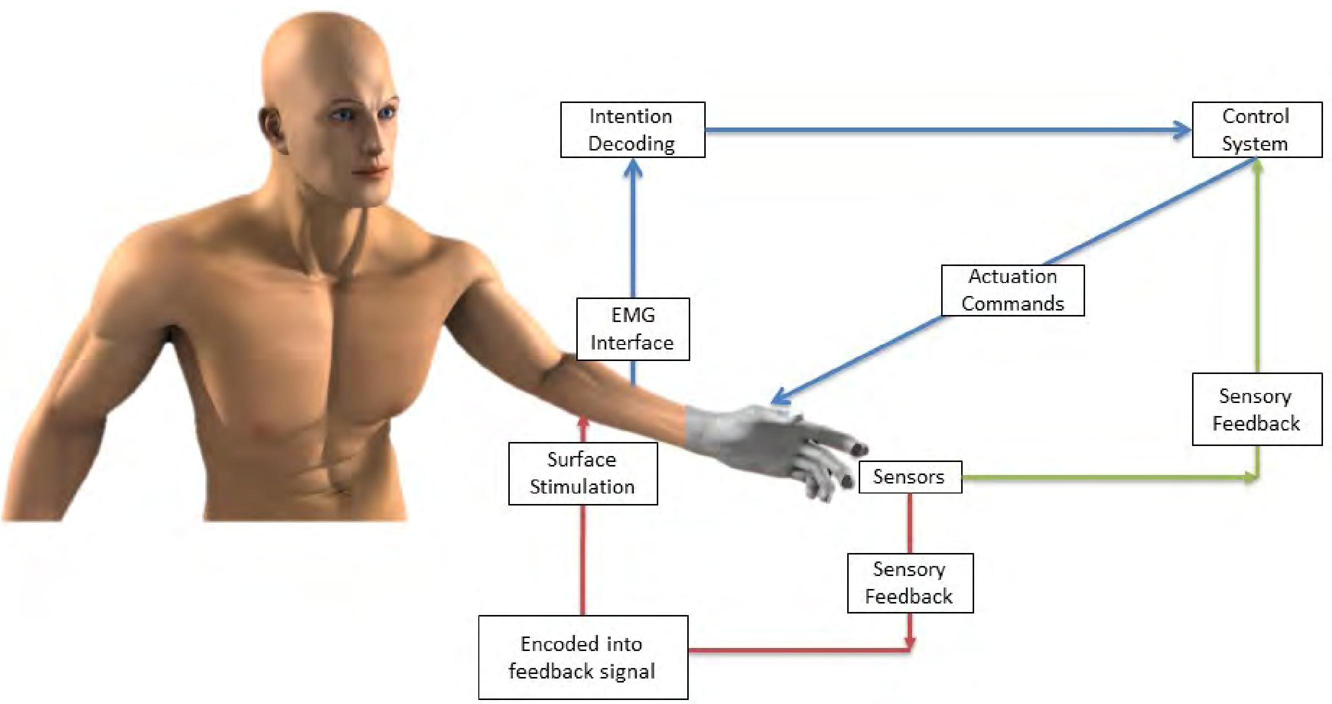

FIGURE 10. Multiple sensory feedback loops (adapted from [106]).

sites over a three day period to a performance comparable to phantom digit sites. Stepp [88] *et al.* showed that incorporating vibrational feedback, subjects continued to increase in performance over an eight day period and they still saw a reduction in performance when the feedback was removed on day eight. However, recently, Strbac *et al.* [107] demonstrated that sensory feedback was greatly beneficial in the beginning of using the prosthetic and learning to reliably manipulate the grasping force though their EMG control. However, overtime the user tended to rely more on feedforward control and their understanding of the relationship between EMG commands and resulting grasping force. Further investigation is therefore required to determine the role of sensory feedback long term and on its role in learning EMG control.

In addition, studies currently examine how sensory feedback assists a user in picking up objects, but no testing on holding these objects for longer periods has been conducted to date. For example, how does the feedback mechanisms work in assisting the user to hold a cup of coffee over the time it takes to drink it? The constant feedback over time, may be helpful, or it may be distracting for the user and the feedback may need to be also incorporated into the control mechanisms to successfully hold objects.

The speed in communicating sensations has not been widely reported on when examining the performance of a sensory feedback system. A healthy peripheral nervous system can take approximately 14-28ms to deliver tactile information [1]. As a result it was suggested by Antfolk *et al.* [34] that any surface stimulation for sensory feedback should be communicated in small percentage of that amount (3-5ms) in order to have a minimal impact on the overall travel time. Additionally the timing delay between visual and tactile information can impact the sense of body ownership in the prosthetic. A Rubber hand illusion test performed by Shimadi *et al.* [94] and an FMRI study on body ownership by Bekrater-Bodmann *et al.* [109] showed that 0-300ms delay occurred no loss in body ownership. This FMRI study also showed significant disconnect between visual information and tactile information when there was a separation of more than 600ms. However, a further refinement study by Ismail and Shimadi [93] suggest that the feedback delay should be less than 200ms to maximise sense of body ownership. Therefore timing becomes very crucial when considering the method of feedback. This gives an advantage to using electrical stimulation and may limit the effectiveness of mechanotactile systems. This effect of timing may also explain some of the conflicting results of techniques such as vibrotactile feedback. Although it can be as low as 10ms to first detect vibration [5], it can be up to 400ms to reach the desired vibration level and frequency [86]. However, although only mentioned in a vibrotactile study by Hasson and Manczurowky [50], haptic drivers can be implemented to decrease start up times of vibration motors.

Although invasive methods show promise for providing a richer sensory feedback experience in the long term, non-invasive methods provide an opportunity to benefit users whilst those more invasive methods are still being developed. In addition, not all users will be willing to undergo further surgery and may instead opt for the non-invasive feedback option. Particularly within laboratory conditions, various approaches to providing sensory feedback through non-invasive methods show promise. A focus, therefore, for the immediate future should therefore be placed on implementing a simple feedback strategy that can be practically used at home every day so that prosthetic users can begin to take advantage of the benefits that sensory feedback could provide them.

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BENJAMIN STEPHENS-FRIPP received the B.E. degree in mechatronic engineering from The University of Sydney, Camperdown, NSW, Australia, in 2001, and the M.Phil. degree from the School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, Wollongong, NSW, Australia, in 2017. He is currently researching minimally invasive feedback for a prosthetic hand for the Ph.D. degree with the School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong.

GURSEL ALICI received the Ph.D. degree in robotics from the Department of Engineering Science, Oxford University, Oxford, U.K., in 1994. He is currently a Senior Professor with the University of Wollongong, Wollongong, NSW, Australia, where he has been the Head of the School of Mechanical, Materials, Mechatronic and Biomedical Engineering since 2011. His research interests include soft robotics, system dynamics and control, robotic drug delivery systems, novel actuation concepts for biomechatronic applications, robotic mechanisms and manipulation systems, soft and smart actuators and sensors, and medical robotics. He has generated more than 300 refereed publications, and delivered numerous invited seminars and keynote talks on his areas of research.

Dr. Alici is a member of the Mechatronics National Panel formed by the Institution of Engineers, Australia. He has served on the International Program Committee of numerous IEEE/ASME International Conferences on Robotics and Mechatronics. He is the Leader of the Soft Robotics for Prosthetic Devices theme of the ARC Center of Excellence for Electromaterials Science. He received the Outstanding Contributions to Teaching and Learning Award in 2010 and the 2013 Vice-Chancellor's Interdisciplinary Research Excellence Award from the University of Wollongong. He was the General Chair of the 2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics held in Wollongong. He was a Technical Editor of the IEEE/ASME TRANSACTIONS ON MECHATRONICS from 2008 to 2012. He is currently a Technical Editor of the IEEE ACCESS.

RAHIM MUTLU received the B.Sc. degree in mechanical engineering from Uludag University in 2007, and the M.Eng. degree in mechatronics and the Ph.D. degree in modeling soft robotic actuators from the University of Wollongong (UOW) in 2009 and 2013, respectively.

He held a post-doctoral position on soft robotics in medical applications with the ARC Centre of Excellence for Electromaterials Science (ACES), Intelligent Polymer Research Institute, UOW. He is currently a Lecturer of biomedical engineering with the School of Mechanical, Materials, Mechatronic and Biomedical Engineering, UOW. His research interests include soft robotic actuators and manipulators, their biomedical applications, prosthetics and orthotics, artificial muscles, bio-inspired robotics, modeling and control of those systems and their optimization, smart manufacturing and 3-D printing technologies, and rapid prototyping.

Dr. Mutlu is an Editorial Board Member of Soft Robotics-Mary Ann Liebert, Inc., and also an Associate Investigator at ACES.