Human machine interaction in exoskeletons: a meta review

Julia Greeven[a]

[a]*Human Machine Interaction Engineer, Project March, TU Delft. The Netherlands.*

Abstract

Introduction: Because of broadened knowledge in the field of exoskeletons, more and more is possible. When an exoskeleton is becoming more self-balancing, a new look at human machine interaction is needed. Crutches, which are currently in use, that has an input device located on it are then no longer necessary. This meta review aims to research different options for giving input and providing feedback in an exoskeleton of Project MARCH.

Method: Through a surficial research several ways for giving input and providing feedback are selected. For input brain-computer interface, motion detection and smart glasses are researched further. Smart glasses and vibrotactile feedback are researched further as an option for providing feedback. The functioning and (dis)advantages of these forms are described in this review. Furthermore, it was examined how these forms can be used for walking in an exoskeleton and whether they already have been used. A research on augmented and virtual reality has also been done to see if this is an interesting opportunity for us to use this and benefit from it.

Results: All these ways to give input or provide feedback have their own advantages and disadvantages. Brain-computer interface has already been used in controlling an exoskeleton. However, to become reliable improvements in hardware are necessary. Smart glasses and motion detection of the arm/hand have not yet been used in controlling an exoskelet. For providing feedback, vibrotactile feedback has already been used within the exoskeleton technology and is a profitable implementation for users. Also, smart glasses are already known in this field and can be used to give the user of an exoskeleton several feedback. Augmented and virtual reality have been used during walking in an exoskeleton for training and feedback, but not in a very extensive way.

Conclusions: Because brain-computer interface can be a drastic implementation, requires extensive training and is not always reliable it is not the most preferable option for us to use in controlling an exoskeleton. However, it is a developing technology and still very fascinating to test in exoskeletons. On the other hand, smart glasses and motion detection are easier to implement and can also be interesting for us to test and use in controlling an exoskeleton. For feedback, vibrotactile feedback will give people with a spinal cord injury the missing haptic feedback back. Therefore, there are great opportunities to make walking in an exoskeleton feel more like normal walking. Also, smart glasses can be a great way to give feedback in an exoskeleton. Augmented and virtual reality are an upcoming technology and can be very interesting within exoskeleton technology. It can serve as a training method or be used with a more educational approach.

Introduction and method

By developing an exoskeleton with Project MARCH, we give greater freedom of movement back to people with a spinal cord injury. People experience the practical advantages of autonomy, such as going and standing wherever he or she want. Because of broadened knowledge in this area, more and more is possible. For example, making an exoskeleton that is more self-balancing. It is still evolving but at some point, there will be a time when the pilot can balance her or himself in the exoskeleton. Then the crutches, which are currently in use, are no longer necessary. And because the input device is now located on the crutches, it means that input and feedback for the pilot has to be given in another way.

Therefore, a new look at human machine interaction is needed. We are looking for ways that are more intuitive for controlling an exoskeleton. It should be more like natural walking and giving input and getting feedback has to ensure good performance for the pilot. Especially when the pilot is unexperienced, it is important that controlling an exoskeleton is easy and universal.

Through a surficial research I selected several ways for giving input and providing feedback that full fil this purpose. These ways I have researched further to see if they are interesting and perhaps can be used in our future exoskeleton. I described the functioning and (dis)advantages of using these forms of input and feedback. Furthermore, I wanted to know how these ways can be used for walking in an exoskeleton and whether it already has been used.

For input I researched the following options:

- Brain-computer Interface
- Motion detection
- Smart Glasses

And for feedback:

- Smart Glasses
- Vibrotactile feedback

Besides, I did further research into another topic, namely Virtual Reality and Augmented Reality. I wanted to see if this is an interesting opportunity for us to use this and benefit from it. Based on the following questions I want to conclude if these above-mentioned options are interesting possibilities and could be realistic for us.

1. What kind of input could be interesting and realistic (for us) to use in controlling an exoskeleton?

   - How do these forms of input work?
   - What are the advantages and disadvantages of this form of input?
   - How can it be used in controlling an exoskeleton?
   - Has it already been used in exoskeletons?

2. How can we provide more and useful feedback to especially inexperienced pilots in an exoskeleton?

   - What do these forms of feedback consists of and how do they work?
   - What are the advantages and disadvantages of this form of feedback?
   - In what way can it help the performance and comfort of the pilot while controlling the exoskeleton?
   - Has it already been used in exoskeletons?

3. How can Augmented or Virtual Reality be used to give the user a feeling as if you are in an exoskeleton and get this form of feedback or use this form of input?

- What is the difference between Augmented Reality and Virtual Reality?
- What are the options with these two techniques in this area?
- What is a realistic option?

Results

Giving input

Brain-computer interface (BCI)

Nerve electrodes are found to be one of the most promising interfaces in the future for intuitive user control. Without a manual interface walking in an exoskeleton will look more like natural walking. The main goal of brain-computer interface is to replace or restore useful function to people disabled by for example spinal cord injury.[4]

Brain-computer interfaces (BCI) uses electrophysiological measures of brain activity to enable communication with external devices, such as computers and prostheses. By modulating changes in electroencephalographic (EEG) activity, BCI users have demonstrated two-dimensional cursor control and the ability to type out messages on virtual keyboards.[4]

The purpose of a BCI is to detect and quantify features of brain signals that indicate the user's intentions and to translate these features in real time into device commands that accomplish the user's intent (*Figure 1*). To achieve this, a BCI system consists of 4 sequential components:

- Signal acquisition: measurement of brain signals using a particular sensor modality. The signals are amplified to levels suitable for electronic processing and then digitized and transmitted to a computer.
- Feature extraction: process of analysing the digital signals to distinguish pertinent signal characteristics from extraneous content and representing them in a compact form suitable for translation into output commands.
- Feature translation: converter of the features into the appropriate commands for the output device.

- Device output: the commands from the feature translation algorithm operate the external device. Feedback from the device enables the user to modify the brain signals in order to maintain effective device performance, thus closing the control loop.[4]

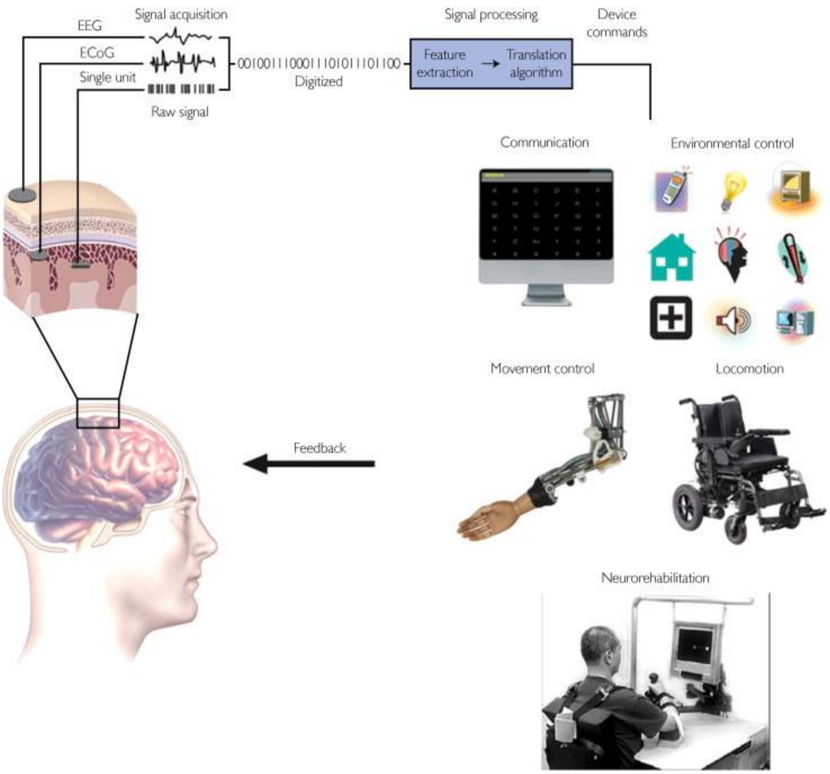

Figure 1. Components of a BCI system [4]

Brain-computer interfaces do not read minds in the sense of extracting information from unsuspecting or unwilling users but enable users to act on the world by using brain signals rather than muscles. The user and the BCI work together. The user, often after a period of training, generates brain signals that encode intention, and the BCI, also after training, decodes the signals and translates them into commands to an output device that accomplishes the user's intention.

Electrical signals from brain activity are detected by recording electrodes located on the scalp, on the cortical surface, or within the brain. So, an implanted brain-computer interface (invasive) or a cap with EEG electrodes (non-invasive). Most of the early BCI work used scalp-recorded EEG signals, which have the advantages of being easy, safe, and inexpensive to acquire. The main disadvantage of scalp recordings is that the electrical signals are significantly attenuated in the process of passing through the dura, skull, and scalp. Thus, important information may be lost. The problem is not simply theoretical: epileptologists have long known that some seizures that are clearly identifiable during intracranial recordings are not seen on scalp EEG.

Furthermore, it requires extensive training to use this method. Given this possible limitation, recent BCI work has also explored ways of recording intracranially. Which has the disadvantage that recording single-neuron entails significant clinical risks and has limited stability.[4] Shown in *Figure 1*, also ECoG activity can be recorded from the cortical surface what requires an implantation of a subdural or epidural electrode array. Results suggest that an ECoG-based BCI could provide for people with severe motor disabilities a non-muscular communication and control option that is more powerful than EEG-based BCIs and is potentially more stable and less traumatic than BCIs that use electrodes penetrating the brain.[3]

Brain-computer interface research and development generates tremendous excitement in scientists, engineers, clinicians, and the general public. This excitement reflects the rich promise of BCIs. They may eventually be used routinely to replace or restore useful function for people severely disabled by neuromuscular disorders. At the same time, this exciting future can come about only if BCI researchers and developers engage and solve main challenges: Signal-acquisition hardware and reliability, BCI validation and dissemination and complexity of the set-up.[5]

All BCI systems depend on the sensors and associated hardware that acquire the brain signals. Improvements in this hardware are critical to the future of BCIs. The recording of neural signals during walking might be affected by motion artifacts, which could bias the decoding and lead to misinterpretation of the neural dynamics associated with the movement, although there is evidence showing that the influence of these artifacts can be reduced by using carefully designed set-ups.[5]

Ideally, EEG-based (non-invasive) BCIs should have electrodes that do not require skin abrasion or conductive gel, be small and fully portable, be easy to set up, operate by telemetry instead of requiring wiring and interface easily with a wide range of applications. In principle, many of these needs could be met with current technology, and dry electrode options are beginning to become available. The achievement of good performance in all environments may prove to be the most difficult requirement.[4] The current state of the art in non-invasive BMI technology does not allow for precise decoding of fine limb kinematics. Therefore, an accepted approach in the literature is to have a shared control paradigm in which the brain activity is used to trigger the movement of a robot/prosthesis that can autonomously perform a functional task.[5]

The complexity of the set-up required to control a device for gait assistance with neural signals. In the recent years, pilot studies have shown how BMIs have been used to control weight-suspended robotic and prosthetic systems. Furthermore, robotic exoskeletons with balance control have also been controlled using brain signals. All these studies are performed with devices that support balance, which minimizes fall risks, and three of them demonstrated successful control with SCI patients.[5] However, the control of ambulatory exoskeletons with a BMI presents additional issues compared to those systems with balance support. Even if it is used by patients with a relatively good condition (e.g., legs weakness and/or certain degree of balance control), they are required to maintain the balance by holding on to a walker or to parallel bars, and to focus on the intention of motion to command the BMI. This kind of set-up would permit the development of assist-as-needed rehabilitative interventions for such patients, which may lead to higher motor improvements. Hence, the validation of a BMI to control an ambulatory exoskeleton requires the design of a protocol with special considerations, such as safety, timings and control of patients' fatigue levels during the experiments. Overall, the day-to-day and moment-to-moment reliability of BCI performance must be improved so that it approaches the reliability of natural muscle-based function.[4]

Figure 2. MindWalker using BCI [9]

There are several headsets with scalp sensors on the market that can be used in conjunction with a personal computer to create a system for controlling third-party software applications. These and similar headsets have been incorporated into several commercial games, some of which claim to enhance focus and concentration via EEG-based neurofeedback. The central issue with these devices is that the nature of the signals they record is not clear. It seems probable that almost all of these devices record mostly nonbrain signals such as electromyographic signals from cranial or facial muscles or electro-oculographic signals from eye movements and blinks. Thus, they are unlikely to be actual BCI systems.[4]

Researchers have been exploring their capabilities for providing control of orthotic, prosthetic, and external movement-assistive devices. Because of above mentioned drawbacks the applicability of BCIs as control interfaces of active movement-assistive devices is limited. This form of interface is also used in controlling an exoskeleton. The MindWalker (*Figure* 2) uses BNCI (brain-neural-computer interface) technology, which can be used to convert either EEG (electroencephalography) signals from the brain, or EMG (electromyography) signals from patient’s shoulder muscles, into electronic commands. The glasses that the user is wearing stimulate the retina with several flashing lights at different frequencies, and depending on which flashing light the users looks at, the brain will generate electrical activity at the same (or a multiple) frequency as the visual stimulus. With this method, different control states are assigned to the electrical brain signals with specific frequencies. The electronic commands are then used to control an exoskeleton attached to the user's legs.[9]

Another exoskeleton which uses a brain-controlled interface is Thertact-Exo (*Figure 3*). Their goal is to develop an exoskeleton that is directly controlled by the brain activity of the user. The user just has to think about walking and the brain's electroencephalography registered by EEG in real time will be decoded. And then serves as an instruction for the exoskeleton begins the walk. They use combinations of techniques, namely virtual reality and tactile and thermal feedback, which can lead to significant improvements in spinal cord injury cases.[10]

Figure 3. Thertact-exo using brain activity for input [10]

Motion detection (arm/hand)

Since we manipulate the physical world most often and most naturally with our hands, there is a great desire to apply the skills, dexterity, and naturalness of the hand directly to the human-computer interface. However, when we work with a computer or computer-controlled application, we are constrained by clumsy intermediary devices such as keyboards, mice, and joysticks. In an effort to change this, people have been designing, building, and studying ways of getting computers to "read" users' hands directly, free from the limitations of intermediary devices. The development of electronic gloves as interfaces to computer-controlled devices has been an important step in this direction.[7]

A variety of technologies have been used to capture mechanical and gestural information from the hand. They can be divided into position tracking, which uses optical, magnetic, or acoustic sensing to determine the 3-space position of the hand, and glove technologies, which use an electromechanical device fitted over the hand and fingers to determine hand shape.[7]

Hand position is characterized by the location of the hand in space and the orientation of the palm. Three technologies used predominantly to track the position of the hand are optically based (using cameras to examine the hand from a distance), magnetically based or acoustically based. Optical tracking uses small markers on the body (LEDs or reflecting dots), which a series of two or more cameras surround the subject can pick out the markers in their visual field. Software correlates the marker positions in the multiple viewpoints and uses the different lens perspectives to calculate a 3D coordinate for each marker.

Another method uses a single camera to capture the silhouette image of the subject, which is analysed to determine positions of the various pans of the body and user gestures.

Magnetic tracking uses a source element radiating a magnetic field and a small sensor that reports its position and orientation with respect to the source. They are generally accurate to better than 0.1 inches in position and 0.1 degrees in rotation. Magnetic systems do not rely on line-of-sight observation, as do optical and acoustic systems, but metallic objects in the environment will distort the magnetic field, giving erroneous readings. They also require cable attachment to a central device (as do LED and acoustic systems). However, the current technology is quite robust and widely used for single or double hand-tracking.

Acoustic trackers use high-frequency sound to triangulate a source within the work area. Most systems send out pings from the source (mounted on the hand, for instance) received by microphones in the environment. Precise placement of the microphones allows the system to locate the source in space to within a few millimetres. These systems rely on line-of-sight between the source and the microphones, and can suffer from acoustic reflections if surrounded by hard walls or other acoustically reflective surfaces. If multiple acoustic trackers are used together, they must operate at nonconflicting frequencies, a strategy also used in magnetic tracking.[7]

Glove devices measure the shape of the hand as the fingers and palm flex. Over the past decade, especially in the last few years, many researchers have built hand and gesture measuring devices for computer input, for example the DataGlove (1987) and the CyberGlove (1998).[7] They use multiple sensors or strain gauges located in the glove on the different positions to sense finger or wrist bending. The CyberGlove by James Kramer use a small electronic box which converts the analog signals into a digital stream that can be read by a computer’s standard serial port. A 3-space tracker can be mounted on the glove to get hand position in space. Informal experiments have found the CyberGlove's performance to be smooth and stable, with resolutions within a single degree of flexion. A useful feature of the CyberGlove is the capability to change the A/D hardware sensor offsets and gains from software, permitting the sensors to be tuned to use the full A/D range on a per-user basis. It is a comfortable glove, easy to use, and has an accuracy and precision well suited for complex gestural work or fine manipulations.[7]

In many applications, the hand's graphic image is displayed in an interactive computer environment and used as a tool for "point, reach, and grab" interaction. The gloves are used as a master for a graphical hand in a virtual environment. The user could grab, move, and throw objects with the graphical hand, as well as use finger postures and motions to select from on-screen menus.

The advantage of this model of interaction is naturalness— users' actions correlate closely with those that might be performed on physical objects. However, in each of these applications, the DataGIove functions as little more than a 3D joystick with several buttons. They first considered implementing the virtual hand as a dynamic object in the simulated environment so that grabbing, pushing, and other interactions would be physically based. However, lacking the appropriate computing power to use this scheme in real time, we approximated the functionality with posture recognition. In fact, the DataGIove was occasionally replaced by a Spaceball—a six-degree-of-freedom force input device with eight buttons—since its software interface closely resembled that of the DataGIove, with button events substituting for posture recognition. Not surprisingly, many researchers and companies developing systems for virtual environments favour 3D joysticks over the more expensive glove devices.[7]

More advanced use of the glove takes advantage of the extra capabilities of the hand over a 3D joystick. AT&T Bell Laboratories" used a DataGIove in the same way as the systems described above with the addition of two thumb-based gesture controls they called "clutch" and "throttle." They used clutching for incremental transforms, such as rotation. The screen object followed the rotation of the hand only when the thumb was brought against the index finger. Thus, object manipulations could be ratcheted, instead of twisting the hand uncomfortably. Their gesture recognition algorithm is a hybrid, using an extension of Dean Rubine's excellent method of feature analysis. They've achieved high recognition rates for both trained and untrained users.[7]

Glove interfaces in teleoperation and robotic control are important for facile, dexterous control of the remote end. Two research projects have used the DataGIove to control a dexterous robot hand. AT&T constructed algebraic transformation matrices to map human hand poses to robot hand poses. The transformation matrices compensated for the kinematic differences between the human hand, as measured by the DataGlove, and the robot hand. The user controlled the robot hand by mimicking the desired poses.[7]

As research continues, hand- and finger-tracking devices will improve, along with gesture recognition and interface software. Despite many advances in this area, glove-based input or more generally, whole-hand input, remains in its infancy. For the most part, the user must still wear a device such as a glove, or work in a special environment such as a room brightly lit for video cameras. Achieving the goal of "deviceless" natural computer interaction with the hands and body requires advances in many areas, including freeing the user from electrical connecting cables, improving the speed and accuracy of tracking devices, lowering manufacturing costs, and developing more commercial applications for the technology.[7]

In this research, I haven’t found a project where they used glove-based input for controlling a whole exoskeleton. I do found studies where hand-gesture recognition interface systems have been used for the control of external robotic arms. The interface was specifically developed for individuals with upper-level spinal cord injuries (SCIs) to perform a variety of simple object-retrieval tasks. One camera was used to interpret the hand gestures and locate the operator’s face for object positioning.[9]

A similar interface was developed by Martin et al. and used several infrared sensors to measure hand movements to control an active arm support for patients suffering from muscular weakness. They rely on hand gestures for controlling the exoskeleton movements. Hand gesture recognition for Human Machine Interface is an active research topic, but image-based approaches require computationally demanding algorithms and constraint environment, which were not compatible with their used exoskeleton project.[13]

Smart glasses

Smart glasses are wearable computer glasses that combine few key components which work together to create the effect of extra items added to the real world, also called an augmented reality. While early models can perform basic tasks, such as serving as a front-end display for a remote system, as in the case of smart glasses utilizing cellular technology or Wi-Fi, modern smart glasses are effectively wearable computers which can run self-contained mobile apps. Some are handsfree and can communicate with the Internet via natural language voice commands, while others use touch buttons. Like other computers, smart glasses may collect information from internal or external sensors. It may control or retrieve data from other instruments or computers and it may support wireless technologies like Bluetooth, Wi-Fi, and GPS.[15]

The display of augmented reality glasses is also known as the combiner. This name is an accurate description of the component. It combines glass lenses which allow natural light to pass on through to the eyes with digital LED or OLED displays which send the computer-generated images to the eyes. Thus, when one wears augmented reality glasses, they see images from a double source: the real world outside and the computer-generated objects.[8]

The AR mobile or web app cannot exactly see through your eyes. It needs a camera to record the images in the real world, which is attached to the AR glasses. The registration consists of icons (which the wearer cannot see) through which the computerized part of the devices places an AR object in the real world. The icons or markers use various landmarks from the real-world image for guidance, such as the corner made between two walls, the lines of the window, the geometrical shape of a carpet, etc. Then, a programmed app or software suite has to combine the two types of images – the one supplied by the camera and the one generated by the registration with the aid of the markers. The result of this combination is what you actually see through the augmented reality glasses.[8]

One of the important issues to consider choosing AR glasses is field of view. The usual human field of view is around 210 degrees horizontally and 150 degrees vertically. AR glasses cannot reproduce these numbers, first of all due to the physical limitations of placing the lenses in a headset. Then there is the issue of the computing power needed to process and display the digital objects with a reasonably high fidelity and resolution. At the present, a 50-degree field of view is already considered large for augmented reality glasses.[8]

Smart glasses are fitted with several features that contribute as a human machine interface. They provide the user with the option to give input. These options are a multi-touch gesture touchpad, buttons, speech recognition technology, gesture recognition and eye tracking. By using these options, it is possible to control and give further instructions an exoskeleton. Unfortunately, there are some drawbacks of using smart glasses. They could project text or video into your field of vision which ensures a lot of potential for distraction. It can be dangerous to have less aware of the surroundings. Furthermore, by using your hands for the options buttons, touchpad and gesture recognitions the pilot of the exoskeleton can also be distracted and could lose his or her balance.

Other drawbacks of using smart glasses are the risk of losing the Bluetooth or Wi-Fi connection, privacy concerns and the risk of running out of batteries. Concerns have been raised by various sources regarding the intrusion of privacy, and the etiquette and ethics of using the device in public and recording people without their permission. Today most Augmented Reality devices look bulky, and applications such as navigation, a real-time tourist guide, and recording, can drain smart glasses' batteries in about 1–4 hours. Battery life might be improved by using lower-power display systems or wearing a battery pack elsewhere on the body (such as a belt pack or companion smart necklace).[15]

In controlling exoskeletons, smart glasses have not been used for input yet. Only for serving as a body support for people with injury or paralysis and assisting movement, an exoskeleton made use of an augmented reality viewer showing three-dimensional spaces to be traversed by the patient for rehabilitation.[14] In addition, smart glasses are more used in providing users with feedback. More research about this, can be read in the second research question.

Figure 4 Man wearing smart glasses for augmented reality [8]

Eye detection for input

Human Computer Interface (HCI) control input needs to be methods lend themselves to mobility and/or hands-free use are good candidates. Eye tracking systems are a common method for the control of spelling devices or computer cursors in patients with severe movement impairments. Several eye-trackers have been developed, including camera-based methods, which measure changes in corneal reflection while infrared light is projected to the eye, and electrical-based methods that measure the electrooculographic (EOG) potential from surface electrodes.

A study proposed an innovative system based on EOG and a programmable central pattern generator to control a lower-limb prosthesis. The control method was composed of two steps: First, an EOG-based eye-tracking system generated high-level control commands (such as faster, slower, or stop), according to specific eye movement sequences executed by the user; and second, a pattern generator, following the high-level commands derived from the user's eye motion, provided the low-level commands for the control of the actuators.[9]

In another study, EOG was used to control two-dimensional movements of an external robotic arm that resembled the human arm configuration. Eye movement patterns such us saccades, fixation, or blinks were detected from the raw eye gaze movement data by a pattern-recognition algorithm and converted into control signals according to predefined protocols. The authors suggested that one option to extend the movement control to three-dimensional space was to switch between predefined action planes in which the EOG control would still be two-dimensional.

While eye movement interfaces proved to be very accurate in two-dimensional space, three-dimensional gaze-tracking is more challenging. The three-dimensional gaze-tracking problem consists of mapping pupil coordinates for left and right eye to a three-dimensional point referenced to the user's head coordinated. A recent study presents an ultra-low-cost binocular three-dimensional gaze tracking system, which the authors plan to use to control wheelchair navigation or end point control of robotic arms.[9]

Also, eye movement detection interfaces can distract the user, because of making certain movements with the eye. Then the user could be less concerned with what is happening in the surroundings. Eye movements are also easy and fast to make. Therefore, wrong movements can be made and incorrect input can be caused.

Feedback

Vibrotactile feedback

Biofeedback is the process of gaining greater awareness of many physiological functions of one's own body, commercially by using electronic or other instruments, and with a goal of being able to manipulate the body's systems at will. Humans conduct biofeedback naturally all the time, at varied levels of consciousness and intentionality. Biofeedback and the biofeedback loop can also be thought of as self-regulation. Biofeedback may be used to improve health, performance, and the physiological changes that often occur in conjunction with changes to thoughts, emotions, and behaviour. Recently, technologies have provided assistance with intentional biofeedback.[21]

Vibrotactile feedback is a simple and compact mechanism commonly used in non-invasive haptic feedback systems because it’s safe, straightforward to implement, and frees the user from having to maintain visual attention of the actuator. Many vibrotactile feedback systems are used to convey information through a tactile interface when visual attention was deemed inefficient or unnecessary.

The human skin has a specialized type of receptor in certain parts of our skin called a Pacinian Corpuscle that is tuned to detect these vibrations. These little onion-like receptors are exquisitely sensitive to vibrations of up to 1000 hertz (cycles per second, a measure of frequency). For comparison, the fundamental frequency of human speech is in the low hundreds of hertz. Under the right conditions, our skin can actually feel many of the sounds we hear, including speech. Like tactile feedback devices, vibrotactile feedback devices also consist of one or more actuators in contact with the skin. Tactile feedback devices are challenging to construct because these actuators must be closely spaced and must exhibit high displacement relative to their size. The good news with vibrotactile feedback is that both requirements are significantly lessened. The receptors in the skin that detect vibrations have much larger receptive fields than those that detect tactile stimuli. This means that the number of vibrotactile actuators required for a given area of skin is only a small fraction of the number of tactile actuators required in the same area. The displacement requirements are also much more forgiving. Tactile actuators require displacements of up to about 2 centimetres to accurately reproduce pressures on the skin surface. On the other hand, due to the sensitivity of the skin to vibration, vibrotactile actuators can get away with just a fraction of a millimetre of displacement.[22]

Vibrotactile feedback devices are relatively easy to construct and vibration feedback is important for many parts of tactile perception. However, why do we need any other sensory channels in haptics? Unfortunately, as anyone who has tried a vibrotactile feedback device can attest, vibrotactile feedback on its own tends to be quite limited in its realism and richness. In the real world, vibrations are usually created as a secondary part of a holistic haptic interaction. Imagine swinging a hammer in virtual reality. When it strikes the surface of a glowing hot sword, a high-quality vibrotactile actuator would accurately simulate the vibration of the strike. Except, without the other sensory channels you would be missing the weight and shape of the hammer in your hand, the pressure of the hammer against your skin as you grasp it, and the force of the blow stopping your arm and hand. Without these cues, the virtual hammer wouldn’t feel much like a real one despite the accurate vibrations. Therefore, having vibrotactile feedback without tactile or force feedback is not enough.[22]

Another real challenge with vibrotactile feedback is on the software side. A developing of the software that simulates the complex physical interactions that produce haptic vibrations is necessary. By faithfully simulating these interactions, a more accurate and realistic vibrotactile sensations can be produced.[22]

Human skin has long been recognized as a receptor for communicating information. Skin sensations such as pressure, vibration, and stretch can convey tactile messages that are carried to the brain via afferent nerves. For example, tactile feedback can be used to encode pressure and vibration measurements from a prosthesis to the skin of a user. To train human movement, kinematics can be measured in real time and compared with predefined desired kinematics, and tactile feedback amplitude or frequency can then be modulated proportionally to error signals to alert users of desired changes. Similarly, tactile feedback has been used to train repetitive movements such as swimming or gait in which case feedback is initiated in periodic pulses instead of continuously. Another approach is the expert-trainee paradigm in which the expert performs movements, which are followed by the trainee via haptic feedback based on the kinematic errors between the expert and trainee.[20]

Traditional methods of teaching motor skills often center on an instructor providing targeted feedback to adjust the trainee’s movements. This feedback can come in the form of verbal cues, such as “lift your arm higher,” or visual cues that range from demonstrating the proper movement to reviewing a sophisticated motion capture recording. It is also common for a coach or therapist to grasp the limb of the trainee and move it along the proper trajectory so that he or she can experience the desired motion. One potential drawback of these traditional methods is that the feedback is not provided in real time, so trainees may be unsure of precisely when and how to correct their motions. In more recent years, advances in motion detection technology have made it feasible to assess human movement instantaneously and with high accuracy, creating the possibility of teaching motor skills using new interaction methods. In particular, multi-modal interaction devices that incorporate tactile feedback to guide an individual’s motions have become increasingly popular and span a wide range of application areas. The idea of using real-time tactile cues to correct motion errors is appealing because the subject can receive spatially localized feedback while performing the motion normally, without needing to shift their visual attention.[17]

Vibrotactile feedback has been shown to be an effective means of delivering tactile cues to humans. The small size of vibrotactile actuators allows them to be embedded in lightweight garments that do not hinder the movement of the wearer. Actuators placed in almost any location on the skin can deliver vibrotactile cues that the wearer can detect, and modulating the frequency and amplitude of vibration provides variation in the stimuli that users can distinguish. A study found that when frequency and amplitude of vibrations of an actuator on the forearm varied coherently, users were able to discriminate between the different vibrotactile stimuli with higher accuracy. Another study explored vibration as a sensory substitute for controlling manipulation forces of a prosthetic hand, and they similarly found that varying the vibration parameters enabled users to distinguish between multiple stimuli.[17]

One promising application of a tactile motion guidance system is to allow rehabilitation patients to practice motions on their own and receive guidance on how to improve their movements without the constant presence of a coach or therapist.

However, the use of tactile feedback in motor skill acquisition has been shown to have mixed results, and the long-term effectiveness of the feedback has been relatively unexplored. A study has developed a system that delivers vibration cues around the waist to control body posture. They successfully demonstrated that users can follow the body tilt motions of a trainer using an array of vibration actuators and that patients can use the system to modify their medial lateral trunk tilt to improve their postural sway. Greater benefits of the feedback were seen in the more complex tasks, and patients preferred to receive the feedback continuously rather than at discrete moments; longer term retention has not yet been tested.[17]

The fidelity of haptic feedback varies greatly between systems and can impact how useful the feedback is to the user. Haptic motion guidance systems often use expensive motion sensing systems and/or expensive tactile actuators, e.g., making these systems impractical for use in everyday settings such as the home. Furthermore, a key aspect of the systems is that the tasks focused on controlling an end effector (tennis racquet, rowing oar), and the precise orientation of the user's limbs was not considered. In certain rehabilitation populations, such as left hemisphere stroke, the orientation and coordination of the joints may preclude optimal task completion. Thus, there is considerable interest in the effectiveness of tactile feedback provided by lightweight, lower-cost vibrotactile actuators worn on the user's body to correct precise joint orientation.[17]

Nowadays, prosthetic hands have achieved remarkable mechatronic capabilities. However, a lot of amputees wearing myoelectrical controlled prostheses do not use them regularly or at all due to a lack of tactile sensory feedback. Current grasp information in prosthetic users occurs through visual observation (77 %), listening (67 %) and residual limb sensations (57 %). Haptics for total impairment aims to restore missing tactile or proprioceptive information vital to prosthetic grasp to prolong sustained prosthesis use. A major challenge is orchestrating spatial and temporal stimulation patterns and energy demands such that they give rise to congruent neuronal representations of vibration, contact, force, pressure, slip or muscle impedance during long-term use.[20]

Haptic feedback for upper limb prostheses restores the sense of touch by relaying force, pressure, and slip measurements to the user. Force and pressure feedback are commonly used in tactile devices to relay information about grip force. This information is typically transmitted mechanically, such as through skin tapping, or through electro- or vibro-stimulation. Patterson et al. translated grip pressure from an object to hydraulic pressure in a cuff around the upper arm. By comparing combinations of pressure, vibration, and vision feedback, they found that pressure feedback resulted in the highest grasp performance. Rombokas et al. found that vibrotactile feedback applied to the upper arm in force-motion tasks improved virtual manipulation performance for able bodied and prosthetic users.[20]

While a variety of lower limb prostheses exist, relatively few provide sensory feedback as compared to upper limb prosthetics. However, the absence of feedback can lead to abnormalities in gait coordination, deficient balance, and prolonged rehabilitation. To relay ground-to-prosthesis contact force information, a study developed a tactile system consisting of a cuff of four silicone pneumatic balloons placed around the thigh that respond monotonically to pressure patterns recorded by force sensors in the insole of the user. Six healthy subjects were able to differentiate inflation patterns and direction of pressure stimuli, recognize three force levels and discriminate gait movements with 99.0 %, 94.8 %, 94.4 % and 95.8 % accuracy, respectively (Fan et al.).[20] Another study mapped the force recorded in the insole to vibrotactile feedback on the thigh skin, providing information about gate-phase transition (Crea et al).[20] They demonstrated that the spatial and temporal relationships between vibrotactile time-discrete feedback and gait-phase transitions can be learned. In a study on twenty-four transtibial prostheses users, they conveyed body motion through vibratory feedback proportional to signals from force sensors placed under the prosthetic foot. Vibratory feedback improved postural stability and reduced response time for avoiding falls. Proprioceptive feedback in lower-limb prostheses was investigated by Buma et al. using a spatial electro tactile display of the prosthetic knee angle during gait. Subjects wore electrodes on the medial side of the thigh just above the knee, and the results showed that intermittent stimulation reduced habituation after 15 minutes.[20]

In the field of prosthetics, in which sensory information is also missing, questionnaires have been used to derive user preferences for future upper-limb prostheses. The addition of sensory feedback was considered as one of the major future improvements in prosthetics. In studies with lower-limb amputee subjects and sensory feedback, the applied stimulation methods vary largely. Besides the choice for a stimulation method, also different feedback parameters were investigated in these studies. The sensory feedback usually resulted in a better gait symmetry or increased confidence during walking. The described stimulation methods can also be applied in wearable exoskeletons, but the optimal feedback parameters will most likely differ, because the focus for prosthetics is on the prosthetic leg use and restoring symmetry, while for wearable exoskeletons both legs are involved.[26]

Another study also developed a vibrotactile feedback device that provides phase-based proprioceptive feedback to the user based on the COP location of the prosthetic foot. The device was shown to reduce variability in stride length, step width, and trunk sway in novice prosthetic leg users. From these results we might infer that the COP is an important part of proprioception that should be restored in transfemoral amputees. Less significant changes in the stride length variation may have been observe. The obvious next step is to retrofit the device to work with amputees and to prove that the improvements translate well. Another potential testing group could be those with peripheral neuropathy. This condition, which is commonly associated with diabetes, results in the loss of sensation in the distal extremities like feet. Assuming the potential subjects still have feeling in the thigh, our feedback system could be used without modification. The results should directly translate over to this group of people; however, experiments would be necessary to confirm this.[24]

The results of several sets of experiments show that vibrotactile feedback of body tilt can be used to help control body motion under a variety of conditions and tasks. While more work is needed, vibrotactile feedback may eventually be a valuable adjunct to balance rehabilitation that can be used by physical therapists and individuals with balance dysfunction. Further refinement of prosthetic devices for balance rehabilitation using vibrotactile feedback is currently ongoing, including testing of a slim, light belt-like device, which may greatly enhance the clinical applicability of this emerging technology.[19]

David Eaglemen in his TedTalk at Google also talks about vibrotactile feedback vests and creating new human sense[2]: “They are working with patients with prosthetics legs. For somebody with a prosthetic, it is actually hard to learn how to walk because you are not feeling your leg. You have to actually look where the leg is to understand where it is sitting at al moments. So, they just hooked op pressure and angle sensors into a prosthetic, and then you feel that on your torso. And it turns out, this is unbelievably helpful in getting someone to just use it and walk, because it’s just like your real leg. And you are feeling what your real leg is doing. It’s just you feel it on a slightly different patch of skin. That is quite easy for the brain to figure out.”

Figure 5. David Eagleman in a vibrotactile feedback vest [2]

The company Tactile Navigation Tools develops a vibrotactile feedback vest embedded with sensors that can detect objects or people nearby and convert the signals into vibrations felt by the body. The vest has different types of sensors, including lidar, a laser-based system (used in driverless cars) ultrasound, a type of high-pitched sound (used by bats) and infrared, a type of electromagnetic radiation used by some animals to detect body heat from their prey. When the sensors detect an object, their signals will be converted into vibrations in a corresponding part of the vest. For example, when the vest senses a dog in the wearer's lower left field of view, vibrators on the lower left part of the vest (as viewed by the wearer) will activate. The device will represent a third dimension (depth) using the frequency of vibration. The device is designed to be intuitive, but the brain still needs to be trained to interpret the vibrations. However, when someone gets used to the vibrations and what they mean, it's going to become hardwired in the brain, until the person doesn't have to consciously think about it.[18]

Another vibrotactile feedback vest used in a study by Morrison et al.[27] is made of two layers, an inner layer consisting of one size-fits all adjustable harness (*Figure 6a*) and an outer layer consisting of an enclosing vest (*Figure 6c*). The harness houses 32 actuators, moveable to ensure they are placed exactly on each different shaped body. The lower harness fits around the legs, to safeguard that the harness stays pulled down and keeps the actuators in place while the participants move around. The actuators are operated in overlapping patterns to provide different haptic synaesthesia sensations such as sense of movement, shiver and states of activation and/or calming as well as providing navigational cues. They explored the positioning and combinations of the actuators with a kinesiologist trained in neurophysiology.[27]

Figure 6. The vibrotactile vest: adjustable harness (a) front and (b) back and (c) outer shell and skirt-apron [27]

For the initial patterns, 29 actuators were used (*Figure 7*). These patterns try to emulate the hands-on work that a kinesiologist neurophysiologist does in activating sequential points of the body. In addition, they emulated the natural touching they give each other for calming-comforting (e.g. stroking the back to calm or comfort a person), guidance-navigation (e.g. placing hands on nape of back and shoulder as if to support and guide an elder) or information-instruction (e.g. stopping the body with pulses to the solar plexus).

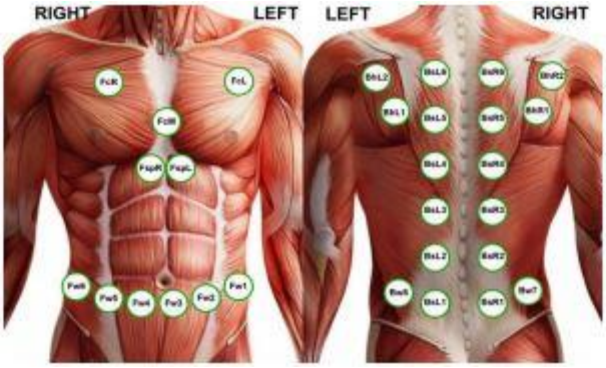

Figure 7. Placemet of actuators [27]

Vibrotactile feedback has not only been used in helping people with prosthetics to get sensory feedback back. For people who are walking in an exoskeleton it can also be very helpful. For example, vibrotactile feedback can helps to ensure a straight body position, gives a warning when an obstacle is approaching or give sensory feedback back to the upper body when the legs touch the ground. Wearable exoskeletons can be a powerful tool for the facilitation of ambulation of complete Spinal Cord Injury (SCI) subjects, which has several psychological and physical advantages. However, exoskeleton control is difficult for this group of users and requires a long period of training. People with SCI not only lack the motor control, but also miss the sensory information from below the level of the lesion, which is for example very important in their perception of body posture and makes balancing with an exoskeleton difficult. It is hypothesized that through sensory substitution part of the missing sensory information can be provided and might thereby improve the control of an exoskeleton. Furthermore, (sensory) feedback plays an important role in the learning of motor tasks and adding sensory feedback will therefore improve the learning process of the exoskeleton control. However, it is not known which information would be most important to receive while using an exoskeleton and how this feedback should be provided.[26]

In a study the possibilities of providing vibrotactile feedback about the Center of Mass (CoM) during walking in an exoskeleton were investigated. The results of this study showed that healthy subjects could successfully interpret the provided vibrotactile cues and change their walking pattern accordingly. Vibrotactile stimulation was either provided in a concurrent (over the complete CoM movement) or terminal (only when the desired CoM displacement was reached) way. The latter led to a better accuracy and can be easily implemented in a wearable exoskeleton where a certain amount of CoM displacement is needed to initiate stepping.[25]

An example of an exoskeleton that uses this form of feedback is the Thertact-Exo (*Figure* 3). They developed a thermal and tactile sleeve that will be used with the exoskeleton and the virtual reality environment. They use it to reproduce what is going on in virtual reality and in the real world. However, they are still submitting this developing for a patent so there is not much to read about it.[23]

A few other studies have also investigated the application of sensory feedback in wearable exoskeletons. And only in the study of De Castro, a limited number of SCI subjects were involved, who could use the feedback and walk without continuously looking at their legs. Similar to the lower-limb prostheses, the stimulation methods in the various studies varied (pressure cuff, electrostimulation or haptic force feedback) as well as the feedback parameters (knee torque), knee angle, hip angle, swing phase and force under the feet. There is a clear need for sensory feedback in wearable exoskeletons, but it is not clear which stimulation methods and which feedback parameters should be used. To our knowledge, there are only a few studies that involved questionnaires to evaluate stakeholder perspectives of exoskeleton technologies, but sensory feedback was not the main focus of these studies. In the study of Gagnon et al. the learnability of exoskeleton use was evaluated, amongst others, by asking whether the sound of the exoskeleton and the instructions by the therapists were helpful. Both questions were answered positively: 77 and 97% respectively on a scale of 0 to 100.[26]

Smart glasses

Information about how smart glasses work and the (dis)advantages can be read in a previous research question. Smart glasses can provide life monitoring services and information about the environment and can also be equipped with augmented reality technology. Glasses that add information alongside or to what the wearer sees, can be used well in giving feedback to the user. The use of Augmented Reality through smart glasses offers an interesting way of providing hands-free access to contextual information regarding the system under investigation – information that has been optimised for workers in that plant. Sectors including healthcare, logistics, engineering and construction are already putting these devices to use in countless ways.[29]

In recent years, wearable devices have become increasingly attractive and the health care industry has been especially drawn to Google Glass because of its ability to serve as a head-mounted wearable device. The use of Google Glass in surgical settings is of particular interest due to the hands-free device potential to streamline workflow and maintain sterile conditions in an operating room environment. There are promising feasibility and usability data of using these glasses in surgical settings with particular benefits for surgical education and training. Despite existing technical limitations, Google Glass was generally well received and several studies in surgical settings acknowledged its potential for training, consultation, patient monitoring, and audio-visual recording.[30]

Figure 8. Philips healthcare with Google Glass [30]

Smart glasses have also been used in exoskeletons that are used as ‘wearable robot suits’. These exoskeletons boost the human body in terms of strength and endurance. This technology is currently used for rehabilitation in the health sector and for handling heavy equipment in the industry. The rise of bionic technology, like ‘wearables’ and ‘exoskeletons’, push the physical boundaries of the human body. The use of smart glasses in this field have the potential to support logistic employees when it comes to process execution or optimization and communication.[31] Furthermore, wearable technology represents the next stage of development - devices go along seamlessly and using them is easy with hands and eyes free. With the technology it is easy to provide variable accurate and additional information for a mobile worker without disturbing the actual work with several devices or disruptions of the work flow.

The WalkON Suit (*Figure 9*) is one of the exoskeletons that uses see-through display glasses for feedback. The user can monitor operating status using these glasses, which enables the head to be positioned up.[28] Since the sensory function, as well as the motor function, of complete paraplegics is impaired, they are not able to recognize their postures. Thus, they need to observe their leg movements frequently for maintaining balance. For example, they need to know which foot will move forward (i.e., swing forward) to make the appropriate trunk movement for balancing. This is still necessary even after being fully adapted to the powered exoskeleton.[33]

The posture to observe their lower limbs, however, is not easy for complete paraplegics wearing a powered exoskeleton. Since the flexion angle range of the neck is limited, they need to slightly lean forward to observe the leg movements. Moreover, they need to bend their neck even more excessively when staring at the screen to operate the robot, because the display is often within exoskeleton technology installed at the crutches or at the chest. It should be noted that leaning forward not only makes the overall posture unstable, but also imposes a large burden on the shoulder joints. Therefore, the developers of the WalkOn Suit use a smart glass to provide the user of feedback. The system of the glasses receives the operation status of the WalkON Suit (e.g., the motion modes) via Bluetooth serial communication. In addition to the motion modes, the remaining battery level, the total number of steps and the system error status are displayed on the glasses. As the WalkON Suit must operate safely even if the Bluetooth connection is lost, the data are transmitted only from the robot to the glasses.[33]

The glasses include a transparent screen, which shows a progress indicator, the foot positions, a warning indicator and an analysis result after completion of walking. The transparent screen shows an image overlapped with the environment. In the display that the user sees, a donut chart shows how long the user has walked with respect to the maximum step counts. On the center of the donut chart, the number of steps and the current motion mode are displayed; e.g., the walk mode. The foot positions are also shown, which allows the user looking forward while walking. In addition to the necessary information related to motion modes, the glasses also show warning messages if any potential hazard is detected, as in Figure 9e. When the operation is terminated, the total operation time and the total number of steps are displayed.[33]

Augmented and Virtual Reality

Augmented Reality (AR) is an interactive experienced of a real-world environment where the objects that reside in the real world are enhanced by computer-generated perceptual information. Sometimes across multiple sensory modalities: visual, auditory, haptic, somatosensory and olfactory. This technology expands your physical world, adding layers of digital information onto it. Augmented reality can be displayed on various devices: screens, glasses, handheld devices, mobile phones, head-mounted displays. It involves technologies like S.L.A.M. (simultaneous localization and mapping), depth tracking (briefly, a sensor data calculating the distance to the objects), and the following components: cameras and sensors, processing (like a computer), projection and reflection. Augmented reality apps typically connect digital animation to a special 'marker', or with the help of GPS in phones pinpoint the location. Augmentation is happening in real time and within the context of the environment, for example, overlaying scores to a live feed sport events.[35]

Figure 9. The WalkON suit with see through display glasses [33]

Augmented reality technology has many possible applications in a wide range of fields, including entertainment, education, medicine, engineering and manufacturing.[36] It also gradually being introduced into modern agricultural technology and is currently used in satellite exploration, crop growth tracking and GPS guidance systems.[35]

Researchers have begun to address problems in displaying information in AR, caused by the nature of AR technology or displays. Work has been done in the correction of registration errors and avoiding hiding critical data due to density problems. In some AR systems, registration errors are significant and unavoidable. For example, the measured location of an object in the environment may not be known accurately enough to avoid visible registration error. Under such conditions, one approach for rendering an object is to visually display the area in screen space where the object could reside, based upon expected tracking and measurement errors. This guarantees that the virtual representation always contains the real counterpart. Another approach when rendering virtual objects that should be occluded by real objects is to use a probabilistic function that gradually fades out the hidden virtual object along the edges of the occluded region, making registration errors less objectionable.[36]

In the previous paragraph about smart glasses, augmented reality is already introduced within the exoskeleton technology. By adding information alongside or to what the wearer sees, smart glasses can be helpful in giving the user feedback about the surrounding and the operating status of the exoskeleton. In another way, this augmented reality technology could be used for training the user to control the exoskeleton. Walking in an exoskeleton is time bound because a too long session in it has a risk that spots will appear on the skin. These spots are localized damage to the skin and/or underlying tissue that usually occur over a bony prominence as a result of usually long-term pressure, or pressure in combination with shear or friction. Therefore, it is not always possible for the pilot (the one in the exoskeleton) to train and get more advanced in controlling the exoskeleton. In addition, there can be errors that can occur in the exoskeleton. The opportunity to train at home for example by using augmented reality, could be a solution for the missing time. You can add a walking exoskeleton in your training area with the certain obstacles and then practice with scrolling through the selection menu. This selection menu is a menu that the user goes through with the input device buttons to activate the different gaits of the exoskeleton. When selecting gaits in the augmented reality, the user will see the augmented exoskeleton walking over the real obstacles. Also, the different options of the selection menu can be seen in the augmented reality. By using this technology, real time walking in an exoskeleton is not only necessary to train the pilot using the interface. And it is a more extensive option than only scrolling through the input device, activating a gait and don’t see anything happening.

To make the experience more real and have also the surrounding area moving, a virtual reality technology can provide a solution. Virtual reality (VR) is a computer-generated environment with scenes and objects that appear to be real, making the user feel they are immersed in their surroundings. This environment is perceived through a device known as a Virtual Reality headset or helmet. VR allows you to immerse ourselves in video games as if you were one of the characters, learn how to perform heart surgery or improve the quality of sports training to maximise performance.[37] Using this technology for training, the pilot can see through a VR device and it will look like he or she is in an real exoskeleton. Because the obstacle can also be added in the virtual reality, this kind of training can be done at home. The exoskelet can walk over virtual obstacles by selecting different gaits and it will look like a real training. A nice surrounding can also be added to the VR, for example a competition environment in an arena to give the whole experience.

Virtual reality could also be used with a more educational purpose. It can be used to enhance student learning and engagement. VR education can transform the way educational content is delivered; it works on the premise of creating a virtual world — real or imagined — and allows users not only see it but also interact with it. Being immersed in what you're learning motivates you to fully understand it. It'll require less cognitive load to process the information. In the field of exoskeleton technology, you can show people who don't have a spinal cord injury how it is to always move forward in a wheelchair. And what kind of directions or everyday movements are impossible. Furthermore, VR can show you how it will be to walk in an exoskeleton and go over obstacles. It will be a good learning opportunity to people about this technology.

A review was carried out to collect data from different clinical trials and then to categorize and explore them to find the effectiveness of VR, AR, or gamification when used in combination with an exoskeleton or robotic device for the rehabilitation of poststroke patients. It was found that very little work is done to make use of these technologies for rehabilitation of lower limbs when compared to upper limbs, and that there are a wide variety of exoskeleton-based devices currently in use. Apart from this, the review also states that these exoskeleton-based devices are rarely available for home-based trials. This shows that there is a considerable gap in the transition of rehabilitation services from a clinical environment to a home-based setting. Future work should focus on the successful application of VR, AR, or gamification technology to engage poststroke patients in rehabilitation therapies done at their homes. In addition, commercial, off-the-shelf games may be deployed easily, but efforts must be dedicated to designing games for rehabilitation to keep in mind the user and allow for customization to facilitate their motivation.[40]

Exoskeleton technologies bring new capabilities and improve endurance and safety in industrial settings. They are designed to increase in industrial productivity and can prevent common workplace injuries. Although they are not a new concept, the integration of exoskeletons in plants is not a trivial matter. Combining wearable robotics with Virtual Reality holds great promise for industrial applications. A study proposes a VR-based decision tool for the exoskeleton integration in industrial lines that will aid in the identification of the optimal areas and tasks for application, the fine tuning of the active elements of the exoskeleton based on simulation results and the effective and safe training of workers into the correct use of different exoskeletons.[41]

The Thertact-exo, already mentioned above, is an exoskeleton that uses virtual reality training. They use an outdoor setting with grass, sand and stones and several sounds in the virtual reality. The idea is that these richer effects may help improve neuroplasticity. [23] This is the brain's ability to reorganize itself by forming new neural connections throughout life. Neuroplasticity allows the neurons (nerve cells) in the brain to compensate for injury and disease and to adjust their activities in response to new situations or to changes in their environment.[39]

Discussion and Conclusions

Combinations

During this literature research, searching for different human machine interaction options, I also came across exoskeleton technology in which these options were combined. A lot of techniques are combined with vibrotactile feedback for the missing haptic information for people with a spinal cord injury. So is brain-computer interface often combined with vibrotactile biofeedback.[6] A tactile information channel will be a critical component of any BCI designed to control an advanced neuroprosthetic device. Likewise, is a motion detection glove and virtual reality combined with vibrotactile feedback to have a more real experience. An exoskeleton that combines multiple things, is the Thertact-exo. They use visual and auditory VR, combined with brain-controlled exoskeleton with tactile and thermal feedback.

Discussion

My literature research was not a systematic review what means that I did not use systematic methods to collect secondary data, critically appraise research studies and synthesize findings quality or quantitatively. Therefore, I may have missed some proper articles about the different applications of exoskeletons. That means that the information I found and wrote down in my research, may not be the only information about these human machine interaction options and the use within exoskeleton technology.

While researching motion detection, I couldn't find applications of this technology in 'whole' exoskeletons and found most of the literature about hand prosthetics. I was more searching for the technology that input to the exoskeleton can be given by swinging your arms so walking will look more natural.

Conclusions

For using brain-computer interface in exoskeletons, improvements in the hardware are necessary. The recording of neural signals during walking might be affected by motion artifacts, which could bias the decoding and lead to misinterpretation of the neural dynamics associated with the movement. IEEG-based (non-invasive) BCIs should have electrodes that do not require skin abrasion or conductive gel, be small and fully portable, be easy to set up, operate by telemetry instead of requiring wiring and interface easily with a wide range of applications. In principle, many of these needs could be met with current technology, and dry electrode options are beginning to become available. The achievement of good performance in all environments may prove to be the most difficult requirement. Despite that this way of giving input to an exoskeleton could be a great opportunity to have a hands-free interface, the reliability of BCI performance must be improved so that it approaches the reliability of natural muscle-based function. However, it is a great technique to test once and see what the options are.

Using motion detection and smart glasses for giving input, has not been used in exoskeletons yet. Therefore, it is difficult to know in advance what the opportunities are within the exoskeleton technology. It will be interesting to test, but is not the most preferable.

Vibrotactile feedback for people in an exoskeleton is, after reading a lot of literature, a very interesting option to research further and to test. It will give people with a spinal cord injury the missing haptic feedback back, like the pressure of the feet on the ground and a straight body posture. Therefore, I see great opportunities to make walking in an exoskeleton feel more like normal walking.

Using smart glasses as an option for feedback, will also be very interesting. Having feedback in the field of view (instead of looking down on the crutch) allows the pilot to look more ahead and have a straighter posture. Despite some smart glasses have already been tested in a previous MARCH year, I think it is not useless to test others. Every year there are new glasses and they are more and more sophisticated. Especially, it is important to look for glasses that are reliable and will not distract the pilot during walking.

Augmented and virtual reality are an upcoming technology and can be very interesting within exoskeleton technology. It can serve as a training method or be used with a more educational approach. The results of this technologies in this review are not all based on literature, but should be more perceived as a recommendation. That it could be interesting to research further and to test.

The next step of this research is to get in contact with companies who has experience with these technologies or sell some of these products. For buying several products it is not easy to test it immediately, it involves also a lot of software. Therefore, consultancy of companies will be very useful.

Follow up

I tried to get in contact with several companies, but unfortunately it has not yet succeeded. Only at this moment, I am trying to make an appointment with a company with smart glasses. But we will have to wait for how that will turn out.

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