Journal of Neural Engineering

PERSPECTIVE

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To cite this article: L H Kim *et al* 2018 *J. Neural Eng.* **15** 013002

IOP Publishing Journal of Neural Engineering

J. Neural Eng. **15** (2018) 013002 (9pp) https://doi.org/10.1088/1741-2552/aa966a

Perspective

A new psychometric questionnaire for reporting of somatosensory percepts

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Received 15 May 2017, revised 10 October 2017
Accepted for publication 27 October 2017
Published 16 January 2018

Abstract

Objective. There have been remarkable advances over the past decade in neural prostheses to restore lost motor function. However, restoration of somatosensory feedback, which is essential for fine motor control and user acceptance, has lagged behind. With an increasing interest in using electrical stimulation to restore somatosensory sensations within the peripheral (PNS) and central nervous systems (CNS), it is critical to characterize the percepts evoked by electrical stimulation in a standardized manner with a validated psychometric questionnaire. This will allow comparison of results from applications at various nervous system levels in multiple settings. *Approach*. We compiled a summary of published reports of somatosensory percepts that were elicited by electrical stimulation in humans and used these to develop a new psychometric questionnaire. *Results*. This new questionnaire was able to characterize subjective evoked sensations with good test-retest reliability (Spearman's correlation coefficients ranging $0.716 \leqslant \rho \leqslant 1.000$, $p \leqslant 0.005$) in 13 subjects receiving stimulation through neural implants in both the CNS and PNS. Furthermore, the new questionnaire captured more descriptors ($M = 2.65$, $\mathrm{SD} = 0.91$) that would have been missed by being categorized as 'other sensations', using a previous questionnaire ($M = 1.40$, $\mathrm{SD} = 0.77$, $t(12) = -10.24$, $p < 0.001$). Lastly, the new questionnaire was able to capture different descriptors within subjects using different patterns of electrical stimulation (Wilk's Lambda $= 0.42$, $F(3, 10) = 4.58$, $p = 0.029$). *Significance*. This new somatosensory psychometric questionnaire will aid in establishing consistency and standardization of reporting in future studies of somatosensory neural prostheses.

Keywords: human cortical stimulation, neuroprosthetics, neuromodulation, electrical stimulation, psychometric questionnaire, somatosensory percepts

S Supplementary material for this article is available online

(Some figures may appear in colour only in the online journal)

1. Introduction

Neural prostheses to restore lost motor function have made remarkable advances over the past decade [1]. The restoration of motor function using electrical stimulation spans target sites in both peripheral and central nervous systems. In contrast to the advances in motor restoration, the restoration of somatosensory feedback has lagged behind. Yet somatic sensation plays an essential role in fine motor control and user acceptance of a prosthesis [2–4]. For example, electrical stimulation applied through microneedles in the nerve stump can evoke sensations to upper extremity amputees [5] that allow object discrimination using a myoelectric prosthesis [6, 7]. While such microstimulation is referred to as single fibre activation, it is unlikely that only a single fibre would be affected by such stimulus [8] and that it would be sufficient to mimic the neural encoding of a population of neurons that cover the full range of sensory modalities and describe the state of a limb [1, 2]. Nonetheless, previous studies with single fibre activation identified possible stimulation sites for restoring somatosensation and are useful in developing multichannel microstimulation methods [1, 2, 5, 6].

In spite of these advances in peripheral nerve stimulation, individuals with more proximal injures will require central nervous system (CNS) stimulation. This will be a more complex and difficult task in terms of technical implantation and invasiveness of the procedure. One potential brain target we [9, 10] and others [11] have proposed is the thalamus. Others are exploring the somatosensory cortex as a target for electrical stimulation [2, 12–14]. With multiple groups attempting to develop somatosensory neural prostheses, we identified a gap in the methods by which we measure somatosensory percepts evoked by electrical stimulation in humans.

For our earlier studies we used a psychometric questionnaire designed for thalamic microstimulation [15]. Previous work by Gracely [16–19] established the sensory and affective descriptor scales of painfulness and their reliability, objectivity, and validity. When we applied different patterns of electrical stimulation instead of the continuous high frequency electrical stimulation applied by Lenz [15], our subjects used different terms to describe the percepts elicited [9]. While free reporting of evoked senses by the subject on his own may be the least restrictive collection method that is used [6, 20–23], the results may be more difficult to compare across study subjects, different stimulation types and/or areas. The sensations evoked by the same stimulus can be described using a variety of words by different people. However, in order for somatosensory prostheses to be developed we need to compare the effects of electrical stimulation applied to multiple nervous system levels and compare results from multiple labs. Collecting the subject's free form report in addition to providing a structured questionnaire with exemplary common descriptors [12, 24–26] could optimize both the characterization and the comparison of evoked senses. To this end, we sought to develop a new structured psychometric questionnaire that could facilitate the characterization of various percepts evoked by electrical stimulation at multiple system levels. We compiled a summary of published reports of somatosensory percepts that were elicited by electrical stimulation in humans and used this information to develop a new psychometric questionnaire.

2. Materials and methods

2.1. Developing the somatosensory questionnaire

Somatosensory descriptors obtained with electrical stimulation were compiled from clinical settings and the published literature. A systematic literature review was conducted on 2 July 2014 and updated on 22 November 2016 on MEDLINE and EMBASE databases using a PRISMA (preferred reporting items for systematic reviews and meta-analyses) search protocol [27] as follows:

Search protocol for MEDLINE

1. Electric Stimulation/
2. electric stimulation therapy/ or deep brain stimulation/ or surgical procedures, operative/
3. electric stimulation therapy/ or deep brain stimulation/ or spinal cord stimulation/ or transcutaneous electric nerve stimulation/ or vagus nerve stimulation/
4. electrotherapy.tw.
5. electr* stimulation.tw.
6. brain stimulation.tw.
7. thalamic stimulation.tw.
8. nerve stimulation.tw.
9. spinal cord stimulation.tw.
10. electr* stimulation therapy.tw.
11. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10
12. ((somato or somatic) adj2 (sense or senses or sensation or sensations or percept or percepts or response or responses or effect or effects or psychophysic*)).mp.
13. ((somat* or sens*) adj1 (percept or percepts)).mp.
14. ((perceive* or elicit* or evoke* or somatic) adj2 (sense or senses or sensation or sensations or somatosensation or somatosensations or percept or percepts)).mp.
15. 12 or 13 or 14
16. 11 and 15
17. limit 16 to (english language and humans)
18. remove duplicates from 17

Search protocol for EMBASE

1. electrostimulation/ or electrostimulation therapy/ or electrosurgery/
2. transcutaneous electrical nerve stimulator/ or transcutaneous nerve stimulation/

   3–17 Same as steps 4–18 used in MEDLINE

Duplicated original articles were excluded, as were review articles, published abstracts from conference proceedings, and any articles with no mention of stimulation of any type or reports of elicited percepts. Subsequently, the fully reviewed articles that lacked any descriptors for elicited percepts, were also excluded. Studies to be included for the somatosensory questionnaire were selected independently by two authors (LHK and RSM) then compared to reach a consensus for the final selection.

Somatosensory descriptors from each identified study were also collected independently by the two authors (LHK and RSM) and any discrepancies were resolved by consensus. In total, 241 descriptors were compiled from the 136 records reviewed from the literature search and the frequency of use for each descriptor was examined across all reviewed articles. While some papers reported frequency of elicited percepts for specific stimulation sites, others lacked quantification since eliciting percepts was not their primary goal (table S1, supplementary (stacks.iop.org/JNE/15/013002/mmedia)). Thus, an occurrence of a specific percept was considered only once per study, regardless of how frequently that percept appeared within that study.

While including all identified descriptors would provide the most inclusive questionnaire, having to go through a checklist of 241 descriptors would not be practical. In our previous studies, we discovered that not all of the 41 descriptors in the Lenz questionnaire [15] were being used. We found the tingling percept being used significantly more often than mechanical, movement or temperature types of percepts when electrical stimulation was applied via micro or macro-electrodes [9]. Thus, the frequency of use for each of the 41 descriptors from Lenz questionnaire [15] was examined across the 136 papers identified from the literature search. Aiming to identify additional descriptors that would be used as frequently as the ones already incorporated into the validated Lenz questionnaire [15], we chose the 50th percentile in frequency of use of the 41 descriptors as a cut-off mark for inclusion of the additional descriptor into the new questionnaire (table S2, sheet 2, supplementary). This meant that if 6 papers reported this new percept, it would achieve the 50th percentile among the 41 original descriptors in the Lenz questionnaire [15]. Thus, of the 241 descriptors collected from 136 records, if a descriptor appeared in more than 6 records we included it in our new questionnaire (table S2, sheet 1, supplementary). Percepts such as desire and/or urge to move were included for completeness. In general, descriptors regarding intensity and saliency were excluded as they are captured more objectively using intensity or other types of ratings. For example, transient sensations will be quantified by changes in the intensity ratings during the testing period. Continuous sensations will be indicated by no change in the intensity ratings during the testing period. Sensations relating to the location of the body where they were felt were also excluded as they would be collected by location mapping.

2.2. Subjects

After the systematic review was performed and the new questionnaire developed, it was validated in 13 subjects with previously implanted electrical stimulating devices. The patients had either pain or movement disorders and had placement of peripheral nerve, spinal cord or deep brain stimulators (DBS) for these indications 7 d to 16 years prior to testing. Stimulation was applied via their implanted pulse generators, Soletra or Itrel-3 using the N'Vision clinician programmer (Medtronic, Minneapolis, MN). These are constant voltage systems and have the option to alter pulse width (60–450 μs), frequency (2–185 Hz), amplitude (0–10.5 V) of the stimulus pulses and the duty cycle of the pulses applied. Table 1 details the subject demographics, their device location, indications, and the parameters of electrical stimulation that were tested.

2.3. Validating the somatosensory questionnaire

All subjects were trained on the use of the somatosensory questionnaire. They were informed that the descriptors on the questionnaire are common exemplary percepts, which can be evoked by electrical stimulation but are not an exhaustive list of all possibilities. The subjects were instructed to choose as many and/or none of the descriptors for each trial to fully describe their subjective experience. If they felt limited in any way for choice of descriptors, they were instructed to freely provide additional descriptors. Naturalness was described as 'something that you might encounter in everyday life [15] but not something you became sensitized to due to your condition or its treatment (e.g. pain or DBS)'. To avoid any vagueness and ambiguity between the descriptors, they were differentiated to the subjects by the experimenter in terms of the nature of possible equivalent natural source to evoke similar sensation. For example, tickle sensation would result from someone else tickling the subject while itch sensation can include internal itch from a mosquito bite. Tapping sensation was exemplified by someone else tapping on the subject's body part, whereas pulsing was described to be of an internal sensation such as a sense of blood pulsing through the subject's body. Prick sensation was ascribed to being similar sensations caused by a thumbtack, a pin or a needle at a localized point of the body, while sharp sensation was contributed to a sensation caused by a sharp object in a less localized manner than prick sensation such as a knife edge pressed against the skin. Since it is not intuitive for subjects to differentiate between flutter, vibration, and buzz based on the frequencies from psychophysiological findings, they were provided with similar natural source of vibration to which they can relate. Flutter was defined as a sensation similar to involuntary small vibratory movement of the subject's body parts such as the common expression of having butterflies or 'fluttery' feeling in the stomach or involuntary fluttering of an eyelid. Vibration was described to be vibrating at a faster frequency than flutter, but not as fast as a buzzing sensation like a cell phone vibrating against the skin. Buzzing sensation was further exemplified by very fast vibratory sensation you get when buzzing your lips together. Lastly, while electric current was described as a sensation of electricity running through the body, shock sensation was described to be a jolting electric sensation that could cause discomfort but is not painful. These definitions are presented in appendix A (supplementary).

We applied the subject's usual parameters of stimulation and various patterns of stimulation by altering the duty cycle of the implantable pulse generator using the Clinician Programmer (Medtronic N'Vision, Minneapolis, MN). For each subject, we first increased the voltage using their usual stimulus parameters until a clear sensation was felt. We provided their usual continuous stimulation for up to one minute, while the patient answered the questions. They were given a randomized list of descriptors differentiated as either non-painful or painful sensations. Their reported sensations were then recorded by the experimenter on the new questionnaire. Stimulation was off for at least 30 s between each stimulus pattern applied. The duty cycle was altered by applying 0.1 s ON/0.5 s OFF stimulation (16.7% duty cycle), 0.2 s ON/0.4 s OFF stimulation (33.3% duty cycle), and 0.1 s ON/0.1 s OFF stimulation (50.0% duty cycle). Then the four different types of stimulation (usual continuous and the various duty cycles) were applied 2–4 times further to assess for reproducibility.

2.4. Content validity

Our new questionnaire was designed to capture all elicited percepts evoked by electrical stimulation applied to both central and peripheral nervous systems. Since the previously

Table 1. The locations of electrical stimulation devices and the testing of electrical parameters and patterns for each subject.

Subject (sex)	Stimulator device location	Device placement date	Diagnosis	Testing electrical stimulation parameter	Patterns tested (# of repeats for each stimulus parameter)
A (F)	Spinal	7/11/2013	Peripheral nerve injury pain	270 μs pulse width (pw) 100 Hz at 2.4 V 10 Hz at 3 V	Continuous (×2) 3 Duty cycles (×3)
B (F)	Spinal	4/17/2003	Complex regional pain syndrome (CRPS)	270 μs pw 50 Hz at 2.9 V 100 Hz at 2.5 V	Continuous (×2) 3 Duty cycles (×3)
C (F)	Spinal	12/15/2005	Tethered cord, diastematomyelia	360 μs pw 50 Hz at 4.5 V	Continuous (×3) 3 Duty cycles (×3)
D (M)	Spinal	12/6/2012	Angina	210 μs pw 50 Hz at 4.0 V	Continuous (×3) 3 Duty cycles (×3)
E (M)	Occipital region	2/6/2014	Occipital neuralgia	360 μs pw 40 Hz at 4.7 V	Continuous (×3) 3 Duty cycles (×3)
F (M)	Thalamic	2/7/2005	Essential tremor	120 μs pw 185 Hz at 3.5 V	Continuous (×3) 3 Duty cycles (×3)
G (F)	Spinal	6/13/2014	peroneal nerve injury	300 μs pw 50 Hz at 5.3 V	Continuous (×3) 3 Duty cycles (×3)
H (M)	Occipital region	4/17/2014	Atypical face pain	390 μs pw 35 Hz at 5.0 V	Continuous (×3) 3 Duty cycles (×3)
I (F)	Occipital region	7/5/2012	Atypical face pain	360 μs pw 55 Hz at 1.5 V	Continuous (×3) 3 Duty cycles (×3)
J (M)	Occipital region	3/13/2014	Occipital neuralgia	360 μs pw 60 Hz at 1.65 V	Continuous (×3) 3 Duty cycles (×3)
K (F)	Thalamic	7/25/2008	Radial nerve injury	120 μs pw 50 Hz at 1.4 V	Continuous (×3) 3 Duty cycles (×3)
L (M)	Thalamic	1993, 1998	Brachial plexus avulsion pain	180 μs pw 185 Hz at 1.7 V	Continuous (×4) 3 Duty cycles (×3)
M (M)	Thalamic	9/26/2011, 11/7/2011	Parkinsonian tremor	90 μs pw 185 Hz at 2.5 V	Continuous (×4) 3 Duty cycles (×3)

utilized questionnaire [15] was designed specifically for thalamic microstimulation, we predicted that our questionnaire could characterize more percepts that are induced by various types of electrical stimulation, in addition to thalamic stimulation. Thus, a paired-sample *t*-test was conducted (SPSS 16.0) to compare the composite means of descriptors captured among 13 subjects using the new somatosensory questionnaire and the Lenz questionnaire [15]. The composite mean of descriptors for each stimulation parameter applied within a subject was obtained by averaging the number of descriptors used by the subject in each trial. Furthermore, to determine if the new questionnaire could capture various percepts that could be elicited using different stimulation parameters, a one-way repeated-measures analysis of variance (ANOVA) compared the effect of parameter type on composite means of descriptors captured across different parameters (SPSS 16.0, IBM, Armonk, NY). For subjects A and B who were tested using 2 different frequencies each, only the first frequency setting across the parameter types (continuous and 3 duty cycles) were included for analysis with remaining subjects. Post-hoc comparisons between conditions were made using a paired *t*-test.

2.5. Reliability

Test-retest reliabilities were calculated with Spearman's rank correlation coefficients (SPSS 16, IBM, Armonk, NY). Composite average of Spearman's rank correlation coefficients was determined across different stimulation parameters within each subject.

3. Results

3.1. Somatosensory questionnaire development

We identified 134 studies and 2 textbooks that reported on the sensations elicited by electrical stimulation (figure 1).

241 descriptors were identified from the reviewed literature which varied by stimulation types, locations, and parameters. The parameters varied included frequency (1–530 Hz), pulse width (10–300 μs), amplitude (0–18 mA or 0–4 V) and train duration (0–5 s). Stimulation was applied in the central and peripheral nervous systems with different types of electrodes such as electrocorticography electrodes, macroelectrodes, and microelectrodes. Other stimulation types

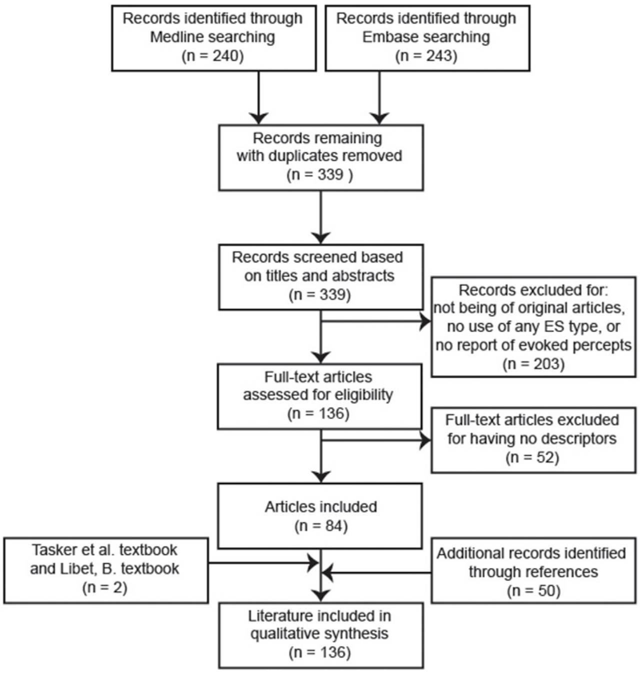

Figure 1. A systematic literature review flow chart as per PRISMA guidelines [27].

such as transcutaneous electrical nerve stimulation (TENS), transcranial direct-current stimulation (tDCS), and transcranial magnetic stimulation (TMS) or magnetic cortical stimulation (MCS) were also identified within the collected studies. Table S1 (supplementary) provides a detailed description of all the percepts collected from each study with reference to the original studies, study participants, specific stimulation site, electrical stimulation type and/or parameters. From a total of 241 descriptors, 13 new descriptors met the selection criteria of having been reported in more than 6 studies. The following descriptors were added in the new questionnaire: flutter, buzz, movement without motor activity, urge to move, prick, tap, shock, pulsing, numb, painful stinging, painful pulsing, painful uncomfortable, painful unpleasant (figure 2).

Table S2 (supplementary) reports the number of studies in which each percept appeared. The percept 'desire and/or urge to move' only appeared in 5 studies. However, we are interested in the development of neural prostheses and are aiming to elicit this kind of percept. Therefore, we included this for completeness. Percepts which describe intensity and/or location such as 'strong' and 'localized' were not added as new descriptors despite being mentioned in more than 6 studies, because they can be measured and recorded more objectively using intensity ratings and location maps.

3.2. Somatosensory questionnaire validation

Measures of reliability range from unacceptable ($\rho \leqslant 0.5$) to excellent ($\rho \geqslant 0.9$) using Spearman's rank correlation coefficients. A test-retest reliability value greater than 0.7 ($\rho \geqslant 0.7$) indicates acceptable reliability [28]. The averages of Spearman's rank correlation coefficients for each subject were significantly greater than 0.7 ($0.716 \leqslant \rho \leqslant 1.000$, $p \leqslant 0.005$; table 2).

The additional percepts we identified were characterized using the new questionnaire. There was a significant difference in the means of descriptors chosen using the new questionnaire ($M = 2.65$, $SD = 0.91$) and the Lenz questionnaire [15] ($M = 1.40$, $SD = 0.77$); $t(12) = -10.24$, $p < 0.001$). Overall, although the new questionnaire is similar to the Lenz questionnaire [15], more percepts which would have been missed as 'other' were identified through the additional descriptors (figure 3(A)). A variety of percepts were also elicited within subjects using different stimulus parameters. A one-way repeated-measure ANOVA found a significant effect of stimulation parameter type, Wilk's Lambda = 0.42, $F(3, 10) = 4.58$, $p = 0.029$. Six paired sample t-tests were used to make post-hoc comparisons between conditions. There was a significant difference in the mean of descriptors chosen under continuous stimulation ($M = 2.10$, $SD = 1.10$) versus 16.7% duty cycle stimulation ($M = 2.72$, $SD = 0.88$; $t(12) = -2.508$, $p = 0.028$), versus 33.3% duty cycle stimulation ($M = 2.87$, $SD = 0.89$; $t(12) = -3.657$, $p = 0.003$), and versus 50.0% duty cycle stimulation ($M = 2.73$, $SD = 1.20$; $t(12) = -2.912$, $p = 0.013$, figure 3(B)). On the other hand, there was no significant difference in the mean of descriptors chosen using any of the different duty cycle stimulation. These results suggest that different electrical parameters have an effect on percepts and descriptors chosen within subjects. Specifically, our results suggest that subjects used significantly fewer descriptors during continuous stimulation than during cycling stimulation.

4. Discussion

This study is the first to summarize the somatosensory percepts that can be elicited by electrical stimulation in the human nervous system and to use this to inform a new psychometric questionnaire. The questionnaire was able to characterize subjective evoked sensations with good test–retest reliability in subjects receiving stimulation using commercial neuromodulation systems in both the CNS and PNS. Furthermore, it captured more descriptors that would have been missed by being categorized as 'other', using the previous questionnaire [15]. Lastly, the new questionnaire could capture more and different descriptors within subjects receiving different duty cycle stimulation compared to continuous stimulation.

Currently, there are multiple delivery methods for electrical stimulation in humans. The new questionnaire was designed to capture somatosensory percepts that could be induced by electrical stimulation, regardless of specific type or location. Thus, the reliability of the questionnaire and its content validity should extend beyond our study to subjects with different neurological conditions and various neural implants. We were able to capture 11 of 13 additional descriptors using electrical stimulation in thalamic, occipital, and spinal regions. However, we could not elicit feeling of 'movement without motor activity' and 'urge to move' percepts using our methods. Others have reported such percepts by stimulating other brain regions such as primary motor, premotor, supplementary motor and posterior parietal cortex [29–32]. Therefore, our inability to evoke such sensations was likely due to not

☐ Totally Natural ☐ Almost Natural ☐ Possibly Natural ☐ Rather Unnatural ☐ Totally Unnatural

☐ Clearly on the skin surface ☐ Definitely below the skin surface ☐ Both

☐ Not painful ☐ Painful: ______________________ (see bottom for options)

Interoceptive:	Exteroceptive:		
Proprioceptive/ Kinesthesia	Tactile		Temperature
☐ Vibration	☐ Touch	☐ Electric current	☐ Warm
☐ **Flutter**	☐ Pressure	☐ **Shock**	☐ Cool
☐ **Buzz**	☐ Sharp	☐ **Pulsing**	
☐ Movement through body or across skin	☐ **Prick**	☐ Tickle	
☐ **Movement without motor activity**	☐ **Tap**	☐ Itch	
☐ **Urge to move**		☐ Tingle	
		☐ **Numb**	

Painful:	
Mechanical:	drilling / stabbing / squeezing / tugging / tearing / dull / splitting / **stinging**
Temperature:	hot / burn / cold
Movement:	spread / flash / flicker / throb
Tingle:	itch / electric current/ **pulsing**
Emotion:	frightful / nauseating / cruel / suffocating / fatiguing / **uncomfortable / unpleasant**

Figure 2. The new somatosensory questionnaire with additional descriptors shown in red (grey in the print version).

stimulating in these cortical regions. Given that these two percepts are important senses to target for developing sensorimotor neuroprostheses, they should be retained in the questionnaire.

4.1. Limitations in the development of the questionnaire

Our literature review identified a lack of standardization in reporting details of the location of the stimulation, and its stimulation parameters (pulse width, pulse duration, frequency, amplitude). These factors are critical in determining which structures will be activated [33–37]. Even when using the same stimulus parameters, electrode design can affect current density. For example, bipolar electrodes produce more localized current flow and activate less tissue than monopolar electrodes [38]. Furthermore, significantly more after-discharges were present following cortical stimulation using bipolar electrodes compared to monopolar electrodes, but similar muscles and movements were induced by both types of electrodes [39]. In order to use electrical stimulation for somatosensory restoration, sensations obtained at a particular site using a specific current density must be known. Thus, reporting the stimulation parameters and the electrode types should allow for better comparisons in future studies.

Another limitation from our systematic review of the collected studies is that they involved stimulation in subjects with pathological conditions, such as epilepsy, brain tumors, motor disorders, chronic pain, major depressive disorder, stroke, amputees and others undergoing neurosurgery. Although some studies included healthy controls, how comparable the elicited percepts in pathological conditions are to normal is a valid concern. As such, Selimbeyoglu and Parvizi [40] identified perceptual and behavioral phenomena induced by electrical brain stimulation and classified any presence of after-discharges or seizures. After-discharges may occur following direct cortical stimulation and can lead to seizures [39]. By accounting for the coinciding stimulation induced after-discharges, perceptual and behavioral phenomena that occur with electrical brain stimulation may be distinguished from the auras in seizures. Regardless, valuable information can still be translated to healthy brains from pathological ones. For example, Penfield's work [29, 30] in patients led to the confirmation of somatotopic organization of primary sensory and motor areas in humans, following the initial discovery of a motor map in the primate motor cortex in 1917 by Leyton and Sherrington [41]. The whole brain is not necessarily pathological especially in patients with focal brain lesions, focal epilepsy or motor disorders. Current understanding is that functions occur through interconnected neural networks or connectomes, rather than focal areas of excitation or inhibition.

4.2. Limitations of the questionnaire

There are several inherent limitations of a survey type of questionnaire, such as individual differences in general and state of vigilance at the time of testing. State of vigilance can be addressed by repeated applications on multiple days or times and more applications of each stimulus. A major challenge is the individual differences present in the subjective experience itself and the self-reports that affect inter-subject reliability. Cultural identity, socio-economic status, level of intelligence and education can all affect the subject's response biases such as acquiescence and a gravitation towards extreme ends of a scale [42]. While providing definitions of somatosensory descriptors prior to testing helps to minimize possible language barriers, future applications of the questionnaire may benefit from having graphic depictions of evoked percepts similar to those used for emotional scales [43]. Furthermore,

Table 2. Validation of the somatosensory questionnaire. (A) Test-retest reliabilities within each subject are shown by the average Spearman's rho (ρ). Additional descriptors captured with new somatosensory questionnaire are *italicized*. (B) An exemplary calculation of how each average Spearman's rho was obtained for one subject. Each Spearman's rho obtained from two trials for a particular stimulation parameter were averaged across all stimulation parameters. Overall, the averages of Spearman's rank correlation coefficients for each subject ($0.716 \leqslant \rho \leqslant 1.000$, $p \leqslant 0.005$) indicated acceptable reliability [28].

(A)

Subject	Average ρ	Average p	Percepts evoked by electrical stimulation
A	0.716 ($N = 8$)	$p = 0.002$	*Pulsing (62.50%), Tap (43.75%)*, Movement through/ across body (43.75%), *Prick (37.50%)*, Tingle (31.25%), Electric current (31.25%), *Shock (25.00%)*, Sharp (6.25%), *Flutter (6.25%)*
B	0.784 ($N = 8$)	$p = 0.001$	*Pulsing (50.00%), Tap (50.00%)*, Movement through/ across body (50.00%), Electric current (18.75%), Tingle (18.75%)
C	1.000 ($N = 12$)	$p < 0.001$	Movement through/ across body (100.00%), *Buzz (100.00%)*
D	0.958 ($N = 12$)	$p < 0.001$	*Pulsing (92.00%), Tap (50.00%), Buzz (8.33%)*
E	0.869 ($N = 12$)	$p < 0.001$	Electric current (66.67%), Tingle (58.33%), Movement through/across body (41.67%), *Pulsing (41.67%), Tap (33.33%)*
F	0.866 ($N = 12$)	$p < 0.001$	Tingle (83.33%), *Shock (83.33%)*, Electric current (75.00%), *Pulsing (58.33%)*, Movement through/ across body (25.00%), Non-painful throb (8.33%), Painful-tingle, *stinging*, throb, pulsing, *discomfort, uncomfortable* (8.33%)
G	0.828 ($N = 12$)	$p < 0.001$	*Pulsing (75.00%)*, Tingle (58.33%), Vibration (50.00%), Electric current (50.00%), *Tap (41.67%)*
H	0.904 ($N = 12$)	$p < 0.001$	Electric current (100.00%), Vibration (83.33%), *Pulsing (75.00%)*, Tingle (50.00%), *Numb (16.67%), Flutter (16.67%), Buzz (8.33%)*
I	0.878 ($N = 12$)	$p < 0.001$	Vibration (100.00%), *Pulsing (75.00%), Flutter (16.67%)*, Pressure (8.33%), *Buzz (8.33%), Tap (8.33%)*, Tickle (8.33), Tingle (8.33%)
J	0.724 ($N = 12$)	$p = 0.005$	*Pulsing (66.67%)*, Vibration (33.33%), Movement through body or across skin (25.00%), *Tap (16.67%), Buzz (16.67%), Numb (8.33%), Flutter (8.33%), Prick (8.33%), Shock (8.33%)*, Sharp (8.33%), Electric current (8.33%)
K	0.802 ($N = 12$)	$p < 0.001$	*Pulsing (75.00%), Buzz (75.00%)*, Vibration (66.67%), Tingle (66.67%), Electric current (50%), *Tap (25.00%), Numb (25.00%)*, Warm (16.67%), *Flutter (8.33%)*
L	0.857 ($N = 15$)	$p = 0.001$	Tingle (92.30%), *Pulsing (46.00%)*, Itch (15.38%), *Buzz (7.69%)*
M	0.799 ($N = 15$)	$p < 0.001$	Vibration (83.33%), Electric current (83.33%), Tingle (66.67%), *Pulsing (25.00%), Numb (25.00%), Buzz (8.33%), Flutter (8.33%)*

(B)

Patient	Frequency (Hz)	Pulse width (μs)	Duty cycle (%)	Volts	Spearman's rho	Spearman significance
A	100	270	100.00 (Continuous)	2.4	0.857	0.000
	100	270	100.00	2.4		
	100	270	16.67	2.4	0.516	0.012
	100	270	16.67	2.4		
	100	270	33.33	2.4	0.790	0.000
	100	270	33.33	2.4		
	100	270	50.00	2.4	0.641	0.001
	100	270	50.00	2.4		
	10	270	100.00	3.0	0.818	0.000
	10	270	100.00	3.0		
	10	270	16.67	3.0	0.665	0.001
	10	270	16.67	3.0		
	10	270	33.33	3.0	0.790	0.000
	10	270	33.33	3.0		
	10	270	50.00	3.0	0.651	0.001
	10	270	50.00	3.0		
Average					0.716	0.002

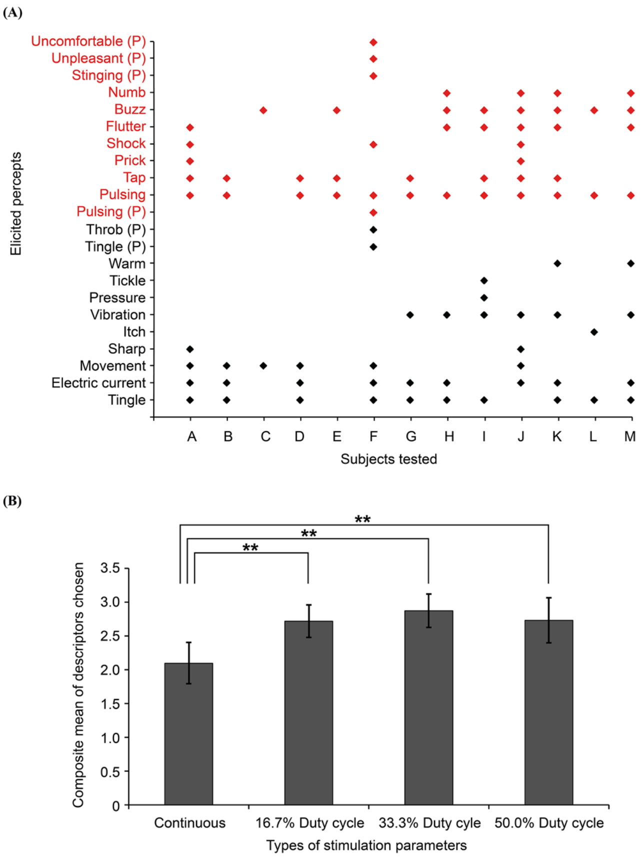

Figure 3. (A) Additional descriptors captured by the new questionnaire, regardless of how many times we encountered each one. The descriptors shown in red (grey in the print version) would have been missed as 'other percepts' using the previous Lenz questionnaire [15]. Only the percepts indicated with (P) were painful. All others were non-painful. (B) A significant effect of stimulation parameter type on composite mean of descriptors chosen across trials for each parameter within subjects using the new questionnaire, Wilk's Lambda = 0.42, $F(3, 10) = 4.58$, $p = 0.029$. Subjects used significantly fewer descriptors during continuous stimulation than during duty cycle stimulation (16.7%, 33.3%, or 50.0%). However, there was no difference in number of descriptors chosen when comparing one duty cycle stimulation to another duty cycle type.

psychophysical measurements such as those used with object discrimination tasks may improve inter-subject reliability of percepts evoked by electrical stimulation. A combination of subjective self-reports with objective task-dependent measures facilitated by evoked percepts have been used by several research groups in the field of somatosensory neuroprosthetic development [5, 6, 12, 21, 23]. Sham and blind stimulation could also be applied to measure individual response bias and identify possible unreliable self-reports.

In addition, intensity, salience and valence of the evoked sensations can affect attention and motor learning ([44], reviewed by [45, 46]). Yet, our questionnaire was designed to characterize the somatosensory aspects of evoked sensations, not attention or learning. Researchers investigating the affective components of evoked percepts may use additional existing questionnaires of valence such as the self-assessment manikin (SAM) [43], and Stroop paradigms that better address salience and attentional bias [47, 48].

An ideal questionnaire for utility and applicability also needs specificity to differentiate between responses. The importance of specificity in characterizing elicited percepts becomes evident during a task performance. Differences in stimulation intensity and locations provided additional somatosensory feedback for discrimination of object stiffness and shape recognition, respectively in a human subject with intrafascicular multichannel electrodes [7]. In this respect, our questionnaire excluded descriptors of intensity, salience, valence, or location that could increase the specificity of evoked percepts. However, these aspects can be quantified more objectively using intensity rating scales, SAM, Stroop paradigms, and location maps. As in our previous experiments [9, 10], specificity of our questionnaire could be optimized by collecting additional information, such as intensity ratings, duration and locations of evoked percepts.

In summary, this report is the first to summarize the somatosensory percepts that can be elicited by various methods of electrical stimulation in human subjects. Through a systematic review, we collected the subjective somatosensory sensations and used these to develop a novel somatosensory questionnaire. Our questionnaire was validated in subjects with implanted devices in the CNS and PNS. This new somatosensory psychometric questionnaire will aid in establishing the standardization of subjective reports in future studies, which is an important step to develop somatosensory neural prostheses.

Acknowledgments

Funding for this work was provided by the Alberta Heritage Foundation for Medical Research (AHFMR) as part of the SMART interdisciplinary research team. ZHTK was a Clinical Scholar of AHFMR. LHK is now funded by Parkinson Alberta and the Cumming School of Medicine.

Author Contributions

LHK and RSM conducted the literature search to develop the new questionnaire. LHK and ZHTK designed and performed the experiments to validate the questionnaire, interpreted results and drafted the manuscript. All authors approved the final draft of the manuscript. ZHTK supervised all the work for this research.

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