Evaluation of transcutaneous electrical nerve stimulation parameters for rehabilitation of median and ulnar nerve injury

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***Abstract*—The rehabilitation techniques currently available for patients who suffer from injury to the ulnar or median nerve tends to give suboptimal results. Typically, adults who are operated due to a complete transection of the median or ulnar nerve never regain normal sensibility in the injured hand leading to severe limitations in terms of hand function. One of the biggest challenges in sensory rehabilitation is to keep the nerve cells in the somatosensory cortex active during the process of axon regeneration (phase 1), as the neurons otherwise relocate their resources, which is very hard to reverse.**

Transcutanous electrical nerve stimulation (TENS) can stimulate the peripheral nerve and thus also stimulate the nerve cells normally receiving sensory information from the hand during phase 1, utilizing what is called referred sensations. This report presents an evaluation of how different input parameters; pre-pulse amplitude, pulse amplitude and frequency, affect the experienced hand sensations created by a TENS device. The study is based on data collected from tests performed on 29 healthy adults, where the perceived sensations were characterized in terms of location, naturalness, intensity and type of sensation using a stimulation pattern randomizing program. In addition, the equipment was tested on three patients who had undergone surgical repair of the median or ulnar nerve.

The results show that there is a clear correlation between the input parameters pre-pulse and pulse amplitude and the sensory feedback. The sensation intensity increases with the amplitude, and the opposite relationship was found for experienced naturalness. The patient testing suggested that the technique has potential as a rehabilitation method.

Introduction

NERVES are the basic units of the peripheral nervous system, and transfer efferent nerve signals from the brain to muscles and afferent signals from peripheral receptors to the brain. Their anatomical structure consists of an enclosing layer, the epineurium, which is a layer of connective tissue wrapped around the entire nerve. Inside the epineurium are bundles of nerve fibers, called axons, which are the units that transmit the electrical impulses. The axons transfer the impulses via changes in their membrane potential, caused by electrochemical nerve impulses (action potentials), and the nerves act as common pathways for these signals. Nerves are classified depending on in which direction they transmit signals, and are either motor, sensory or mixed. Motor nerves transmit signals from the brain to the muscles, whereas sensory nerves instead provide pathways for information from the peripheral to the brain. Mixed nerves are a combination of both. [1]

The median and ulnar nerves are the main nerves supplying muscle and sensory receptors in the hand. They are both mixed nerves but the median nerve is mainly sensory whereas the ulnar nerve is mainly motor (ie controlling muscles in the hand). The palm and fingers contain a large number of sensory receptors where the receptors in the thumb, index, long and radial half of the ring finger as well as the radial part of the palm convey to the median nerve, see figure. 1. Information from sensory receptors in the ulnar part of the ring finger and from the little finger as well as from the ulnar part of the palm are conveyed in the ulnar nerve. In addition the median nerve control the majority of the muscle in the thenar whereas the ulnar nerve supply the majority of muscles in between the fingers as well as the hypothenar muscles. Both nerves originate from nerve roots that are part of the brachial plexus, which is a network of nerves in the shoulder that carries both motor and sensory signals between the spinal cord and arms, including the hands. [2]

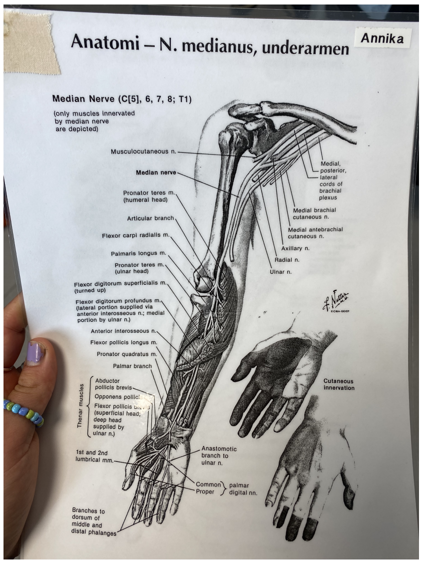

Figure 1: Median nerve.

Injuries to these nerves are reasonably common, with over 100 cases per year in Sweden, and is in more than 90% of cases a result of a cut injury, which results in nerve laceration. The majority of these are accidental cuts, caused by knives,

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glass etc, whereas some are related to suicide attempts. Less common, but still occurring, are median and ulnar nerve injuries caused by crush injuries, gun shot wounds and surgical accidents. 60% of nerve injuries concerning the hand affect young people in the age group 16-35, who often suffers a lifelong reduced ability to work. [3]

After an injury to the median or ulnar nerve, the epineurium is surgically repaired by sewing the two cut ends together. This improves the chances of the proximal axon to re-grow and re-innervate the peripheral sensory receptors and muscles. [3] Shortly after the injury, wallerian degeneration follows, which is a process where the axons begin to degenerate, as a result of lesions due to mechanical force. The end of the axon distal to the injury begins to break down 24-36 hours after the trauma, leaving behind an empty epineurium. After this stage, the axon can begin to grow back, a process which is fairly slow where the axon in best case grows at a rate of 1 mm per day. [4] [5] This time period, when the axon regrow, is called phase 1 in the nerve regeneration, and usually lasts 3 to 6 months; from the incident resulting in injury to when the patient regains some feeling in the hand. [3]

During this time, rehabilitation is a challenge, since sensory and motor information can't be transferred to and from the hand as there are no axons to lead the signals. The nerve cells in the sensory regions in the brain, the primary somatosensory cortex (S1), need to be continuously stimulated or else its resources will relocate, a process called functional reorganisation. For the dynamic brain, the 3-6 months during which no sensory signals can be transmitted from the hand to the sensory cortex, is enough to result in severe loss of sensory function. [3]

Current rehabilitation methods

Sensory rehabilitation methods currently available during phase 1 include utilizing mirror neurons to activate the sensory cells of concern in S1. This is done by observing other people touching their hands, as well as the patient touching their own hand while trying to imagine sensation. The regain of sensory functions following this kind of rehabilitation are for patients over the age of 16 often limited to regaining only protecting sensation, that is, enough sensation for the patient not to accidentally hurt their hand because of the loss of feeling. Rehabilitation to improve motor function after this kind of nerve injury often has better results, thus, the need for new sensory rehabilitation methods is more urgent. [3]

TENS

Transcutaneous electrical nerve stimulation (TENS), is the use of electric current with low voltages, applied to the intact skin, to stimulate nerves for therapeutic purposes. The device producing the current is small and low in cost and energy consumption, and delivers current across the skin via anode and cathode electrodes. [6] The nerves are stimulated via electrical pulses sent by the device with electrodes placed on the skin covering the nerve, changing the membrane potential of the axons generating action potential. By changing different parameters, such as pulse amplitude, wave form, frequency and electrode placement, a variety of sensations in terms of intensity, location and naturalness can be achieved. [7] [8] The types of pulses used for this project are square waves, and can be divided into two sections; a pre-pulse and a main pulse, see figure 2.

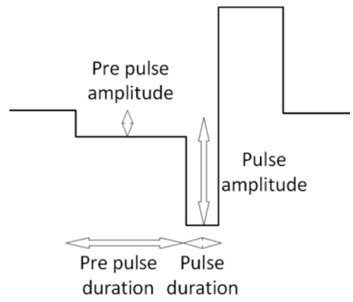

Figure 2: Square wave with pre-pulse and main pulse

The purpose of the pre-pulse is to prepare the nerve for the main pulse by changing the membrane potential, without reaching action potential. [7] Using TENS, it is possible to stimulate the damaged nerve during phase 1, thus keeping the sensory nerve cells in S1 active, improving the results of sensory rehabilitation. This is done by placing the stimulating electrode proximal to the injury. Even though the nerve is stimulated on the wrist or forearm, this will create sensation in the hand and fingers, regardless of if the nerve is intact or not distally. This is due to a phenomenon called "referred sensation", which means that the brain always will interpret the signal from the axons as coming from the end of the organ, in this case the hand, in which the nerve normally leads to. [3]

TENS for rehabilitation

The purpose of this report is to evaluate which variables might be of most relevance for the possible use of TENS as an ulnar or median injury rehabilitation method. This study investigates how the three parameters; frequency, pulse amplitude and pre-pulse amplitude, impact the following feedback sensations; naturalness, level of sensation (sensation scale), location of sensation and sensation type. This is done by analysis of data gathered from standardized tests of 29 healthy test subjects, as well as by exploratory testing on three patients with ulnar or median nerve injuries.

METHOD

Equipment

To perform the study some testing equipment was provided by the biomedical institution at Lund University. This equipment included two software programs installed on a computer and a circuit board used as an electrical stimulator. The circuit board had been custom made for the purpose of hand stimuli, and was capable of producing pulses of an amplitude ranging from 0.1 to 10 mA and frequencies from 1 to 100 Hz. [9] In addition, reusable electrodes were required to stimulate the test subjects nerves and to power the TENS device. Both softwares were previously developed in LabVIEW by Nebojsa Malesevic and Carolina Rudervall, where the first one could be used to freely enter different parameters and instantly stimulate, see figure 3 for an overview of the program.

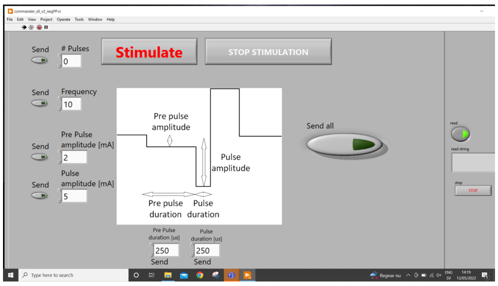

Figure 3: Interface of "threshhold and upper value"-finder software

The second software instead works as a randomizer, where a number of parameters are entered, after which an interactive test sequence consisting of a chosen number of impulses is started, see figure 4.

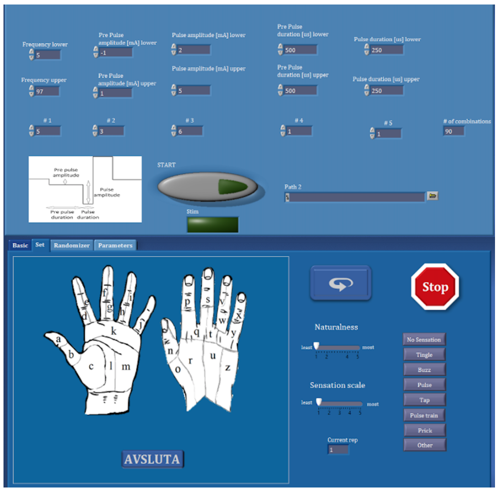

Figure 4: Interface of the randomizer software

Parameters

The parameters regarding the pre-pulse and pulse amplitude were individualized, but remaining parameter's values were kept constant. When choosing these values, a number of factors were considered. Firstly, the number of stimuli was set to 90, based on a balancing between getting enough data points and keeping those data points of good quality, with the risk of the test subjects losing concentration if the test was too time consuming. Based on our own experience from familiarizing with the program, we came to the conclusion to try and keep the test time under 45 minutes. The number of combinations is the product of the number of intervals set for the frequency, the pre-pulse amplitude, the pulse amplitude, the pre-pulse duration time and the pulse duration time. As we had previously decided, based on advice from our supervisor, to limit the study to investigate only the first three of the just mentioned parameters, the number of variations for pre-pulse and pulse duration time was set to 1. The number of variations for the three remaining parameters were then chosen as follows; frequency was set to 5, pre-pulse amplitude to 3 and pulse amplitude to 6. The interval for frequency, which was kept constant for all, ranged from 5-100 Hz. The pulse duration was set to 250 ms, and the pre-pulse duration was set to double the time, 500 ms.

Test protocol

The results of the study is based on data from a test group consisting of 29 healthy adults, gathered through the second LabVIEW program for randomizing stimulation patterns. The test subjects were all volunteers, and are therefore not a completely accurate representation of the general public in terms of age and gender. The average age of the test group was 22.3 years, with a span ranging from 19 to 25 years. 54.8% of the test subjects were female, and 45.2% were male. Before participating, the test subjects had to fill out a form regarding if they had any risk factors that would make the test unsafe to perform or result in inaccurate data. Only subjects that agreed they had none of the risk factors were allowed in the study. The subjects were also given information about the nature of the test prior to participating, both via email days before and also in person right before starting the test. When performing the tests, two electrodes were placed on the subject's wrist and just below the arm crease respectively, see figure 5. These electrodes were then connected to the stimulator, which in turn was connected to the computer containing the testing software. The subject's non-dominant arm was tested in all cases, in order to keep the dominant hand free for interacting with the interface. The participant was also asked to place their arm on a pillow, to standardize the position for which the test was performed.

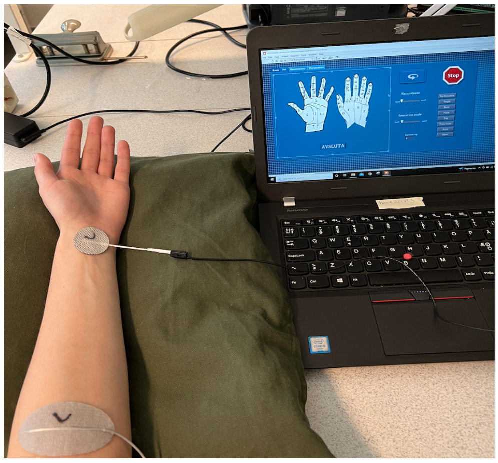

Figure 5: Test setup

Then, the subject's lower pulse amplitude threshold value was found by using the first labview program. For this, the frequency was set to 50 Hz, the number of pulses set to 100 and the pre-pulse amplitude set to 0 mA. For the pulse amplitude, a starting value of 1,5 mA was used and then slowly increased by 0,1 or 0,2 mA per stimulating impulse until the participant experienced sensation. To prevent psychological impact, the test subject was asked to look away while stimulus was induced, to ensure that the perceived sensation was real and not imaginary. After the lower threshold value was found, the pulse amplitude was gradually further increased to find the upper threshold value. The test subject was asked to inform when the sensations in the hand began to feel uncomfortable or unpleasant, and this value was used as the upper limit. The upper and lower pre-pulse amplitude values were determined to +- half of the lower pulse amplitude threshold value. The randomizer program in LabVIEW was then used, where the pulse and pre-pulse amplitude values were set to the just-determined thresholds. Remaining parameters were the same for all test subjects. The randomizer was then started, and the participant was asked to fill out the location, the sensation scale, the naturalness scale and the sensation description for all received stimulation patterns. Naturalness was defined so that an artificial sensation similar to real sensations gave a high score on the naturalness scale, whilst an artificial sensation not similar to real sensation gave a low score. The lower part of figure 3 shows the interface which the test subjects interacted with. In addition to the program, the test subjects were also given a written description of all the sensation types (buzz, tingle etc). They were then informed about the features of the program, such as the repeat and stop button, and that once a sensation description was chosen, the next stimuli would follow immediately and that it wasn't possible to go back to previous stimuli. The tests took on average 30-45 minutes, and once a test was complete the data containing both input and output parameters was saved as a text file. Lastly, the test subjects received a feedback form regarding their experience of their ability to keep concentration during the test, if they perceived it uncomfortable and if it was difficult to grade the sensations based on the alternatives given.

Analyzing the data

After all the tests were performed, the data was analyzed in MATLAB. First the input values; frequency, pre-pulse and pulse amplitude, were compared with the output values; sensations, naturalness, sensation scale and location. To be able to do this, some of the parameters had to be normalized. The frequency parameter was standardized to a scale ranging from 1-5 and represented as shown in the table I below.

The pre-pulse was divided into three categories, negative, none (zero) and positive. This was done by a sorting function in MATLAB.

The Pulse Amplitude parameter was the one with most variation between the participants. The amplitude span, from threshold to upper value, varied in size due to normal variations between individuals. The lowest threshold value was at 1.7 mA and the highest at 2.9. mA. For the upper values, the lowest was at 3.5 mA and the highest at 8.5 mA. The span was then divided into six intervals based on the data from all test subjects, with an equal number of data points in each interval. This enabled analysis of the whole amplitude span, containing all the data, to be performed. Important to note is that this resulted in all spans not containing data from all of the test subjects. The six intervals are represented in the table II below.

Table I

Nr	Interval (mA)
1	1.70 - 2.83
2	2.83 - 3.97
3	3.97 - 5.10
4	5.1 - 6.23
5	6.23 - 7.37
6	7.37 - 8.50

Table II

Freq(Hz)	Std. Freq
5 Hz	1
28 Hz	2
51 Hz	3
74 Hz	4
97 Hz	5

As mentioned and seen in figure 4, the sensation scale goes from 1 to 5, but due to a bug in the labVIEW program, regardless if 3, 4 or 5 was picked, it was registered as a 3 in the datafile. We realized this after all the tests were performed and therefore decided to represent the sensation scale as 1, 2 and 3+, to be able to use the data.

The hand was in the program divided into 26 fields labeled with letters from a to z as seen in figure 14. Each field relates to a number, see appendix - figure 17, which were used to be able to calculate how frequently that specific location was picked. If more than one field was picked, the location was represented by the sum of all the locations picked. By implementing a counter in Matlab, it was possible to calculate how often each field was chosen, this by summarizing the times it was picked individually and together with other locations.

In total 2610 data points were collected, 90 stimuli patterns times 29 participants, but for some analyses all data correlated to no sensation was taken out and 1817 data points were used. This was done for example when naturalness was compared to frequency.

We started to analyze the input values against the output values but realized by time that some output values against each other also could be interesting to observe. Naturalness was compared to sensations scale and the different sensations.

RESULTS

Sensations

As shown in figure 6, No sensation was the most commonly chosen alternative (29.5% of impulses) for describing how the stimuli was experienced. Buzz was chosen almost as often, at 27.1% of the occasions, making it the most common actual achieved sensation. Looking at figure 7, it's clear that the sensations have a dependency on the frequency of the impulse, where prick, tap and pulse are dominating the lowest frequency interval, while buzz and tingle drastically increase in occurrence when studying the higher frequencies. The difference between frequency interval 1 and 2 is the most noticeable; buzz and tingle, which both are close to non-occuring in the first interval, quickly become the two most chosen sensations in interval 2, and then become even more occurring according to what looks like a logarithmic relationship, as the frequency increases further. Prick, pulse and tap seem to have the opposite relationship with frequency, decreasing for the higher frequency intervals. Pulse train do not occur very often for either of the intervals, but seem to increase slightly with frequency. As for the dependence of pre-pulse amplitude, see figure 8, buzz and pulse occurs more than two times as much for the positive pre-pulses as for the negative ones. Remaining sensations also vary slightly depending on the pre-pulse, the biggest difference being between negative and positive values. The bar chart for zero-valued pre-pulses was almost identical to the chart for negatively charged pre-pulses. There is a clear relationship between the pulse amplitude and the experienced sensations, see figure 9. Whilst buzz, tap and pulse has a clear increase in occurrence when the pulse amplitude is increased, tingle instead decreases. The occurrence of pulse train and prick is harder to categorice. Possibly, they are both increasing slightly beyond certain intervals, but the relationship to pulse amplitude is not very clear.

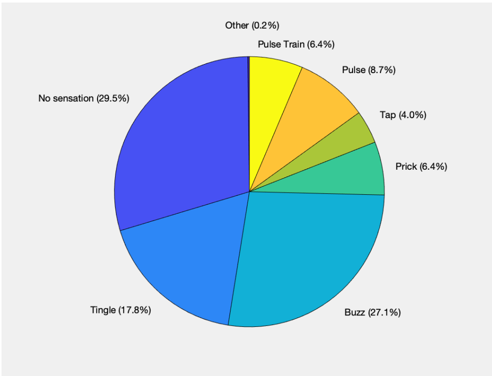

Figure 6: Distribution of sensations including “no sensation” and “other”.

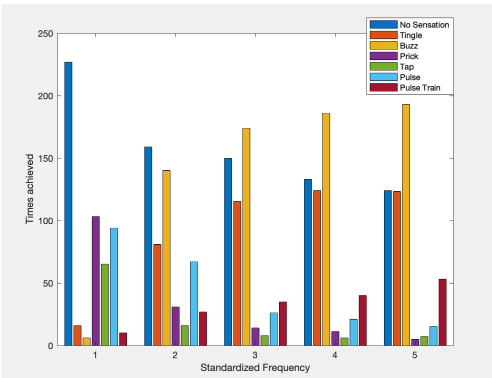

Figure 7: Bar chart of experienced sensation depending on the standardized frequency. .

Naturalness

The frequency does not seem to have an impact on the perceived naturalness of the sensations, see appendix - figure 19. The pre-pulse amplitude appears to play a bigger role in affecting naturalness, as can be seen in figure 10. A naturalness of 1 occurs only 50 times for the negative pre-pulse amplitude values, but over 150 times when the pre-pulse

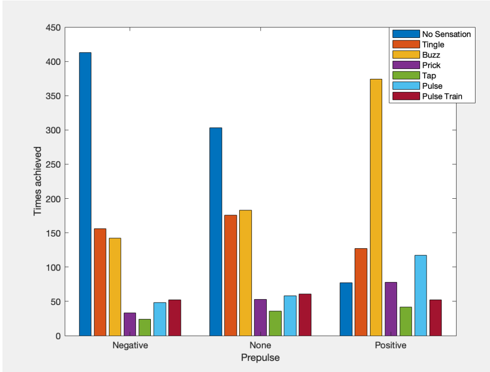

Figure 8: Bar chart of experienced sensations depending on negative, none or positive prepulse.

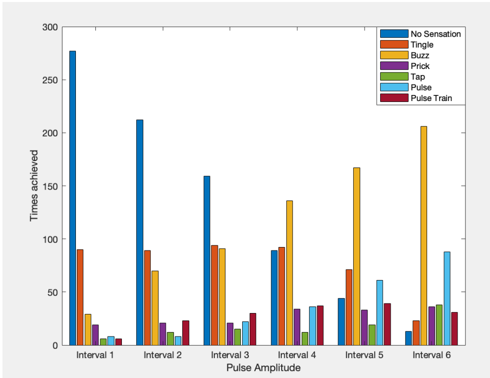

Figure 9: Bar chart of experienced sensations depending on pulse amplitude in the six intervals.

amplitude is positive. For the impulses with zero pre-pulse amplitude, the occurrence of the lowest naturalness score is circa 75 times. The pulse amplitude also seems to have an impact on the perceived naturalness. As can be seen in figure 11, bars one and two, representing the least natural sensations on the scale, grow higher as the pulse amplitude increases. The third bar, corresponding to a 3 on the naturalness scale is fairly constant throughout all the pulse amplitudes, whereas bars 4 and 5, describing the most natural sensations, decrease for higher pulse amplitudes. This is especially true for the fifth bar, which goes from occurring around 70 times to only 5 times.

Sensation scale

The frequency does not seem to have a significant impact on the sensation scale, the distribution is similar in all five intervals as seen in appendix - figure 20. A sensationscale score of 3+ is dominant in all intervals, but increases slightly with the frequency.

Whether the prepulse is positive or negative seem to impact the experienced sensationscale, figure 12 . Sensationscale 1 occur twice as much for negative pre pulses compared to positive, and sensationscale 3+ 200 times more for positive than negative.

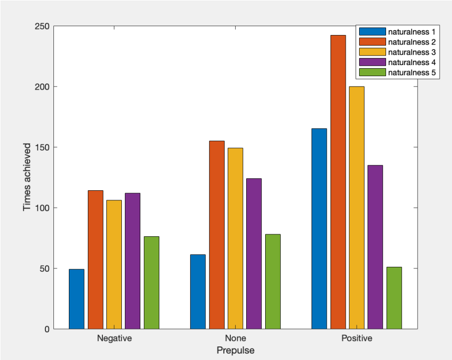

Figure 10: Bar chart of experienced naturalness depending on negative, none or positive prepulse.

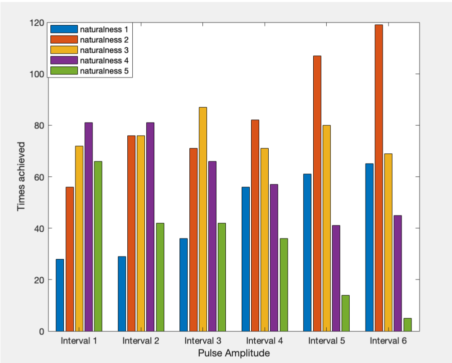

Figure 11: Bar chart of experienced naturalness depending on pulse amplitude in the six intervals.

In figure 13 the distribution of the sensationscale over the 6 pulse amplitude intervals can be seen. Sensationscale 1 is highest in interval 1 and then decreases, whereas sensationscale 3+ is more frequently experienced for higher pulse amplitudes.

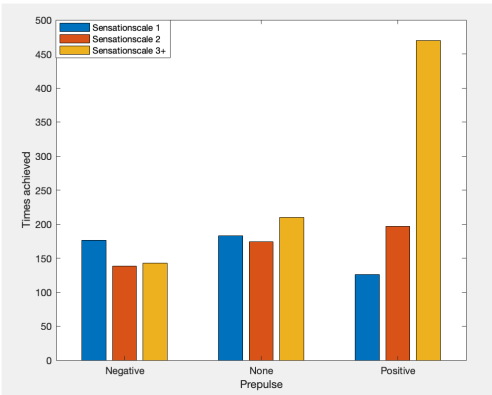

Figure 12: Bar chart of experienced sensationscale depending on negative, none or positive prepulse.

Location

How frequently different locations in the hand were experienced is shown in figure 13. The thumb, (field a,b,c) and the middle finger (field f,g) are the most commonly picked locations. The backside of the hand is colored in the same shade since all locations were picked less than 40 times.

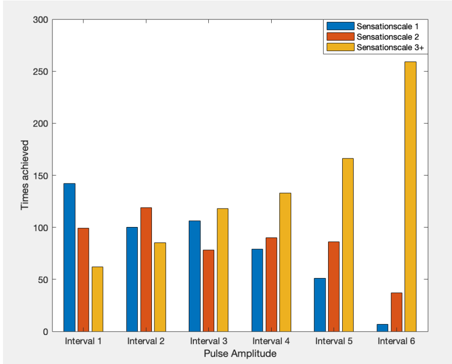

Figure 13: Bar chart of experienced sensationscale depending on pulse amplitude in the six intervals.

A correlation between higher frequency and the amount of times locations were picked is to be seen in appendix - figure 22. The five fingers and the palm are registered in all intervals, and the overall occurrence increases with higher frequencies, meaning no specific location correlated to a frequency but rather higher frequencies resulted in more experienced sensations. A similar correlation is represented in figure 15 where the locations are distributed over the six pulse amplitude intervals. All locations are registered in the intervals and the amount of times picked increase by higher pulse amplitude. Sensation in the little finger is picked significantly fewer times than the others, but is also shown to increase with a higher pulse amplitude. Similar to frequency, higher pulse amplitudes results in more experienced sensation rather than to a specific location.

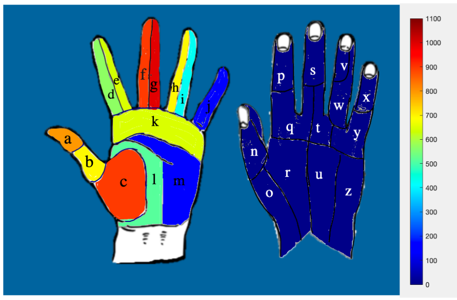

Figure 14: Hand map of the different locations and how frequently they were experienced.

Correlation and causality between outputs

The experienced naturalness differs depending on what type of sensation was experienced, see appendix - figure 21. Buzz and pulse were experienced as less natural (naturalness scale 1-2) the majority of times, whereas tingle and prick more often was scored as a 4 or 5 on the naturalness scale. The

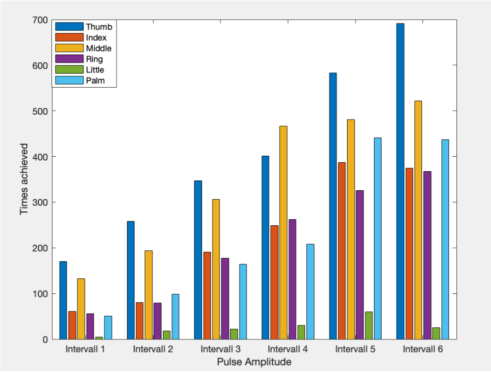

Figure 15: How frequently the fingers and palm were selected depending on the pulse amplitude.

perception of prick and pulse train varies more. There seems to be a correlation or causality between how the naturalness vs sensation intensity is perceived. The higher the impulses were rated on the sensation scale, the lower the score they got on the naturalness scale, see figure 16.

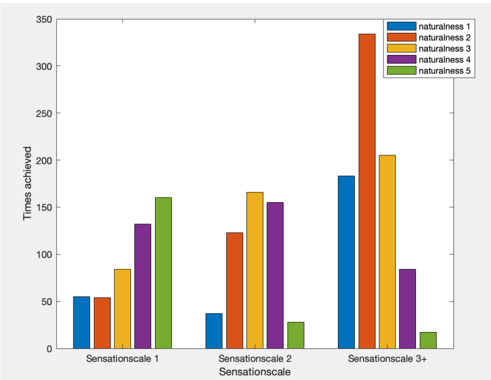

Figure 16: Bar chart of experienced naturalness depending on the sensation scale.

Feedback from the tests

A compilation was made of the feedback form seen in appendix, figure 18. Overall the participants could keep good concentration during the test seen in the first bar chart. The difficulty to grade the sensations based on the given characterization tools varied. A majority picked alternative 3, meaning neither easy nor difficult. The test experience was overall good, 68% had a good experience but 12% thought it was uncomfortable.

Some aspects collected from the participants regarding the test were:
1. Easy to forget to fill in everything for every stimuli (location, sensationscale and naturalness),
2. That you couldn't go back to change your answer,
3. Got used to the stimulation after a while which made it harder to feel sensations at lower amplitudes.

Discussion

The results demonstrate various relationships between input and output parameters as well as between different output parameters. These relationships in turn seem to be dependent on each other. For example, naturalness is dependent on the pulse amplitude; as the pulse amplitude increases, the experience of natural feeling sensations decreases. Looking further, the pre-pulse amplitude has the same effect; a positive (increased) pre-pulse amplitude results in less natural sensations. Furthermore, an increase in the pre-pulse amplitude and the pulse amplitude respectively leads to higher scores on the sensation scale, that is, increases the intensity of the sensations. Given this information, it's likely that the mathematical relationships can be described as a joined function as follows:
$N = f(g(x, y))$,
Where N is naturalness, f is the relationship to sensation scale, g is the sensation scale, which is dependent on x=pre-pulse amplitude and y=pulse amplitude.
As the function f is inversely proportional to naturalness, it is reasonable to assume that a low (negative) pre-pulse amplitude as well as a low pulse amplitude is desirable to achieve naturally feeling sensations. With this in mind, the amplitude values are a trade-off between natural stimuli and the risk of having a high occurrence of no sensation.
As expected, the results showed that a decrease in pulse amplitude increased the risk for no sensation. In addition, the same thing was true for the pre-pulse amplitude. A bit surprising is that even if the absolute value was identical, there was a significant difference in how often no sensation was experienced between positive and negative pre-pulses. A possibility is that this could be explained by the nature of membrane and action potential of nerve cells. The purpose of the pre-pulse is as previously mentioned to "prepare" the nerve cells for the forthcoming pulse by moving charges from the cathode to the anode creating a potential.
When the pre-pulse amplitude is positive, it is conceivable that this also increases the membrane potential, bringing it closer to the action potential of typically 40mV. If this is true, it's arguable that a negative pre-pulse amplitude would have the opposite effect, hyperpolarizing the cell below its resting potential equally as much as the positive amplitude raises the membrane potential. With this reasoning, the cases where the pre-pulse amplitude was zero, and the membrane potential may be assumed to be the resting potential (around -70mV), should give results that are an average of the results for positive and negative pre-pulses. This is not quite the case for the plot describing the number of times different sensations were achieved depending on the pre-pulse, see figure 8. Looking at the bars for no sensation, there is a slight drop in times no sensations were registered for a pre-pulse value of zero compared to the negative pre-pulse. When comparing this to the no sensation bar belonging to positive pre-pulses, the drop in occurrence is significantly bigger. This could be explained by a number of reasons, including that the polarization process of cells isn't linear. It may take more energy to lower the membrane potential below the resting potential than it takes to bring it up closer to action potential.

Another possibility could be the symmetry of the impulse values. Since the parameter values were discrete and not continuous, it may be that a portion of the impulses did not cause sensation when the pre-pulse value was zero, and that the addition of a negative pre-pulse did not have much of an effect since the next discrete pulse amplitude value was high enough to override the hyperpolarization and still cause sensation. If the lowest pulse amplitude value was close to induce action potential, the positive pre pulse may have been enough to exceed this threshold value in most cases.
Figure 14 shows that the test subjects rarely experienced any sensation on the back of their hand. This is consistent with theory, as neither the median or ulnar nerve, which are the nerves stimulated with the electrode placements used, provide sensation to this area. For future testings, it might be favourably to exclude this hand map, and instead focus on diving the palm and front of the fingers into more specific areas.

Ethics and sustainability

The electrical stimulator is cheap, low in energy consumption and intended for temporary use during rehabilitation sessions. The components of the device are also replaceable would something fail, which prolongs the life of the impulse generator. This makes the equipment both economically and environmentally sustainable, especially given its uniqueness and benefits in providing rehabilitation during phase 1. The study has been approved by the Swedish Ethical Review Authority, which means they deemed it ethically responsible to perform the study on humans. The equipment has hence been tested and assessed, and it has been established that it's safe to use the intended way. Furthermore, the device doesn't require any supervising professionals, but can be used independently by the patients themselves. This, in combination with its small size makes it widely available for patients, as they can use it in their own homes without the need for assistance. Availability is a weighty factor in deeming the rehabilitation method socially sustainable as well.

Error sources

This is a subjective study based on the participants' experiences, which of course impact the result. The subjectivity, however, has been eliminated as much as possible by having a large number of participants and the same routines for all tests. Another thing regarding the participants is a variation in the placement of electrodes in relation to the median nerve, caused by naturally occurring differences in anatomy.

As mentioned earlier, some participants experienced it easy to forget to fill in all information for each stimulus. This can be seen since no location, sum 0, is registered 843 times whilst only 743 no sensation is registered, meaning some have forgotten to choose location. This could have had an impact on the distribution map of location, see figure 14, where some field might have been chosen more.

The fact that we just were able to extract information whether the sensation scale was 1,2 or 3+ might also have influenced the result. In some comparisons, for example sensation-scale plotted against frequency, appendix - figure 20, we were not able to see any correlations but might have done so if we had the whole scale.

The 6 intervals for pulse amplitude can also be a bit misleading since the range was so different for the participants. In figure 9, we see that no sensation is extremely high in the first interval which can be explained by the fact that many participants had not reached their threshold there. Some participants' highest value is almost equal to another participant's threshold affecting the distribution in the middle intervals. This obviously impacts the result when comparing pulse amplitude to other parameters, but some form of standardization needed to be done to be able to analyze the data.

CONCLUSION

The results show several correlations between the input parameters and the perceived sensations. The most important findings include that an increase in pre-pulse amplitude as well as in pulse amplitude results in stronger sensations, but simultaneously leads to a decrease in perceived naturalness. A trade-off has to be made between the naturalness and the intensity of sensation when choosing parameters, where further patient testing is required to find which attribute is more important for the sake of rehabilitation. With the pre-pulse amplitude set to a positive value, the risk of not experiencing any sensation drastically decreases. The equipment shows potential as a rehabilitation method in phase 1 following median or ulnar nerve repair. The addition of more electrodes is probably necessary to enable the device to be effective on a larger group of patients, including those whose injury is more proximal.

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APPENDIX

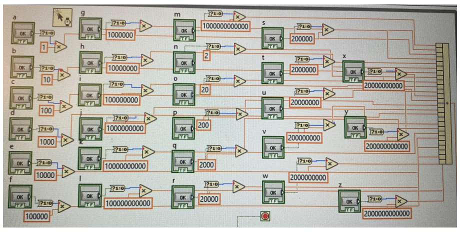

Figure 17: Location field letters connected to numbers in LabVIEW

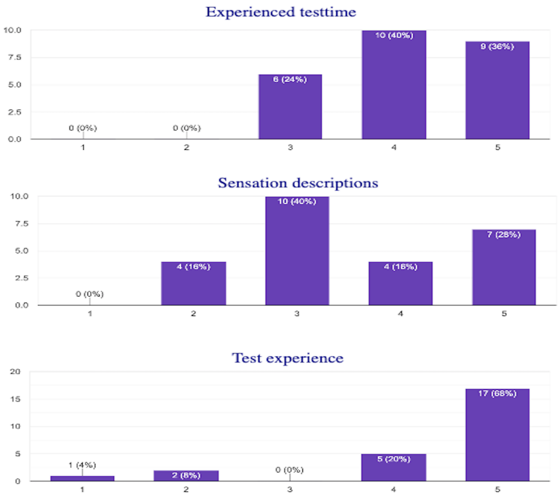

Figure 18: Feedback from the test subjects.

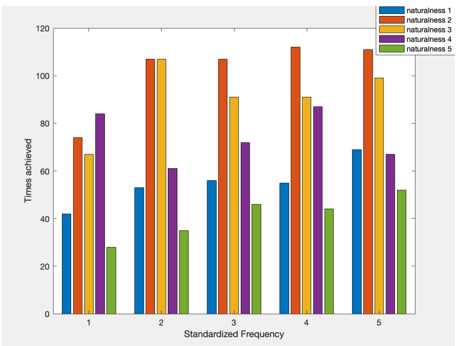

Figure 19: Bar chart of experienced naturalness depending on the standardized frequency.

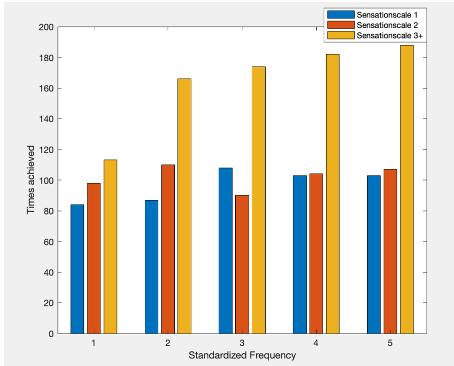

Figure 20: Distribution of sensationscale for the different frequency intervals.

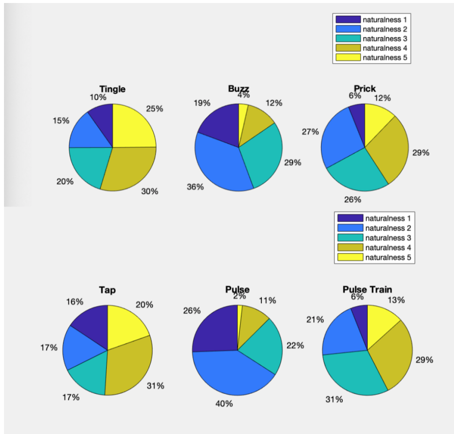

Figure 21: Circle charts describing the distribution of experienced naturalness for every sensation description, with the exception of “other” and “no sensation”.

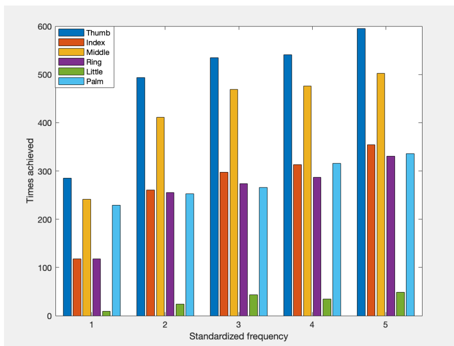

Figure 22: How frequently the different fingers and palm were selected depending on the frequency.