HYBRID VIBRO-ELECTROTACTILE STIMULATION: REVOLUTIONIZING SENSORY FEEDBACK IN PROSTHETIC LIMBS

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Abstract— *Hybrid vibro-electrotactile stimulation (HyVE) is an effective way of achieving maximum sensory feedback for prosthetic limb users. By combining electrical signals and mechanical vibrations, HyVE maximizes the benefits that each form of stimulation provides the user. For instance, electrotactile stimulation, the process of sending electrical currents through the skin, is the quickest way to provide sensory feedback to the brain when a prosthetic limb interacts with its environment because electricity travels faster than mechanical systems can. Like vibrotactile stimulation, electrotactile stimulation is minimally invasive when compared to nerve reinnervation, a surgical method of sensory substitution. However, when comparing electrotactile stimulation to vibrotactile stimulation, electrotactile is the more invasive of the two, giving it a slight disadvantage. Additionally, it is not as accurate as vibrotactile stimulation when sending signals to the brain.*

Vibrotactile stimulation, the process of using electromagnetic motors to create vibrations on the skin, has the advantage of directly contacting the tactile sensors, providing localized sensory feedback. However, with more moving parts, there is a greater chance that the parts will break or wear down over time. When used individually, each method provides an adequate level of sensory feedback, but still faces the limitations mentioned above. When the two are combined, they occupy the same space and can send signals at the same time, making HyVE just as compact and efficient as one method of tactile feedback by itself, but with the sensory capabilities of both.

Key Words—Dual modality, Electrotactile stimulation, Hybrid vibro-electrotactile stimulation, Prosthetic limb, Sensory substitution, Vibrotactile stimulation

IMPORTANCE AND HISTORY OF PROSTHETIC LIMBS

The human body works as a composite system – it cannot perform a task without every part functioning in its intended manner. When an organ fails, it is damaging to the body but may not be immediately disruptive to a person's everyday life. On the other hand, if something a person consciously controls – such as an arm or a leg – were to disappear, it would instantly disrupt their daily routine. In the United States alone, over 500 people deal with this reality coming true every day. Between vascular diseases, traumatic incidents, and other severe illnesses, such as cancer, amputations are performed at an alarming rate. There are currently over 2 million people in the United States living without four functioning limbs, and well over half of them are using a prosthetic limb as a replacement [1]. Prostheses designed for upper limbs specifically are unique because they are responsible for replacing significantly intricate and complex motor functions, such as writing and grasping. The complexity of these functions is why, despite tremendous breakthroughs, there will always be room for improvement in the design of upper limb prostheses.

Although this idea of artificially replacing limbs has been around for centuries, practical technological advancements on prostheses were relatively stagnant until around 1990 due to any progress being either unsustainable or dangerous [2]. For instance, in 1898, Dr. Vanghetti proposed the Sauerbruch-Lebsche-Vanghetti cineplasty method, which involved directly connecting the prostheses to the amputee's muscles. This turned out to be a dangerous method that could result in scarring and wearing down of the muscles [3]. After 1990, prosthetic limbs began to be equipped with microprocessors, resulting in what is now considered modern prosthetic limbs, which are a less invasive way to allow amputees to control their limbs. Since that breakthrough, various other technological advancements have created significant progress in the functionality of prostheses, with many upper limb prostheses emulating real limbs to a great extent [2]. Although prostheses today move like real limbs, there are still serious problems that must be addressed regarding how they provide tactile feedback to the user.

The Problem with Current Prosthetic Limbs

Prosthetic limbs today, as with many aspects of modern society, have been outfitted with extensive technologies, making them realistic and multifunctional. However, one feature that has not yet reached this level of innovation is the tactile feedback provided by the artificial limbs. Given how advanced prostheses are, one would expect amputees to have no problem using prosthetic limbs as a person with fully functional limbs would. Unfortunately, this is not the case, as many amputees reject their prosthetic limbs, instead going without any device to improve the functionality of their limbs. It has been estimated that as many as 40% of prosthetic hands are rejected by their users because it is often easier and more practical to receive sensory feedback from their stump [4]. Without proper sensory feedback, the user feels a lack of control when using the prosthetic limb, leading to that person being less willing to use it [4]. Prosthetic limbs have the potential to be life-changing device, but because of the high rate of rejection, this is not always possible. They can essentially restore complete function to an amputee's limbs, allowing a person to perform all the actions that are impossible with one or no hands. However, prosthetic limbs cannot be as reliable and realistic as real limbs if there is not a great improvement in sensory feedback.

Another large problem with current prostheses is that they do not maximize sustainability. For a medical device or process to be considered sustainable, it essentially must fit under three separate criteria: it must improve quality of life, be accessible to as many patients as possible, and promote participation and partnership between both current and future generations [5]. Currently, prosthetic limbs graze the tips of each of these criteria, but they still lack the qualifications necessary to fully embody them. Current prosthetic limbs typically fall into two basic categories: technologically advanced limbs sold for obscenely expensive prices, or limbs with limited functionality that more can consider to be affordable. Sensory substitution, while lacking in all versions, is immensely superior in prostheses with appropriate technologies. However, if all current prostheses were to take advantage of the technology available, prices would inevitably rise, making any form of a prosthetic limb an impossibility to someone unable to afford the expensive advanced technology. Until a compromise is reached between price and magnitude of improvement on the quality of life of a prosthetic limb user, prosthetic limbs will always fall short of being considered a truly sustainable device.

WHAT IS SENSORY SUBSTITUTION? WHY IS IT IMPORTANT IN PROSTHETIC LIMBS?

When a person's skin interacts with the environment, the information is taken in through mechanoreceptors in the skin. Interaction with the mechanoreceptors triggers action potentials, or nerve impulses, to travel through the Peripheral Nervous System (PNS) to the Central Nervous System (CNS) [4]. Through this process, a person will be able to instantly detect in what way their hand has interacted with the environment. The hand could feel a pressure, vibration, temperature, or other sensory inputs, and the brain decodes the information to figure out as much as it can about the inputs. After decoding, the brain will have figured out the characteristics of the surface, the strength of the pressure, and even the stability of the person's grasp [4]. Knowing the stability of one's grasp is especially important because it will allow the user to ensure they do not apply too little pressure and drop an object while also not applying too much pressure and damaging the object. When a person does not have real skin, but instead a prosthetic hand, the artificial limb must use sensory substitution to relay information about the environment to the user [6].

In reference to prosthetic limbs, sensory substitution is the process by which the artificial limb replicates the senses that would be felt by a real hand. The goal of sensory substitution is to replicate the mechanoreceptors and action potentials of real skin as much as possible. To accomplish this task, the prosthetic limb must have sensors to capture the information, a method of converting the information, and a stimulator to convert the information received into information the user can understand [6]. The stimulation can either be sent through the PNS to the CNS via stimulation of the surface of the skin, or it can be sent straight to the CNS [7]. This overall process, called a sensory feedback loop, is overviewed in Figure 1.

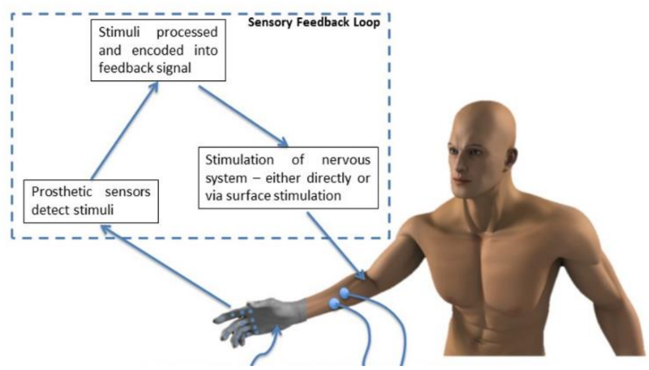

FIGURE 1 [4]
The sensory feedback loop consists of sensors to detect stimuli, a method of processing the stimuli, and a method of conveying the information to the user.

In the case of sensors sending information to the surface of the skin, the stimulator is the device that converts signals into the action potentials that the human brain can understand and make decisions upon. Aiding in this interpretation of information is a phenomenon known as phantom digit somatotopy. People with upper limb amputations often report awareness of a phantom limb where their real limb used to be [7].

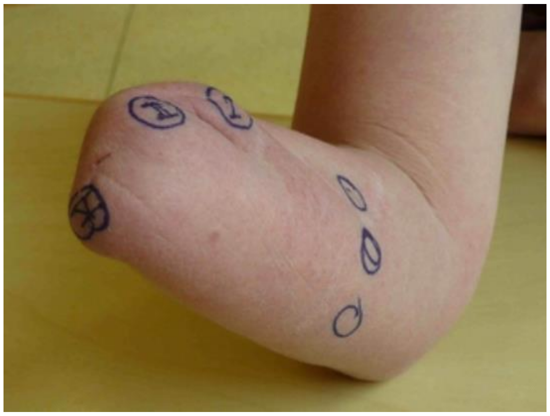

FIGURE 2 [7]
This forearm stump demonstrates a map of which regions on the skin elicit a sensation in certain phantom fingers. The thumb is represented by (I), the index finger by (II), and the little finger by (III). Other stump control areas are identified by (O), but do not elicit a sensation on the phantom hand.

Furthermore, when a touch is applied on an amputee's forearm stump, the pressure can be recognized as a pressure on different sections of the phantom hand. As shown in Figure 2, a map can be made on the forearm stump, with certain regions corresponding to certain fingers and sections of the hand [7].

Mechanical Stimulation Methods

There are many ways to take advantage of sensory substitution to create prosthetic hands that provide realistic feedback to the user. Some of the methods utilize the sensory substitution map on the stump, while others rely on the user associating certain sensations with various external interactions on the prosthetic hand. Mechanical stimulation methods are one form of sensory feedback that rely on mechanical processes to send signals to the user. Two forms of mechanical stimulation are mechanotactile pressure and vibrotactile stimulation. While both methods use mechanical systems, they also take advantage of the myoelectric property of muscles, which allows human muscles to send information and signals received from the mechanical systems [4].

Mechanotactile pressure involves applying pressure to the skin at various points to alert the user to how the prosthetic hand interacts with the environment. By using this method, the user can distinguish between hard and soft surfaces and determine the strength with which an object is being grasped [4]. One way to communicate the strength of the grasping force is to attach a winding belt motor to the upper arm [8]. While the idea seems like it would be effective in theory, mechanotactile pressure is not very practical in providing effective sensory feedback. This is because the device itself is very large, and as part of the arm is missing, there is not a lot of space where the devices can be implemented. Additionally, this method of feedback is limited in its success because users experienced confusion with recognition of forces in regions of the skin neighboring each other [4].

Alternatively, mechanical stimulation can be achieved through vibrations, a process known as vibrotactile stimulation. The vibrations can be sent through linear and rotary electromagnetic motors or various nonelectromagnetic actuators, although it is more common to use electromagnetic motors. For whichever method is chosen to provide vibrotactile stimulation, the goal is to provide vibrations that have different amplitudes and frequencies to allow the user to distinguish between various inputs [4][9]. Optimal results are obtained when the motors send sinusoidal waves to the bicep region as a series of pulses, rather than continuous vibrations [4]. Each motor attached to the skin activates the Pacinian corpuscle mechanoreceptors, which are nerve endings that respond to vibrations and pressure. These motors send a frequency and force with a small current so that the user can distinguish the force without feeling any pain. For example, in an experiment performed at the University of Twente, the current was set to 44 milliamps, which was found to be an appropriate level for comfortably distinguishing the vibrations [10]. Feedback is then supplied at various hand positions to let the user know how the hand is oriented without looking at it. Additionally, different feedback is supplied when the hand grasps an object and alerts the user as to how strongly the object is being gripped. The combination of knowing hand position and grasping force are the most important aspects of tactile feedback, and vibrotactile stimulation helps to provide the user with both [10].

Vibrotactile stimulation offers benefits to the user that mechanotactile pressure fails to achieve. For instance, vibrotactile stimulation can be attained through relatively small motors, taking up a smaller amount of space on the arm, so several of these motors can be applied to the same arm, as demonstrated in Figure 3 [4]. Taking up as little space as possible is essential because it poses less of a burden to the user and allows for the addition of more motors, increasing the overall performance of the sensory feedback system. The use of vibrotactile stimulation has been shown to be superior to visual feedback alone with respect to grasping objects. It has also been shown to increase the user's sense of control [4]. Although vibrotactile stimulation helps the user to have more control when using a prosthetic hand, there are areas of weakness that must be addressed.

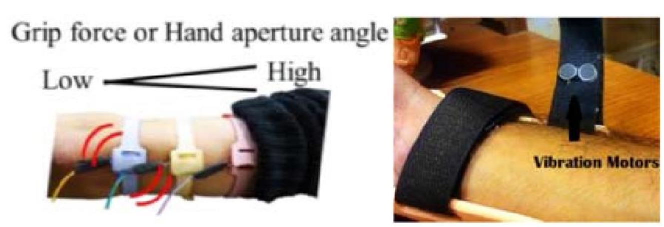

FIGURE 3 [4]

Three vibrating motors applied to the same arm (left) and two vibrating motors connected on the same arm band (right).

Despite the benefits that vibrotactile stimulation provides, this method has not taken over as the predominant method of tactile feedback for a few reasons. For instance, there is a small delay between activating the motor and generating the vibration. Although it is a small delay on the magnitude of milliseconds, humans are used to near instantaneous feedback when touching and grasping objects. Therefore, a small delay between performing an action and feeling the results takes away from the sense of embodiment that tactile feedback helps to provide the user in the first place [4]. Additionally, the bandwidth of vibrotactile motors is limited, restricting the amount of information that can be sent to the user, reducing the effectiveness of the tactile feedback system [4]. Along with these drawbacks, vibrotactile stimulation can be difficult to make reliable because the user's perception of vibrational frequencies can change based on how tightly the motor is attached to the skin [4].

These drawbacks lead to the conclusion that mechanical stimulation methods are unsustainable as a permanent solution to restoring limb function in amputees. In pursuing one of the main goals of a sustainable technology, maintaining quality of life, both mechanotactile pressure and vibrotactile stimulation fall short of achieving that goal. The method for creating mechanotactile pressure devices involves implementing bulky devices that can wear down muscles over time [10]. The fatigue that these devices creates outweighs the improvements in quality of life of the sensory feedback because it makes using the limb a hassle for the user. Vibrotactile stimulation, while lighter and smaller, still does not fully meet this measure of sustainability. As mentioned previously, the delay between interaction between the prosthetic device with the environment reduces the user's sense of control over the device. To ensure quality of life, prosthetic limbs should be seamlessly integrated into a person's life, but mechanical devices for sensory feedback are not capable of doing so.

Electrotactile Stimulation Methods

Electrotactile stimulation is an alternative method of providing sensory feedback to a prosthetic limb user. It involves carrying electrical signals from the application site up through the tissue through electrodes placed directly on the skin. These electrodes act as transducers, converting the electrical signals from the microprocessors within the prosthesis to a stable flow of electrons, or current, that the human body can recognize and process. The current is passed through the skin while avoiding more sensitive sensory-motor structures, such as muscles and motor nerves [9]. Since the current is localized to the application site and is relatively low, the risk of damaging the tissue and sensory-motor structures is minimal.

In Figure 4, an arm bearing four independent channels in an electrode array is depicted. Each channel has both an anode and a cathode, creating a closed loop for the current to flow through. To best accommodate for a comfortable fit, the electrode array is covered with hydrogel to prevent unwanted chemical reactions from occurring when the stimulation is active. This electrode array was used in a study evaluating electrotactile stimulation as a method of reproducing both pressure feedback and slip feedback but is fairly standard of electrotactile stimulation devices. The combination of electrodes in a multi-loop interface is typical because it provides localized feedback, as well as gives the opportunity for the device to target specific areas to activate varying responses, such as pressure and slip feedback.

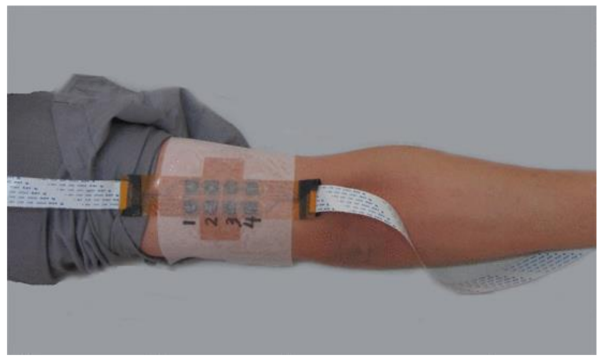

FIGURE 4 [11]
A multichannel electrode array, labeled 1-4, is depicted on an able-bodied subject.

In this study, conducted by a team of researchers from the State Key Laboratory of Mechanical System and Vibration, Institute of Robotics, School of Mechanical Engineering, Shanghai Jiao Tong University concluded that pressure and slip feedback used together can act as a partial replacement for visual feedback [11]. These two forms of artificial feedback can be achieved through electrotactile stimulation by targeting different aspects of the skin and body. For example, to replace pressure feedback, high-frequency electrical signals were sent to Merkel cells, which are responsible for detecting pressure and can recognize frequencies above 75 Hz [11]. An increase in the current frequency as well as pulse width were necessary for the subjects to recognize the artificial feedback as pressure. When the pulse intervals became smaller, the subjects could no longer distinguish between them, and therefore perceived the sensation as continuous pressure. These small adjustments got rid of any delay in feedback, making electrotactile stimulation more appealing than vibrotactile stimulation due to its seemingly instantaneous response. Additionally, since electrotactile stimulation lacks the motors required to move the components of a vibrotactile stimulation device, it consumes far less power.

However, there are still many reasons that electrotactile stimulation is not the primary option for artificial tactile feedback. For one, it is a far more invasive approach to attaining sensory substitution than vibrotactile substitution. While the current is still applied on the surface of the skin, it is designed with the sole purpose of traveling through the skin and tissue. This process is, of course, tested and regulated, but has still been proven to elicit less than desirable sensations (both localized and referred), including vibrations, tingling, pressure, itching, prickling, and general pain or discomfort [9].

Electrotactile stimulation also fails to fully integrate sustainability into its design. This form of sensory substitution incorporates direct nerve stimulation which can be an effective form of tactile feedback, but unfortunately creates a foreign sensation that has been classified as unpleasant at times [10]. Electrotactile stimulation, like various forms of mechanotactile stimulation, fails to seamlessly integrate its sensory feedback into the user's life.

HYBRID VIBRO-ELECTROTACTILE STIMULATION

Both vibrotactile and electrotactile stimulation methods have innate design constraints that prevent users from achieving maximum sensory feedback. Despite the constant improvements being made to each design, they will not reach levels of sensory substitution comparable to natural tactile feedback from those without prosthetic limbs. To maximize the benefits from each, a team of senior IEEE members - lead by Marco D'Alonzo, who earned his Ph.D. in Biorobotics from the Scuola Superiore Sant'Anna, Pisa, Italy - decided that instead of researching the benefits and drawbacks of each form of tactile stimulation, they would research the way the two forms interacted with and complemented one another. They hypothesized that combining the two modalities into one compact device (now known as hybrid vibro-electrotactile stimulation) would allow both forms of stimulation (electrotactile and vibrotactile) to benefit the user from one target site on the skin [9].

Although electrotactile and mechanotactile stimulation methods have individual contributions to sustainability of the design of a prosthetic limb, neither exhibits a fully functional model of a sustainable device. It is for this reason that the hybrid model is so effective at delivering sensory feedback - it maximizes the benefits each form of stimulation provides, ensuring that the device is as sustainable as possible.

Description of Technology

The HyVE interface consists of both vibrotactile and electrotactile stimulation interfaces. As shown in Figure 5, the electrotactile component consists of a concentric electrode with an outer anode and inner cathode, while the vibrotactile component consists of a stack of three coin type vibration motors (otherwise known as a vibel) placed directly over the central cathode. The electrocutaneous device is designed so as to not disrupt the mechanical vibrations of the vibrotactile device: it is thin, self-adhesive, and disposable [9]. A more durable design would be costly, and more importantly, it would be bulky and would risk altering the mechanical vibrations from the vibrotactile stimulation. The vibrotactile device houses its motors within a rigid plastic shell from which it produces mechanical vibrations. These vibrations are easily altered in frequency and amplitude, which is essential to adjusting the device to get the most efficient responses.

The reasons the vibrotactile device is placed directly over the electrocutaneous element range from simple explanations, such as to save space, to more complex answers relating the parallel nature of the electrical current and the mechanical vibrations. The device's compact nature is essential, because in the case of amputated limbs, there are limited locations in which the stimulation can be received. Additionally, the shared target site "[allows] the delivery of sophisticated stimulation patterns exploiting the two parallel information streams. It could be used as a general purpose haptic interface in numerous applications and body sites to convey multidimensional, multimodal information in a compact fashion" [9]. This refers to the idea of the interaction between the two elements of the device. The two forms of feedback relay independent information of one another but can be used complementary to one another. By placing the two streams of information on the same target site, feedback of two distinct yet related parameters can be relayed from one object. For example, when grasping an object using a prosthetic hand, a user could sense the pressure due to the pulse of the electrotactile stimulation, while also recognizing the size of the object and the type of grasping motion from the mechanical vibrations of the vibrotactile device.

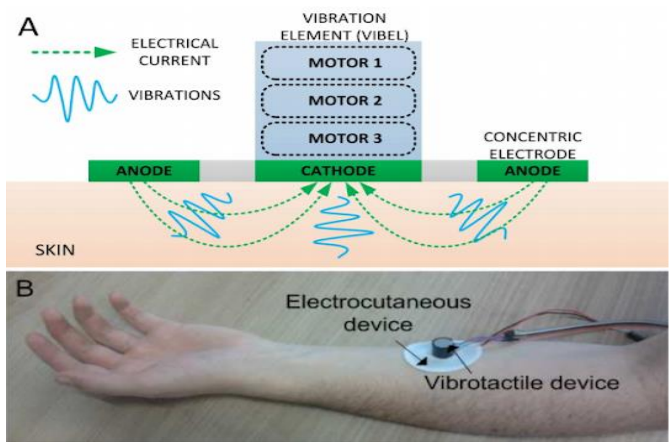

FIGURE 5 [9]
A concentric electrode in surrounded by an outer anode and inner cathode with a vibel attached directly to the central cathode. Together, these parts makes up the hybrid vibro-electrotactile stimulation system.

Even though the two stimulation methods are typically thought to be substitutes, they convey different information to different parts of the body. Because of this, they are able to complement one another, despite being thought to play the same role in the act of sensory substitution. Vibrotactile stimulation is most notably applied directly to mechanoreceptors which are very receptive to vibration, such as Pacinian or Meissner's corpuscles [9]. While electrotactile stimulation still applies its feedback directly to the skin, it is then sent throughout the skin and has the potential to affect a variety of receptors, not just those on the surface of the skin.

Advantages and Future Potential of a Dual Modality System

The combination of these two stimulation methods maximizes the sensory feedback achieved, both by utilizing the limited space efficiently, and by manipulating the complementary nature of the two forms of feedback and shaping their interactions to improve sensory feedback recognition. In Figure 6, results of the experiments performed by D'Alonzo's team using electro- and vibrotactile stimulation individually are compared to the results of the dual modality system. When comparing these results in terms of recognition rate (RR), which measures how quickly and accurately participants responded to external stimuli, vibrotactile stimulation had an RR value of 29% with a standard deviation of 7% and electrotactile stimulation had an RR value of 44% with a standard deviation of 4%. Comparatively, the hybrid modality coding resulted in an RR value of 56% with standard deviation of 11% for HyVE9 and an RR value of 72% with a standard deviation of 8% for HyVE9Z [9]. HyVE9 contains three electrical stimuli with multiple levels of vibrotactile stimulation, while HyVE9Z is identical except for replacing the third level of vibrotactile stimulation with no stimulation [9].

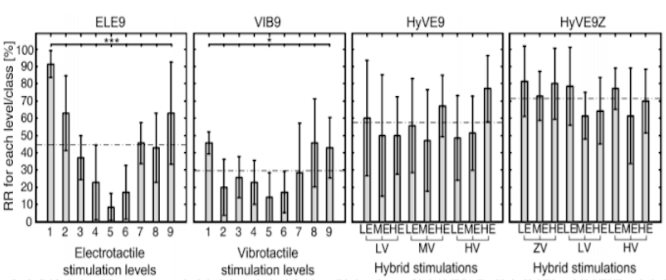

FIGURE 6 [9]
A comparison of the reaction rates between electrotactile stimulation, vibrotactile stimulation, and two methods of hybrid stimulation.

The tests performed by D'Alonzo and other researches have shown that a dual modality system of both electrotactile and vibrotactile stimulation is an improvement upon either modality individually. However, this experiment is one of the first of its kind, and there are a number of opportunities to continue to research and improve upon the methods currently being tested. There are many variables that can be changed, such as the levels of vibrotactile stimulation or the pulse widths and frequencies for electrotactile stimulation. Although prostheses have not reached the level of sensory feedback that real limbs provide, the research done on the technology in HyVE has decreased the gap between the two. Eventually, prostheses using hybrid systems will result in increased acceptance of artificial limbs as recognition rates improve over time.

POTENTIAL DIFFICULTIES IN THE IMPLEMENTATION OF HYVE TECHNOLGY

In a holistic evaluation of the HyVE technology, it is important to evaluate potential negative consequences of adding technological systems to the human body. Given how little is known about how the human body responds to certain stimuli, any disturbance creates the potential for unintended side effects, ranging from mild to serious [12]. For instance, as discussed previously, the Sauerbruch-Lebsche-Vanghetti cineplasty method resulted in scarring and wearing down of the muscles [3]. The technology used in HyVE differs from Dr. Vanghetti's cineplasty method in that the device is placed on the skin, rather than attaching directly to the muscles. However, this does not mean that HyVE technology will not experience any difficulties with implementation.

Two of the concerns that arise with methods of sensory feedback are muscle fatigue over time and the dangers of sending electric current through the skin [10]. While these issues may not become fully apparent until the devices are widely used, it is possible to evaluate how HyVE prosthetic limbs will address the potential problems. The size of the dual modality system has been addressed by D'Alonzo's research, showing that the device is compact and relatively flat [9]. The more significant concern is the danger of the electrical component of the system. If the current is set too high, the pulses begin to feel uncomfortable to the user [10]. The HyVE system minimizes the chances of this discomfort by localizing the current to a small area. Overall, while there are some potential concerns regarding the technology, the issues have been addressed and prevented by the design and implementation of technology into the HyVE system.

HYVE'S IMPACT BEYOND PROSTHETIC LIMBS

Clearly, the technology used in HyVE has an important and highly beneficial application in prosthetic limbs, but its impact does not stop there. The concept of combining mechanical and electrical systems can be used in various devices that output sensory feedback to a user. The HyVE interface represents a new application of previously known and used methods. This new application opens the door for future research to be done in various fields of engineering [9].

The combination of vibrotactile stimulation and electrotactile stimulation in a compact device responds nearly instantly to external stimulations while allowing maximum freedom of motion. This combination of benefits results in a device that satisfies modern definitions of sustainability that are concerned with ensuring equality and quality of life for everyone. Loss of a limb takes away from that equality but having a prosthetic device that can provide feedback nearly as effectively as real limbs restores the equality. As the technology in HyVE devices improves at emulating real limbs, the devices will keep promoting sustainability.

Impact on Other Devices

The multimodal interface used in HyVE can be applied to a range of portable systems, including navigation systems for the blind, video games, or rehabilitation systems [9]. Some of the most promising application are in recovering lost motor functions in rehabilitation systems [13]. Although not proven conclusively, having concurrent feedback in real time can offer benefits in motor learning, a process by which training results in a lasting change in motor performance [13]. Specifically, the concept of haptic guidance, which involves guiding a subject through a motion, can lead to strengthening of muscles and tissue, provoking motor plasticity to prevent stiffening, and reinforcement of correct movements [13]. The haptic feedback systems used to create these positive results could benefit from a dual modality system such as that used in HyVE. The technology has not been extensively tested in these types of systems, but there is great potential for the technology to improve the efficiency systems and extend beyond the scope of prosthetic limbs.

Importance for Future Research for Engineers

In addition to application to other portable devices, the technology of HyVE opens the door to extensive research for engineers. Combining different forms of mechanical stimulation, including indentation, rotation, and stretching, with different forms of electrical stimulation, including pulses and interferential currents, can increase the efficiency of processes that only use one form of modality in their current use [9]. When applied together, the two modalities would act simultaneously in time and space. The different modalities can target specific receptors to create specific sensory experiences for the user [9]. With a vast number of combinations of modalities and potential applications, the technology implemented in HyVE allows for extensive future research and discoveries.

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ACKNOWLEDGEMENTS

We would like to thank our writing instructor Tyler McAndrew for his helpful feedback in the beginning stages of our paper, and our co-chair Jenna Delozier for giving us advice on how to proceed with our paper. We would also like to that our chair, Richard Velan for showing us how to make our paper more impactful. Additionally, we would like to thank our friend Jackson Perry for his support, inspiration, and boosting our morale.