Non-Rectangular Neurostimulation Waveforms Elicit Varied Sensation Quality and Perceptive Fields on the Hand

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Abstract

Electrical stimulation of the nerves is known to elicit distinct sensations perceived in distal parts of the body. The stimulation is typically modulated in current with charge balance rectangular shape that, although they are easily generated by the stimulators available on the market, they are not able to cover the entire range of somatosensory experiences required in daily life. In this regard, we have investigated the effect of electrical neurostimulation with four non-rectangular waveforms in an experiment involving 11 healthy able-bodied subjects. Weiss curves were estimated for different subjects, showing different charges required to elicit a sensation based on the shape. The localization and dimensions of the sensations reported in the hand also differed between waveforms showing larger areas for non-rectangular waveforms. Finally, the possibility of distinguishing different charge- and amplitude-matched stimuli was demonstrated through a two-alternative-forced-choice (2AFC) task, showing the ability of participants to successfully distinguish between waveforms. This study shows that by using different waveforms to stimulate nerves, it is possible to affect not only the required charge to elicit sensations, but also the quality of sensation and its dimension, in terms of area and location.

Introduction

Human skin is a complex organ made up of different receptors that respond with different dynamics to interactions with the outside world[1–4]. Although each receptor is activated by stresses of a different nature, the natural sensation of touch is the result of a synergistic activation of the various receptors in the skin[5]. For individuals with nerve damage, this synergistic activation has been difficult to replicate artificially and is a topic of great research interest.

The restoration of sensory feedback is mainly based on the electrical stimulation of nerves using invasive or non-invasive techniques[6–9]. Invasive techniques are based on the stimulation of nerves using implantable electrodes such as spiral cuffs[10], Longitudinal Intrafascicular Electrodes (LIFEs)[11,12], Transverse Intrafascicular Multichannel Electrodes (TIMEs)[13] or Utah Slanted Electrode Arrays (USEAs)[14], or using epidural stimulation[15]. On the other hand, non-invasive techniques are based on the use of superficial electrode positioned on residual limb at the position the main peripheral nerves (TENS)[16–18]. Whatever the kind of interface, electrical stimulation is typically performed using rectangular charge-balanced waveforms. Rectangular waveforms are easily generated using the stimulators available on the market, and even if they typically elicit sensations described as electrical or unnatural[19–22]. However, several studies have shown that modifying the geometrical parameters of the rectangular waveform it is possible to affect neuron excitability[23–25] as well as modify the quality and location of sensations[26–28].

The study of non-rectangular waveforms turns out to be less thorough than that of rectangular waveforms, due to the more complicated implementation with the current technology. In fact, the main studies on non-rectangular waveforms are mainly related to computational models and computer simulations. In 1992 Wessale et al. performed a study on the comparison between rectangular and exponential waveforms, evaluating the strength duration curve of the two shapes[29]. Results showed that rectangular and exponential waveform exhibit differences in rheobase and chronaxie, and in particular the rectangular shape required a lower current to reach the threshold. This effect was explained by the phenomena of accommodation that entails an increasing of threshold with using stimuli with slowly rising slope. Wongsarnpigoon et al. evaluated six different waveforms in terms of charge, energy and power using computational models and in-vivo experiment on cat sciatic nerve[30]. This experiment showed that no one waveform can be efficient at the same time in the three selected parameters. Sahin and Tie developed a model to compare the effect of non-rectangular waveforms in respect to the rectangular one, showing that the chronaxie of rectangular waveform is lower than the one of non-rectangular waveforms[31]. Wongsarnpigoon and Grill developed a genetic algorithm to determine an energy optimal shape that was identified in the truncated gaussian[32]. Foutz and McIntyre evaluated the effect of non-rectangular waveforms on deep brain stimulation using a computational model[33]. They identified the optimal stimuli in the centered triangular, gaussian and sinusoidal waveforms. However, while these previous studies investigated psychophysical performance of these waveform shapes, no study has yet investigated the changes in sensation quality arising from the use of these waveform shapes.

In this study, we build upon these previous studies and examine the effect of non-invasive electrical stimulation with non-rectangular waveforms on a group of 11 able-bodied subjects. We show that some non-rectangular waveforms can elicit sensations with less delivered charge. We developed three different tests analyzing the strength duration curve of 4 non-rectangular stimuli and the effect on the induced perception on the hand in terms of quality and dimension. Finally, we investigated the ability to distinguish sensations induced by stimuli with different waveforms, showing that the shape of stimuli can influence the kind of sensation reported on the hand.

Methods

Hardware

The waveforms were generated using MATLAB and transferred using the Standard Commands for Programmable Instruments (SCPI) to a function generator (33511B, Keysight, CA, USA). The use of the SCPI protocol was exploited to control of the function generator from the computer, thus allowing the operator to fix the number of pulses of stimulation cycles, the duration of the stimulation, the type of waveform and its characteristics, in terms of shape, amplitude and duration. The interface also allows the user to collect information during stimulation, allowing you to perform psychophysical tasks such as the 2 alternative force choice.

Stimulation was carried out using an isolated bipolar constant current stimulator (DS5, Digitimer, England, UK). The output of the waveform generator was set as input for the DS5 providing current consistent with the desired waveform (Fig 1a).

Waveform Shapes

The waveforms were generated in such a way as to have biphasic waves with balanced charge and an inter-phase delay of 100μs, which is considered safe for long-term neurostimulation[34]. Five different wave shapes were selected: rectangular (Rect), sinusoidal (Sine), triangular centered (TR), linear increasing ramp (LineInc) and linear decreasing ramp (LineDec), as shown in Fig. 1b. Through the MATLAB interface, it was possible to generate waveforms by setting at least two parameters including charge, amplitude and duration of the cathodic stimulation phase.

The sine wave shape was modeled using the formula:

$$I\left(t\right)=A_{cathodic}sin\left(x\frac{\pi}{PW}\right)$$

where $A_{cathodic}$ is the peak current and PW is the duration of the cathodic phase. The total charge of the cathodic phase has been computed as:

$$Q=\int_{0}^{PW}A_{cathodic}sin\left(x\frac{\pi}{PW}\right)dx=2A_{cathodic}\frac{PW}{\pi}$$

The areas of the triangular shape and the two linear ramps have been computed as:

$$Q=A_{cathodic}\frac{PW}{2}$$

To compensate the charge of the cathodic phase, the anodic phase has been generated fixing the amplitude to 10% of the cathodic amplitude. In this way, the duration of the anodic phase has been computed as:

$$PW_{anodic}=\frac{10Q}{A_{cathodic}}$$

Subjects and Ethical Approval

Eleven healthy subjects (6 females and 5 males) with an average age of 26 ± 3 took part in the trial. The number of required subjects was determined via a power analysis with effect size of 1.2, α = 0.05 and minimum power of 0.80. All subjects agreed to participate in the study and signed informed consent. The experimental protocol was approved by the Swedish regional ethical committee in Gothenburg (Dnr: 2019−05446) and the entire research was performed in accordance with the relevant guidelines and regulations in perfect compliance with the Declaration of Helsinki.

Experimental Protocol

The experimentation was carried out in time slots of 3 hours. Participants were asked to sit with their arms placed on a table used as a support and to maintain the position during the experiment. The stimulation electrodes were positioned at a distance of 1.5cm from each other at the median nerve at the wrist. Subjects were given the possibility to ask for a break in every moment, and at the end of every task a small break was done until the subject was ready to restart.

Detection Thresholds

The experimentation was carried out in three different steps. In the first, we sought to determine the minimum current amplitude to elicit a sensation with the 5 different waveforms. Thresholds were obtained using a 1 up / 2 down adaptive psychophysics method with 50μA steps and a threshold set at 10 reversals. The threshold was obtained for 5 different stimulation durations (100μs, 300μs, 400μs, 600μs and 900μs). This test was performed for stimulation with a single pulse and stimulation with a train of 15 pulses at 30Hz.

Data obtained from the detection of threshold was used to fit the Lapique's equation, a relation describing the strength duration curve, in other words, the relation between the minimum current required for stimulation and the pulse dutation[35,36]. Lapique's equation was fitted using robust linear least-square fitting method based on bisquare weights method.

The effective amplitude (rms) of current was taken into account during the fit to make a reasonable comparison between the charge injected during stimulation and also to apply the definition of Lapique's equation:

$$I = b(1 + \frac{c}{d})$$

Where b is the rheobase, c is the chronaxie and d is the duration of cathodic phase. Detection thresholds were fitted to Lapique's equation to estimate rheobase and chronaxie. Considering the effective value of amplitude the several shapes were reported to an equivalent rectangular shape, in this regards it was possible to apply the definition of the Weiss Eq. 3[7] to estimate the required charge to stimulate nerves and induce a recognizable sensation:

$$Q = b(d + c)$$

Description of Elicited Percept

Once the threshold of the different waveforms was obtained, participants described the sensations aroused in the hand from the different waveforms, each with a cathodic phase duration of 400μs, for both single pulses and trains of pulses. The charge of the different waveforms was set to the charge of the rectangular waveform increased by 20%. During this phase, subjects received stimulations with the waveform under investigation and were subsequently asked to describe the location of the sensation in the hand and the quality of sensation reported. All sensations reported by subjects were collected using a custom MATLAB interface. During the task subjects were able to ask for new stimuli until they were ready to describe what they perceived.

To better understand the variation of area the dimensions of sensations have been considered as variation in respect to sensation related to rectangular waveform:

$$\Delta A_{\%} = \frac{100(A_{notRec} - A_{Rec})}{A_{Rec}}$$

where A_{notRec} is the area of sensation induced by non-rectangular waveform and A_{Rec} is the area of sensation induced by rectangular sensations.

Two-Alternative Forced-Choice

The third protocol asked participants to correctly distinguish between pairs of waveforms with different shapes. To ensure that the charge and peak current were the same for all conditions, this protocol was only conducted with the triangular, linear increase, and linear decrease waveforms. Thus, any ability to distinguish between waveforms would be due entirely to the modulation of the waveforms. First, two stimuli were provided with different waveform shapes, with 5 seconds in between. Another 5 seconds after the second stimulus, a third stimulus was provided which matched the first or second. Subjects were asked to identify which stimuli were matched. This protocol was carried out by fixing the charge to the same used in the second protocol by means of a sequence of 30 different combinations of stimuli, thus allowing to have 10 samples for each pair of stimuli (TR-LineInc; TR-LineDec; LineInc-LineDec). The data from 2AFC were instead collected and the values were analyzed by means of an average of the responses reported by the subjects.

Statistical Analysis

To understand consistent dissimilarity between rectangular waveform and non-rectangular waveforms a null hypothesis test using Wilcoxon signed-rank Test was performed through MATLAB considering an alpha level $\alpha = 0.05$. For rheobase and chronaxie, where non-rectangular waveforms have been compared to the rectangular one which was considered as reference, four comparisons where performed, Bonferroni correction was applied, and the obtained p-value was multiplied by a factor four to reduce the possibility of type I error. For the third protocol to statistically validate the data, the one sample Wilcoxon signed-rank test has been performed to determine if the success rate was greater than 50%.

Results

Rheobase and Chronaxie

The data obtained in the detection threshold task were used for the estimation of rheobase and chronaxie for the corresponding waveforms. To obtain a comparison between the waveforms, the types of waveforms used during stimulation were taken into account by means of the current rms. The rheobase and chronaxie values were thus obtained and are reported in Table 1.

For single pulse stimulation, the Rect rheobase (398 μA) was found to be higher than for Sine (349 μA, $p = 0.0392$), TR (349μA, $p = 0.0548$), LinInc (393μA, $p = 0.269$), and LinDec (281μA, $p = 0.168$). The Rect chronaxie (0.656ms) was found to be lower than for Sine (0.846ms, $p = 0.168$), TR (0.944ms, $p = 0.0976$), LineInc (0.757ms, $p = 0.492$) and LineDec (1.359ms, $p = 0.0548$).

Table 1
Median Rheobase current and Chronaxie time obtained from the detection threshold task

Shape	Single Pulse		Train of Pulses	
	Rheobase (μA)	Chronaxie (ms)	Rheobase (μA)	Chronaxie (ms)
Rect	398	0.656	373	0.620
Sine	349	0.846	333	0.736
TR	299	0.944	394	0.750
LineInc	393	0.757	458	0.586
LineDec	281	1.359	349	1.022

Regarding the stimulation with pulse trains, the results differed from single pulse stimulation. No significant variations were found between the waveforms neither for rheobase ($p > 0.32$) nor chronaxie ($p = 0.1569$).

Perceptive Fields and Sensation Quality

The percept localization task aimed to determine if different stimulations could recruit different neural fibers thus affecting the location and quality of the sensations. In Figures 3-4, the location of the sensations and the different qualities of sensations reported by the subjects with respect to the waveform used for stimulation are shown. Non-rectangular waveforms have a higher incidence of sensations perceived as electrical, a fact that may be linked to the higher peak current level and not to the charge injected during stimulation. The mean area of perceptive fields induced by non-rectangular waveforms was compared to those induced by rectangular waveform showing that TR, LineDec and LineInc result respectively in an increased sensation area of 33%, 45% and 53% in respect to rectangular, while for trains of pulses they resulted in an average increase of 53%, 87%, and 73%, suggesting that the maximum amplitude is a key factor in the recruitment of higher number of fibers. For 9/11 participants, stimulation with pulse of train resulted in more diffuse sensations in the hand. This is probably linked to the higher charge injected because of the higher number of pulses, even if the charge of the threshold was lower. Only two participants (S2 and S10) perceived larger sensation areas with a single pulse than with a train of pulses. Overall, these results suggest that the shape of the waveform, in addition to the delivered charge, has an impact on the number of nerve fibers recruited, so in the area of perception, and also on the quality of fibers recruited affecting the quality of perception reported by the subjects.

Two-Alternative Forced-Choice

The 2AFC task was performed with the aim of understanding whether the sensations induced by waveforms having the same charge and same peak current, but different dynamics were differentiable. The data show how it is generally possible to distinguish between triangular waveforms and either of the linear ramps (Fig 5). Also interesting is the description given by the subjects involved who claimed to have concentrated on variations of “rhythm”, “intensity”, “dimension” of the sensation to understand the difference, despite identical stimulation frequencies, amplitude and duration of stimuli. The ability to discern between the two linear ramps, which present similar current slope was on average about 50% of success. Overall, these results suggest that modulating stimulation shape could be another parameter by which to communicate information to an individual, in addition to modulating the pulse amplitude, pulse width, or stimulation frequency.

Discussions

In this study, we investigated the effect of non-rectangular waveforms in non-invasive electrical nerve stimulation. To do this, we developed three different experiments (detection threshold, perception localization, and 2AFC discrimination) to answer three specific questions:

1. Does the shape of stimuli affect the physiological parameters that describe neuron excitability to electrical stimuli?
2. Does the shape of stimuli affect the kind of perception in terms of location, dimension, and quality?
3. Is it possible to distinguish the induced perception of two stimuli with the same charge, amplitude, frequency, and duration, but different shapes?

We found from the detection of threshold task that the shape has an incidence on chronaxie but induces low significant variations on rheobase. From the perception localization task, we found that the shape affects the quality and dimension of sensation on the hand, and finally, from the 2AFC task we found that it is possible to discriminate between sensations elicited with different waveforms but same amplitude, frequency, charge, and duration showing that also the shape has a role in the stimulation. The results suggest that by using TENS it is possible to influence the excitability of neurons and also the capability to recruit different portions of nerve fibers changing the shape of the stimulation.

Rheobase and Chronaxie

The results obtained from the detection of threshold seem to be coherent with results shown by Sahin and Tie[31], who showed how the waveform used during stimulation can have an effect on the stimulation efficiency and therefore influence neuron excitability, especially for chronaxie as shown in Fig. 2. Similar to the findings obtained by Wessale et al., and Sahin and Tie, non-rectangular stimuli resulted in higher chronaxie [29,31]. The influence of shape on rheobase and chronaxie should be considered in future stimulation algorithm development, since those two values affects the efficiency of stimulation. Knowing the values of rheobase and chronaxie of a subject in respect to stimulation shapes may help to develop more efficient stimulation algorithms, capable to stimulate nerve and induce a sensation minimizing the amount of charge required from the hardware and prolonging the battery life of the prosthetic system.

Perceptive Field and Quality

From the description of elicited sensation some interesting aspects emerge, the waveform can influence the induce sensations in terms of quality and dimension. The injected charge is not the only factor influencing neural recruitment, but stimulus dynamics and amplitude are also important. Triangular waveforms and linear ramps generally result in a larger sensory area in respect to the rectangular. The amplitude is also a key factor in arousing sensations perceived as more natural and less electric. In fact, for single pulses, the number of subjects that described sensations perceived as "electric" varied between 3/11 and 4/11 for non-rectangular waveforms, compared to 2/11 of the rectangular shape. With train of pulses the rectangular had an incidence of 1/11 of electric sensations while for the non-rectangular sensations it changes from 2/11 to 4/11. The obtained results suggest that not only the charge and duration of stimuli, but also the shape of the waveform can have an effect on quality and dimension of sensations.

Differentiation of Waveforms

Interesting considerations emerge from the 2AFC task. Subjects were generally able to correctly identify between the triangular waveform and the linear ramps (TR-LinInc $p = 0.048$, TR-LinDec $p = 0.0176$), which, although sharing the charge and amplitude, showed different dynamics. This result shows that the charge injection rate itself can affect the recruitment of neural fibers, influencing factors such as the area of sensation and the quality of sensation. The test also shows that participants were unable to differentiate between sensations elicited by the two linear ramp waveforms. This situation may be caused by the maximum rate of current change. In fact, the centered triangular has faster rates of current change than the two ramps, which featured equal but opposite current change rates. The capability to distinguish between different stimuli represent a big opportunity in neurostimulation modulation, since the possibility of using waveform shape as a new parameter to encode information may give a new degree of freedom in developing algorithm for sensory feedback.

Limitations

Tests were followed in 3-hour slots for each subject within the same experimental session. This may have affected the subjects' ability to concentrate, even with frequent breaks, thus affecting the rheobase and chronaxie estimation introducing a general noise in the threshold estimation, especially regarding train of pulses which were always conducted after the single pulse study, so leading to a general tiredness of subject with a negative impact on concentration.

The large number of thresholds obtained (5 thresholds for 5 waveforms for 2 sessions) in a restricted time could also have led to adaptation effects to electrical stimulation[38], thus increasing the charge necessary to feel a sensation in the waveforms of the final phase of experimentation, so on the estimation of threshold during stimulation with train of pulses. This may have minimized the differences of rheobase and chronaxie between non-rectangular and shapes. To obtain a greater detail of chronaxie and rheobase it would be necessary to perform detection threshold for single pulse and train of pulses in two different sessions, and increase the number of threshold for each task.

The data obtained during the description of elicited sensations, although indicators of a variation in sensations, should be verified more thoroughly through subsequent studies, to verify the stability of the sensations in terms of quality and location. To do this, it would be necessary to reproduce the characterization of sensation in a follow-up study. Collecting data over time it would be possible to statistically validate the effect of non-rectangular waveforms on elicit sensation more diffused in the hand in respect to rectangular. Moreover, this would lead a more detailed correlation between the amplitude of stimuli and the elicit of electrical sensations.

It is also important to investigate how the results obtained during description of elicited sensations and the result of 2AFC are depending to the positioning of the electrodes on the wrist or if results are reproducible also in different types of stimulation, such as through the use of invasive electrodes. The reproducibility of the reported experiment on different kind of interfaces would open the possibility to introduce a new degree of freedom in stimulation, allowing to use the effect of shape during closed-loop control of bionic prostheses.

Future Directions

Although the results of this study are promising there are several aspects that need to be investigated. It would be interesting to evaluate the impact of electrode positioning on the arm to understand if these kinds of results can be obtained also positioning the electrodes in different locations and if it is possible to exploit this approach to maximize the effect of stimulation in situations in which the position of the electrode is forced by the prosthetic socket. Then, when the effect of electrode positioning has been evaluated, the focus of the study can be moved to people with amputations. The possibility to execute the experimental protocol with people with limb loss can also naturally be extended to direct nerve stimulation with invasive interfaces[39,40].

The possibility of integrating stimuli with different shape into more complex algorithms such as biomimetics[41] and neuromorphic[42] should be investigated, to understand if it is possible to improve the quality of stimulation and elicit more natural sensations. Moreover, the implementation of linear amplitude modulation and frequency modulation for sensory feedback should be investigated, and the experiments proposed by Tan *et al*. and Ortiz-Catalan *et al*. [12,26] should be reproduced to understand if the execution of patterned stimulation with non-rectangular waveforms has a different effect on quality and location of perceptions.

Another important topic that must be investigated is the impact of electromyographic control. The control of bionic hands is mainly based on recording and elaboration of electromyographic (EMG) signals from residual muscles of amputees [43–46]. The use of electrical stimulation introduces electrical artifacts in the EMG recording leading to a failure in prosthetic control[47]. The impact of shape on EMG signal should be investigated to understand if it is possible to minimize the effect of electrical artifacts induced by the stimulation process, as well as how they may interact with artifact removal algorithms used to denoise such a signal[48].

Declarations

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Author Contributions

R.C., E.J.E., and M.O.C. designed the study. R.C. developed MATLAB interface, executed the tests and drew the figures. E.J.E. supported data and statistical analysis. M.O.C. and M.B supervised the research. R.C. and E.J.E. drafted the manuscript. All the author reviewed and approved the submitted manuscript.

Data Availability Statement

The simulated and measured data presented in this paper can be found at Open Science Framework (Collu, Earley, Barbaro, Ortiz-Catalan, 2022).

Additional Information

Competing Interests

MOC has consulted for Integrum AB. The rest of the authors declare no competing interests.

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Figures

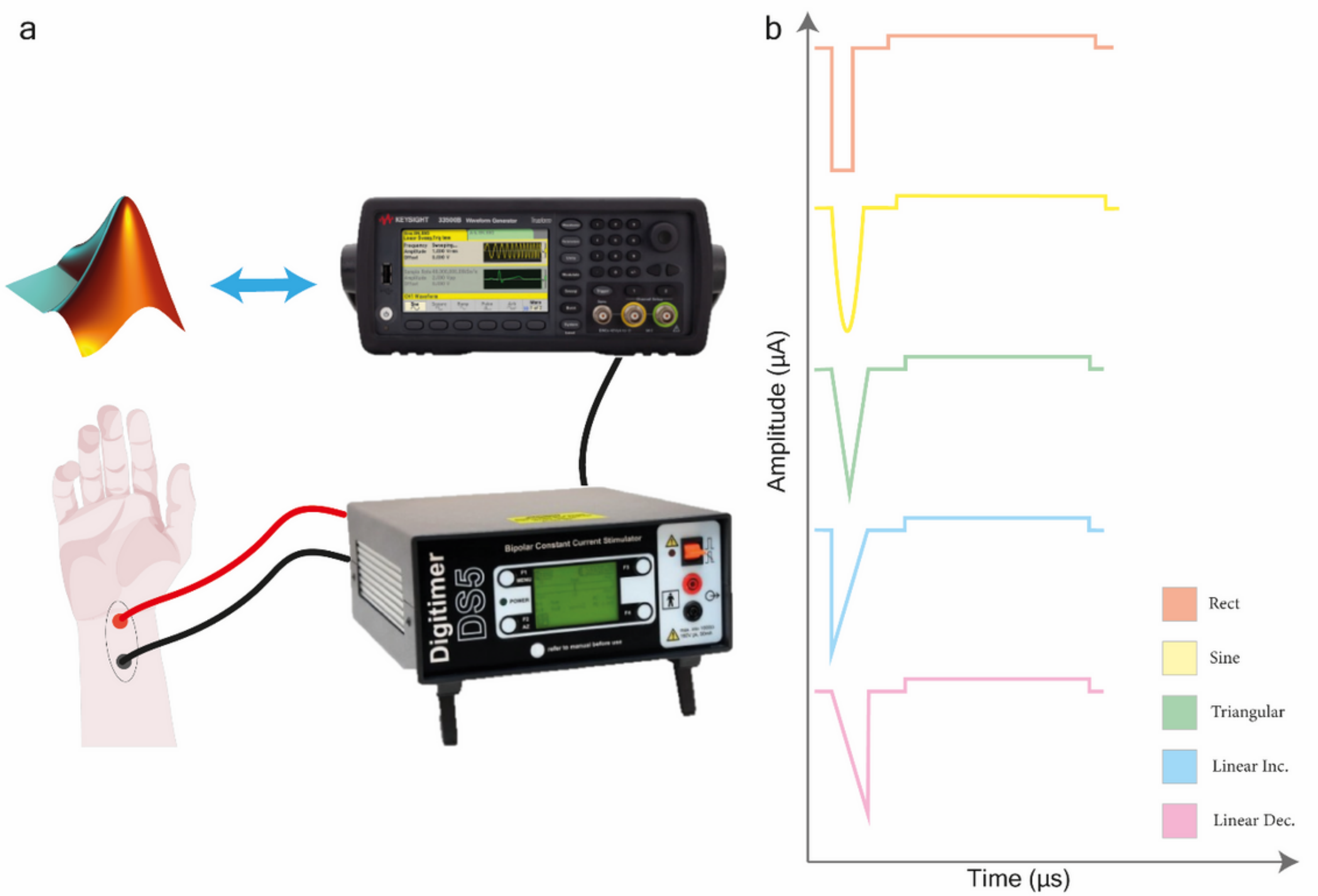

Figure 1

a The setup used is based on a MATLAB interface that allows the user to control the Keysight function generator via serial connection and use of the SCPI standard. The function generator is therefore used to generate the desired voltage waveforms and bring them to the input of the current stimulator DS5, which is connected directly to the electrodes placed on the subject's wrist. **1b** The five waveforms tested in this study are the rectangular, sinusoidal, triangular, linear increasing ramp, and linear descending ramp. The waveforms were generated in such a way as to have an interphase delay of 100us between the cathode phase and the anode phase

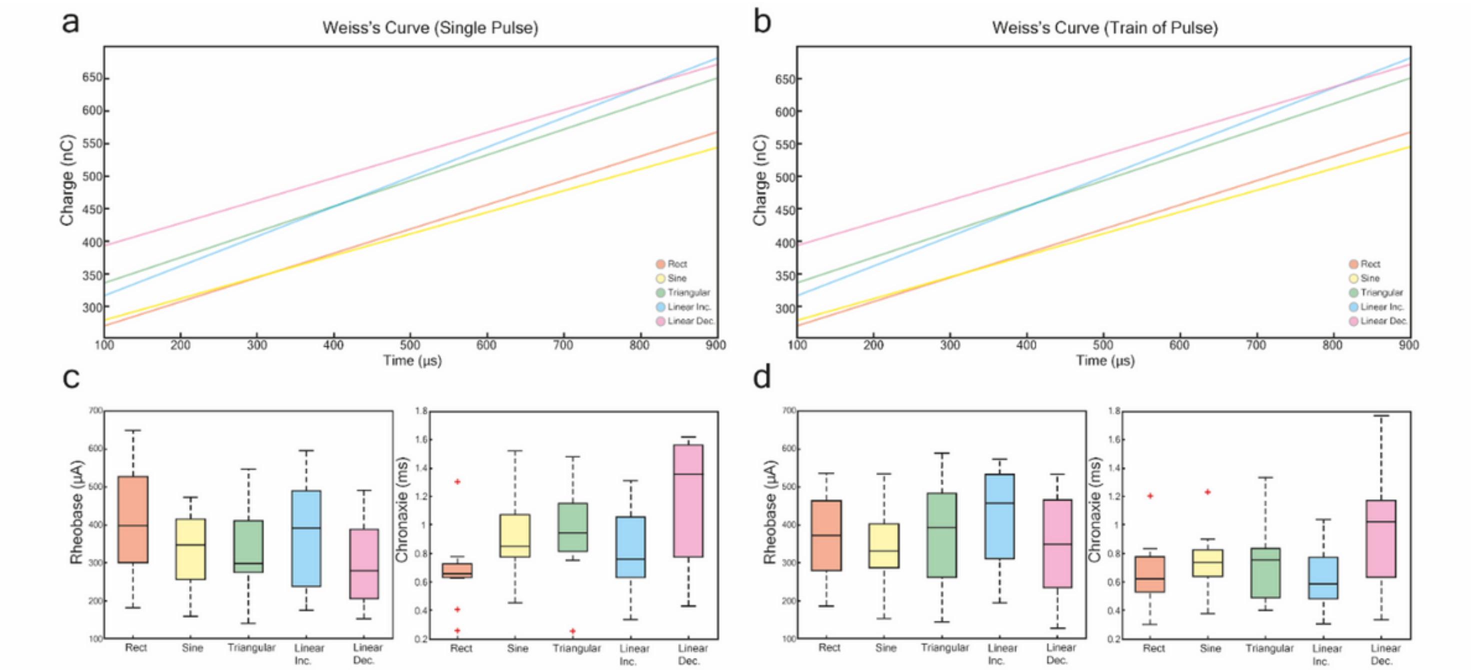

Figure 2

a Weiss's curve obtained fitting the data obtained from stimulation with single pulse. **2b** Weiss's curve obtained fitting the data obtained from stimulation with train of 15 pulses at 30Hz **2c**Rheobase and Chronaxie estimated from the fit of data from stimulation with single pulse.) **2d** Rheobase and Chronaxie estimated from the fit of data from stimulation with train of 15 pulses at 30Hz.

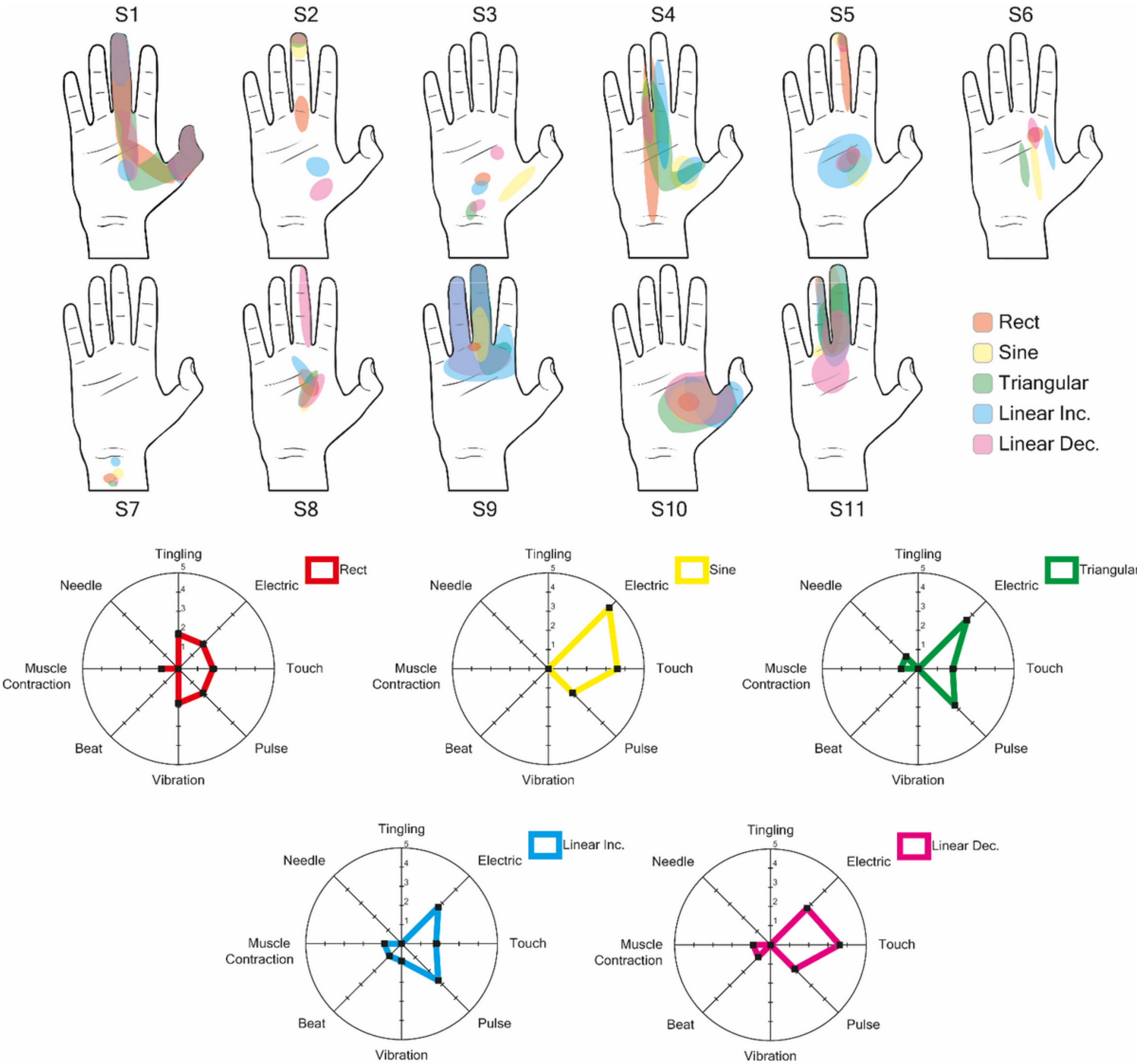

Figure 3

The sensations reported following single-pulse stimulation were reported and superimposed on the same drawing. Although in some cases the sensations share the same point of origin, it can be seen that as the type of waveform varies, the sensation area expands or moves, a phenomenon that could indicate a different activated neural portion or a greater number of fiber recruited. In addition, the sensations reported by the eleven volunteers were collected and graphed with respect to the type of waveform, showing how each waveform has different trends in terms of the type of sensation. In particular, it seems that waveforms with greater amplitude are more likely to arouse electrical sensations. For 9/10 subjects the bigger sensations in terms of area are represented by non-rectangular waveforms (2/11 LineDec, 3/11

LineInc, 3/11 Sine, 2/11 TR), only S1 has reported a bigger sensation for rectangular stimuli. Considering the average dimension of sensations,the mean areas of sensation induce by LineDec, LineInc and TR are respectively the 45.9% , 53.7% and 33.8% bigger than the average area of sensations induced by rectangular waveform. The mean area of sensations induced by sinusoidal waveform is smaller than the average area of sensations induced by rectangular waveform of about the 11%.

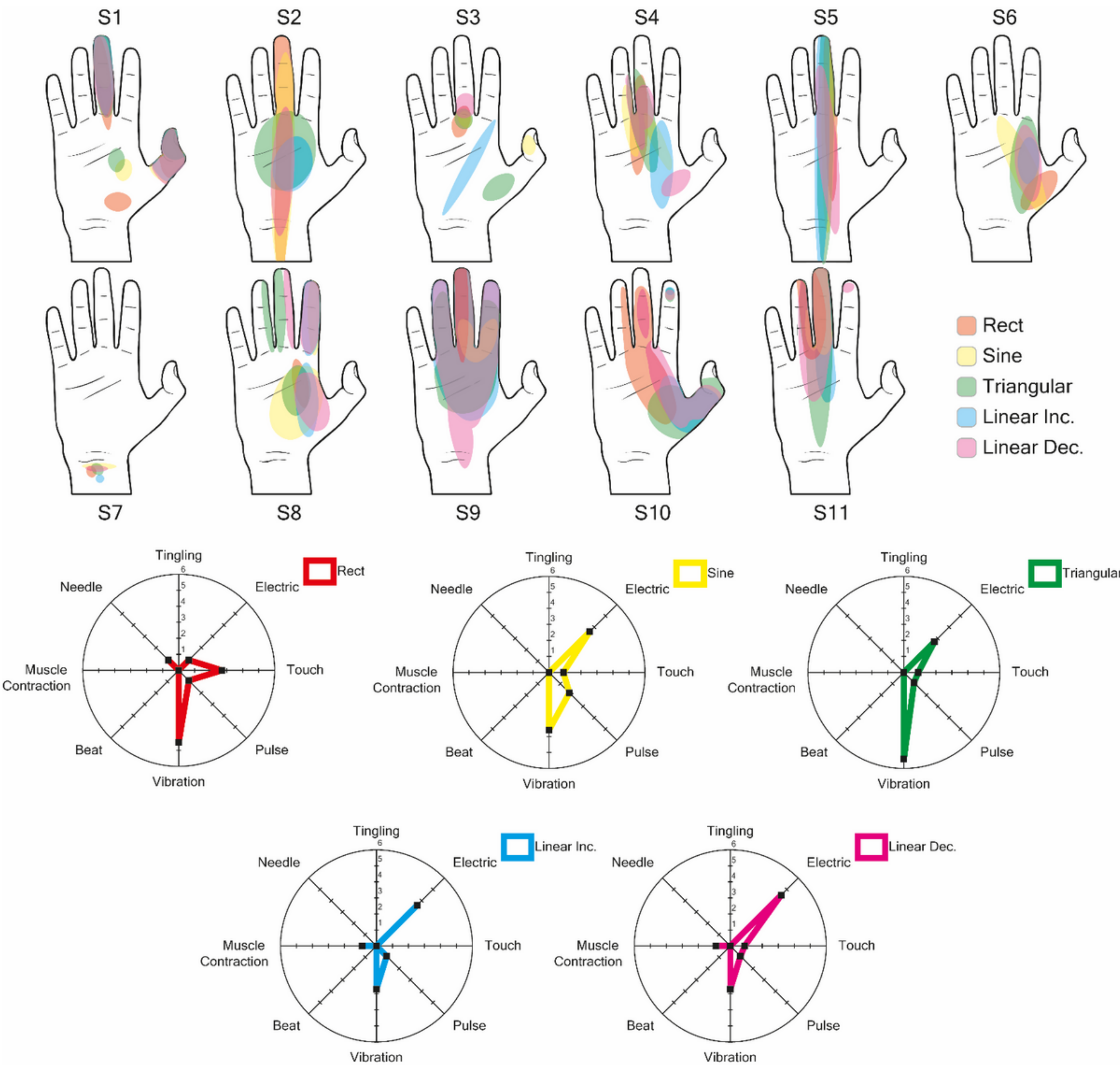

Figure 4

The sensations reported following stimulation by train of 15 pulses at 30Hz were reported and superimposed on the same drawing. As in the case of single-pulse stimulation, it can be seen that the different waveforms have similar points of origin, although the areas of sensations are slightly different, and tend to be wider in non-rectangular waveforms. The increased charge induced by the pulse train also results in a greater portion of the hand affected by the stimulation, indicating that more neural fibers have been affected. In this case, moreover, the induced sensations are moving towards vibrational sensations, and for linear ramps the electrical sensations are more predominant. In every case the bigger sensations in terms of area were induces by non-rectangular stimuli (4/11 TR, 3/11 Sine, 2/11 Dec, 1/11 LineInc). Considering the average dimension of sensations, the mean areas of sensation induce by LineDec, LineInc,TR and Sine are respectively the 87.7% , 73.5%, 53.2%, and 42.5% bigger than the average area of sensations induced by rectangular waveform. induced by rectangular waveform of about the 11%.

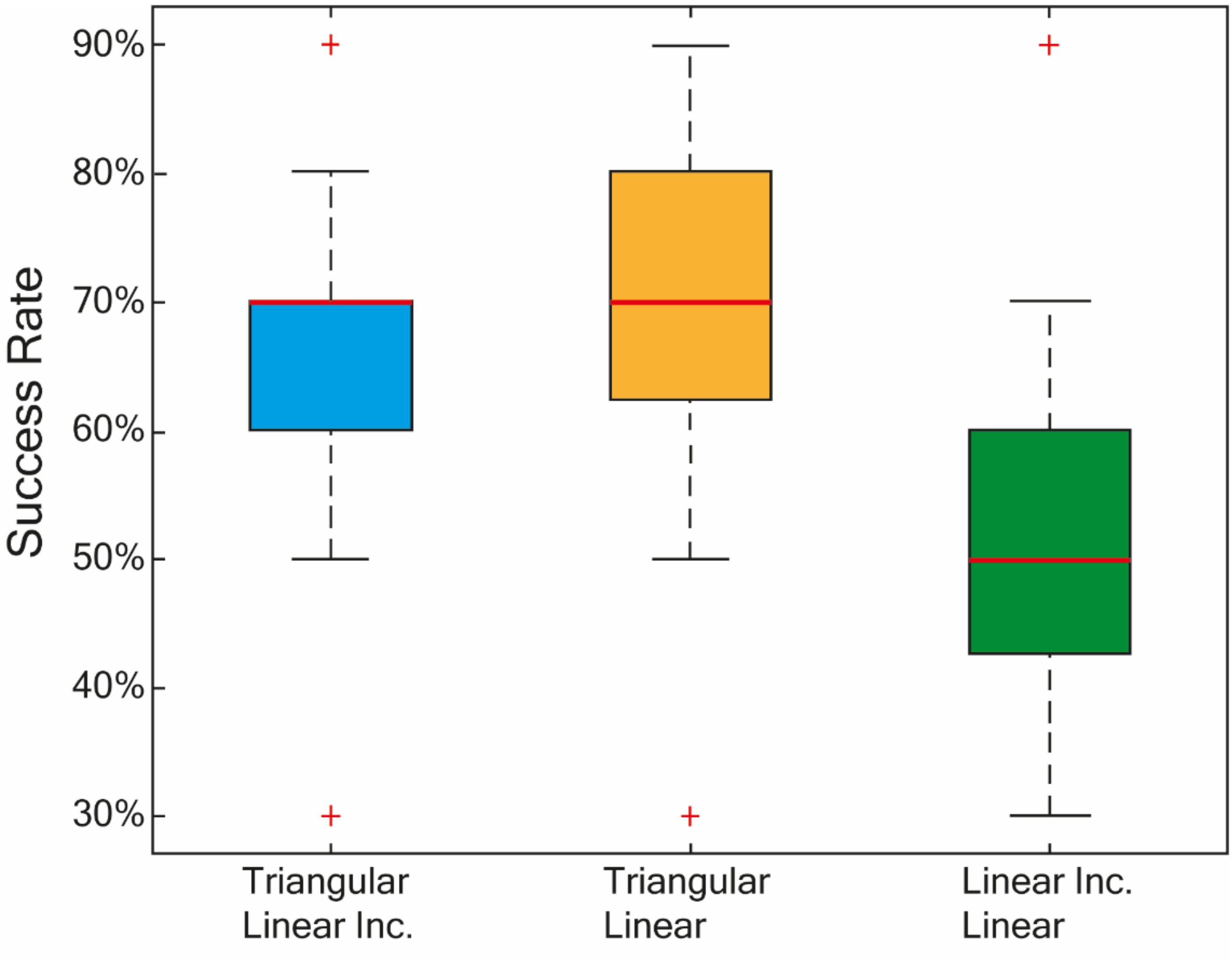

Figure 5

The data obtained by the 2AFC were collected and analyzed. The result shown indicates that in 70% of cases, the volunteers were able to correctly distinguish the stimulation carried out with a linear or triangular ramp, indicating that the dynamics of the waveform can influence the induced sensation. On the other hand, it is more difficult to distinguish between waveforms with similar dynamics as in the case of the comparison between linear ramps, in which the success rate is 50%.