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DEVELOPMENT AND ASSEMBLING OF TEXTILE PRODUCTS

Textile electrodes for bioimpedance measuring

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ABSTRACT

This article deals with the development and comparison of eight different electrodes made out of a cotton fabric substrate, a silver coated yarn and partly conductive finishes, i.e. a PEDOT:PSS Orgacon ICP 1050 dip-coating and a Powersil coating. The purpose is the application especially in the medical field of angiopathy like for bioimpedance measurements during compression therapies. To be able to compare the suitability of the electrodes, various tests have been performed of the coating abrasion resistance, the stability of electrical resistance values, as well as resistance and bioimpedance measurements. Significant differences between the electrodes regarding their resilience and resistance that are visualized in a value-added analysis were found, with one hand-embroidered, one machine-sewn and one commercial electrode showing optimum properties.

Keywords
Textile electrodes,
Bioimpedance measuring,
Smart textiles,
BIA,
medical textiles

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1 Introduction

Bioelectrical impedance analysis (BIA) is commonly used as a significant tool in medical diagnosis. Several BIA applications in health monitoring are widely known and new approaches emerge from recent research. Innovative approaches are also being made in the textile medical engineering. There is an increasing amount of research on smart textiles [1,2]. These are based on data transmission within the textiles, so that formerly external measuring devices and output devices can be integrated in medical textiles. This requires robust and flexible data or power wiring to be integrated into the textiles.

Bioelectrical impedance analysis is a diagnostic tool for physicians and scientists in medical engineering. It is used to determine the body cell mass, total body water, fat free mass, fat mass and other information of the human body [3-5]. For this, four suitable skin electrodes, commonly Ag/AgCl electrodes, are attached to the hand and foot of the right body side. A constant, imperceptible alternating current is introduced into the body via a pair of electrodes, usually at a fixed frequency of 50 kHz. The second pair of electrodes is used to measure the voltage drop caused by the body and to derive the impedance, the total resistance of the body. At the same time the phase shift of the introduced alternating current is determined, which is mainly dependent on the body cell mass. An LCR meter (inductance (L), capacitance (C), resistance (R)) in 4-wire sensing mode is used to perform the measurement. Changes to this common measurement setup can be made in order to focus on specific details. For example, it is possible to alter the measurement path through the body.

A new aspect developed and explored in this paper is the usage of textile electrodes [6,7]. These are required for certain applications where the use of gel-based electrodes is not possible. Gel-based electrodes have the disadvantage that they are made for single measurements. If the patient has these electrodes placed on his body, over time the electrodes cause skin irritation.

Another disadvantage of using electrodes that would require conductive gels is that compression bandages are sometimes applied, for staying on a limb for several days; in that case, electrodes placed beneath the bandages would not be accessible after the bandages application and would become dry with time. To make sure continuous measurements are possible, electrodes capable of functioning without any lubrification and overwhelming the skin dryness must be chosen for the BIA.

As soon as textiles are fitted with sensors or electrodes, the electrodes are exposed to a variety of strain, unlike disposable gel electrodes; the electrodes have to be adapted to clothing's usability constraints. This means that they cannot be thrown away after each measurement. Instead, they become part of the clothing and must perform measurements over a long period of time. For this, they are regularly washed in the washing machine and must still make reliable contact even after numerous washing cycles [8-11]. As Gaubert et al. [8] proved, this requires a strong resistance to water and detergents. The influence of sweat adds to the corrosion of the electrodes in frequent use and when worn for physical exercise. While this supposedly does not change measurement results [12], it can cause the electrode materials to fail over time. In addition to these influences, smart clothing creates a high stress on the integrated sensors due to the friction from body movement [13] and the internal clothing movement [11]. Zaman et al. [14] showed that different textile-based electrodes are damaged after Martindale abrasion resistance tests. The contact breaks after several cycles so that the electrodes fail.

This article deals with the development of textile electrodes for bioimpedance measurements, which are made of a durable woven fabric substrate, comprising a silver-coated yarn and a chemical treatment with two different kinds of conductive coating [15]. Electrodes with different stitch patterns were manufactured and tested for their suitability in a given medical purpose (compression therapy). This includes measurements of the resistance and various tests on how the electrodes react to abrasion, sweat and washing. Finally, a set of bioimpedance measurements was performed to test the response of textile electrodes beneath a fine stocking. Our goal was to develop reusable dry bioimpedance electrodes prototypes, which are simple to produce and consist of materials with acceptable cost. Thus, it should be easy to replicate the electrodes without having to buy special equipment.

Our measurement setup differs from the usual one used for bioimpedance measuring in terms of electrode placement and medical functionality. In the experimental case, we positioned the four electrodes in pairs of two onto the lower leg. One pair was closer to the knee and the other pair was closer to the ankle. This way, the electric current only runs through the leg instead of the trace from hand to foot. We performed a multiple frequency bioimpedance measurement to test the suitability of the electrodes.

2 Materials and Methods

At first, it is described how the textile electrodes are produced, and afterwards, how they have been tested and rated.

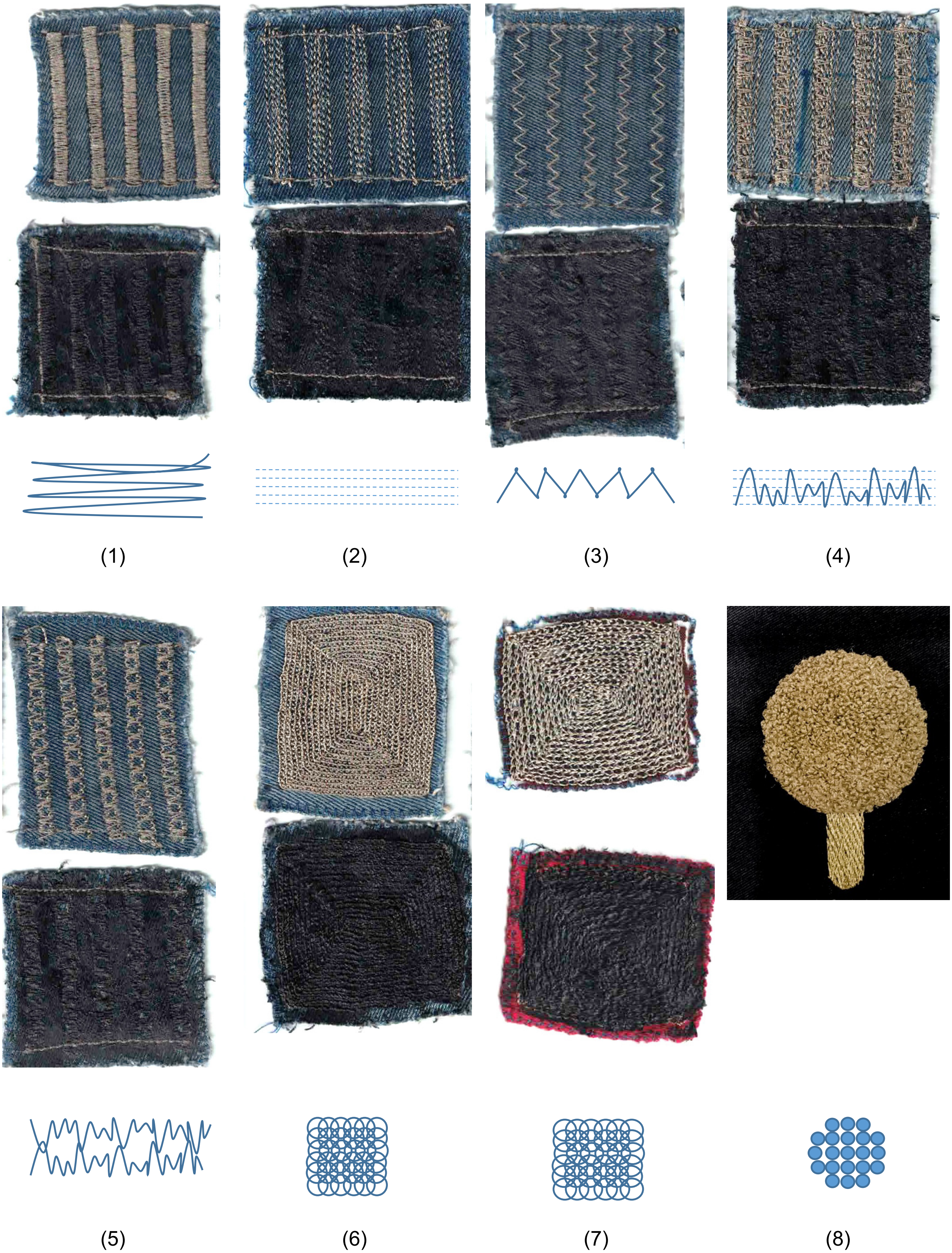


Fig. 1. Electrodes and sewing methods. Pure (upper images) and Powersil coated electrodes (lower images).

In total, eight different kinds of textile electrodes were developed (Figure 1); each type consisting of three variations (besides electrode 8): the untreated electrode (X.3) and two electrodes with different coatings. The eighth electrode is an industrially manufactured moss-embroidered non-coated electrode by the company ZSK Stickmaschinen GmbH, Krefeld, Germany and deals as an industrial comparison. The electrode has a diameter of 20 mm. The yarn is the Shieldex 33/10 dtex with < 4 kΩ/m.

The ground material of electrodes 1-6 is a cotton denim fabric with the dimensions of 55 mm x 45 mm. Electrode 7 is a thinner cotton fabric patch with the same dimensions. Electrodes 1 to 5 consist of five machines stitched (W6 model N1800) rows of conductive yarn that are 5 mm x 35 mm big and have a gap of 5 mm between them. The rows are connected on both sides with the same yarn on their ends. Electrodes 6 and 7 are hand stitched.

The stitching yarn is silver coated yarn (Shieldex 235/34 dtex 2-ply HC+B) with specific linear electrical resistivity <100 Ω/m. In Table 1, the settings and thread tensions of the machine-made electrodes are listed.

Table 1. Sewing program and distance of the electrodes.

Electrode No.	Sewing program of the sewing machine W6 N1800	Seam distance (machine specific units, motor rotations
1	C (zigzag stitch)	0.2
2	A (backstitch)	2.2
3	C (zigzag stitch)	2.8
4	A + E (backstitch plus elastic blindstitch)	3.0 + 1.0
5	E (elastic blindstitch)	1.0
6	Handmade: “Zuu Orookh” (Mongolian stitching method “needle wrapping”) [16]	-
7	Handmade: “Khonin Kholboo” (Mongolian stitching method “sheep formation”) [17]	-

To increase their conductivity, the electrodes X.1 were dip-coated with 2.4 mg/cm² PEDOT:PSS Orgacon ICP 1050 with a sheet resistance of 120 Ω (manufacturer information) and hardened for 4 hours at 60 °C. PEDOT:PSS is a conductive polymer, which is applied in liquid form. Through the oxidation, the polymer first enters the textile and then hardens and works like a hole conductor. Variation X.2 is a Powersil coating of 20.2 mg/cm², applied in two layers with a squeegee and hardened for 4 hours at 60 °C as well. Powersil is a silicon with integrated graphite and carbon black and is applied as a paste.

To find the most suitable electrode for bioimpedance measurements, a variety of stress tests and electrical measurements were performed and evaluated among each other with the value-added rating scale. At first, resistance tests were made to compare the general suitability as an electrode. For this, the multimeter Mastech PM334 was used. The electrodes were measured with crocodile clamps at the first, middle and last row.

To find out how stable and durable the electrodes are against machine washing, they were washed 30 times at 40 C, with detergents for fine laundry and wool, in a laundry bag, followed by spin cycling at 1000 rotations per minute. After each washing process, the electrodes were air dried and then resistance was measured with the multimeter.

The abrasion tests were performed with a Martindale abrasion tester according to the standard DIN EN ISO 12947-1:2007-04. Each electrode was measured after 10, 20, 50, 100, 200, 500 and 1000 cycles with the multimeter.

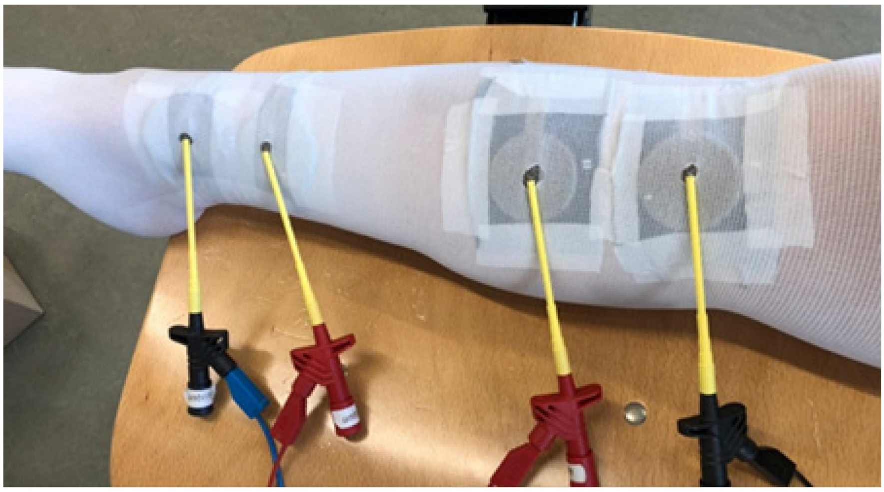


Fig. 2. Bioimpedance measurement with four electrodes.

The last test is the bioimpedance measurement. A four-point measurement at the calf was made, as shown in Figure 2, with the HP 4284A Precision LCR Meter, within a frequency range of 0 - 200 kHz. The outer electrodes inserting an electric current into the lower leg to were placed at a distance of 5 cm from the inner electrodes from which the voltage was measured. These criteria are based on experimental testing methods which are commonly used for physiological evaluation of body fluid [18,19].

3 Results and discussion

First, the resistance of the electrodes was measured, as shown in Fig. 3. Therefore, three electrodes of each type, i.e. three samples of each electrode and each coating variance, were measured on three different positions on the electrode, connecting a multimeter by crocodile clips.

A low resistance is an indicator for good conductance. In the field of textile electrodes, resistances under 10 Ω are good values. Electrodes 2, 4 and 8 are especially well conductive.

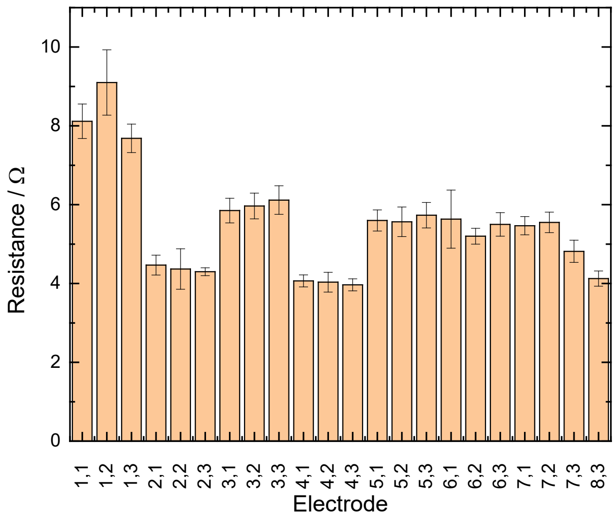


Fig. 3. Resistance measurements of the samples for the eight types of electrodes, whereas X.1 is coated with PEDOT:PSS, X.2 is coated with Powersil and X.3 is uncoated.

The next step is washing, drying and measuring the resistance. The results are presented in Fig. 4. Each electrode was produced three times and each of them were measured three times on different positions (see above) then. Electrodes 1, 3, 5 and 7 were destroyed after ten washing cycles. The remaining electrodes have been washed 30 times in total. We can observe the following results:

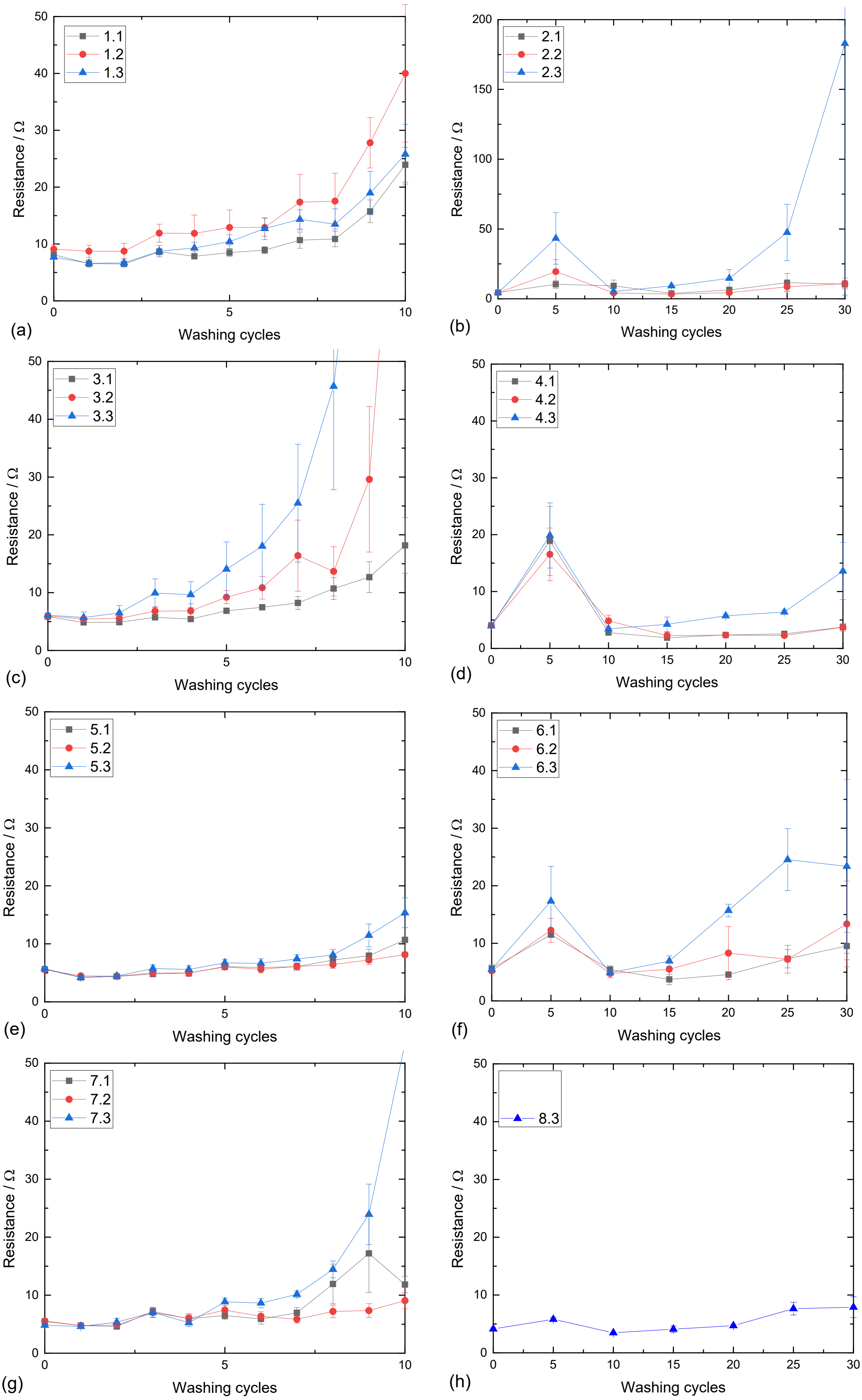


Fig. 4. Resistance measurements of the respective samples for identical wash cycles: (a) electrode 1, (b) electrode 2, (c) electrode 3, (d) electrode 4, (e) electrode 5, (f) electrode 6, (g) electrode 7, (h) electrode 8.

First, the resistances within the same electrode group yield relatively similar values except for (c) and (g), where the resistance value for (c) PEDOT:PSS coated electrode remains quite stable and low, i.e. close to a value of about 15 Ω. The last measurement of the PEDOT:PSS coated electrodes reaches a high value close to 110 Ω, rising sharply from the previous value of 20 Ω. Therefore, we can exclude this one point for the moment in order to get stable and reliable values of resistance. Sample (h) (electrode 8) is an untreated electrode. Thus, the graph depicts only one result for each measurement, and values remain between 3 Ω and 6 Ω.

Second, the resistance value of the untreated sample (g) develops relatively high values after several washing and measuring cycles, which indicates that the resistance has been deteriorated.

Third, the best electrode so far is sample 4 (Fig. 4d) where all resistance test values are lower than 5.5 Ω. This allows us to conclude that washing has little or no significant effect on their resistance. In summary, the resistance of the uncoated and the coated electrodes was compared to find out the impact of the coating and possible advantages or disadvantages through it.

Next, we carried out abrasion resistance tests and with a Martindale abrasion tester machine (Fig. 5). The resistance is measured after 0, 10, 20, 50, 100, 200, 500 and 1000 Martindale cycles. We can see large differences between the electrodes 3 and 4 (Figs. 5c and 5d). While electrode 3 starts with about 60 Ω, it rises above the multimeter range of 30 MΩ after 1000 Martindale cycles.

The electrodes 4 (Fig. 5d) and 8 (Fig. 5h) do not reach 4 Ω and do not show a clear effect of abrasion. This indicates that the denser the sewing, the more durable the sample becomes, and it is highly likely to be useful from a practical perspective. This means that the denser the seams are, the more resistant the electrodes are against abrasion and washing impacts and therefore the quality is steady in the long-term usage.

We found that electrodes 4 and 8 perform best in abrasion tests. Electrode 6 shows a nearly linear resistance increase and doubles its resistance after about 500 cycles. Nevertheless, its abrasion test results are still better than other ones.

The magnitude of the complex impedance, $|Z|$, evaluated by bioimpedance measurements, is depicted in Fig. 6. Criteria for the suitability of bioimpedance measurements are on one hand values higher than 10 Ω, which implies a good skin contact, and on the other hand the values should lie within a range of 30 Ω to 60 Ω at 50 kHz. Therefore, electrodes 4, 6 and 8 seem to be most suitable. Electrode 2 is only usable with a PEDOT:PSS coating but shows a high impedance in comparison to the mentioned electrodes in Figure 6.

Generally, these measurements are made with a common impedance measuring device. Its input impedance is not matched with the high contact resistance between the textile electrode and the human skin. This is the reason for the large error bars, which depend on the contact resistance. In the future, special bioimpedance measuring devices are especially developed for these textile electrodes and the error of the contact resistance will be included into the development. Nevertheless, electrodes 6.1, 6.3 and 8.3 lead to suitable values anyway. We emphasize that the measurement did not intend to measure the fluid content in the body segment.

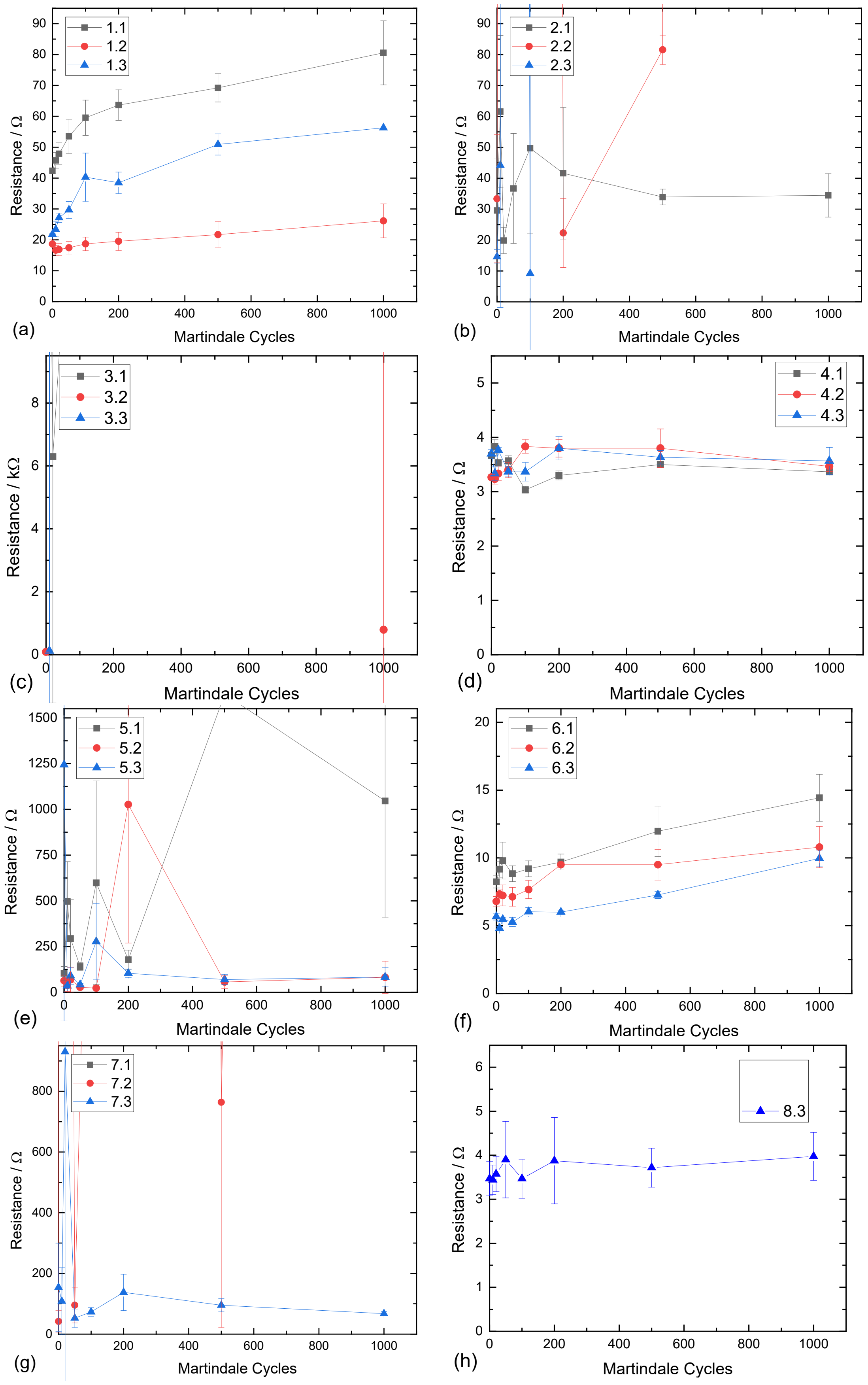
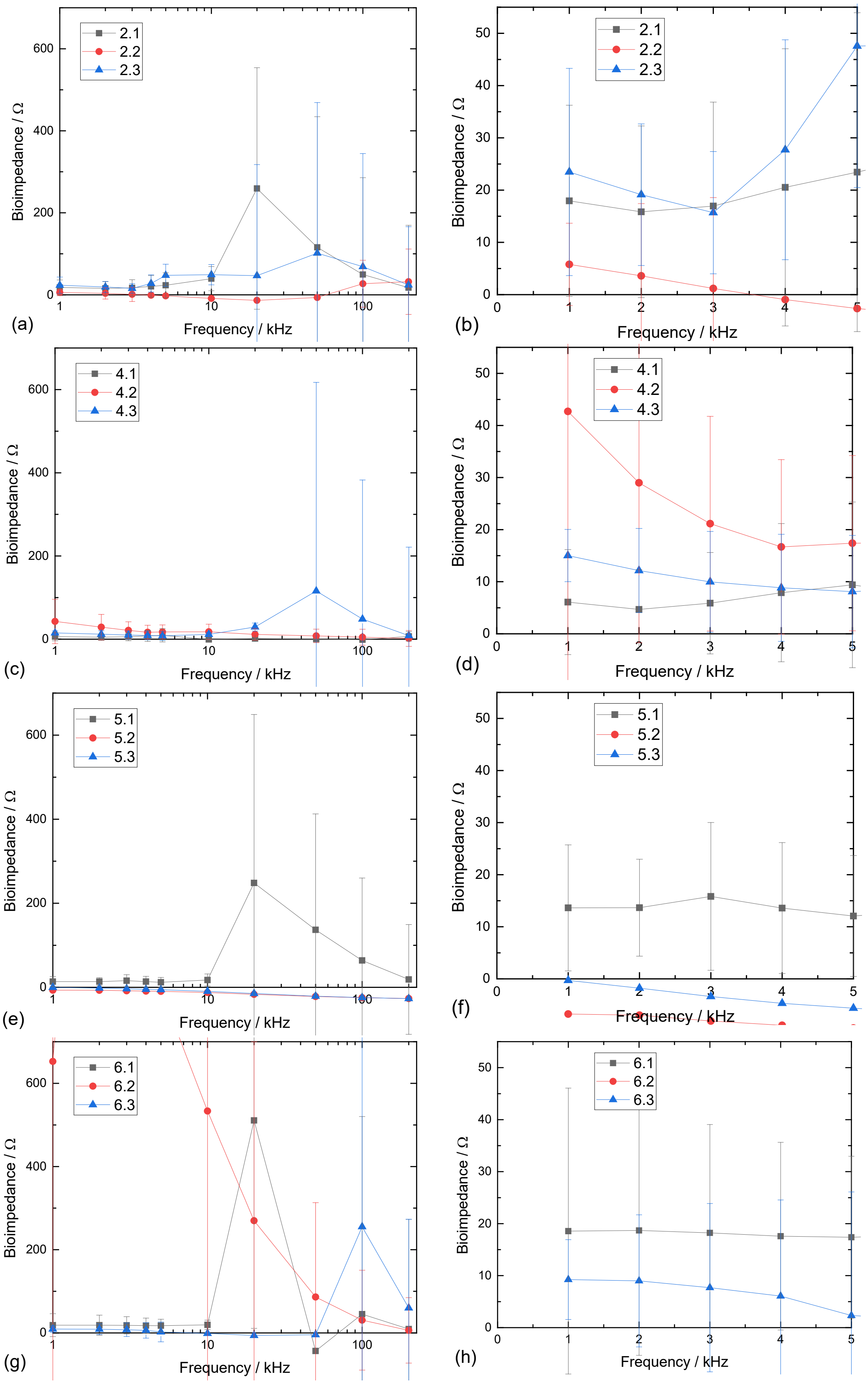


Fig. 5. Resistance measurements of the respective samples abrasion processes: (a) electrode 1, (b) electrode 2, (c) electrode 3, (d) electrode 4, (e) electrode 5, (f) electrode 6, (g) electrode 7, (h) electrode 8.


(a)
2.1
2.2
2.3
Bioimpedance / Ω
Frequency / kHz
(b)
2.1
2.2
2.3
Bioimpedance / Ω
Frequency / kHz
(c)
4.1
4.2
4.3
Bioimpedance / Ω
Frequency / kHz
(d)
4.1
4.2
4.3
Bioimpedance / Ω
Frequency / kHz
(e)
5.1
5.2
5.3
Bioimpedance / Ω
Frequency / kHz
(f)
5.1
5.2
5.3
Bioimpedance / Ω
Frequency / kHz
(g)
6.1
6.2
6.3
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(h)
6.1
6.2
6.3
Bioimpedance / Ω
Frequency / kHz

Fig. 6. Cont.

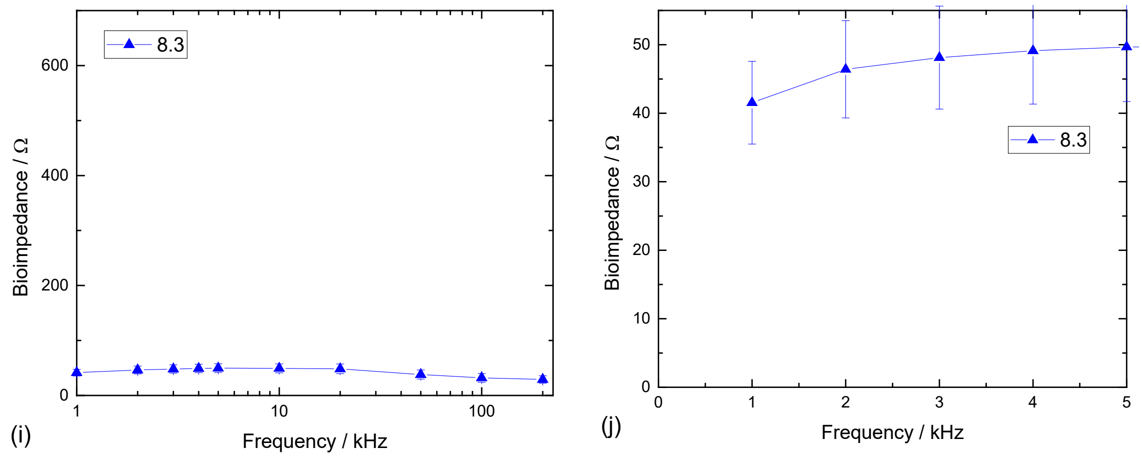

Fig. 6. Bioimpedance measurements |Z| with our textile electrodes on one person: (a) and (b) electrode 2, (c) and (d) electrode 4, (e) and (f) electrode 5, (g) and (h) electrode 6, and (i) and (j) electrode 8. The graphs on the right side depict the magnified view of the graphs from the left side in the range of 0 to 5 kHz and up to 55 Ω.

Table 2 presents the score of each electrode based on its performance. The highest score represents the best results for each or total test. We apply the rating scale using weighted value analysis to determine the most suitable electrode. Criteria include the resistance, the washability, the abrasion resistance, and the suitability for bioimpedance measurements. Since no large differences are visible for specimens with and without coating, all specimens belonging to one sample number are evaluated together. For example, Electrode No. 1-1, No. 1-2, No. 1-3 will be now averaged as electrode #1.

The most important criterion is the resistance, which was weighted with 35%. Washability and bioimpedance suitability were equally weighted with 25 % and the abrasion resistance was weighted with 15%. For each electrode, the first row indicates the rating for the criterion on a scale from 0-10; the second row is the product of the multiplication of the first row and the weighting. It is called the weighted rating. For example, electrode No. 1 received a score of 1.23 for the resistance. This value was calculated from the resistance, which has a weighting percentage of 35%, and a score of 3.5. To achieve the weighted value, the weighting percentage and score were multiplied, resulting in a value of 1.23.

Table 2. Value added analysis of the electrodes

Criteria	**Resistance**	**Washability**	**Abrasion resistance**	**Bioimpedance suitability**	**Σ**
Weighting	35%	25%	15%	25%	100%
#1	3.50	6.00	7.00	0.00	16.50
	1.23	1.50	1.05	0.00	3.78
#2	9.00	9.00	5.00	5.00	28.00
	3.15	2.25	0.75	1.25	7.40
#3	5.50	0.05	0.00	0.00	5.50
	1.93	0.13	0.00	0.00	2.05
#4	10.00	9.00	10.00	8.00	37.00
	3.50	2.25	1.50	2.00	9.25
#5	6.00	8.50	4.00	10.00	28.50
	2.10	2.13	0.60	2.50	7.33
#6	10.00	9.00	9.00	9.00	37.00
	3.50	2.25	1.35	2.25	9.35
#7	8.50	6.50	0.00	0.00	15.00
	2.98	1.63	0.00	0.00	4.60
#8	10.00	10.00	9.00	10.00	39.00
	3.50	2.50	1.35	2.50	9.85

The highest scores were obtained for electrodes no. 4, 6 and 8, as shown in Table 1. We can conclude that the score of electrode No. 8 is the highest as compared to the other electrodes. Electrode no. 8 received the highest weighted score with a value of 9.85 out of 10. Electrodes no. 4 and no. 6 are the following preferred electrodes with weighted total scores of 9.25 and 9.35, respectively.

4 Conclusions

To sum up, electrode No. 8 meets the requirements best. It does not only prove a good range in the resistance, but also is durable against washing and abrasion. The bioimpedance measurements can be performed as desired, too. A disadvantage about this type of electrode are the high production costs. On the other hand, it already has industrial standard, so that a mass production of these electrodes might reach the same quality easily. Electrodes no. 4 and no. 6 are also suitable for medical application electrodes.

For most aspects, the coating seems to be unimportant, besides for the bioimpedance, where it leads to a better skin contact. There we can see that the PEDOT:PSS coating leads to the perfect measuring range.

In the long-term, the electrodes should be machine-made for quicker production processes. In this case, the hand-stitched electrodes might be machine-made too and analyzed again.

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