



# A Review of Electrodes Developed for Electrostimulation

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**Abstract.** Surface electrodes are essential devices for performing functional electrical stimulation therapy and play a direct role in the effectiveness of electrical stimulation. In this paper, four typical electrodes are selected, and their preparation materials and their characteristics are introduced and compared, including metal electrodes, carbon rubber electrodes, hydrogel electrodes, and fabric electrodes. Most of the electrodes used for electrical stimulation at this stage are mainly hydrogel electrodes, which are generally uncomfortable to wear, poorly washable, and do not fit well with human skin. The appearance of the fabric electrode improves the above problems, and its preparation material and its preparation method are introduced in detail. At the end of the paper, the development trend of fabric electrodes has been prospected.

**Keywords:** Electrodes · Electrical Stimulation · Fabric Electrode

## 1 Introduction

Patients with nerve impairment, such as stroke survivors, can benefit from functional electrical stimulation (FES) therapy to enhance their range of motion [1]. It is frequently used in patients who have central nervous system damage as a result of head trauma, spinal cord injury, stroke, or other neurological illnesses to help them move more easily. The nerve tissue that enters the muscle is stimulated by FES using electrodes. Although electrodes can be implanted, it is more frequent and practical to place them on the skin's surface. Due to its noninvasive nature and ease of usage, surface electrical stimulation offers a wide range of clinical uses. The electrode material is a conductor material that is used as both ends of an input or output current in a conductive medium such as a solid, gas, or electrolyte solution. For bioelectric potential monitoring, transcutaneous electrical nerve stimulation, and functional electrical stimulation, electrode devices have been created [2–4]. Most of the current research on electrodes revolves around the measurement of electrocardiographic (ECG) biorhythms to help diagnose heart disease, electromyographic (EMG) monitoring for fitness and rehabilitation applications, or electro-oculogram (EOG) signals and electroencephalography (EEG) to monitor brain activity measurements. Research on electrodes for electrical stimulation is scarce, and

most early electrical stimulation studies used electrodes made of steel [5] or other metal patches placed on saline-soaked gauze simple electrodes [6–8]. Most of the existing electrode technologies use hydrogel electrodes and carbon rubber electrodes. The long-term goal today is to produce comfortable, washable electrostimulation electrodes that are breathable, flexible, and washable. The advent of e-textile printing technology has made fabric electrodes possible, and longer-lasting washable electrodes may become a new trend for future medical devices. This review will discuss the various electrode types applied to electrical stimulation, summarize their advantages and disadvantages, and focus on the potential impact that textile electrodes may have in the field of electrical stimulation as a conclusion.

## 2 Electrode Type

### 2.1 A Fabric Tissue Covered Sheet Metal Electrodes

Most early electrostimulation studies used simple electrodes that were made of metal plates placed on fabric soaked in saline. The metal plates must be made of biocompatible materials, as shown in Fig. 1. Usually, stainless steel or silver chloride electrodes are used. The woven fabric can be cotton but is usually a polymeric textile material that has some elasticity and does not wear out quickly. Sponge-like materials are also used and recommended, Zhou K 2016 HVPC electric pads (stainless steel electrodes with a sponge interface) are also moistened with saline [9]. Water or electrode gel is used to make the fabric conductive. It distributes the current evenly on the skin and the electrodes must be carefully dried to prevent skin burns. In the best case (if completely dry), this dry electrode isolates the metal plate from the skin. However, an unevenly distributed electric field under the electrode during the drying process can cause severe skin burns. The electrode needs to be secured to the skin with an elastic band or must be embedded in clothing or a cast, such as the Bioness (formerly known as the Ness Handmaster) neuroprosthesis [10].



**Fig. 1.** Metal plate electrodes covered by fabric tissue.

## 2.2 Carbon Rubber Electrodes

Before the advent of self-adhesive hydrogel electrodes, carbon-silicon electrodes replaced fabric-covered sheet metal electrodes, as shown in Fig. 2 [11]. In order to make electrodes that were pleasant, conductive, and matched the surface on which they were put, these electrodes employed carbon to boost the conductivity of the soft rubber pad. Carbon rubber has a much higher resistance than metal, preventing large current flow in small areas. While no longer risking skin burns from direct contact between skin and metal electrodes. Although carbon rubber itself does not dry out, it is sometimes required to moisten the area where the electrode and the user's skin come into contact in order to minimize the electrical impedance at that point, which normally decreases the user's comfort. Because of their chemical stability, they are still used for special applications, such as iontophoresis. The fact that hydrogel electrodes are unstable for long periods of time at temperatures above 40 °C is also of concern; therefore, storage and handling in Middle Eastern countries are both expensive and difficult. In these areas, carbon rubber electrodes remain the preferred choice. Gel or water must be used as the skin contact medium when carbon rubber electrode currents are more than 10 mA. This is due to the electric field's ability to penetrate deeper and away from the delicate nerve terminals near the surface as a result of the reduction in impedance [12]. Although Horton et al. 2010 reported that switching the first self-adhesive electrodes with carbon rubber electrodes decreased redness in one patient, there are no diagnostic tests evaluating the efficacy of various electrodes [13].



**Fig. 2.** Carbon rubber electrodes

### 2.3 Hydrogel Electrodes

This electrode technique is an alternative to the conventional metal electrodes employed in prior experiments and is frequently employed in a hydrogel, as shown in Fig. 3. Electrodes have a multilayer structure consisting of multiple layers of the hydrogel. The skin interface layer consists of a relatively low peel-strength conductive gel for direct contact with the subject's skin. It has a moist feel and is relatively easy to remove from the skin. Conductive gels are usually made from polymeric copolymers, such as copolymers of acrylic acid and N-vinylpyrrolidone [14]. In order to create highly low resistance interaction with the skin, hydrogels must have a consistency that is similar to gel and a large amount of water. The best electrical conductivity has been demonstrated by studies for well-constructed hydrogels [15]. But gradually, the water in hydrogels evaporates. The electrodes must then be changed after which this benefit is lost. Furthermore, because of their natural adhesive qualities, they are prone to becoming covered with dirt and bodily tissues. so gradually lose conductance as a result of being unclean.



**Fig. 3.** Hydrogel electrodes

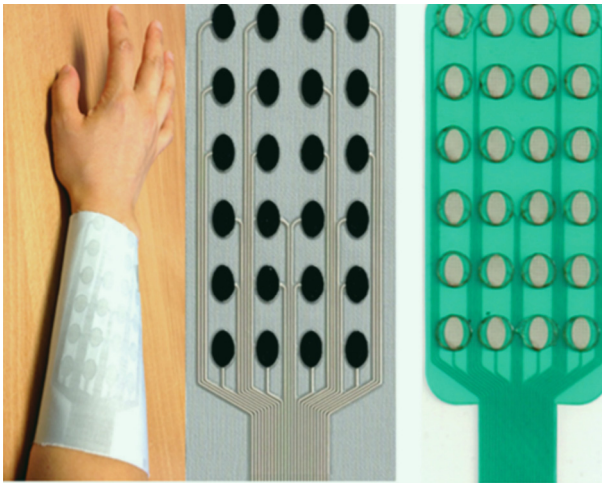
### 2.4 Fabric Electrodes

Electrode design has been a major focus of the e-textile community's efforts for some time, and e-textiles have been utilized effectively with electrical stimulation treatment

today. Features of a Functional electrical stimulation system employing 24 tiny printed electrodes were reported in 2014 by Yang et al., as shown in Fig. 4. The device may provide a range of varied hand postures, like trying to point, squeezing, and extending the hand. The smaller electrodes (1 cm<sup>2</sup>) provide a greater selection of stimulation regions. A polyurethane interface and encapsulation layer are placed between conductive silver traces on the electrodes in this instance, which are screen printed. A carbon-containing rubber paste is used to print the electrode pad itself. In order to make printing more dependable and to use less paste to provide a full conductive route, the interface layer is employed to create a flat finish for manufacturing the conductive traces. The encapsulation layer shields the conductive lines from electricity and protects them physically. The electrodes were printed on polyester-cotton fabric that is considered industry standard [16]. Stewart et al. tested hydrogel electrodes against electrodes constructed of conductive cloth in 2017. They changed the amplitude and rise time of the signal used to stimulate the subject's biceps, among other things. The fabric electrodes outperformed the hydrogel electrodes in all test outcomes, either similarly or somewhat better [1]. According to research by Moineau et al., clothing has also been incorporated with fabric electrodes. They created and put to the test a set of trousers, a blouse, and a jacket that had electrodes constructed from conductive fiber [17]. They had a FES stimulator attached to them, and a method was utilized to determine whether the full motor thresholds, motor, and sensory—the points at which stimulation causes complete muscle contraction—had all been achieved (the point at which the subject cannot tolerate greater intensity). These numbers are contrasted with those obtained by using gel electrodes.

Comparable to gel electrodes in behavior, fabric electrodes conduct power more readily toward the skin's surface, which has more nerve endings, since they have lower sensory thresholds [12]. Additionally, because fabric electrodes' power transmission is less consistent, "hot patches" that are easier to detect may develop. The maximal stimulation threshold is stronger for textile electrodes, while the comprehensive threshold is smaller. The cables attached to each electrode make the system more challenging to operate since they have a tendency to get tangled, and the electrodes require wetting after ten to fifteen minutes in order to function effectively and beautifully. These are the two main issues the authors identified with their system. Studies have also demonstrated increased performance of dry fabric electrodes, eliminating the requirement for wetting, while other work has improved techniques for incorporating power cables into fabric garments [18]. Pain alleviation is a different treatment for which electrical stimulation using fabric electrodes has proved beneficial. Electronic textile electrodes can be used to give electrical stimulation, which can be utilized to block the body's natural signal for expressing painful symptoms. Yang et al. examined a mechanism in 2020 utilizing an interrupting signal that was transmitted via 2 sets of electrodes mostly on the user's leg joints with a current transfer of 100 mA. The interfering current had frequency components around one and ten kHz. The rubber that contained carbon was printed on a cloth that was weaved using a copper cable to create the electrodes that were utilized in the study. This flexible rubber substance forms a strong electrical connection and fits snugly against the surface where it is inserted. Tests showed consistent current transmission, and users said the gadget was pleasant and simple to operate. These accomplishments

suggest that comparable outcomes to those seen in the research can be attained when cloth electrode technology is used for FES.



**Fig. 4.** Fabric electrodes

### 3 Materials for Fabric Electrodes

In the context of e-textiles, a lot of research has been done on electrodes: for transcutaneous electrical nerve stimulation, biopotential monitoring, and functional electrical stimulation, electrode devices have been created. Conventional silver/silver chloride electrodes are made of hydrogels that adhere directly to the skin. However, the performance of these gel electrodes degrades over time due to water evaporation and accumulation of contaminants, making them unsuitable for long-term wear applications. Textile-based dry electrodes exist in wearable therapies and have been used for many applications, including pain relief, stroke rehabilitation, and improved lymphatic function. Metal, which is frequently used to make contact with electrodes or other kinds of wiring, is an obvious material choice for the production of electrical fabric equipment. Flexible silver inks with electrical conductivity up to 3200 Scm<sup>-1</sup> have been created [19]. Silver is a popular candidate due to its high electrical conductivity. It is also biocompatible and chemically stable, but because it is a valuable metal, its price might be too high. Despite its greater susceptibility to corrosion, copper seems to be another popular option for e-textile uses since it is likewise highly conductive and considerably less expensive than silver [20]. Steel has been utilized to create conductive threads for e-textiles because of its excellent mix of mechanical and electrical qualities [21]. Polymers are an alternative to metals, and they offer a variety of acceptable products, such as polyaniline, polypyrrole, or poly(3,4 ethylenedioxythiophene) polystyrene sulfonate (PEDOT: PSS). However, compared to metallic conductors, the conductivity of these polymeric fibers is still at minimum an order of magnitude inferior, which makes them

less effective for extending existing electrical routes. Metals and polymers can be combined to produce materials having polymers' physical characteristics but substantially lower impedance [22]. In order to generate a stretchy screen printing ink with such a light coating impedance of just 6 /sq, Merhi et al. combined PEDOT: PSS with nanofibers, which are tiny silver strands. By using a variety of spinning methods, also including electrostatic spinning or moisture spinning, the above components can be transformed into yarns. In electrostatic spinning, a fine thread of polymer is drawn from a solution using an electric field, and in wet spinning, the polymer is precipitated from a solution in a liquid bath.

## 4 Fabric Electrode Preparation Processes

Fabric electrode systems can be divided into two broad categories: The first method entails utilizing conventional textile production methods like weaving, knitting, or embroidery to include conductive components into the cloth itself. On the surface of already-made fabrics, conductive components are printed or deposited in the second method. Conductive yarns are needed for the first kind of technique. This might be a yarn created by any of the aforementioned methods, or it could just be a wire with the right physical characteristics that can be woven into the fabric. The yarn architecture required for complicated circuits can be made using a wide range of weaving techniques, but the conductive channels can only ever be weaved orthogonal lines [23]. Greater geometric freedom is offered by embroidery, but it is more challenging to employ on an industrial scale since most conductive lines lack the tensile strength and elastic flexibility needed for machine sewing. As part of their research for neuroprosthetic applications, Keller et al. [24] employed embroidery to create smart fabric-based electrode pads and electrode wiring on cloth. Commercial metal-coated yarns, however, display low consistency during embroidery owing to deterioration of the conductive yarn surface, necessitating the usage of pricey, high-quality bespoke silver sputtering yarns made via plasma vapor sputtering [25]. Weaving and knitting have been used to manufacture smart fabrics for various wearable electronic applications (e.g., sensing, display, health monitoring, and power generation). However, these methods are not applicable to the fabrication of wearable FES arrays. Because the conductive routes are constrained to follow the actual placement of the threads within the fabric, woven and knitted technologies place restrictions on the design of the arrays. Due to erroneous gaps between the conductive threads, there is also an uneven distribution of resistance.

There are many different methods available for printing conductive materials. Printing with a stencil is the most basic of them. In this instance, a conductive paste is poured into a stencil that has apertures carved out in the appropriate pattern. The stencil is then removed once the paste has fully dried [26]. This technique works best for basic designs since with extremely small details (less than 1000  $\mu\text{m}$ ), the stencil will become too brittle and distorts, resulting in erroneous printing. Additionally, since every component of the mold must be linked, separate concentric designs are not feasible. Since a lot of material can be put at once, stencil printing is ideal for larger material deposits ( $>1000 \mu\text{m}$ ), whereas other methods that were initially intended for graphic printing need numerous layers to attain the same width [27]. The idea behind screen printing and

aperture plate printing is similar. To produce the specified mask, a screen printer uses a thick metal screen that is only partly covered with latex. A rubber broom is used to push the substance to be printed through the mesh and onto the substrate's exposed surface. A third way to add conductive material to the cloth is through dispenser printing. Here, a pneumatic or mechanical mechanism is used to push the printing material out while a robotic drive moves the nozzles. Dispensing printers can only print lines, which are typically one millimeter wide, therefore they take a while to cover a huge surface. They are more adaptable than screen or stencil printers, though. Dispenser printers may easily be reconfigured with the design concept; however, updating the design involves creating a new template with either technique. Dispenser printers can also adjust the altitude of the nozzle while printing, making it simpler to print over uneven ground or to modify the print density [28]. It is possible to print on sticky or delicate substrates using dispenser printing since it is a non-contact method and only the paste comes into contact with the substrate. With the nozzle placed near the surface and the ink discharged from there, inkjet printing employs a method akin to dispenser printing. While ink used within ink cartridges is applied as individual droplets, dispenser printers generally print utilizing a constant flow of stock. The ink used for inkjet printing has a far lower viscosity than the ink used for screen printing, stencil printing, or dispenser printing in order to produce such tiny droplets [29]. According to the desired pattern, drops can be generated continually or only as needed. Among the most widely used processes for printing graphics is inkjet, which has benefitted from a lot of research attention. Many more printing techniques exist that are less often employed in the production of e-textiles. By using an air stream to transport the ink droplets from the tip to the surface, which is firmly maintained by some other gas coating around them, aerosol printing is a method that is conceptually similar to dispenser and inkjet printing. Dispenser printing offers many of the same benefits as aerosol printing, but it calls for a considerably more complicated setup. In several techniques, the ink is first applied to the substrate within the desired sequence before being transferred to the substrate. These include the printing processes of gravure and flexography, in which the pattern is etched on a cylinder, filled with ink, and then applied to the substrates [30]. These techniques are not frequently employed for small-volume e-textile manufacture because of the high costs associated with roll production and the demanding standards for ink performance. These types of printing methods often need a very flat surface for ink adherence. If this stipulation is not followed, the ink might not stick or further deposits would be needed to make a full conductive route. Given that the majority of textiles don't satisfy these specifications, an interface layer can be positioned between the electrode materials and the cloth. As a paste or for distribution as a laminate, polyurethane is frequently chosen for printing. The substrate must meet certain specifications in order to print. Substrate absorption of printing ink is necessary for a stronger mechanical connection to form after curing [31]. For five to thirty minutes, the majority of printed electronic inks are cured at temperatures between 110 and 140 °C. In certain cases, inks may require 10 to 70 s of exposure to high-power UV light. Since the post-processing is often repeated for numerous layers, the substrate must be sturdy enough to survive it [32].

## 5 Discussion and Conclusion

This paper discusses the application of electrodes in electrical stimulation studies, detailing four typical electrode materials and their properties: metal electrodes, carbon rubber electrodes, hydrogel electrodes, and fabric electrodes. Moreover, the electrodes currently used in electrical stimulation studies generally have problems such as wearing comfort, poor washability, and unsatisfactory fit to the human body. The advantages of fabric electrodes are pointed out, and their materials and preparation methods are described in detail. For textile electrodes, although electronic textile electrodes have been used in many applications, the precise positioning of electrodes is still a challenge. With the future development of fabric electrodes, the performance of fabric electrodes in muscle stimulation will certainly be improved, which will become a major trend in the future of electrical stimulation electrodes.

## References

1. Stewart, A.M., Pretty, C.G., Chen, X.: An evaluation of the effect of stimulation parameters and electrode type on bicep muscle response for a voltage-controlled functional electrical stimulator. *IFAC-PapersOnLine* **50**, 15109–15114 (2017). July
2. Yang, K., et al.: Development of user-friendly wearable electronic textiles for healthcare applications. *Sensors* **18**, 2410 (2018). Aug.
3. Yang, K., et al.: Electronic textiles based wearable electrotherapy for pain relief. *Sens. Actuators, A* **303**, 111701 (2020). Mar.
4. Paul, G., Torah, R., Beeby, S., Tudor, J.: Novel active electrodes for ECG monitoring on woven textiles fabricated by screen and stencil printing. *Sens. Actuators, A* **221**, 60–66 (2015). Jan.
5. Carley, P.J., Wainapel, S.F.: Electrotherapy for an acceleration of wound healing: Low-intensity direct current. *Arch. Phys. Med. Rehabil.* **66**, 443–446 (1985). July
6. Katelaris, P.M., Fletcher, J.P., Little, J.M., Mcentyre, R.J., Jeffcoate, K.W.: Electrical stimulation in the treatment of chronic venous ulceration. *Aust. N. Z. J. Surg.* **57**(9), 605–607 (1987)
7. Griffin, J.W., et al.: Efficacy of high voltage pulsed current for healing of pressure ulcers in patients with spinal cord injury. *Phys. Ther.* **71**, 433–442 (1991). June
8. Peters, E.J., Lavery, L.A., Armstrong, D.G., Fleischli, J.G.: Electric stimulation as an adjunct to healing diabetic foot ulcers: a randomized clinical trial. *Arch. Phys. Med. Rehabil.* **82**, 721–725 (2001). June
9. Zhou, K., Krug, K., Stachura, J., et al.: Silver-Collagen Dressing and High-voltage, Pulsed-current Therapy for the Treatment of Chronic Full-thickness Wounds: A Case Series. *Ostomy Wound Manage.* **62**(3), 36–44 (2016). PMID: 26978858 Mar
10. Ijezerman, M.J., et al.: The NESS Handmaster orthosis: restoration of hand function in C5 and stroke patients by means of electrical stimulation. *J Rehab Sci.* **9**, 86–9 (1996)
11. Baker, L.L., McNeal, D.R., Benton, L.A., Bowman, B.R., Waters, R.L.: *Neuromuscular electrical stimulation: a practical guide*, 3 ed. Rehabilitation Engineering Program, Los Amigos Research and Education Institute, Rancho Los Amigos Medical Center, USA (1993)
12. Zhou, H., et al.: Stimulating the comfort of textile electrodes in wearable neuromuscular electrical stimulation. *Sensors (Basel, Switzerland)* **15**, 17241–17257 (2015). July
13. Houghton, P.E., et al.: Electrical stimulation therapy increases rate of healing of pressure ulcers in community-dwelling people with spinal cord injury. *Arch. Phys. Med. Rehabil.* **91**, 669–678 (2010). May

14. Ahmed, E.M.: Hydrogel: preparation, characterization, and applications: a review. *J. Adv. Res.* **6**, 105–121 (2015). Mar.
15. Wang, L., et al.: Enhanced cell proliferation by electrical stimulation based on electroactive regenerated bacterial cellulose hydrogels. *Carbohydr. Polym.* **249**, 116829 (2020)
16. Yang, K., Freeman, C., Torah, R., Beeby, S., Tudor, J.: Screen printed fabric electrode array for wearable functional electrical stimulation. *Sens. Actuators, A* **213**, 108–115 (2014). July
17. Moineau, A., Marquez-Chin, C., Alizadeh-Meghrazi, M., Popovic, M.R.: Garments for functional electrical stimulation: design and proofs of concept. *J. Rehabil. Assistive Technol. Eng.* **6**, 2055668319854340 (2019). Jan.
18. Catchpole, M.: E-textile seam crossing with screen printed circuits and anisotropic conductive film. *Proceedings* **32**(1), 16 (2019)
19. La, T.-G., et al.: Two-layered and stretchable e-textile patches for wearable healthcare electronics. *Adv. Healthcare Mater.* **7**(22), 1801033 (2018)
20. Acar, G., et al.: Wearable and flexible textile electrodes for biopotential signal monitoring: a review. *Electronics* **8**, 479 (2019). May
21. Perera, T., Mohotti, M., Perera, M.: Stretchable conductive yarn for electronic textiles made using hollow spindle spinning. In: 2018 Moratuwa Engineering Research Conference (MERCon), pp. 544–548 (May 2018)
22. Merhi, Y., Agarwala, S.: Direct write of dry electrodes on healthcare textiles. In: 2021 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS), pp. 1–2 (2021)
23. Kuroda, T., Takahashi, H., Masuda, A.: Chapter 3.2 - Woven Electronic Textiles. In: Sazonov, E., Neuman M.R. (eds.) *Wearable Sensors*, pp. 175–198. Academic Press, Oxford (Jan. 2014)
24. Sardo, P.M.G., Guedes, J.A.D., Alvarelhão, J.J.M., Machado, P.A.P., Melo, E.M.O.P.: Pressure ulcer incidence and braden subscales: retrospective cohort analysis in general wards of a Portuguese hospital. *J. Tissue Viability* **27**, 95–100 (2018). May
25. Biçer, E.K., et al.: Pressure ulcer prevalence, incidence, risk, clinical features, and outcomes among patients in a turkish hospital: a cross-sectional, retrospective study. *Wound Management & Prevention* **65**, 20–28 (2019). Feb.
26. Liu, M., Beeby, S., Yang, K.: Electrode for wearable electrotherapy. *Proceedings* **32**(1), 5 (2019)
27. Yang, K., Torah, R., Wei, Y., Beeby, S., Tudor, J.: Waterproof and durable screen printed silver conductive tracks on textiles. *Text. Res. J.* **83**, 2023–2031 (2013). Nov.
28. de Vos, M., Torah, R., Tudor, J.: A novel pneumatic dispenser fabrication technique for digitally printing electroluminescent lamps on fabric. In: 2015 Symposium on Design, Test, Integration, and Packaging of MEMS/MOEMS (DTIP), pp. 1–4. IEEE, Montpellier, France (Apr. 2015)
29. Karim, N., et al.: All inkjet-printed graphene-based conductive patterns for wearable e-textile applications. *Journal of Materials Chemistry C* **5**(44), 11640–11648 (2017)
30. Honarvar, M.G., Latifi, M.: Overview of wearable electronics and smart textiles. *The Journal of The Textile Institute* **108**, 631–652 (2017). Apr.
31. Komolafe, A., Nunes-Matos, H., Glanc-Gostkiewicz, M., Torah, R.: Influence of textile structure on the wearability of printed e-textiles. In: 2020 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS), pp. 1–4 (Aug. 2020)
32. Paul, G., Torah, R., Beeby, S., Tudor, J.: The development of screen printed conductive networks on textiles for biopotential monitoring applications. *Sens. Actuators, A* **206**, 35–41 (2014). Feb.