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Textile Electrodes: Influence of Electrode Construction and Pressure on Stimulation Performance in Neuromuscular Electrical Stimulation (NMES)

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Abstract—**The major reason for preventable hospital death is venous thromboembolism (VTE). Non-pharmacological treatment options include electrical stimulation or compression therapy to improve blood flow in the extremities. Textile electrodes offer potential to replace bulky devices commonly used in this field, thereby improving the user compliance. In this work, the performance of dry and wet knitted electrodes in combination with pressure application to the electrode was evaluated in neuromuscular electrical stimulation (NMES). A motor point stimulation on the calf was performed on nine healthy subjects to induce a plantarflexion and the required stimulation intensity as well as the perceived pain were assessed. The performance of the different electrode constructions was compared and the influence of the pressure application was analysed. The results show that wet textile electrodes (0.9 % saline solution) perform significantly better than dry electrodes. However, opportunities were found for improving the performance of dry textile electrodes by using an uneven surface topography in combination with an intermediate to high pressure application to the electrode (> 20 mmHg), e.g. by using a compression stocking. Moreover, the smaller of the two tested electrode areas (16 cm^2; 32 cm^2) appears to be favourable in terms of stimulation comfort and efficiency.**

I. Introduction

Nowadays, venous thromboembolism (VTE) is the major reason leading to preventable hospital death [1], wherefore it is of utmost importance to find solutions for preventing and treating VTE effectively. One of the main causes is venous stasis, often as a result of immobility affecting many in-hospital patients with restricted movement [2], which increases the risk of deep vein thrombosis and pulmonary embolism. For prevention thereof, mechanical treatment methods, used in combination or as alternatives to pharmacological treatments [3], include compression therapy in the form of compression stockings [4] or pneumatic compression devices [5], or neuromuscular electrical stimulation (NMES). The principle behind NMES is the assumption that a plantarflexion, artificially induced by activation of the calf muscles by controlled current injection, increases the blood flow which in turn prevents venous stasis [6, 7]. However, user compliance for mechanical methods is often low due to devices being comparatively bulky [8], e.g. intermittent pneumatic compression (IPC) devices, due to pain or discomfort, for example from high-compression stockings, or because methods require time consuming preparations, e.g. electrode placement for NMES. To address these problems, opportunities are seen for NMES garments, for instance stockings with integrated textile electrodes, to simplify the electrode placement and improve the user comfort. The functionality of textile electrodes for electrotherapy has been shown in previous studies for electrodes wetted with water or saline solution, yet the main problem remaining the electrodes drying out during the treatment session. Dry textile electrodes, on the other hand, showed problems related to their comparatively high impedance causing insufficient electrical contact during electrostimulation as well as stinging pain sensations [9-10]. Improvements of the stimulation performance are expected by applying pressure to the textile electrode in order to enhance the electrode-skin contact [11, 12].

No systematic study has been found in literature which investigates the influence of individual electrode construction parameters on the stimulation performance. Therefore, in this study, different electrode constructions were chosen and the performance in terms of stimulation comfort and stimulation efficiency during NMES was compared in dry and wet condition while applying two different pressure levels.

II. Material and Methods

A. Textile electrode fabrication

Textile electrodes were knitted on an industrial flat knitting machine (CMS 330 TC by H. Stoll AG & Co. KG, Reutlingen, Germany) by seamless integration of silver-plated polyamide yarns (Shieldex® 117/17 dtex Z100 by Statex

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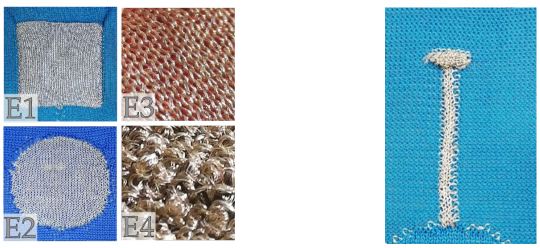
Produktions- und Vertriebs GmbH, Bremen, Germany; two yarns in one carrier) in a polyester surrounding fabric (PET 167/32/1 dtex; three yarns in one carrier), composed of plain knit and, in the electrode area, a double jersey. Thus, the conductive electrode area was placed on the face side of the fabric and the back side was insulated with the PET knit. The different electrode versions are presented in Fig. 1a and in the list below. A knitted lead (5 cm x 0.5 cm) was integrated on the back side of the fabric to connect the electrode area to a 'tail' (0.5 cm x 1 cm, protruding from the surface) where instrumentation could be attached, see Fig. 1b.

- E1: **Square**, smooth surface, small (16.0 cm^2)
- E2: **Circular**, smooth surface, small (16.1 cm^2)
- E3: Circular, **smooth** surface, big (31.7 cm^2)
- E4: Circular, **uneven** surface, big (32.4 cm^2)



(a) (b)

Figure 1. (a) Parameter comparisons for electrode versions E1 – E4. (b) Textile lead with tail protruding from surface.

B. NMES performance

The Swedish ethics committee "Etikprövningsmyndigheten" granted an ethical approval for the test method described below. The electrodes were tested by applying NMES in dry and wet (1 ml/ 16 cm² or 2 ml/ 32 cm^2 of 0.9 % saline solution, applied with a syringe) condition using a conventional battery-driven NMES device (CefarCompex, Guildford, United Kingdom). They were placed on the calf on the best medial and lateral motor points for the individual subject (determined in a standard motor point search using a motor point pen by CefarCompex) so that the movement of the ankle, i.e. a plantarflexion, was visible upon stimulation. Here, the overall stimulation comfort was evaluated on a numerical rating scale (NRS) with 0 as 'no pain or discomfort' and 10 as 'worst imaginable pain or discomfort' with minimum steps of 0.5. In the following, the term 'pain' will be used to indicate both pain and discomfort. To evaluate the influence of pressure application, the electrodes were tested at two different pressure levels, namely a 'high pressure' applied by a compression stocking of class I (pressure gradient from knee to ankle of 15-20 mmHg) pulled over the electrode and a 'low pressure' using a normal sock. The parameters for the NMES were set to a frequency of 36 Hz and a pulse duration of 0.400 ms. A stimulation of 1.5 s ON-time was followed by 3 s OFF-time. The intensity of the stimulation was increased step-wise one level at a time starting from 0 until one of the following points was reached:

1. A clear plantarflexion was visible. In this case, the subject evaluated the pain sensation on the NRS.
2. The subject's maximum tolerable NMES intensity was reached and the test was aborted by the subject.
3. The electrical contact was found to be insufficient and the test was aborted by the examiner.

In total, the procedure was performed on nine healthy subjects (male and female, age 22 - 69) and the tested leg, i.e. left or right, was randomised between subjects.

III. Results

The number of aborted tests per electrode, condition (i.e. wet or dry) and pressure level including the reasons for the abort are presented in Fig. 2. Tests in dry condition resulted in several aborts at both pressure levels whereas none of the tests in wet condition were aborted.

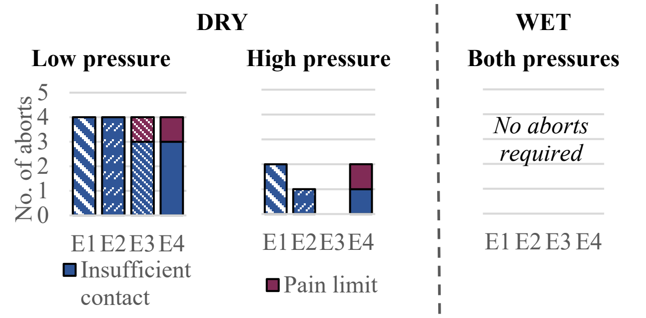


Figure 2. Number of aborts per electrode condition and pressure level.

In the following, the term 'NMES level' will be used to refer to the intensity required to induce a visible plantarflexion. An overview over NMES level and the related maximum and average pain ratings for the non-aborted tests are presented in Fig. 3 for the four different electrodes in two conditions and two pressure levels. Similar behaviours can be seen for the required NMES level in both electrode conditions depending on the applied pressure. Moreover, in wet condition, the average pain rating is similar for both pressure levels while clear differences are visible for the maximum pain ratings.

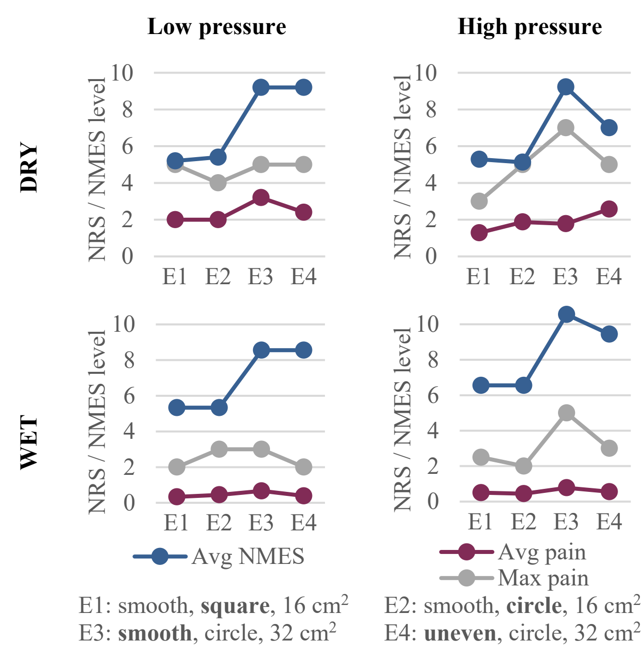


Figure 3. Average and maximum pain rating and average NMES level.

IV. Discussion

A. Condition and pressure influence on stimulation intensity and comfort

The electrode condition was found to exert the biggest influence on the electrode performance with generally higher pain ratings for dry electrodes, supported by findings from literature [13]. Regarding the required NMES level, no significant difference could be determined between dry and wet condition. However, with regard to procedure reliability, dry electrodes performed inferior, requiring multiple aborts mostly due to insufficient contacts. The contact was improved when applying a higher pressure, thus leading to fewer aborts in dry condition. Nonetheless, dry electrodes still could not reach a comparable performance to wet electrodes for which no abort was needed at any pressure level. Hence, wet electrodes seem preferable over dry ones, but opportunities were found to improve the performance of dry electrodes using pressure application.

In wet condition, the pressure application showed a smaller influence than in dry condition. When comparing different electrode topographies, the high pressure application reduced the NMES level for an uneven surface compared to a smooth surface, thus making the stimulation more efficient. However, compared to the low pressure level in wet condition, generally higher NMES intensities were required for a high pressure in wet condition, with statistical significance ($p \leq 0.05$) for three out of four electrodes. This might be due to a redistribution of the fluid caused by the higher pressure, thus creating a 'virtually' larger electrode area and requiring a higher NMES level as the current is spread over a larger area. The average pain ratings, on the other hand, did not differ significantly between the two pressure levels which means that a higher pressure did neither improve nor impair the stimulation comfort in wet condition. This suggests that a higher pressure application might not be advantageous for wet textile electrodes. However, an alternative interpretation is that higher pressures in wet condition might enable smaller electrodes being suitable, as the fluid then creates a larger effective electrode area, thus not impairing the comfort but decreasing the NMES level.

B. Construction influence on stimulation intensity

The stimulation intensity was mainly influenced by the electrode size. At low pressure in both conditions, the NMES level only depended on the electrode size, whereas topography or shape did not show a significant influence on the NMES level. A larger electrode led to a higher required intensity supposedly resulting from a reduced stimulation selectivity. The current injection is less targeted, thus not only stimulating the motor point but also tissue around it. Hence, higher intensities are required to induce a plantarflexion.

At the high pressure level in wet and dry condition, a larger size still increased the NMES level, but here an additional influence of the electrode topography became visible, with an uneven surface reducing the required intensity. This can be related to an improved electrical contact between electrode and skin when the uneven surface is pressed to the calf. Thereby, the skin unevenness can be compensated more easily compared to when having a smooth electrode surface. Therefore, to improve the stimulation efficiency by altering the electrode construction in a situation of high pressure application, an uneven electrode surface is advisable.

C. Construction influence on stimulation comfort

In terms of electrode size, a larger electrode increased both the average and maximum pain rating at low pressure in dry condition. For a high pressure application, the maximum pain was significantly increased both in wet and dry condition, whereas the average pain rating did not differ significantly between the electrode sizes. Nevertheless, the only aborts due to reached pain limits were found for big electrodes (i.e. $32\ cm^2$) in dry condition, which suggests that a larger electrode negatively affected the stimulation comfort within the investigated size range for electrodes placed on the calf. According to literature, a larger electrode is expected to reduce the perceived stimulation pain as a larger area for current dissipation reduces the current density [14], which in turn is presumed to directly impact the comfort [15]. At the same NMES level for all electrodes, this behaviour could be confirmed in the performed study. However, the bigger electrodes required higher NMES levels, as the stimulation selectivity was reduced, which in turn led to a decreased comfort at those higher NMES levels. This implies that, in the range of the investigated electrode sizes, electrodes with about $16\ cm^2$ seem to be preferable over larger electrodes when used in dry condition. Nonetheless, it is expected that a smaller electrode area than $16\ cm^2$ might not necessarily be beneficial as supposedly a limit exists below which a smaller size will impair the comfort again, i.e. the observation cannot be regarded as valid for infinitely small electrodes. In wet condition, on the other hand, only a slight to no influence of the electrode size could be observed on the stimulation comfort. For the high pressure level, the maximum pain rating was affected with a small electrode reducing the maximum pain, whereas the average pain was not significantly influenced, neither at high nor at low pressure. Moreover, at the low pressure level, the maximum pain rating was not affected by the electrode size. Thus, the influence of the electrode size can be neglected in wet condition in terms of pain rating. This observation does not align with the theory that the current density directly impacts the stimulation comfort. Therefore, future research is needed to investigate the current density – pain relation for wet textile electrodes. Nonetheless, a small size was still found preferable to improve the stimulation efficiency of wet electrodes.

An uneven surface reduced the pain in most cases. A lower maximum pain rating was found for the electrode with an uneven surface in all settings except for at low pressure level in dry condition. Here, the same maximum pain rating was found for both topographies. The average pain, however, was only significantly affected by the surface structure in dry condition, with a lower average pain for an uneven surface at low pressure, but a slightly higher average pain for the uneven surface in combination with a high pressure application. In wet condition, similar average pain levels were found at both pressures for the two electrodes with no significant difference.

Hence, in most settings an uneven electrode surface seems to be advisable to improve the stimulation comfort.

The shape showed a significant influence on the stimulation performance in terms of maximum pain rating only in dry condition, both at high and low pressure levels. Here, a higher maximum pain was found for a square electrode at low pressure level and for a circular electrode at the high pressure level. The average pain ratings, however, did not show a significant difference arising from the shape at any condition or pressure. Thus, overall no substantial influence of the electrode shape could be found for the comparison of a circular electrode and a square electrode with rounded corners. This does not align with findings in literature. High current densities are expected to be present in the corners of a rectangular electrode, thus impairing the stimulation comfort [15, 16]. However, rounded corners were chosen for the investigated electrode shape, wherefore current density peaks arising from the design were reduced. Additionally, in the analysis of the size influence, the current density could not be directly related to the stimulation pain in the performed experiments. Thus, the current distribution might not alone be a valid explanation for differences in pain ratings for the investigated electrodes. As a result, no significant influence could be observed for the electrode shape on the perceived pain. This phenomenon is supported by findings in literature where some studies also reported that, opposite to expectations, no shape influence could be observed on the stimulation comfort for conventional electrodes [14].

V. Conclusions and Future Work

Within the tested parameters, smaller electrodes (16 cm^2) and an uneven surface seem to be generally favourable for NMES on the calf, while there was no clear influence of the electrode shape on the stimulation performance. Future work should verify this hypothesis by testing a small electrode with an uneven surface. Concerning the stimulation comfort, both for the size and the topography, the influence on the pain was mostly visible in dry condition whereas in wet condition, the pain was less affected by the electrode construction. This implies that choosing an optimum electrode construction is more important for dry electrodes than for wet electrodes, as the dry system is less stable and therefore impacted to a bigger extent by the chosen electrode parameters. In terms of required stimulation intensity, the NMES level was mainly affected by the electrode size with small electrodes (16 cm^2) improving the stimulation efficiency, and also showing positive effects on the stimulation comfort in dry condition. Regarding the pressure influence, the electrode performance was significantly improved in dry condition by the high pressure application, particularly for electrodes with an uneven surface. However, in wet condition, a higher pressure application was not found to be advantageous as it did not show an effect on the stimulation comfort while the stimulation efficiency was significantly reduced.

Concluding, the wet condition using a smaller electrode, an uneven surface and low pressure application resulted in the best comfort and lowest energy consumption. For future work, it is suggested to investigate the application of an even higher pressure (> 20 mmHg) to improve the performance of dry textile electrodes. This way, a combination of NMES and compression therapy for treatment of VTE could be facilitated by integration of textile electrodes into compression stockings. However, it must be considered that too high pressures can as well lead to discomfort [17]. Moreover, the influence of the current density on the pain during stimulation should be investigated specifically for textile electrodes.

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