A Study on Reducing Skin Irritation in Multi-Channel TES for Painless Force Feedback

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Abstract**—**Reducing unwanted skin irritation during transcutaneous electrical stimulation (TES) is essential for providing clear virtual sensations in virtual reality (VR) systems, leading to a more immersive experience. We investigated general characteristics of parameters in the TES, including the number of channels and pulse width of the stimulation signal, which may affect reducing skin irritation with 3D electromagnetic computer simulation with numerical neuron models. The results showed that the increasing number of channels and the declining pulse width attenuated skin irritation to 44.5 %.

Keywords—transcutaneous electrical stimulation; multi-channel; computer simulations; peripheral stimulation; skin irritation; selective stimulation

I. Introduction

Virtual reality (VR) is a promising training technology that provides a safe and controlled environment, making it a powerful tool in various fields, such as military training, emergency response, and extreme sports [1]. To ensure the effectiveness of training in VR, it is crucial to provide users with realistic and immersive virtual interaction, which can be achieved through the provision of adequate force feedback [2]. This actuator-based force feedback system has been used in VR systems, but the high cost and large size limit the adaptation in many fields [3].

As a potential alternative, transcutaneous electrical stimulation (TES) is one of the solutions for providing force feedback in VR systems without complex mechanical equipment. TES can provide sensory feedback including physical force, posture, and movement by electrically stimulating sensory nerves in the muscles [4]. Nevertheless, the use of electrodes attached to the skin may result in unpleasant skin irritations caused by the stimulation current flowing through the skin [4]. This may be a critical point in terms of generating a plausible force sense with a sufficient level of application.

Observing the system change induced by the gradual change of parameters could provide insights into reducing unintended skin irritation during the stimulation. Although the efficiency of parameters has been searched in several TES studies [5,6], including a multi-channel study reporting decreased pain, these studies focused on finding efficient parameters that produce desired stimulation but not on the accompanied skin pain disrupting a sensation of the induced sense.

Therefore, this study aims to investigate the effects of parameter changes on achieving intended force feedback while reducing skin irritation in a multi-channel TES system. Based on a computer simulation, we evaluated the system's efficiency with the varying numbers of stimulating channels and stimulation pulse widths by estimating the evoked force feedback and skin irritation resulting from nerve firing. The results of our study may provide insights into the characteristics of TES system parameters that can help mitigate the skin irritation.

II. Methods

To find the varying features of system parameter changes, a two-step numerical simulation procedure was implemented. First, a quasi-static finite element model simulator (Sim4Life; ZMT Zurich MedTech, Switzerland) was run to calculate the stimulation current intensity of the TES system based on the selected parameters in the upper arm model. Next, a neural model simulator (NEURON; Yale University, USA) was used to evaluate the firing of sensory fibers, indicating the existence of sensations in the skin and muscle.

A. Model Design

The human forearm modeled in the simulation was simplified as a cylinder, as per the method used in [6]. To examine the impact of the modeled structure on TES stimulation results, we compared the outcomes of a single-layer model consisting solely of muscle with those of a more complex five-layer model including skin, fat, muscle, bone, and bone marrow (see Fig. 1A and 1B). To guarantee a stable conductivity between the electrode and skin, a 1 mm-thick hydrogel layer was modeled and inserted between the electrodes and the surface of the cylinder, which is covered by skin material in both models (see Fig 1C). Material properties are derived from [7]. Detailed information about the models is provided in Table 1.

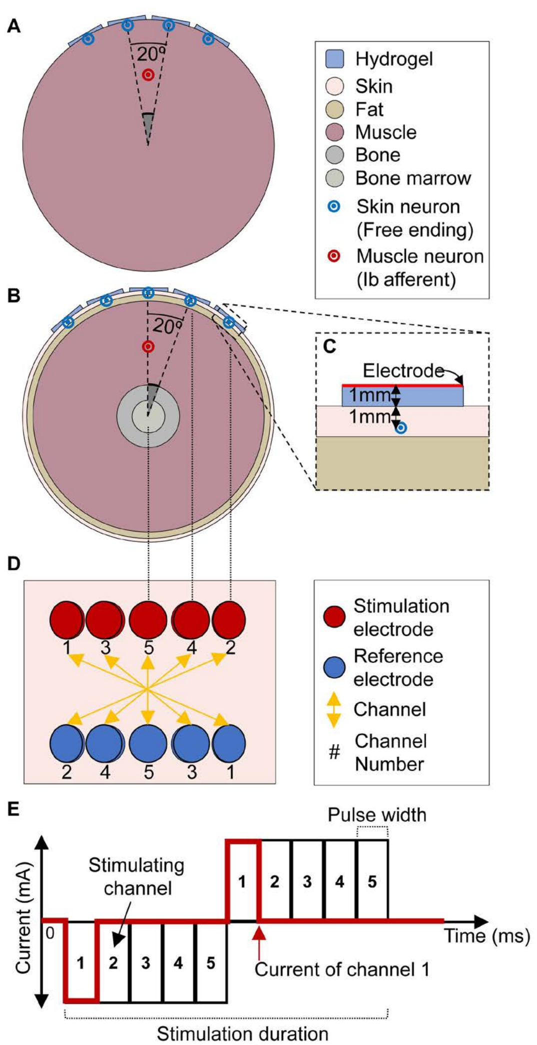

Fig. 1. Model and stimulation configuration. (A) The single-layer model with four-channel distribution. (B) The five-layer model with five-channel distribution. (C) Detailed view of electrode and skin fiber. (D) Channel configuration. (E) Stimulation design.

Each stimulation channel consisted of a stimulation electrode and a reference electrode with a diameter of 15 mm. The stimulation and reference electrodes were positioned 50 mm apart along the longitudinal axis, and each channel was symmetrically arranged from side to side with respect to the center of the cylinder (see Fig. 1A and 1B). Each channel was spaced apart by 20 degrees because the narrower gap could result in excessive overlapping currents from different electrodes. The components of each channel position were appropriately crossed to ensure that the expected current flow focused on the target (see Fig. 1D).

TABLE I. MODELING CONFIGURATIONS

Model	Length (mm)	Radius (mm)	Layer thickness (mm)				
			Skin	*Fat*	*Muscle*	*Bone*	*Bone marrow*
Single-layer	200.0	50.0	0.0	0.0	50.0	0.0	0.0
Five-layer	200.0	50.0	1.5	2.5	33.5	6.0	6.5

We utilized the McIntyre-Richardson-Grill model to numerically model the sensory afferents in both the skin and muscle [8]. The skin afferents were positioned at a depth of 1 mm below the electrodes with diameters of 5 µm, indicating the free nerve ending that senses pain in our modeling. The muscle afferents, on the other hand, were positioned at a depth of 23 mm, directly above the center of the cylinder with a diameter of 20 µm, indicating the presence of a type Ib afferent that senses imposed forces on muscles. All nerve models are aligned parallelly to the longitudinal axis and have a length equal to that of the cylinder models.

B. Stimulation Design

The stimulation method used in this study was based on a previous multi-channel TES study [5] that divided stimuli in the temporal domain and reported less skin pain during the experimental phase. The stimulation signals for all channels were biphasic to ensure charge balancing. For simplicity, each pulse was set to have an identical current strength and a pulse width. The order of stimulation for the channels was sorted from farthest from the center to closet to the center as described in Fig. 1D. Whole stimulations were performed sequentially, without resting intervals between pulses. Fig. 1E illustrates one cycle of the stimulation signal.

C. Selectivity Index: A Metric for Assessing TES Efficiency

In order to evaluate the effectiveness of each parameter pair in reducing skin irritation, we assessed whether the maximum stimulus intensity that did not cause skin irritation was sufficient to trigger force feedback. During the computer simulation-based analysis, we defined selectivity index (SI) as the following equation:

$$SI(n_{ch}, T_{pw}) = \min_{i \in S} I_{th}^{i}(n_{ch}, T_{pw}) / I_{th}^{m}(n_{ch}, T_{pw}) \quad (1)$$

$I_{th}^{i}(n_{ch}, T_{pw})$ is the minimum current amplitude which is enough for firing neuron i when the simulation is set with pulse duration T_{pw} in n_{ch} channels. S represents the groups containing all of skin neurons, while subscript m describes the muscle neuron inducing force feedback. The current variable I_{th} was computed by the numerical simulation with considering variables T_{pw} and n_{ch}. Since the SI represents the maximum current intensity that can be applied for muscle neuron stimulation without triggering skin neurons which evokes skin pain, an increase in the SI indicates that the system is more capable of providing strong force feedback with less skin stimulation.

D. Investigation Range of Parameters

We considered varying numbers of channels and stimulation duration. Five channel distributions composed of one to five channels were evaluated during the simulation phase. Since a wide stimulation range may cause distorted force feedback due to stimulating unintended sensory fibers, an excessive number of electrodes were not considered during the evaluation process.

In the case of determining stimulation duration, we selected stimulation duration within 5 ms with considering a frequency range. For this reason, a fixed frequency of 200 Hz was applied during the simulation, which is the maximum frequency satisfying the duration length. We examined eight fixed stimulation duration parameters (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 ms) to see their effects on the model.

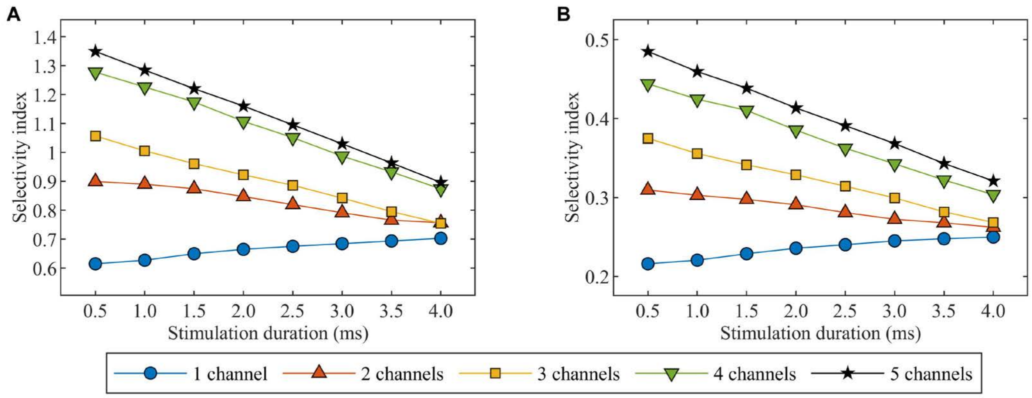

Fig. 2. Changes of selectivity index accoding to number of channels and stimulation duration. (A) A single-layer model. (B) A five-layer model.

III. Results

With the numerical analysis simulations mentioned above, we found that increasing the number of channels led to better SI regardless of cylinder models. As stimulation duration increased, the SI converged to a specific range that was lower than that of multi-channel cases but higher than any single-channel case (see Fig. 2). Thus, all multi-channel cases showed the best result with 0.5 ms duration, while the single-channel case showed the best result with 4.0 ms duration.

In the single-layer model (see Fig. 2A), the highest SI was 1.349, which is 219.3% higher than the lowest SI of 0.615. In the five-layer model (see Fig. 2B), the highest SI was 0.485, which is 224.5% higher than the lowest SI of 0.216.

IV. Conclusions

Our results suggest that increasing the number of channels results in a more dispersed stimulation on the skin surface, leading to an improvement in neuron selectivity. For the same intensity of stimulation of the muscle nerves, the five-channel distribution had minimally reduced skin irritation to 45.6% in the single-layer model and to 44.5% in the five-layer model, compared to the single channel. Although the effect of the increasing channel number was underestimated due to the difference in neuron modeling from reality, the findings of [5] which reported no skin irritation when using two stimulation channels, imply that our analysis results showed a similar stimulation trend compared to the actual experimental condition.

We observe that the SI converges as the stimulus duration increases. This may be a result of the attenuation of multichannel effects and the decrease in current amplitude required to fire the neuron as stimulus duration increases [5,9].

Although the five-layer model had lower SI than the single-layer model due to the high insulation of the surface layer [6], the trend of the effect coming from changes in parameters remained consistent. These results suggest that parameter selection can be effective across different model structures and may be adaptable to different individuals for the actual stimulation.

Lastly, during the simulation, we did not take into consideration other control parameters, such as electrode placements and various stimuli waveforms. So further investigations of neuron models and conditional parameters, which were not regarded in this study, would be helpful in providing more accurate feedback for practical applications in VR and other fields such as medical prostheses and rehabilitation.

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References

[1] J. Moskaliuk, J. Bertram, and U. Cress, “Impact of virtual training environments on the acquisition and transfer of knowledge,” Cyberpsychol. Behav. Soc. Netw., vol. 16, no. 3, pp. 210-214, 2013.

[2] G. C. Burdea, “Haptic feedback for virtual reality,” in Virtual Reality and Prototyping Workshop, vol. II, pp. 17-29, 1999.

[3] S. Tanaka, K. Ushiyama, A. Takahashi, and H. Kajimoto, “Movement-free virtual reality interface using kinesthetic illusion induced by tendon vibration,” in EuroHaptics 2020, vol. 12272, I. Nisky, J. H.-O’brien, M. Wiertlewski, and J. Smeets, Eds. Berlin: Springer, 2020, pp. 316-324.

[4] R. Rangwani and H. Park, “A new approach of inducing proprioceptive illusion by transcutaneous electrical stimulation,” J. Neuroeng. Rehabil., vol. 18, no.73, pp. 1-16, 2021.

[5] A. Pena, J. Abbas, and R. Jung, “Channel-hopping during surface electrical neurostimulation elicits selective, comfortable, distally referred sensations,” J. Neural Eng., vol. 18, no. 5, p. 055004, 2021.

[6] M. Goffredo et al., “A two-step model to optimise transcutaneous electrical stimulation of the human upper arm,” COMPEL: Int. J. Comput. Math. Electr. Electron. Eng., vol. 33, no. 4, pp. 1329-1345, 2014.

[7] P. A. Hasgall et al., “IT’IS Database for thermal and electromagnetic parameters of biological tissues. V4.1.” 2022. Distributed by IT’IS Foundation. doi: 10.13099/VIP21000-04-1.

[8] C. C. McIntyre, A. G. Richardson, and W. M. Grill, “Modeling the excitability of mammalian nerve fibers: influence of afterpotentials on the recovery cycle,” J. Neurophysiol., vol. 87, no. 2, pp. 995-1006, 2002.

[9] W. M. Grill, and J. T. Mortimer, “The effect of stimulus pulse duration on selectivity of neural stimulation,” IEEE Trans. Biomed. Eng., vol. 43, no. 2, pp. 161-166, 1996.