Can electrical pulses be adapted to create life-like perceptions?

An investigation of parameters effect on the sensations during TENS

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2020

Master´s Thesis in

Biomedical engineering

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Abstract

The next big step to improve prosthetics and make the lives of people living with certain physical disabilities less restricted is to provide them with sensory feedback. Today most feedback systems used in prosthetics are mechanical but with the recent developments in sensors and the processing of their input electrical stimulation is becoming an increasingly promising way to convey touch, pressure and movement. This thesis investigated the effect of five parameters on the characteristics of the sensations generated by electrical stimulation of the hand nerves using transcutaneous electrodes. Two pulses were used, a small and long pre-pulse in combination with a large and short main pulse. Their amplitudes, durations and the frequency of the stimulation were used to create different combinations that were used to explore how each parameter affects the resulting sensation. The results show that what type of sensation is generated and if it is felt on the surface of the skin or deeper within the hand is easily affected by adapting the stimulations parameters. How natural the feeling was and where on the hand it appears is more complicated but can be somewhat influenced by changing these parameters. They also imply that another pulse under the perception threshold before the main pulse or having multiple pulses might affect the results in a different way than just changing the size of one pulse.

Preface

This project was carried out at Lund universities department of biomedical engineering in 2020 and would not have been possible without the help and advice of mentor Nebojsa Malesevic and examinator Christian Antfolk.

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Introduction

We use our hands for almost everything, but it is not until one of them, or their function, is lost that we really come to realize how important they are for our independence, productivity and comfort. Without our hands lifting a fork to the mouth, writing one's name with a pen or zipping up a pair of jeans becomes close to impossible without the assistance of another person. This means that the loss of a limb and its subsequent loss of autonomy is not only physically debilitating but can also have detrimental mental effects since independence is lost. Trying to give back as much of that independence as possible is a high priority to allow the person to regain a bit of their normal life. It is not until we try to recreate or replace a hands function that we realize how hard it is and that our hands truly are some of nature's most refined tools. Every task our hands perform consists of a collection of small movements in the hands 15 joints, in combination with additional movements of the wrist, elbow and shoulder. There is constant feedback from biological sensors in the joints, skin and muscles that allow the body to automatically adjust position, pressure and the speed of a movement to perform the task at hand. This information is simultaneously sent in a constant stream to our brain so we can be aware of what is happening. To emulate this, prosthetics are becoming more complicated and can now with a series of accelerometers, force sensors and gyroscopes record information comparable to the one the body would gather.

The next big step towards a realistically functioning prosthetic hand is to transmit this feedback to the user of the prosthesis. This needs to be done in a way that makes it easily distinguishable so the feedback can be interpreted and used in a way that actually improves function and the life-quality of the user. Though there are many studies that use electrical nerve stimulation to generate different sensations there is a lack of studies that report exactly how different parameters affect the results. This is what this thesis will be focused on. It will investigate how five different parameters can affect the sensation that is perceived when electrically stimulating the hand nerves as well as if there is a way to predict the location of the feeling in the hand. It was investigated using transcutaneous electrical nerve stimulations (TENS) on a health individual with fully functioning hands. The hope is that this information will help improve the feedback given to amputees with electrical stimulation by checking the feasibility of using the chosen parameters to control the sensation and its location. Hopefully, it can help other groups doing research in the same area by making it easier for them to determine what parameters can affect the sensation and how. In the end helping improve prosthetics precision and dexterity but also making the prosthesis feel more like an extension of the person’s body and less like an inanimate tool thereby increasing its use.

Theory

The need for prosthetics

There are 158 000 amputations performed every year in the United States of America and about 2 million people live with some form of limb loss and although most of these are lower extremity amputees about a fourth had some form of upper limb loss. Amputations mainly occur both due to injury or symptoms related to decreased blood circulation from diabetes, other vascular diseases, or other diseases and is more common in older individuals and upper limb loss happens due to traumatic injuries to a larger extent than lower limb loss. Though most of these amputations are transcarpal amputations, meaning the fingers are amputated, there is also a significant amount of transhumeral, transradial and other amputations where the hand and more is removed (Dillingham TR, 2002). In these cases, the desire or need of a prosthetic might be greater.

Among upper extremity amputees a bit over 55% have and use a prosthesis and among the ones that do almost all of them use it for over 8 hour a day on average 24 days each month. Since the use is so extensive it makes it very important to make sure the prosthesis lives up to the demands and needs of its user. Many of the users state cosmetic reasons as their main reason for wearing the prosthesis and they consider comfort and the appearance the two most important aspects. Aside from this and a lowered cost they wanted improvements like better functionality and sensory feedback though the desires vary depending on the kind of prosthesis used (Raichle KA, 2008) (Kyberd PJ, 2011) (Wijk U, 2015).

The importance of prosthetic feedback

Fulfilling the desire for better functionality and feedback could not only improve motor patterns and precision by providing something similar to proprioception but also give a sense of the hardness, weight or movements of an object in or against the prosthetic limb. It would decrease the risks of falling, dropping objects or damaging oneself or the prosthesis in many ways. To make this possible there needs to be a good way of communicating with the nervous system and giving it signals that can be easily interpreted and distinguished from one another by the user. This could be done either onto the skin, directly into the central nervous system or the peripheral nerves that would have reached the damaged limb and been responsible for the feedback of the limb when it existed.

Research to find a way of making this a reality has been conducted for 50 years and even though much improvement have been made it is still not good enough to be so simple and user friendly that it is popular in prosthetics today (Sensinger JW, 2020). A lot of the people that choose not to use their prosthesis do so because of the lack of sensory feedback and even though body-powered prostheses give some feedback the increasingly popular myoelectric prosthetics need to improve in this aspect (Raichle KA, 2008). A study into the needs and wants of people with prosthetics showed that most people with prosthetics today seem to value being able to feel grip force and movement as very important and the ability to sense position and the start and end of contact with an object as important. Most also seemed to value grasp and hold feedback as their first priority so these are probably the areas that should receive the most attention. (Cordella F, 2016) (Lewis S, 2012)

Feedback techniques

The main issue that needs to be solved is that there is no good way to convey this information from the technology to the user. There are many different ways of conveying the sensory feedback and different groups prefer different methods. This has led to the development of various methods, some of the most common ones are vibrotactile, mechanotactile and electrotactile feedback. (Stephens-Fripp B, 2018) Vibrotactile feedback is given to the subject by small actuators vibrating against the skin with different speed and force so the stimulations can be distinguished from each other and used to mean a certain type or level of feedback. Mechanotactile feedback is provided by a force applied to the skin with different force levels that are usually interpreted as different levels of strength used when holding an object. When choosing what method to use there are a few aspects to take into consideration, mainly how many levels can easily be discriminated between, how practical and easy to use is both the method and the devices and of course the comfort of the user. This last point is where electrotactile feedback, if not properly adapted to the user, can fall short. Though it is easy to identify different types and levels of input, and the method is practical, it can be uncomfortable or even painful for the user if the amplitudes of the pulses are not properly adjusted. If the pulse is properly adapted to the intended user, this ought not be a problem. The popularity of electrotactile feedback will most likely increase in with the improvements in sensory information that can be recorded and then needs transmitting to the body. Using electricity provides more adaptability and enables communication of more types of sensory input, not only pressure but potentially also the speed and angle of a movement.

Electrically stimulating nerves

There are many different ways of electrically stimulating nerves, and all of them have their own advantages and disadvantages. Much of the research done on nerve stimulation is done with percutaneous implants since they offer high precision (Nghiem BT, 2015). For this type of stimulation cuff electrodes, Utah-array electrodes and regenerative electrodes are popular. The major downsides with using a device that requires breaking the skin barrier and is in direct contact with the nerve is that there is a risk of infection both when implanting, but also as long as it remains, where the cable penetrates the skin. There is also the risk of the implant damaging the nerve and in the long term that the device might elicit a foreign body response that impedes the function of the implant. Still, using one of these implants might be the best option for future prosthesis feedback, since they provide the best possible accuracy. It would still be a mistake to rely solely on invasive methods while researching the possibilities and limitations of the method. This would both slow the research down and make it harder to find suitable test subjects since the risk of nerve damage is larger and could significantly reduce the subject's life-quality. To avoid these issues transcutaneous electrical nerve stimulation (TENS) can be used instead. Using TENS could also be a good alternative for the users that are unwilling to go through surgery.

Transcutaneous Electrical Nerve stimulation (TENS)

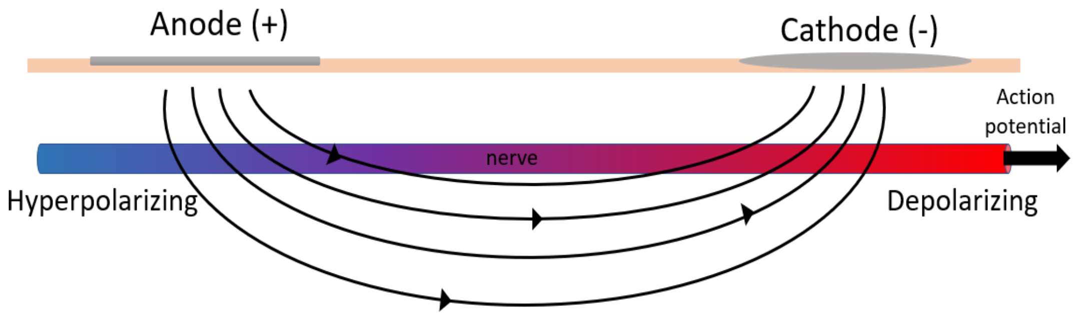

Figure 1, The way electrodes affect the polarization of an axon

TENS is a common, non-invasive and cheap way to electrically stimulate the nervous system using electrodes attached to the skin and a small device that sends electrical pulses. It stimulates the nerves by generating an electric field and affecting the membrane potential of the axons underneath the electrodes as seen in figure 1. The cathode, when placed over a nerve, depolarizes the membrane potential generating an action potential. The anode on the other hand makes the membrane potential even more negative, or hyperpolarized, potentially making action potentials unable to travel in that direction.

Polarization does not happen in the entire nerve at the same time but some of the nerve's fascicles will be activated and others not depending on electrode placement, the pulses strength and other parameters. One of the things that greatly affect which neuron's axon will generate an action potential is its diameter. The myelin sheet enveloping the axon makes the axon impenetrable for ions except for where there is no myelin sheet, at the Ranvier's nodes. The electrical stimulation will excite the larger axons first since there is more distance between each Ranvier's node and the node is larger than in a smaller axon. This means that electrical stimulation generates pulses in the nerves in the opposite way of how it is done naturally with the smaller neurons first then the larger if needed. (JT. Mortimer, 2018)

There are usually five parameters considered when using TENS, frequency, pulse duration, pulse amplitude, electrode placement and wave form. They all supposedly affect the resulting sensation and some of them have been more thoroughly investigated than others (Jung JK, 2016). In this investigation the first three will be investigated in combination with a potential of combining the pulse with a small pulse before the pulse, here called a pre-pulse. This pre-pulse would, like the main pulse, have an amplitude and a duration but would be smaller. To investigate its contribution, and if it has any, it should be small enough not to generate an action potential by itself but would still affect the tissues ion concentrations before the main pulse occurs. The location is very important since changing the location of the electrodes over the nerve makes the pulses appear more or less intense depending on how the tissue between the nerve and electrodes changes and if the placement becomes more or less off center. Since the anatomy of each person is slightly different the optimal position on one test subject might not be the same as on another. Though the differences may be small, they can result in a very large difference in how the stimulation is perceived. These individual differences and the difficulty of keeping electrode placement identical in each test made location a very complicated parameter to investigate and it was therefore excluded.

Risk of electrical stimulation

Stimulating with electricity can affect the body in various different ways, but after years of use most risks have been explored. For example, electrical stimulation can interfere with the function of electrical devices like pacemakers, induce seizures in people living with epilepsy and stimulation is not recommended during pregnancy. Since the stimulation can increase blood circulation it can pose a risk of dislodging a thrombus and of spreading localized infections or cancer cells throughout the body. For a user that isn't suffering from neither of these issues and is generally healthy there is little risk of nerve or tissue damage as long as the parameters are kept reasonable and stimulation to the head and genitals is avoided. (Johnson, 2007) The most common issue is temporary skin irritation as a response to the electrode adhesive and this passes quickly once stimulation is terminated and the electrodes removed. This means that the investigation is no large risk to the test subject.

Therapeutic uses of electrical stimulation

Electrical stimulation of nerves can not only be used for giving feedback to prosthetic users but there is also a wide array of therapeutic applications. Electrical stimulation has long been used as an analgesic and though the evidence of how well it works for different issues is inconclusive it is a quite popular method of relieving chronic pain of many kinds (Grover CA, 2018). There are also some that suggest that electrically stimulating damaged nerves may improve their healing by reducing the time needed for it to heal (Ju C, 2020). When using TENS for these things it could also be good to be able to control what kind of sensation is generated which increases the possible uses of this thesis.

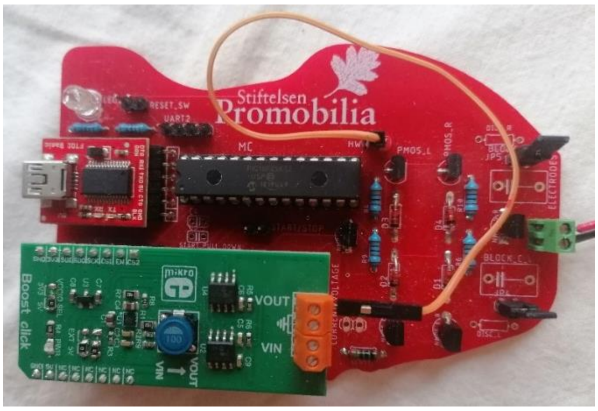

Figure 2, The device used for the stimulations

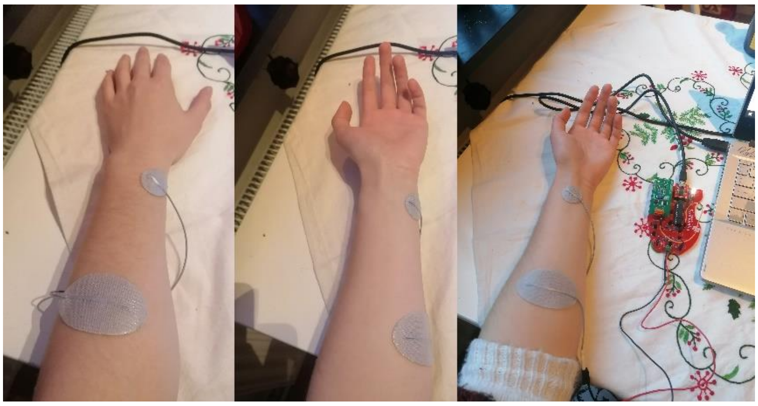

Figure 3, The test setup while stimulating the radial, ulnar and median nerve

Methodology

To enable easy testing and recording of the parameters used and the results of each stimulation a small circuit, seen in figure 2 and 3, connecting the electrodes to a computer was used. LabVIEW was used to create a program where parameters could easily be chosen for each test round and that could randomize them so no specific order could be detected during testing. The program was also adapted to easily record the result reported by the test subject. An instruction was sent from the computer to the circuit which then sent the pulses to the arm through two reusable nerve stimulating electrodes. The electrodes were placed on the lower arm, with the cathode placed over one of the nerves in the arms distal part and with the anode closer to the elbow as seen in figure 3. All three major nerves that exist in the lower arm were used, the median, ulnar and radial, one at a time. They are mixed nerves meaning they both innervate the muscles of the forearm, controlling the hand

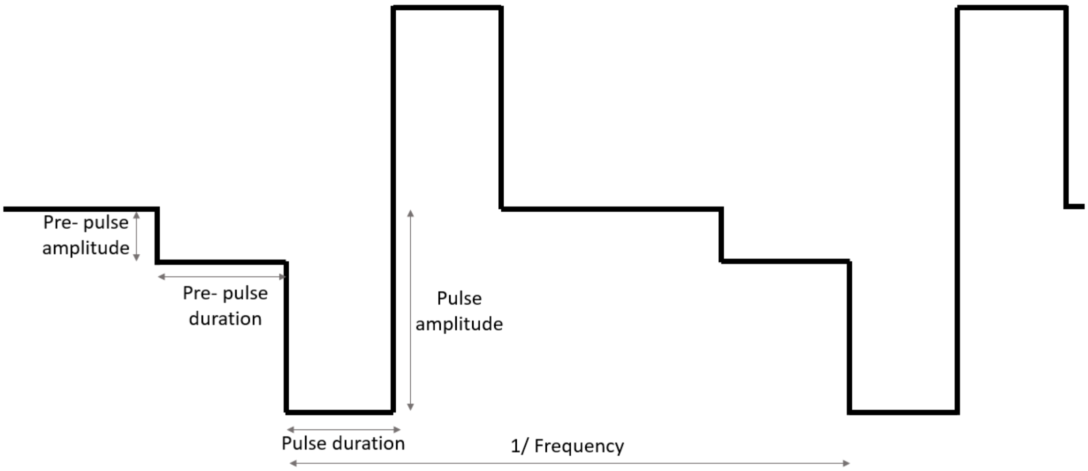

Figure 4, Explanation of the parameters used and wave shape

and wrist, and send the sensory information of the hand towards the central nervous system. All though at the point where the cathode is placed the axons leading to the muscles have already connected to the muscles meaning the nerves mainly consist of afferent neurons. The placement over each nerve was slightly varied between tests since exactly the same spot is hard to find repeatedly. Small changes in placement can greatly affect the resulting sensation and they were thereby varied in a way as to try and include every possible slight change in placement to make the results of these tests as useful as possible and to attempt to exclude its effect. For the radial and ulnar nerve 20 tests each were done and for the median 40, of which 20 were performed with negative pre-pulse amplitudes.

Parameters

Five parameters were investigated for their potential effect on the sensation, and its location. These were frequency, pre-pulse amplitude, pulse amplitude, pre-pulse duration and the pulse duration. They can be seen in figure 4. All the parameters were tested at three different levels to see how they could affect perception and some of them were adjusted after some testing to better fit the setup. The frequency was tested in three different levels, 5, 52 and 99 Hz to give an as wide of a spectrum as possible. The pre-pulse duration was tested at three different settings, 250, 625 and 1000 μs. Pulse duration was adapted to be shorter than any of these spans and was therefore set to 150, 200 and 250 μs. Since the goal of this thesis was to investigate paresthesia, a sensation appearing seemingly without any physical cause, without motor response and to minimize both pain and the occurrence of stimulation under the threshold of perception the pulse amplitude was set to 2, 3.5 and 5 mA. Most pulses at 2 mA were perceived and pulses over 5 mA were often painful and would more often lead to a motor response. The pre-pulse amplitude was mainly kept under or close to the perception threshold and was tested at both positive and negative currents. It was tested at six different levels, -5, -2.5, 0, 1, 2 and 3. The small number of levels for each parameter were chosen to minimize the time necessary for each test round and to allow for as many repetitions as possible for each combination of parameters in hopes that it will minimize the effects of chance. The wave shape was square during all the testing.

Table 1,The parameter levels used

	Frequency (Hz)	Pre-pulse amplitude(mA)		Pulse amplitude(mA)	Pre-pulse duration(μs)	Pulse duration(μs)
Levels	5	-5	1	2	250	150
	52	-2.5	2	3.5	625	200
	99	0	3	5	1000	250

Data collection

Recording what sensation, how it felt and where in the hand it appeared was as previously mentioned done using LabView. What options and categories were used was decided based on a psychometric questionnaire for reporting somatosensory percepts (Kim LH, 2018) with some changes to make it easier to respond and analyze the results. Four major categories were chosen, location, sensation, naturalness and the superficiality of the sensation. For location, the front and back of the hand was divided into 13 areas each based on a small amount of testing to see what areas could be discriminated from each other and where sensation appeared during stimulation. There was then a letter given for each of the areas and these will be used when referring to each area for the rest of the report as seen in figure 5. Area A to H as well as K and L are generally considered areas served by the median nerve while area N to U are covered by the radial nerve. The ulnar nerve serves area I, J, K, M and V to Z though there are some overlap between the nerves in some of the adjacent areas. The areas considered most important are the areas that in daily life are used the most, for example the inside of the fingers and the palm. In the questionnaire there are 18 different sensations, six interoceptive, or internal sensations, and 12 exteroceptive, or external sensations, but for this project eight options were chosen. These were, *no sensation*, *tingle*, *buzz*, *pulse*, *tap*, *twitch*, *current* and *pain* and were mainly chosen based on which sensations were perceived by most of their test subjects. The sensations that were excluded for this project were flutter, vibration, movement though the body, an urge to move, touch, pressure, sharp, prick, tickle, itch, shock and numb. Pain was chosen to be part of the sensation category and not a category of its own since it can be hard to figure out the underlying sensation when pain is perceived. The naturalness was rated on a scale of 1 to 5 with a lower number being less natural and a higher number being more natural and the superficiality of the input was rated as on the surface of the skin, inside the tissue or both.

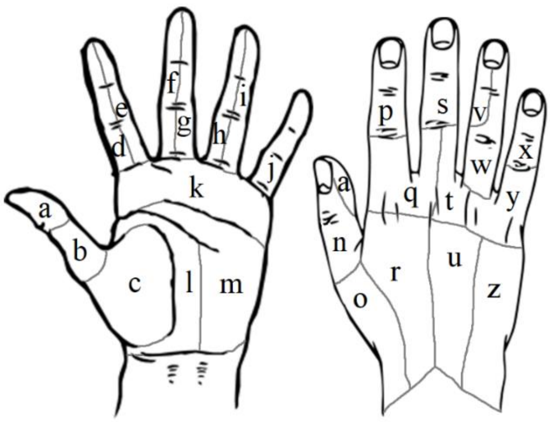

Figure 5, The areas the hand was divided into

When testing, the test subject would respond in LabView by clicking the buttons that fitted what they perceived, starting with location since it is the

Figure 6, The program used during testing

hardest to pinpoint and remember, then moving on to naturalness and superficiality. Sensation was reported last as a new pulse automatically was sent when sensation had been chosen. The user interface of the program can be seen in figure 6. If the test subject was unsure or wanted to feel the same pulses again the input could be repeated by pressing the blue button with the arrow in the interface and if something went very wrong with the testing it could easily be terminated by pressing the stop button to then be restarted. In some cases, a sensation button might accidentally be clicked before the other data was reported or a similar mistake committed. Since this would lead to incomplete results for that combination, in that test run, that result was eliminated during data analysis when all incomplete data had been identified. Other mistakes in reporting were continuously recorded during testing and adjusted after each test run. The occasional motor response occurring during testing and if any issues with the equipment were experienced was also noted by hand when they appeared. The user interface of the program can be seen in figure 6 where the areas comprising the thumb have been selected.

The results were stored in .txt files with one row for each stimulus containing the parameters and results divided into columns. Each category’s options were coded with numbers to make them easier to analyze. These can be seen in appendix A, table 2. When all the testing was done the data was analyzed using MATLAB to give a sense of how the parameters affect each result category.

Each test run consisted of 243 randomized stimulations, each possible combination of parameters appearing once, and took between two and two and a half hours. The number of test runs done consecutively varied from day to day from only one in a day to six in one day.

Subject

All testing was performed on a 24 year old female test subject, without known neurological disorders, who was thoroughly familiarized with the program, set up and classifications before testing started.

Results

When testing the subject did not perceive any differences between the first and the last test run in a day. There were also no perceived differences from the first day testing and the last though this has not been verified by analyzing the collected data.

Sensation

All eight sensations that were chosen from the survey were experienced during the testing and how common they were can be seen in figure 7. Looking into how the different parameter levels affect the sensations was done by either focusing on a certain sensation and seeing what parameters had generated it or by focusing on a combination of parameter levels and seeing what sensations were created. In this case the first option will most likely provide the best overview of how

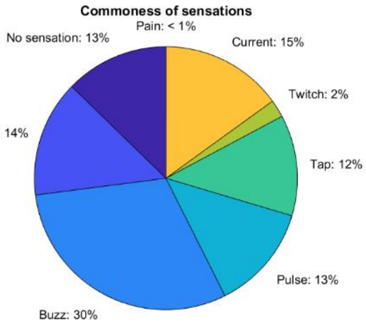

Figure 7, Pie chart of how common each sensation was

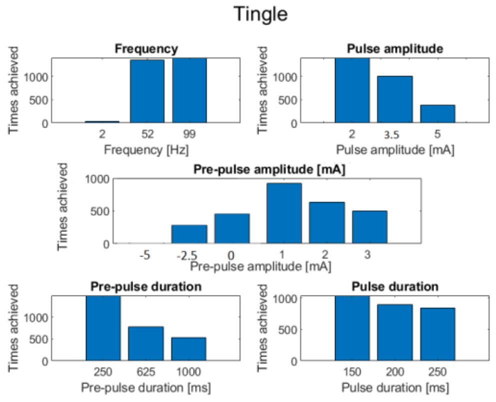

Figure 8, The distributions of parameter levels when tingling was felt

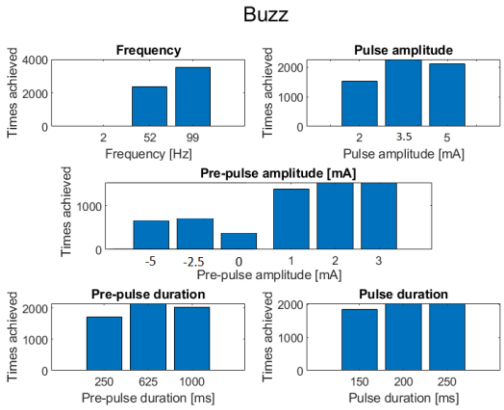

Figure 9, The distributions of parameter levels when buzzing was felt

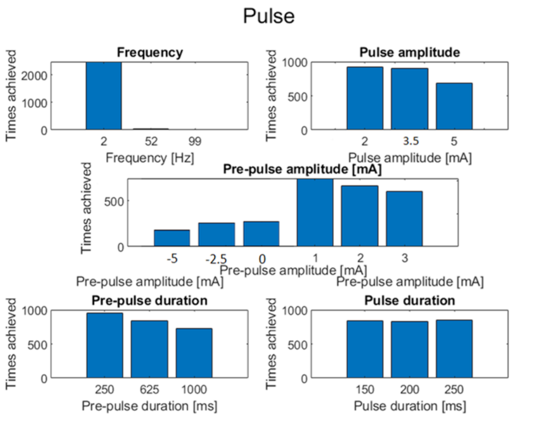

Figure 10, The distributions of parameter levels when pulsing was felt

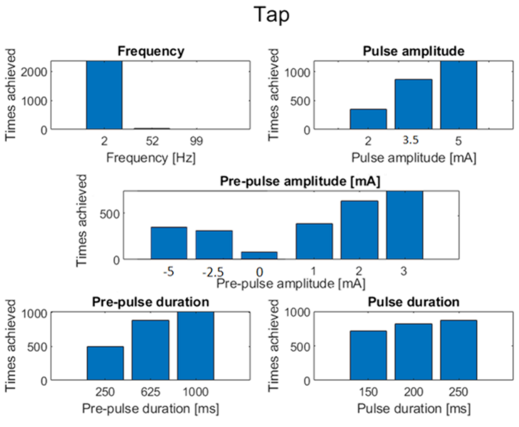

Figure 11, The distributions of parameter levels when tapping was felt

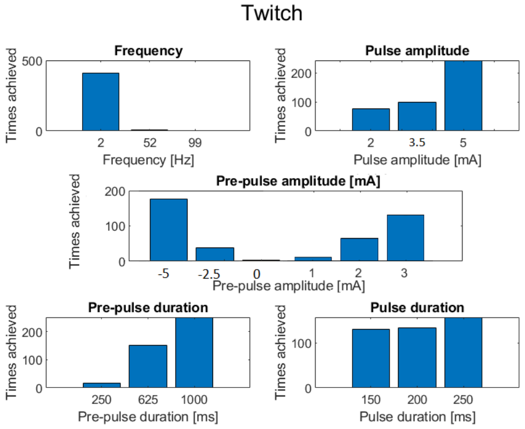

Figure 12, The distributions of parameter levels when twitching was felt

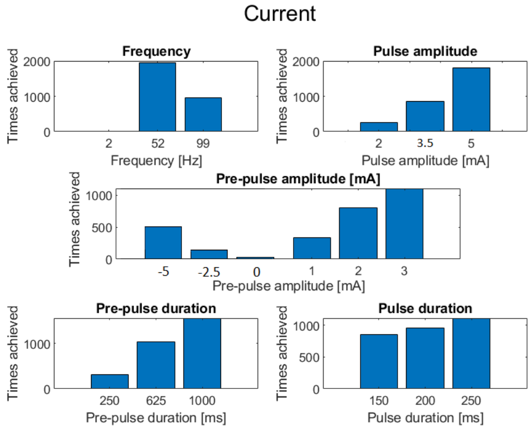

Figure 13, The distributions of parameter levels when a current was felt

the parameters affected the perceived sensation. How many times each sensation was generated by each parameters level can be seen in figure 8 to 13.

Figure 8 shows that a *tingling* sensation mostly occurred when the frequency is high, but both the pre-pulse and pulse amplitudes were low and when the pre-pulse duration was short. As can be seen in figure 9 the *buzzing* sensation was most common when the frequency and amplitude was higher, and the pre-pulse amplitude was as large as possible in either a positive or negative direction. In this case the durations of the pre-pulse and pulse seemed to barely affect the result. Both *pulsing*, *tapping*, and *twitching*, seen in figures 10, 11, and 12 respectively, almost only occurred when the frequency was very low but while a *pulsing* sensation was more common with low pre-pulse amplitudes both *tapping* and *twitching* were more common when then pre-pulse amplitude was further from zero. *Pulsing* was more common when the pulse amplitude was low or medium while *tapping* and *twitching* was more common when the amplitude was high. The *pulse* sensation was slightly more common at shorter pre-pulse durations. *Tapping*, and *twitch* seemed to follow the opposite trend, occurring more often when the pre-pulse duration was longer. For all three sensations pulse duration seems to have had very little effect. Figure 13 shows that feeling a *current* through the hand was more likely to happen when the frequency was 52 Hz or more, when the pre-pulse amplitude was as far from zero as possible and when the pulse amplitude was high. The sensation also occurred more often when the pre-pulse and pulse durations were longer. *Pain* was rare and only occurred twice, when all parameters were high except the pulse duration that was high one of the two times and low the other as seen in appendix B, figure 56. No sensation at all was felt mostly when the frequency and amplitudes were small and the durations short which can also be seen in appendix B, figure 57.

To see how the parameters interact together to create a certain sensation, in a certain location, deep within the hand or on its surface, figure 14 to 19 shows each combination of parameters as a ring, cross or plus sign, increasing in size depending on how common it was. The x-axis shows the frequency in Hertz with the big squares and the pulse duration in µs as the markers position in horizontal direction within the square. The y-axis displays the pulse amplitude and pre-pulse amplitude in the same way with the pulse amplitudes shown by what square the marker is within and the pre-pulse amplitude as the height within the square. The last parameter, the pre-pulse duration(µs) is represented with the different markers as seen in the legend of each figure. These figures in combination with the ones previously presented show the differences from one sensation to another.

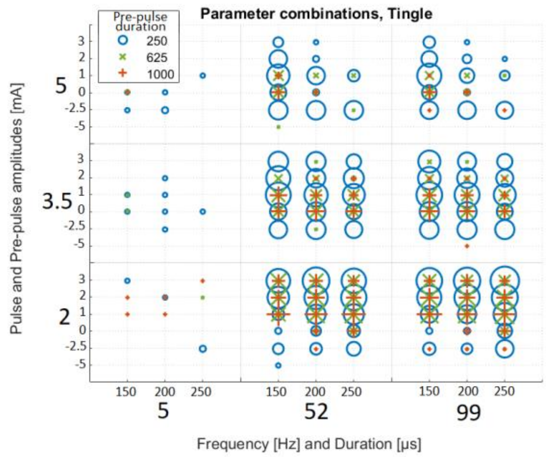

Figure 14, The combinations of parameters that generated tingling

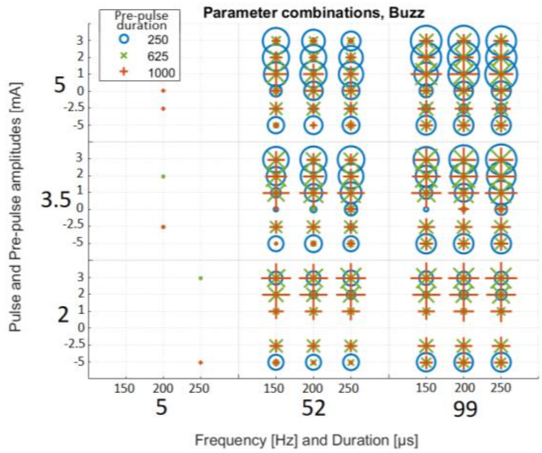

Figure 15, The combinations of parameters that generated buzzing

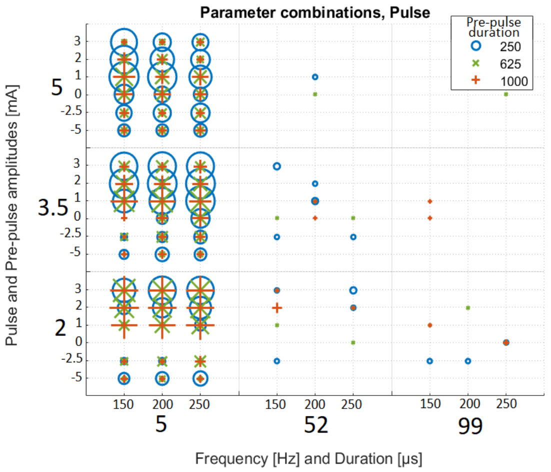

Figure 16, The combinations of parameters that generated pulsing

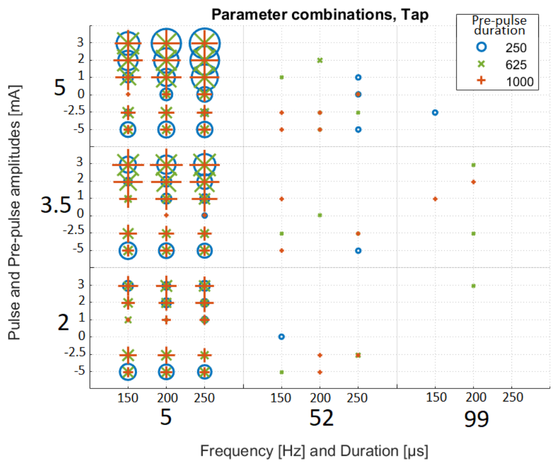

Figure 17, The combinations of parameters that generated tapping

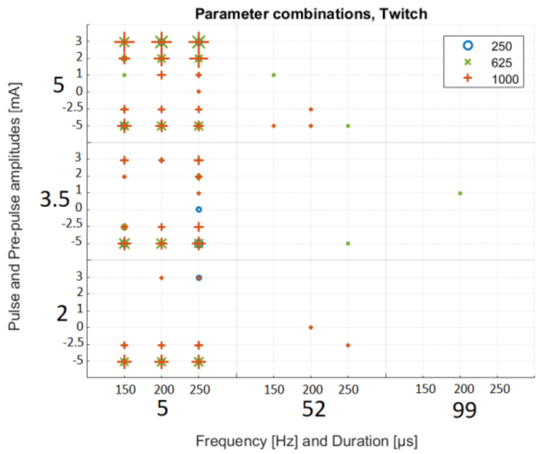

Figure 18, The combinations of parameters that generated twitching

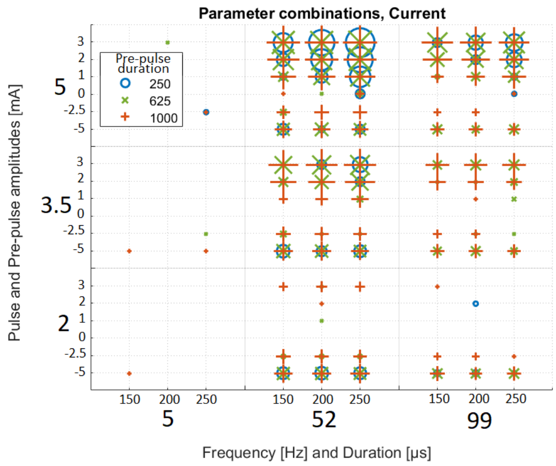

Figure 19, The combinations of parameters that generated a current

Location

The stimulations were felt in all the areas the hand was divided into, except for one. While stimulating the median nerve with one surface electrode almost the entire palm was reached and stimulating the radial nerve reached large

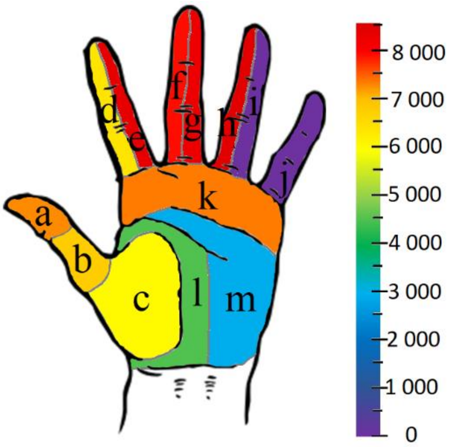

Figure 20, Heat map of how often sensation appeared in each area when the median nerve was stimulated

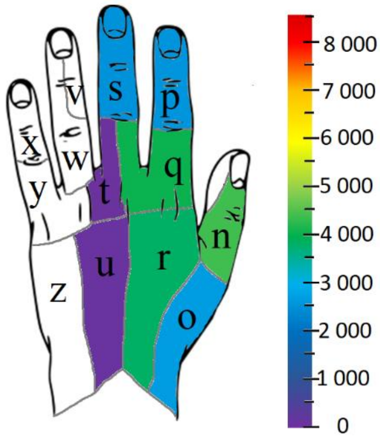

Figure 21, Heat map of how often sensation appeared in each area when the radial nerve was stimulated

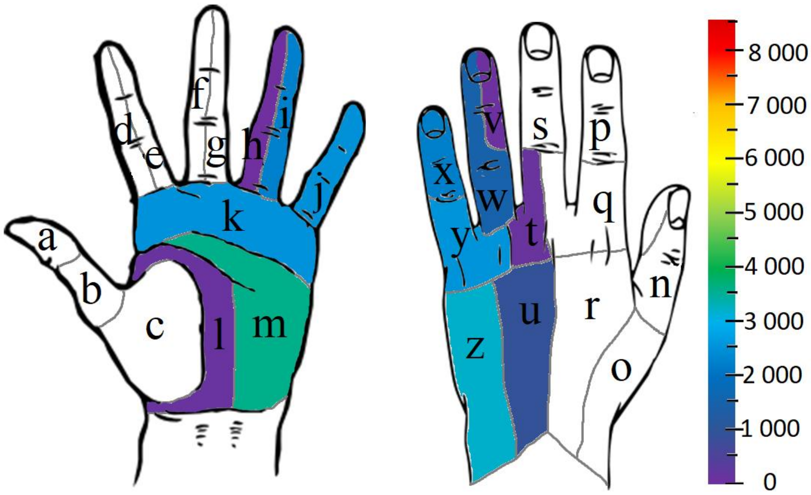

Figure 22, Heat map of how often sensation appeared in each area when the ulnar nerve was stimulated

areas of the back of the hand. How often each area was stimulated can be seen in figure 20 to 22, one for the tests of each nerve. The front of the fingers and top the least common were the backside of the fingers. It is important to keep in mind when looking at both this map of the hand and the other figures displaying the results that the median nerve was used for 40 tests and the ulnar

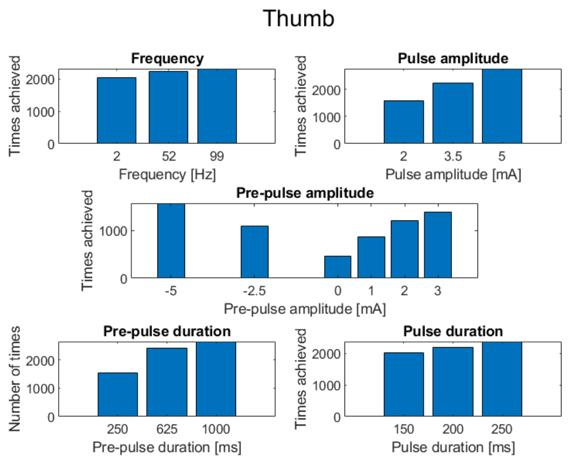

Figure 23, The parameters every time the thumb has sensation

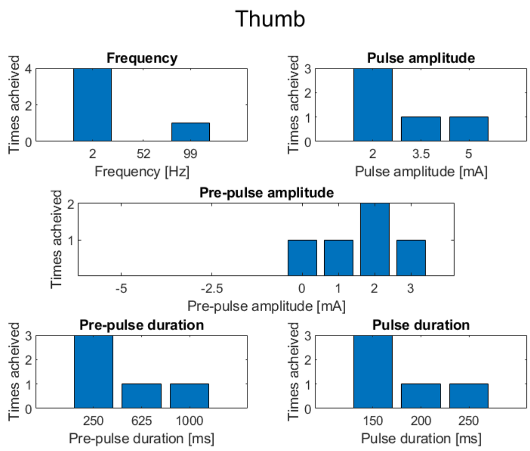

Figure 24, The parameters when only the thumb was stimulated and radial for 20 tests each. This means that there were fewer tests stimulating the back and side of the hand than most of the palm and that even though it of the palm were the most common areas where a sensation was felt and might look like that area was harder to stimulate that is not necessarily the truth. In

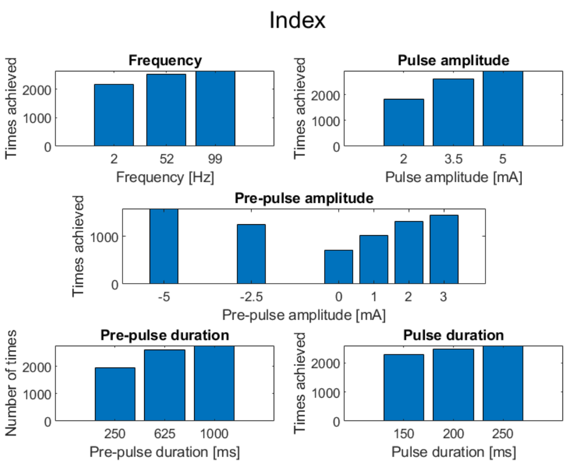

Figure 25, The parameters every time the middle finger has sensation

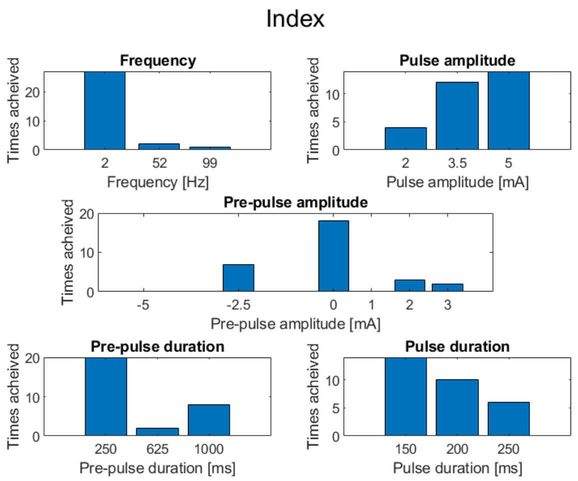

Figure 26, The parameters when only the middle finger was stimulated

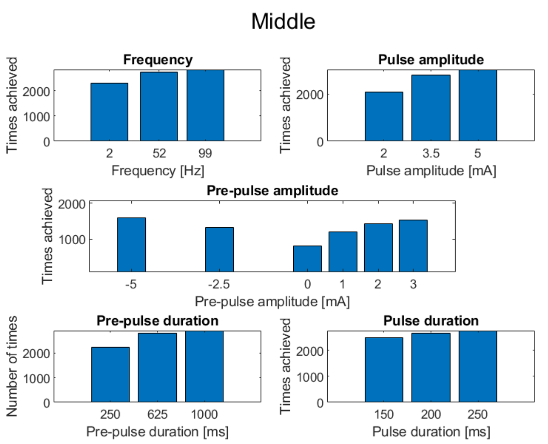

Figure 27, The parameters every time the index finger has sensation

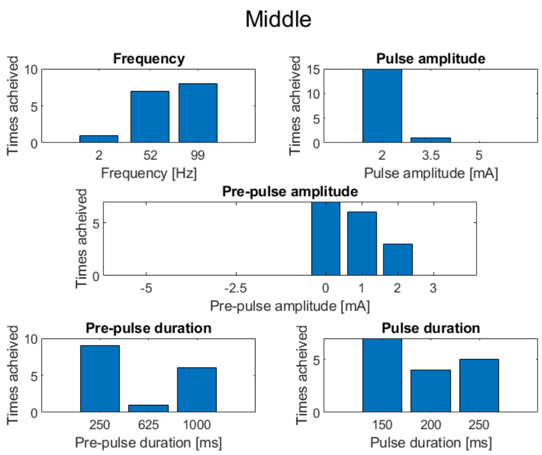

Figure 28, The parameters when only the index finger was stimulated

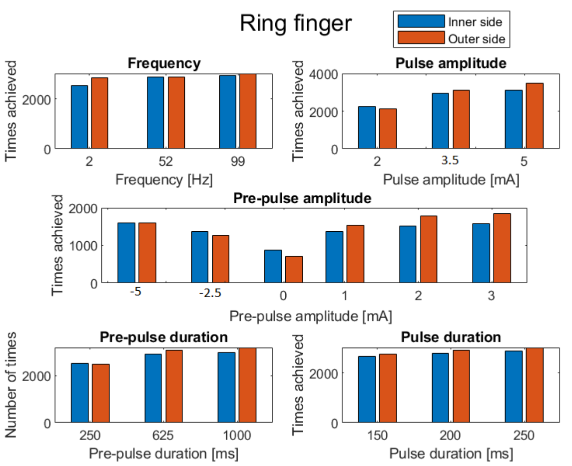

Figure 29, The parameters every time the ring finger has sensation

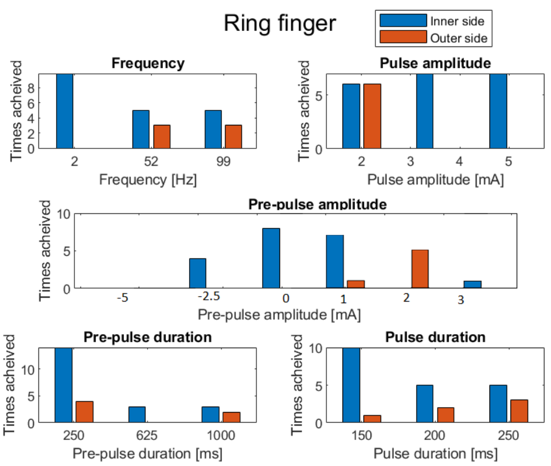

Figure 30, The parameters when only the ring finger was stimulated

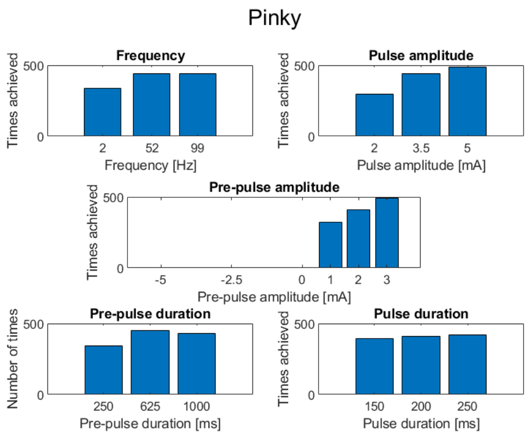

Figure 31, The parameters every time the pinky has sensation

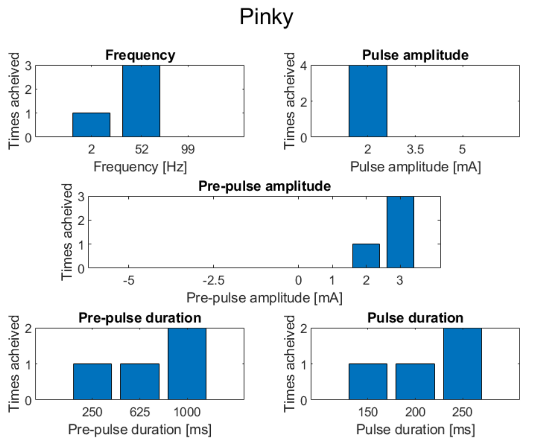

Figure 32, The parameters when only the pinky was stimulated

future testing this might be avoided by testing negative pre-pulses on the radial and ulnar nerve as well.

How the location of the sensation is affected by the parameters can be hard to examine since the location can vary slightly between each stimulation but since this investigation divided the hand into 26 areas, each referred to by a letter, this part will present the distribution of parameters for each time a certain area or combination of areas were excited.

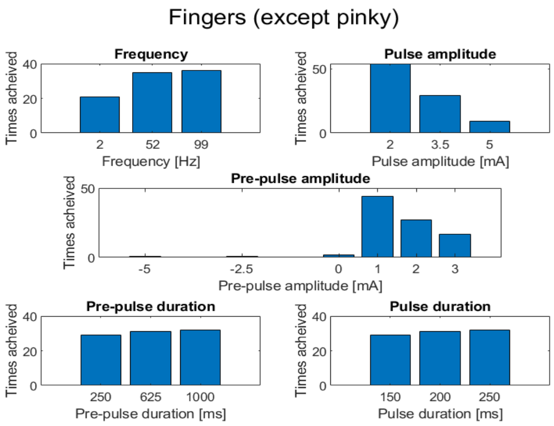

Figure 33, The parameter every time all finger (except the pinky) had sensation

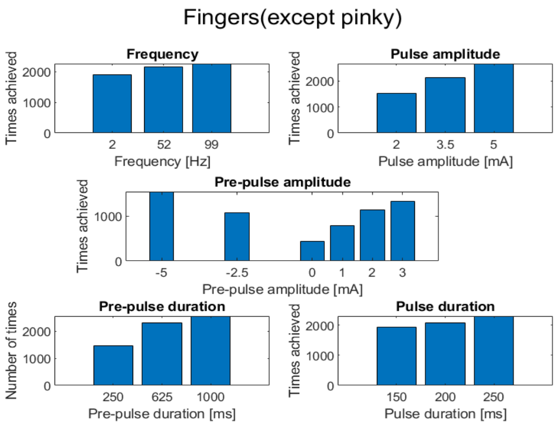

Figure 34, The parameters when only the fingers (except the pinky) was stimulated

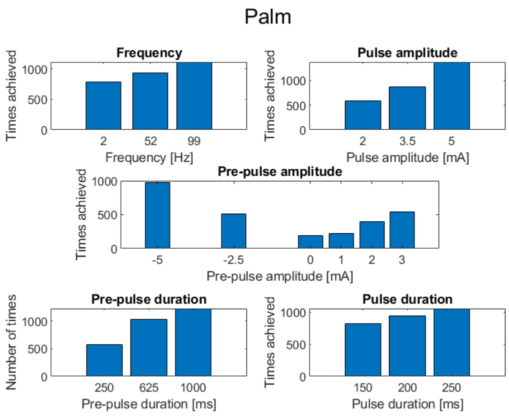

Figure 35, The parameters every time the palm had sensation

In figure 23 to 32 each figure is paired with the one next to it, the first one shows every time that area (on the inside of the hand) was stimulated and the second when only that area was stimulated. Figure 23 and 24 shows the distribution of parameters for the thumb, figure 25 and 26 the index finger. The middle finger's, ring finger's and pinky's distributions can be seen in figure 27 paired with 28, 29 with 30, and 31 with 32. The histograms of the ring finger are, as can be seen, split into two parts, the inner and outer, since the inner side is connected to the median nerve and the outer to the ulnar nerve and only one nerve was stimulated at a time. Figure 33 is paired with 34 and shows the times all the fingers except the pinky was stimulated. Ultimately figure 35 shows the distribution for the palm. As can be seen there are very little differences between the first figure in each pair and though the second shows clear differences between each area there are very few samples for each of them.

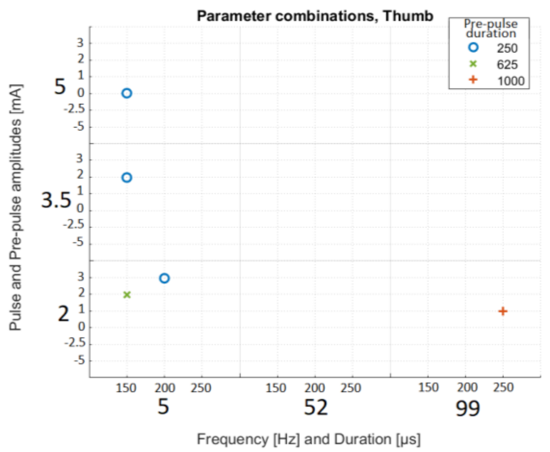

Figure 36, Parameter combinations when only the thumb was stimulated

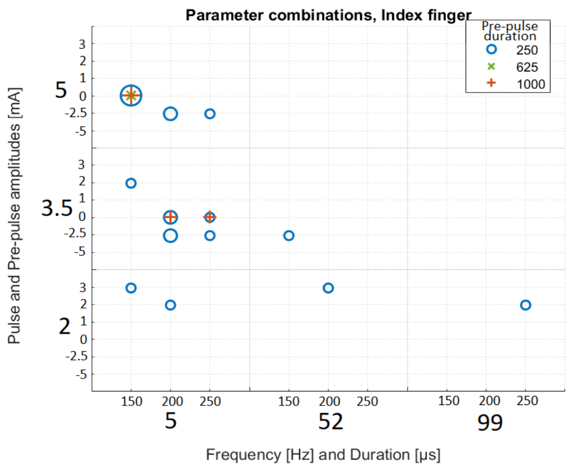

Figure 37, Parameter combinations when only the index finger was stimulated

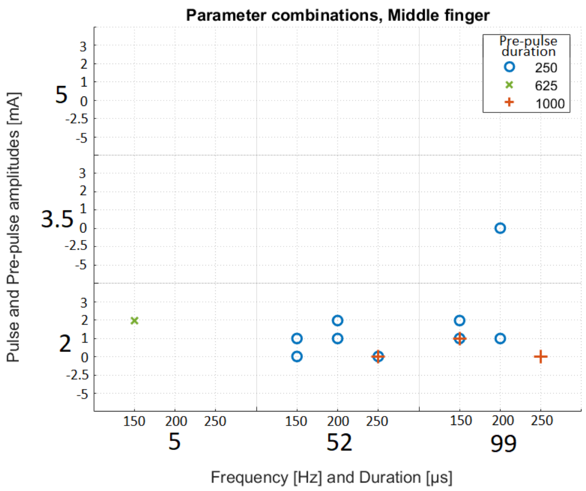

Figure 38, Parameter combinations when only the middle finger was stimulated

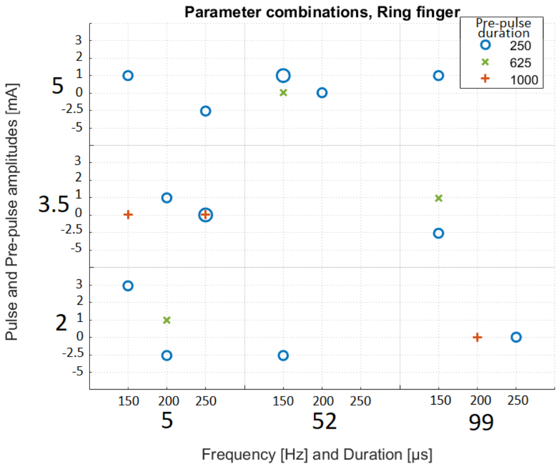

Figure 39, Parameter combinations when only the ring finger was stimulated

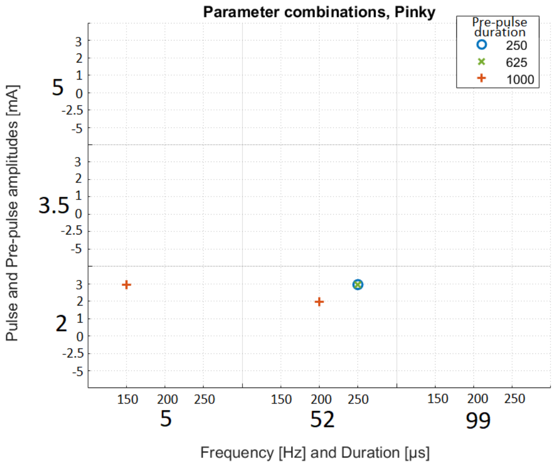

Figure 40, Parameter combinations when only the pinky was stimulated

In figure 36 to 40 we see the distribution of the parameter combinations from figure 24, 26, 28, 30 and 32. These are the combinations that made the feeling appear only in the location in question and nowhere else in the hand with focus on the fingers since these were the only larger areas that were stimulated without other parts of the hand reacting at the same time.

Superficiality

As for sensation, the overall distribution of how superficial the sensations were can be seen in the pie chart in figure 41. It shows that the sensation mostly was felt both on the surface and underneath it and that it was less common that feeling appeared on the skin as opposed to deeper in the hand. The commonness of the depth of the feeling for each parameter of the pulse is displayed in figure 42, 43 and 44.

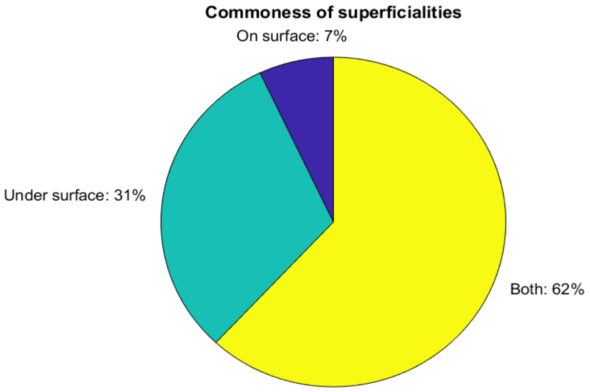

Figure 41, The commonness of the three superficialities

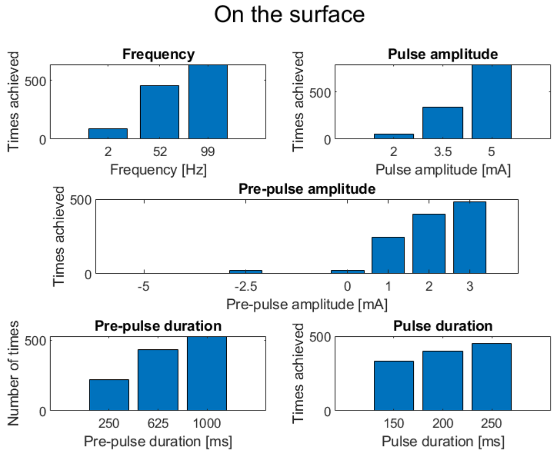

Figure 42, The parameter distribution when the sensation was felt on the skin

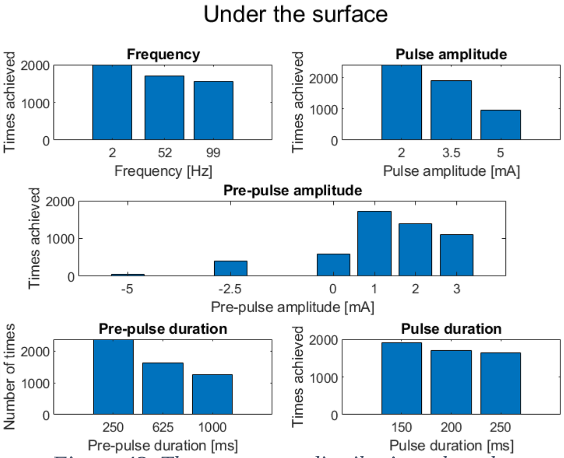

Figure 43, The parameter distribution when the sensation was felt underneath the skin

Furthermore figure 42 shows that a high frequency, pulse and pre-pulse amplitude and longer durations for both pulses resulted in the sensations appearing more often on the surface of the skin. That the opposite parameter settings more often resulted in a deeper feeling is shown in figure 43. Figure 45 and 46 shows, how these parameters in combination with each other make the feeling

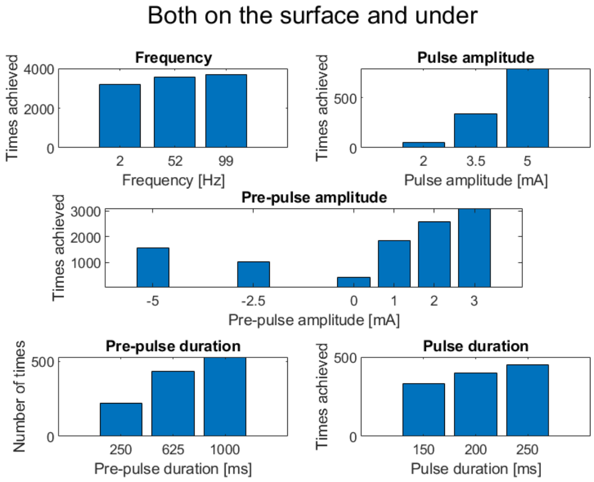

Figure 44, The parameter distribution when the sensation was felt in both

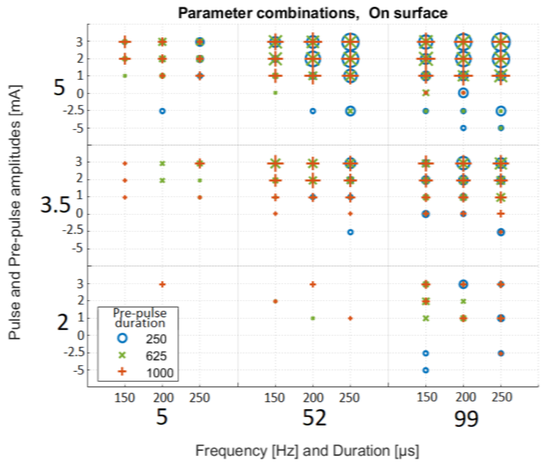

Figure 45, The parameter combinations when the feeling was felt on the surface

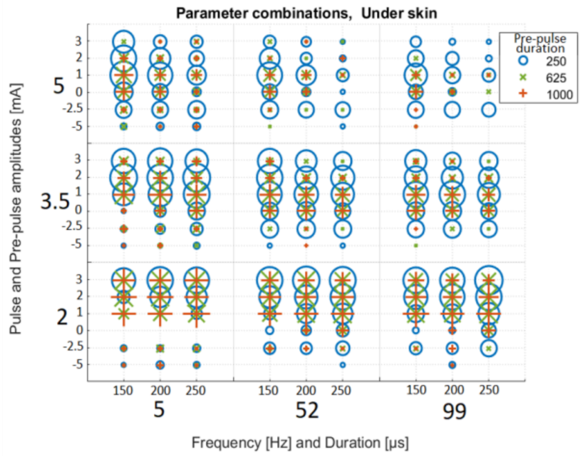

Figure 46, The parameter combinations when the feeling was felt underneath the skin

created by the stimulation deeper or more superficial. As previously mentioned, a low frequency with a low pulse amplitude and a small pre-pulse seems less likely to create a superficial sensation and more likely to make the feeling appear deeper into the hand or both on the surface of the skin and underneath it.

Naturalness

How natural the feelings created felt was rated on a scale of most unnatural (1) to most natural (5) and the distribution of the parameters for the different levels can be seen in figure 47. The figures of the parameter combinations for the naturalness can be seen in appendix B, figure 67 to 71. They are quite similar and mostly show that most of the stimulations resulted in a feeling in the natural part of the scale but do not shown much that cannot already be interpreted from figure 47.

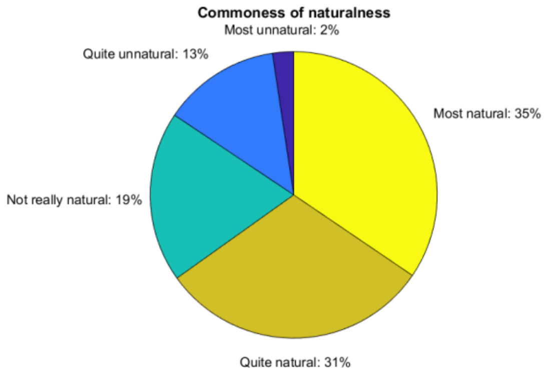

Figure 47, The commonness of each naturalness

Pre-pulses

To see if having a small pulse, before the main pulse, most of the data needs to be excluded and the focus put on comparing the results from the pre-pulse amplitude. The possible effect from the pre-pulse being smaller than the perception threshold is investigated by comparing the pie charts within figure 48, 49 and 50.

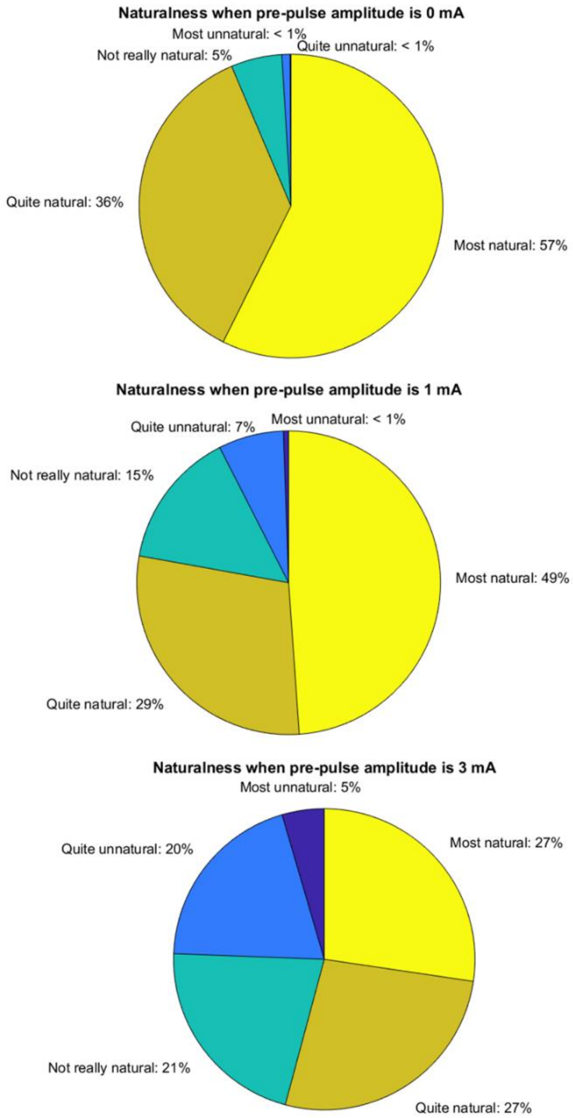

Figure 48, The effect of the pre-pulse on naturalness

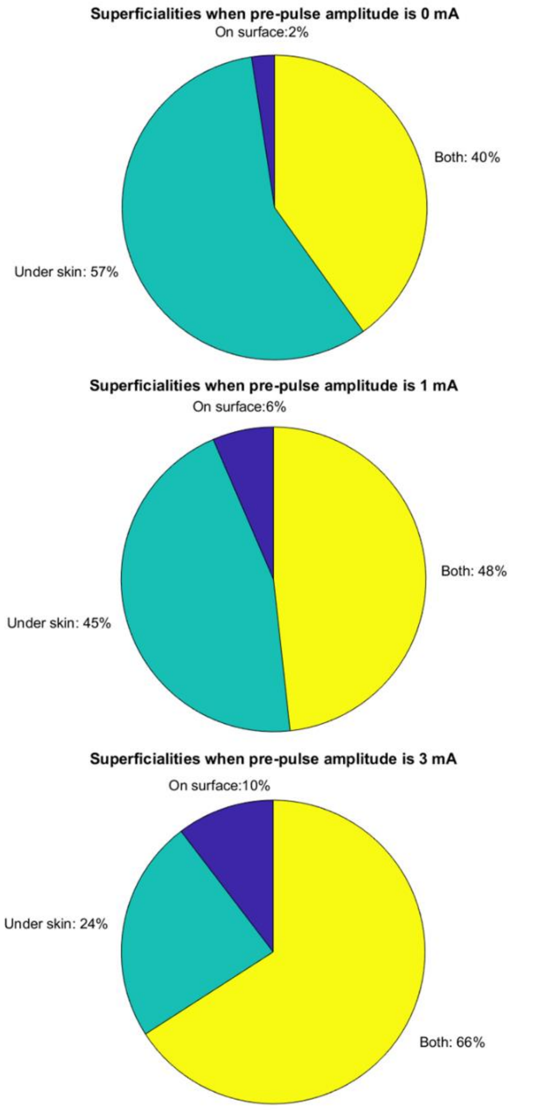

Figure 49, The effect of the pre-pulse on the superficiality

Comparing the three pie chart in figure 48 shows that a pre-pulse made the stimulation feel less natural by several percent as it increased. The next three, in figure 49, shows an increase in the ratio of superficial sensations both by itself and in combination with a deeper feeling when the pre-pulse amplitude becomes higher. The last three displays the pre-pulses effect on the sensations,

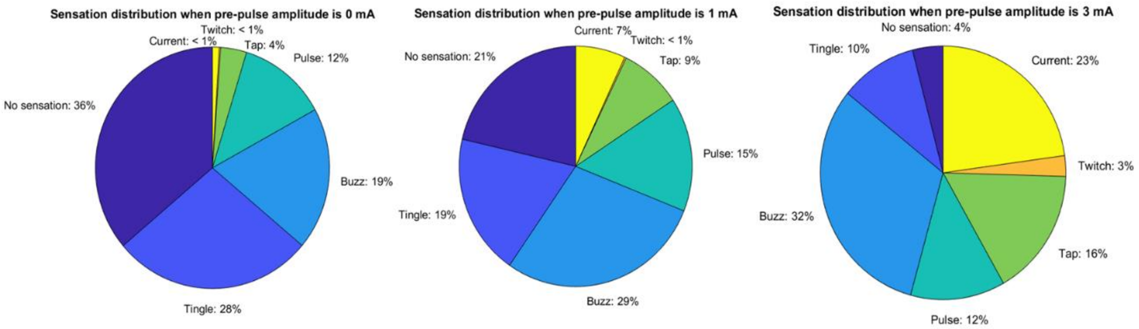

Figure 50, The effect of the pre-pulse on the sensations decreasing how often *no sensation* and *tingling* appeared and increasing the proportion of the other sensations. Focusing on pre-pulse amplitude 0 and 1 mA in figure 12 to 17 and comparing the differences between those two levels to the difference between 1 mA and 2 mA shows that the difference between the first pair mostly is larger than and more pronounced than the differences between the second pair. This can be seen in figure 50 for the sensations and in figure 49 for superficiality. In figure 36 to 40 it is impossible to tell if there was any difference between the two levels.

Furthermore, comparing the negative to the positive pre-pulse amplitudes in figure 14 to 19 and 45 and 46 makes it clear that although the effects are similar, they are not always the same. For example, while an increase in positive pre-pulse amplitude would increase the proportion of “On surface” sensations the negative ones did not. In the case of naturalness, the effect was seemingly the same on both the negative and positive side but some of the sensations show a difference between the two sides. When looking at figure 14 showing what parameter combinations generated tingling the difference between the -2.5 mA and the 2 or 3 mA is quite big when the pulse amplitude was low and high. At the 2 mA pulse amplitude *tingling* was rarer when the pre-pulse was negative while at the 5 mA pulse amplitude tingling was rarer when the pre-pulse was positive rather than negative. *Tapping* and *currents* also seems to be affected by the polarity of the pre-pulse since the ratios of these were much higher when the pre-pulse amplitude was positive and the pulse amplitude was high but almost the same between positive and negative pre-pulses when the pulse amplitude was lower. The *buzzing* sensation was more common when the pre-pulse was positive for all pulse amplitudes and was rarer at a low negative pre-pulse amplitude than when there was no pre-pulse at all in the case of the higher pulse amplitudes. Just like *tingling*, the effect of positive verses negative pre-pulse amplitudes on *pulsing* depends on the pulse amplitude. At the lower pulse amplitude, the positive pulse amplitudes generated a higher number of *pulsing* sensations than the negative ones while the higher pulse amplitude had an almost equal number of occurrences for the negative and positive pre-pulses. The only sensation that showed an almost completely symmetric reaction to positive and negative pre-pulses is *twitching*.

Another thing to note considering the pre-pulses is that with the same duration (250 µs) and a pulse amplitude of 3.5 mA and a pre-pulse amplitude of 2 mA, or a pulse amplitude of 2 mA and a pre-pulse amplitude of 3 mA the occurrences were not as high for both. For example, in figure 14 a pulse amplitude of 2 mA with a pre-pulse amplitude of 3 resulted on *tingling* more often than the revers and in figure 15 the opposite was true for *buzzing*. These differences can be seen in all categories except for naturalness.

Discussion

As seen in figure 7 *buzzing* was the most common sensation and *twitching* the least common, aside from these the others appeared more or less as often. The results shown about the sensations implies that the parameters do affect what sensation is felt and though *no sensation* was generated by only one level for each parameter some were quite close. *Pulsing*, *taping* and *twitching* was very close to only being identified when the frequency was very low (5 Hz), while *tingling*, *buzzing* and *current* almost exclusively appeared when the frequency was higher (52 or 99 Hz). Still, this is the parameter with the most straight forward result. The amplitude and duration of the pre-pulse and pulse seem to mainly have the same effect on the sensations, with higher amplitudes of both skewing a low frequency stimulation toward *twitching* or *tapping* and a lower amplitude towards *pulsing*. The same also happened for the durations though the pre-pulse durations seemingly affected the result more than the pulse-duration. For example, it can be seen in figure 12 and 18 that the sensation almost never was identified as *twitching* when the pre-pulse amplitude was short (250 µs). Meanwhile the pulse duration seemingly did not elicit an increase nor decrease in *twitching* sensations. The frequency of the *pulsing* sensation occurring on the other hand shows no increase dependent on neither duration. *Tapping* is the low frequency sensation that shows the most complicated relationship with pre-pulse duration, figure 17 shows it occurred more often when the amplitudes were big or in the case of the pre-pulse amplitude either very high or very low. For the higher frequency sensations higher amplitudes made the *buzzing* and *currents* more common and lower did the same for *tingling* and the pulse duration once again seemed to have little effect on the results. In this case the current shows a different dependency from the two other sensations very rarely appearing when the pre-pulse duration was short, especially when the pulse duration also was short.

Considering all this together it is very difficult, using only these results, to predict exactly what sensation will be felt by the subject when choosing a certain set of parameter levels but there certainly seems to be combinations that increase the probability of certain sensations appearing and decreasing others. For example, a *buzzing* will most likely be felt if a high frequency is used in combination with high pulse amplitudes and a short pre-pulse duration and if the pre-pulse duration instead is increased it will most likely feel closer to a *current*.

As mentioned in the results, the diagrams showing the distribution of parameters every time a certain finger was stimulated (figure 22 to 32) are all very similar and show no specific differences that imply a way to stimulate a certain digit. Though the diagrams showing only the times each finger was stimulated are very different it is hard to use these to draw any conclusions about how to choose a specific location using a combination of parameters. This is primarily due to the small amount of datapoints and the numbers varying so much between each finger. Looking at figure 27 would imply that the middle finger most likely would be reached by using a middle to high frequency, high pre-pulse and pulse amplitudes and either a very short or very long pre-pulse amplitude. The index finger would instead require a low frequency, any amplitude level or pulse duration and the pre-pulse duration again being very short or very long. Too stimulate all fingers at once, except for the pinky that cannot be reached by the median nerve, either a low pulse amplitude with a positive pre-pulse amplitude and a long pre-pulse duration or a higher pulse amplitude and a shorter pre-pulse duration appears to be the best choices. But once again the number of data points that hints at these parameters being optimal is very small in comparison to the complete number of times that they were used.

The feelings appeared both on the surface and within the hand but sometimes also appeared either on the surface or underneath it. The feeling was mostly identified as on the surface when the frequency, pre-pulse and pulse amplitudes were high but seems to not depend on the durations at all while it felt deeper when a lower frequency was combined with a lower pulse amplitude, moderate to high pre-pulse amplitudes and shorter pre-pulse durations.

The results of the naturalness show that a longer pre-pulse duration in combination with extreme pre-pulse amplitudes and high frequency makes the sensation more likely to feel less natural. Overall, the sensations were deemed closer to natural than unnatural as seen in figure 45, but it was noted by the test subject that the feeling never was truly natural.

Each category seems to be affected by different parameters to different degrees, while the sensations clearly are very affected by the frequency its effect on the naturalness seems to be much weaker and the effect of the pre-pulse duration seems to matter more. The parameter that seems to have the smallest effect on the results is the pulse duration. Small differences can be seen but in neither of the four categories does it seem to play a major role in deciding the result. This could possibly be because the pre-pulse duration, that is longer and has larger differences between each level, takes over the effect that pulse duration would have on the sensation.

It is clear from figure 48 to 50 that the pre-pulse does affect the results of electrical stimulation but if this is only in the way another pulse of any amplitude would affect the results or if the pulse being under the perception threshold changes the effect is hard to decide from the data provided by these tests. The previously mentioned figures show no big difference in the effect of a very low pre-pulse amplitude or one over the perception threshold. The best way to further investigate the effect of a sub-threshold pre-pulse is to compare the difference in results from the pre-pulse amplitudes in figure 14 to 19 for the differences between 0-1 mA and 1– 2 mA as was done in the result. This comparison shows that there is a larger difference between the first pair than between the second which might imply that the existence of a second pulse affects the results more than the actual size of it. Still it is very clear that the size of the pulse has a big effect and with the data gathered here it is impossible to say if having a pre-pulse smaller than the perception threshold really affects the resulting sensation more, or in a different way, than just having a combination of two pulses of any size does.

Comparing the differences between the positive and negative pre-pulse amplitudes shows that some categories are more affected by the polarity of the pre-pulse amplitude than others. For some of them, mainly superficiality, the effect seems to be independent from the pulse amplitude and affect all pulse amplitudes the same while for others, like the *tingling* sensation, the combinations of pre-pulse and pulse amplitudes give different results. This implies that negative amplitudes could be practical to further improve the differentiation of one feeling from another and further investigations into the effects should be done. As mentioned in the last part of the results there is also a slight difference in results depending on the order of the pulse of different sizes, a pre-pulse that was smaller than the pulse didn’t result in the same result as if the amplitude levels were switched. This implies that the order of pulses could matter and that perhaps one combination of pulses in different sizes could be distinguishable from another with the same sizes. If this would be determined to be true it would offer even further possibilities to give different types of feedback.

The method chosen to test the thesis and see if the properties of the electrical stimulation can be adapted to decide what the person will feel when stimulated worked adequately in most ways but certain changes could have made the results clearer and easier to interpret. The major issue lies in the of choice parameter levels that was made. By choosing more levels for each parameter and above all making sure that the levels chosen were actually within the area of most interest from the beginning the process could have been made more effective and the results could have provided more useful information. Making the parameter levels more symmetrical, testing more levels and focusing more on the specific areas of interest would not only make the results easier to interpret but it would also provide more information. An increase in the number of levels would make it possible to investigate the relationships between the different parameters better and make it easier to see any trends that might exist. Since the pain response appeared very rarely, we can conclude that the max limit for the pulse amplitude was well chosen. The lower limit on the other hand was not as easily defined as there was a lack of sensation quite often. This lack of sensation happened over a range of parameter levels but was more common when the amplitudes were small, the durations short and the frequency low. That the spread was as big as it was means that the lower limit possibly should be increased but since it also sometimes occurred at the higher amplitudes some sensationless stimulation would probably still appear and is more likely to be the result of faulty equipment, poorly placed electrodes or the negative pre-pulse perfectly cancelling out the positive pulse complex. Even if the placements of the electrode and the use of only one stimulating electrode was adequate and reached almost the whole hand further investigations into the effect of using multiple electrodes at once could be beneficial. It could provide some control over what areas are stimulated and if using electrode at all three nerves at once all parts of the hand could be stimulated at the same time.

Though the data implies that certain combinations of parameters will increase the chance that a certain sensation will be generated, at a certain location and at a certain depth, it is important to point out that none of this is statistically significant since all the tests were done on the same individual. The best way to improve the results of the investigation would thereby be to increase the number of test subjects and to do the testing not only on individuals that are healthy and still have both hands but also on individuals that have suffered limb loss or might benefit from sensory feedback in other ways. Testing on only one individual means that the results cannot be generalized or considered anything more than implications that parameters possibly could be chosen and paired together to create specific sensations in a certain finger or part of the hand and that more testing needs to be done. Not only on a large number of individuals but another thing that needs to be considered is that the effect of stimulation might not be experienced in the same way by someone lacking a hand or with nerve damage. More research is needed on this kind of sensory feedback using the individuals it is targeted toward to combat misunderstanding of what the intended users actually want and need. Future research into the effects of parameter levels would therefor preferably be done on individuals to a larger extent.

The testing would preferably also be done for a longer period of time to see how the body adapts to the stimulations long-term and if potentiation or habituation occurs as a response to the repeated and frequent stimulation, making the user more or less sensitive to the stimulation as time passes. It would also be interesting to see to how much the user will improve their use of the prosthesis in the long run and to what extent the brain will re-organize to adapt to the new way of living. By now TENS can be considered an old technology and through the many years of use it has been shown to be safe as long as the pulse amplitudes are kept low and the frequencies are not too high. The method might not provide the precision of implanted electrodes, but it is easy to use and can be implemented without the patient needing to undergo any further surgery, a thing many amputees are hesitant to do since they are worried about the risks. (Engdahl SM., 2015)

Though the size of the test group needs to be significantly increased one of the strengths of this thesis is the large amount of data that was collected on one individual, which would be hard to achieve on a large group of test subjects. This makes the differences between each category more significant and reduces the risk of them being a result of chance. It could also be considered a strength that the testing was done in an environment very similar to that of a person that would rely upon the sensory feedback in their everyday life. This could help identify potential future issues and the same type of distractions were present during testing as in everyday life.

The goal of this thesis was to investigate the effect of five parameters on the sensations electrical stimulation would elicit in the hand, where it would appear and how artificial it felt. Though nothing has been proven the results shows that on this specific individual the parameters did affect all four categories, sensation, location, naturalness and superficiality but had a larger effect on sensation and superficiality than location and naturalness. This implies that further investigation could be of interest and that a more details study of the possibilities electrical feedback can provide could be a good use of time and resources. Though more research needs to be done to ensure the effects of each parameter this thesis shows that further research could prove fruitful and help provide a way to give people with physical disabilities more freedom and independence which could prove essential to both their mental and physical wellbeing.

Conclusion

The sensations elicited during stimulation showed a dependency on what parameters were used and so did the superficiality. How natural the sensation felt and in what part of the hand it appeared proved harder to control but also seems to be affected by some of the parameters. In conclusion it can be said that more research into what parameters will generate a certain sensation needs to be done and that the addition of a pre-pulse shows some potential to make the kind of feedback created more diverse.

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Appendices

Appendix A

Table 2, Coding for analysis of the parameters used

Sensations	No sensation	Tingle		Buzz		Pulse	Tap		Twitch	Current		Pain	
	1	2		3		4	5		6	7		8	
Superficiality	On surface			Under the skin						Both			
	1			2						3			
Naturalness	Most unnatural		Quite unnatural					Not really natural		Quite natural		Most natural	
	1		2					3		4		5	
Location	a	b	c	d	e	f	g	h	i	j	k	l	m
	10^{0}	10^{1}	10^{2}	10^{3}	10^{4}	10^{5}	10^{6}	10^{7}	10^{8}	10^{9}	10^{10}	10^{11}	10^{12}
	n	o	p	q	r	s	t	u	v	w	x	y	z
	$2*10^{0}$	$2*10^{1}$	$2*10^{2}$	$2*10^{3}$	$2*10^{4}$	$2*10^{5}$	$2*10^{6}$	$2*10^{7}$	$2*10^{8}$	$2*10^{9}$	$2*10^{10}$	$2*10^{11}$	$2*10^{12}$

Appendix B

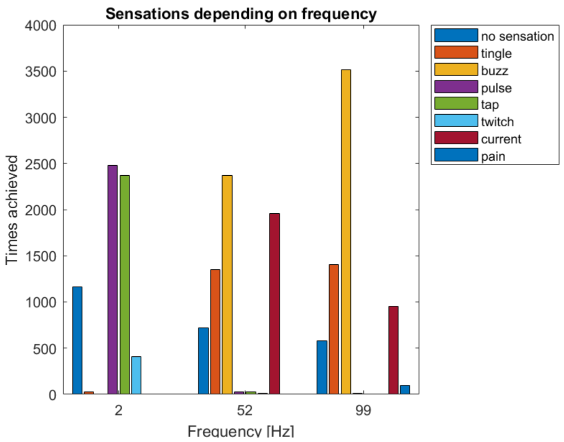

Figure 49, How common each sensation was at each frequency

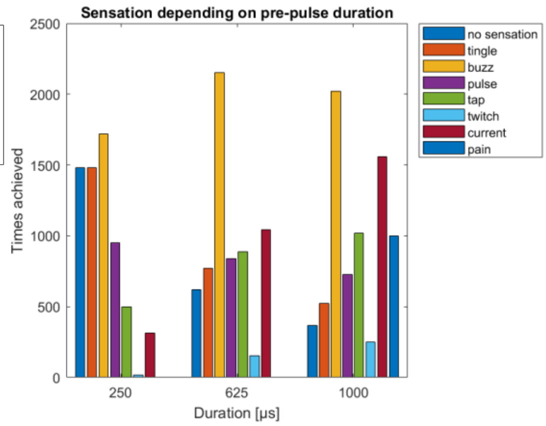

Figure 50, How common each sensation was at each pre-pulse duration

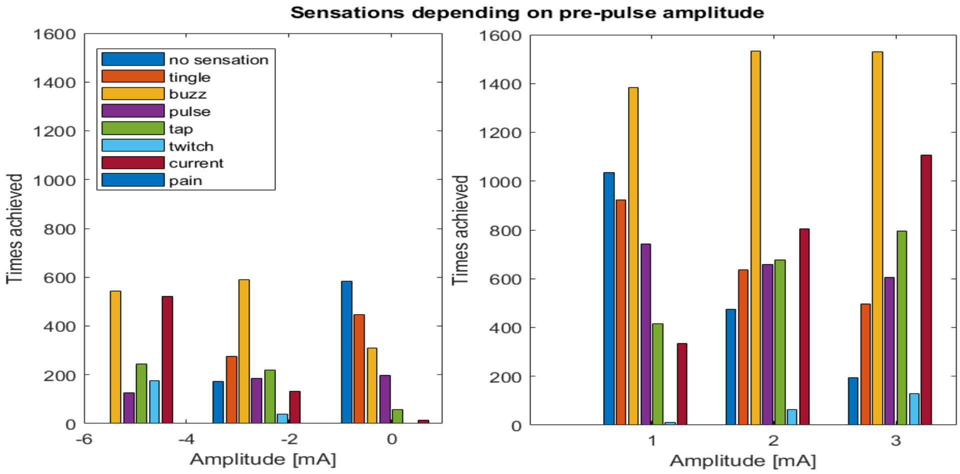

Figure 51, How common each sensation was at each pre-pulse amplitude

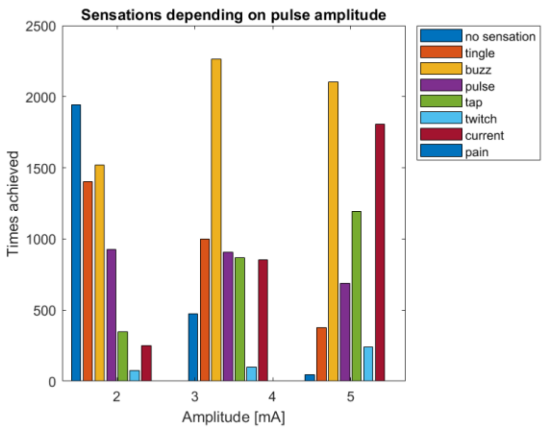

Figure 52, How common each sensation was at each pulse amplitude

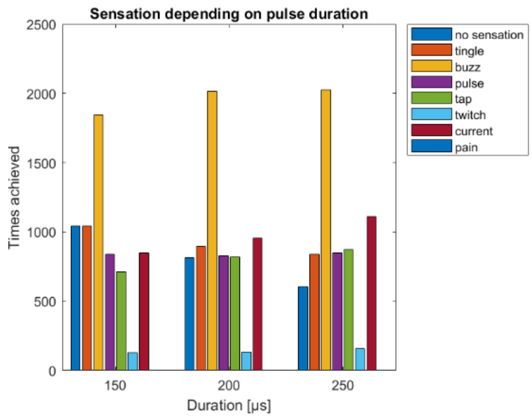

Figure 53, How common each sensation was at each pulse duration

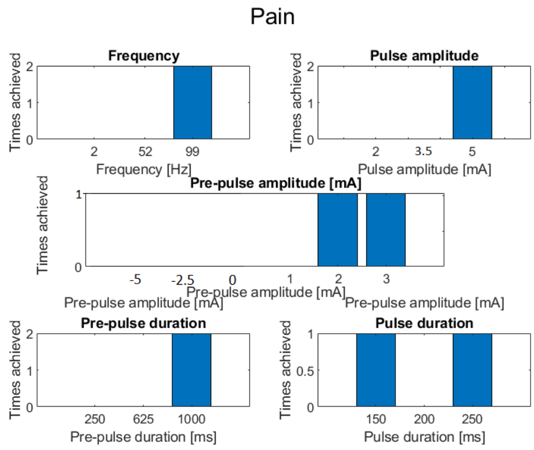

Figure 54, The distributions of parameter levels when pain was felt

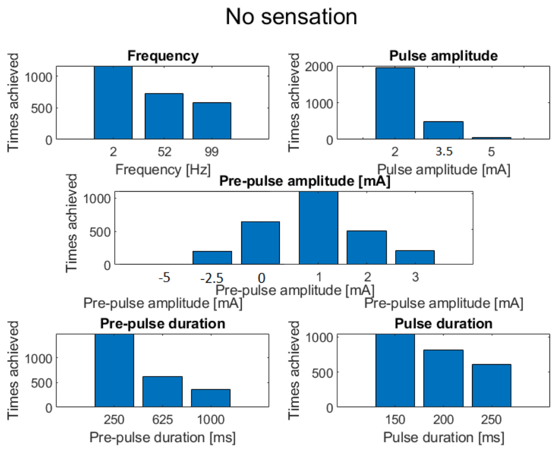

Figure 55, The distributions of parameter levels when no sensation was felt

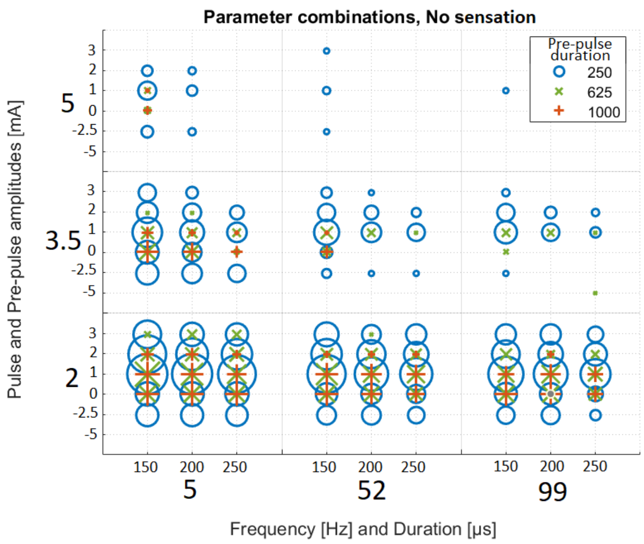

Figure 56, The combinations of parameters that generated no sensation

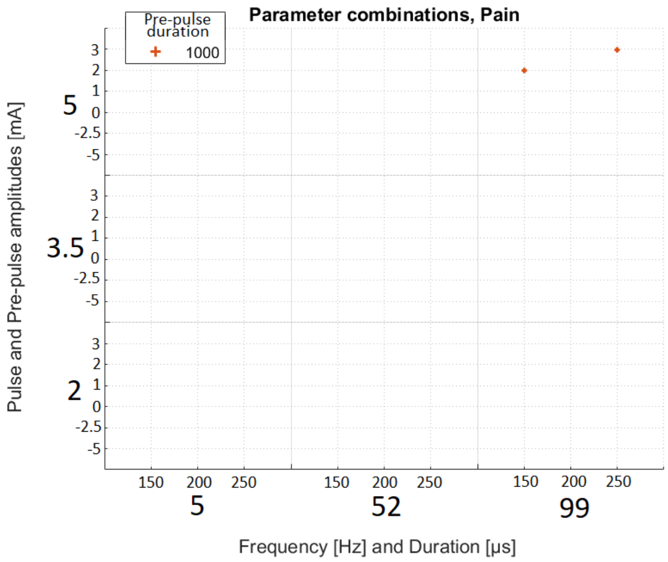

Figure 57, The combinations of parameters that generated pain

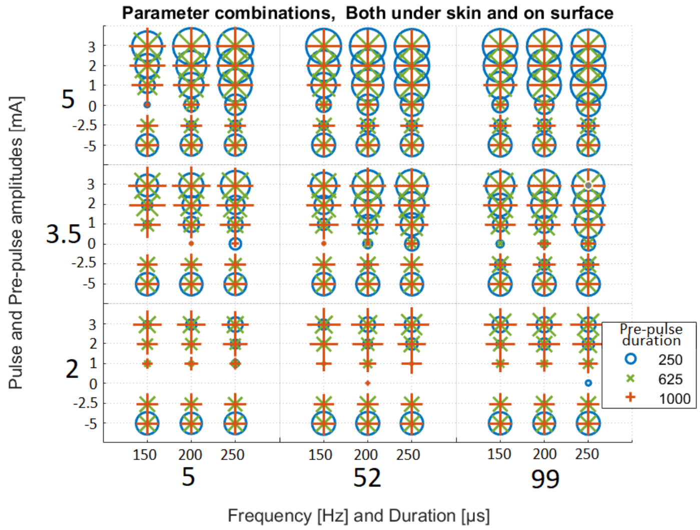

Figure 58, The combinations of parameters that generated a sensation was felt both under the skin and on its surface

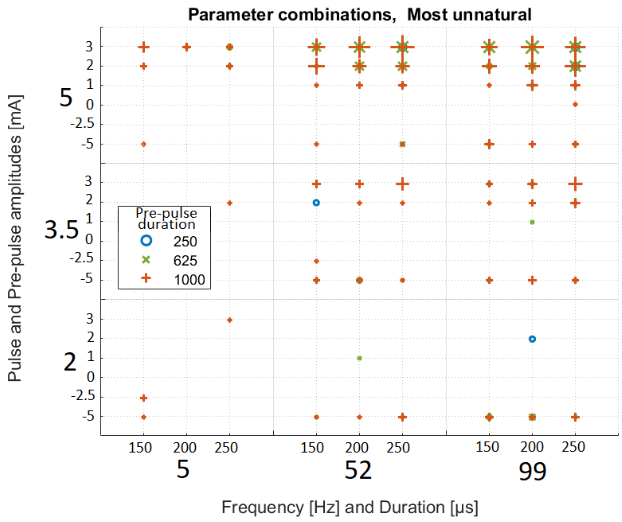

Figure 59, The combinations of parameters that generated a sensation was felt was quite unnatural

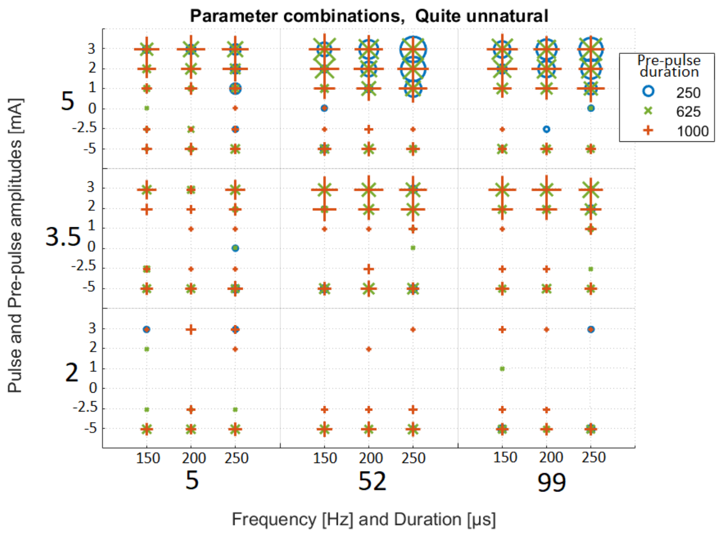

Figure 60, The combinations of parameters that generated a sensation was felt quite unnatural

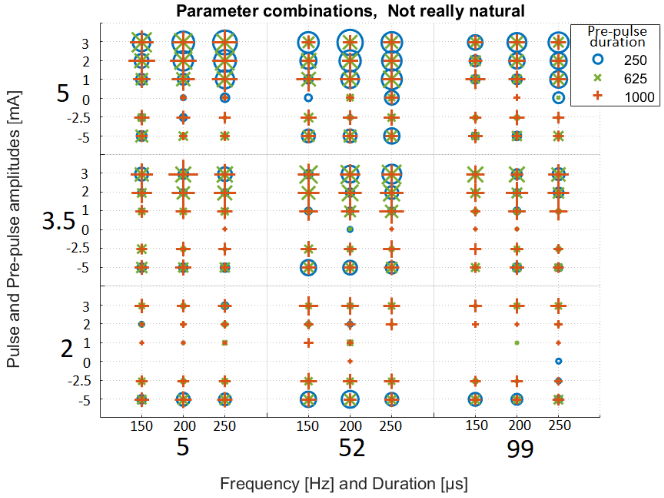

Figure 61, The combinations of parameters that generated a sensation was felt no really natural

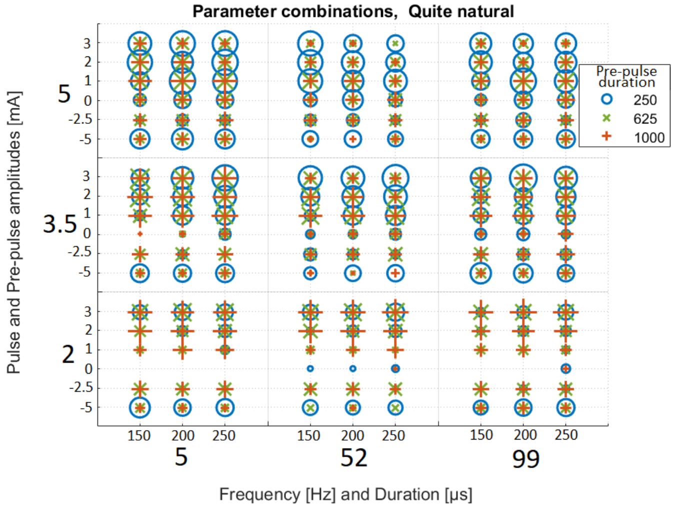

Figure 62, The combinations of parameters that generated a sensation was felt quite natural

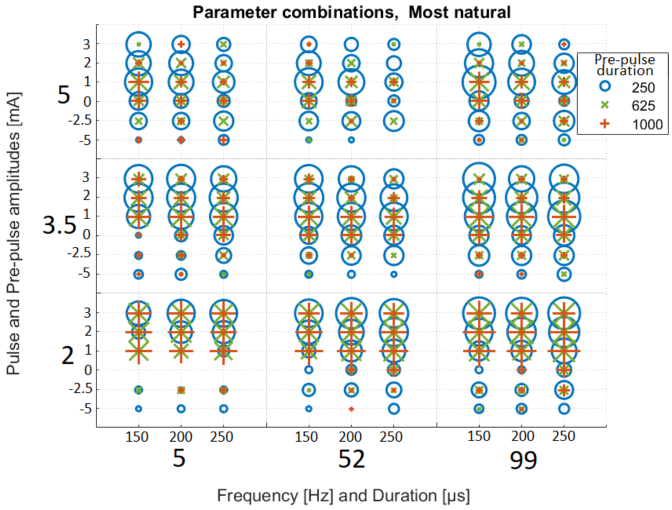

Figure 63, The combinations of parameters that generated a sensation was felt most natural