Measurement of EMG activity with textile electrodes embedded into clothing

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Abstract. Novel textile electrodes that can be embedded into sports clothing to measure averaged rectified EMG have been developed for an easy use in the field tests and in clinical settings. The purpose of this study was to evaluate the validity, reliability and feasibility of this new product to measure averaged rectified EMG. Validity was tested by comparing the signals from bipolar textile electrodes (42 cm²) and traditional bipolar surface electrodes (1.32 cm²) during bilateral isometric knee extension exercise with two electrode locations (A: both electrodes located in the same place, B: traditional electrodes placed on the individual muscles according to SENIAM, n=10 persons for each). Within-session repeatability (coefficient of variation CV %, n=10) was calculated from 5 repetitions of 60 % maximum voluntary contraction (MVC). Day-to-day repeatability (n=8) was assessed by measuring three different isometric force levels in five consecutive days. Feasibility of the textile electrodes in field conditions was assessed during maximal treadmill test (n=28). Bland-Altman plots showed a good agreement within 2SD between the textile and traditional electrodes demonstrating that the textile electrodes provide similar information on the EMG signal amplitude as the traditional electrodes. The within-session CV ranged from 13 to 21 % in both the textile and traditional electrodes. The day-to-day CV was smaller ranging from 4 to 11 % for the textile electrodes. A similar relationship (r²=0.5) was found between muscle strength and EMG of traditional and textile electrodes. The feasibility study showed that the textile electrode technique can potentially make EMG measurements very easy in the field conditions. This study indicates that the textile electrodes embedded into shorts is a valid and feasible method for assessing the average rectified value of EMG.

Key words: validity, repeatability, isometric, knee extension, VO2 test

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1. Introduction
Surface electromyography (EMG) has been widely used in measuring muscle activity in athletes and patients. Although wireless transmission of EMG signals to the storing computer has become a standard, the measurements are still difficult to implement in out-of-laboratory settings. This is due to the fact that the electrode placement with skin preparation require careful handling and that the measurement system includes lots of wires to be secured to avoid movement artefacts. Often the measurement devices are also quite heavy and clumsy to be carried with during daily training exercises.

The development of washable textile electrodes has opened up possibilities to manufacture shorts, shirts and other clothing equipped with the textile electrodes that can record muscle activity during normal locomotion without skin preparation and problem of wires hanging around the body (Lintu et al 2005, Scilingo et al 2005). Potentially the use of textile electrodes can have applications from elite athletes to ergonomics and clinical settings evaluating outcome of rehabilitation.

Typically, electromyography is based on measurement and analysis of individual muscles separately, which is necessary in basic science. In many practical applications single muscle measurements, however, are not very useful because of the system complexity. The present methodology allows monitoring the level of muscle activity from a group of agonist and synergistic muscles during training, for example. Besides athletes, the present application may be used in ergonomics, for example, to monitor the ability to relax muscle groups that are not needed to perform the task. As an example, to avoid chronic pain and injuries, the patient could use the device when training to relax the contralateral arm while performing tasks with a computer mouse with the other arm.

Because the traditional bipolar surface electrodes have been accepted for assessing EMG activity both in sports and clinical settings, in this study, we used the traditional electrodes as a “standard” to which the signal amplitude from the textile electrodes embedded in shorts was compared when assessing validity. Such a system with textile electrodes is primarily intended to assess interlimb and segmental coordination and the EMG signal amplitude in athletic tests, during athletic training and to be used as biofeedback device for rehabilitation purposes. The purpose of this study was to assess the validity and reliability of the textile electrodes during muscle strength tests, and their feasibility during maximal treadmill test in order to implement this novel innovation to measure EMG in field conditions.

2. Materials and Methods

2.1. Study subjects
A total of 50 healthy volunteers aged 20-48 years participated in four separate experiments. In the first experiment 3 males and 7 females (28±7 yrs, 168±6 cm, 63±1 kg) were measured in isometric conditions using two types of electrodes that were placed to the positions shown in figure 1a. In the second experiment, ten males (24±3 yrs, 176±5 cm, 73±3 kg) were measured in isometric conditions using electrode positions
shown in figure 1b. In the third experiment day-to-day repeatability of the textile electrodes was assessed from eight subjects (32±8 yrs, 172±8 cm, 68±4 kg, 4 women and 4 men). In the fourth experiment, EMG was measured using the shorts with embedded textile electrodes from twenty-eight males (25±3 yrs, 178±1 cm, 71±8 kg) in a treadmill test. Six of the subjects participated in both experiment one and experiment three. After all procedures were explained to the subjects, they signed informed consent. The study was approved by the ethics committee of the University of Jyväskylä.

2.2. Study design
A summary of the study design is given in Figure 1. The validity of textile electrodes to measure average rectified value (ARV) of EMG was evaluated by comparing the outcome from bipolar textile electrodes and traditional bipolar surface electrodes in the quadriceps muscles using two different positioning for the traditional electrodes (electrode positions A and B, Fig. 1). Reliability was tested by measuring withinsession repeatability (short-term precision) and day-to-day repeatability (long-term precision) of the electrodes. All of these tests were isometric contractions performed in a seated position with knee joint at 120° angle. The knee extension ergometer (Leg Ext/Curl Research, Hur Oy, Kokkola, Finland) had a force transducer attached to the lever arm at the ankle. The torque produced was stored to a computer with a sampling frequency of 200Hz. Average torque and ARV of EMG were calculated from 1 s period at the time of a constant torque production (Fig.2).

Feasibility of the textile electrodes was assessed by measuring EMG during maximum oxygen consumption (VO2max) test on a treadmill. Mean values from each variable were taken from the last 30 s at each velocity.

2.3 Apparatus
2.3.1. Shorts with embedded textile electrodes. The shorts were a knitted fabric similar to elastic clothing used for sport activities. To obtain the EMG signal the shorts were equipped with conductive electrodes and wires integrated into the fabric. The purpose of the wires is to transfer the EMG signals from the electrodes to the electronics module attachment point in the shorts’ waist area, where the electronics module is attached during the measurements (Fig. 3). The memory capacity of the module is approximately 4 hours of data and it contains a rechargeable battery.

In the shorts the textile electrodes were placed so that the bipolar electrode pair lay on the distal quadriceps muscles. The reference (grounding) electrode was placed longitudinally at the lateral side (Fig. 3). Two sizes of shorts, medium (three pieces) or small (one piece) were available in this study. One medium and one small size shorts were equipped with a 20 cm zipper in the hem to enable simultaneous measurement on the opposite leg using traditional electrodes. The electrodes were of similar magnitude in both shorts (conductive area of 42 or 39 cm², respectively). Proper fit of the shorts (in addition to sufficient moisture of the electrodes, see below) enables necessary contact of the electrodes and skin, and provides friction which
prevents the electrode displacements during joint motions. We noticed that the small size shorts were not tight enough and the electrodes could move in relation to the skin for some of lean individuals due to the differences in body shape and size. We tried to prevent the movement by applying adhesive tape around the thigh on top of the shorts. On the other hand, the medium size shorts were too tight for some subjects and we left the zipper open in the short’s hem and wrapped the tape around the thigh. The results show that these procedures were many times unsatisfactory causing temporary loss of contact and movement artefacts between the skin and the electrode (see also Discussion). The size of the shorts, electrode location and electrode size were constraint of the product that the researchers could not influence at the time of this study.

The conductive electrodes consist of conductive yarns including silver fibres and non-conductive synthetic yarns woven together to form a fabric band. Electrical resistance of the yarn with silver fibre is typically 10 $\Omega$ / 10 cm, in dry electrodes. The textile electrodes were sowed onto internal surface of the shorts. The wires transferring the signal from electrodes to the electronics module attachment point have been made of steel fibers with short piece of silver coated fiber at the end to enable reliable soldering to the connector pins. The connection between the electrode and the wire was secured so that there would be no artefacts from any movement. The wires are connected to the electronics module, which is attached to the connector in shorts. A rubber sealing between the connector and module keeps the moisture outside the electronic contacts. The connection design and mechanical construction prevent any motion of the detachable metal-to-metal contacts thus eliminating the mechanical artefacts. All contacts in shorts and module are gold plated, which keeps the contact resistance low over time.

The electronics module (weight 53.4 g) contains signal amplifiers and A/D-converters for each channel, microprocessor with embedded software, data memory and interface to PC as well as wireless transmitter-receiver to enable signal storage and monitoring online with a wrist top computer. The EMG signals were measured in a raw form with a sampling frequency of 1000 Hz and a frequency band of 50 Hz – 200 Hz (-3 dB). The signal gain factor prior A/D conversion was 1220 and for the A/D-conversion a 12-bit ADC component was used.

The raw EMG signals were first rectified and then averaged over each 100 ms intervals without overlapping. Thus 10 consecutive samples from raw signal create one rectified, averaged data sample. This 10 Hz data was stored in ASCII format in the memory of the module, which was downloaded to a PC using a custom software. From the 10 Hz EMG data ARV was calculated from 1 s window during a stable torque signal (Fig. 2). The frequency of 10 Hz was selected to enable 4 hours of data storage in the module. Were the frequency increased, the sampling time would have decreased. In laboratory conditions it would not have been any problem to increase the frequency, but in the field, to where this product is meant, it is useful to have enough memory storage capacity.

Two channels, one from each leg were recorded. To ensure proper signal conduction the electrodes were moisturized with tap water before dressing on the shorts. When wetted, a membrane covering the electrodes prevents the electrode-skin interface from drying. The textile electrode technique has been proved
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to be safe and can be used in human studies. Furthermore, the shorts with textile electrodes can be washed repetitively without decreasing their performance (Scilingo et al 2005).

2.3.2. Traditional surface electrodes. Traditional bipolar silver/silver-chloride electrodes with sensory area of 13.2 mm² (Blue sensor M-00-S, pre-gelled adhesive electrodes, Medicotest A/S, Denmark) were used to compare the textile electrode ARV to the traditional surface EMG ARV. The skin was shaved, abraded and cleansed at the sites where the electrodes were placed. The signal was amplified with ME6000 Biomonitor using frequency band 7Hz – 500 Hz (Mega Electronics Ltd., Kuopio, Finland), telemetrically transmitted and stored with a sampling frequency of 1000 Hz into a computer. The signal was further conditioned with the same parameters as the textile EMG signal; rectified, filtered with band pass filter 50-200 Hz and averaged over the 1 s window. For the purpose of presenting the data in a figure the signal was also averaged over 100 ms non-overlapping intervals to illustrate the signals with the exact same conditioning of the textile EMG signal (Fig. 2).

2.4. Protocols

2.4.1. Validation protocol A. Ten subjects (28±7 yrs, 168±6 cm, 63±1 kg, 3 males and 7 females) participated in the Validation A protocol. Four pairs of the traditional electrodes were placed side-by-side onto the exact location where the textile electrodes would contact the skin with interelectrode distance of 50 mm (Fig.1). In this setting the electrode impedance was considerably higher than the typically accepted 10 kΩ. It must be noted that in this setting the electrode pair is not oriented along the muscle fibers. This setting however, validated the textile electrodes providing the signal from the exact the same location for both the textile and traditional electrodes.

After a standardized warm up, the subjects were seated in a knee extension device which measures force separately from left and right leg (Hur Oy, Kokkola, Finland). The subjects first performed three maximal isometric knee extensions bilaterally (MVC) with strong verbal encouragement. The highest torque recorded was considered as the maximum from which a 60% level was calculated. Then the subjects performed three bilateral repetitions at 60% of the MVC. There was at least 1 minute rest between the contractions.

The procedure was repeated twice: 1) the textile electrodes recorded from the left thigh and the traditional electrodes from the right thigh, and 2) traditional electrodes recorded from the left thigh and textile electrodes from the right thigh. Thus, the comparisons between the signals from the average of the four pairs of traditional electrodes and the textile electrode pair were done during the same performance from different legs (right vs. left), or from the same leg in two different performances. The shorts were equipped with a 20 cm zipper in the hem. When recordings were done with traditional electrodes the zipper was opened and the hem turned up to avoid contact of the textile electrodes with skin and other electronics.
2.4.2. Validation protocol B. Ten males (24±3 yrs, 176±5 cm, 73±3 kg) participated in the Validation B protocol. The traditional bipolar electrodes with interelectrode distance of 20 mm were placed onto the muscle of the vastus lateralis (VL), rectus femoris (RF) and vastus medialis (VM) according to the locations and orientations recommended by SENIAM (Hermens et al 1999). After the warm up and maximal isometric knee extension the subjects performed five repetitions of 60% of the MVC. The procedure was repeated twice as was done in the Validation A protocol.

In addition, thickness of subcutaneous fat was measured with ultrasonography (Aloka SSD 280LS, Japan) using 7.5 MHz linear probe from the exact locations of the traditional electrodes and from the mid point of the both textile electrodes (upper and lower). The mean value of the subcutaneous fat thickness of the two textile electrodes were used for additional comparisons.

2.4.3. Reliability studies. Ten males (24±3 yrs, 176±5 cm, 73±3 kg) participated in the within-session repeatability test. In this study the repeatability of textile electrodes were tested by measuring at 60% of the MVC at 120° knee angle five times with one minute rest between the repetitions. This test was performed on the same subjects and electrode setup as described in the Validation B protocol.

Eight subjects (32±8 yrs, 172±8 cm, 68±4 kg, 4 women and 4 men) participated in day-to-day repeatability protocol. The repeatability was tested by measuring two repetitions of three different force levels on five consecutive days. These absolute force levels were the same for every subject and they were determined from the weakest subject’s at 40 % (level 1), 60 % (level 2) and 80 % of the MVC (level 3). EMG was recorded with the textile electrodes only. Each subject wore the same shorts daily, and they were asked to put them on as they would any type of shorts but to be careful with the hardware. We did not control if the electrode location was exactly the same on each day but aimed to establish the repeatability as it would be in true field conditions.

2.4.3. Feasibility study. Twenty-eight males (25±3 yrs, 178±1 cm, 71±8 kg) performed on a VO$_{2\text{max}}$ treadmill test while wearing the shorts with embedded textile electrodes. The subjects had heterogeneous background; 12 were training endurance running (including top national long distance runners and orienteers) and 16 participated in recreational exercise. Three-minute ramp model with 1 km/h steps was used for the VO$_{2\text{max}}$ test. The initial speed varied individually from 5 to 11 km/h. The treadmill was stopped briefly after every ramp in order to take lactate samples. We monitored the success and failure of the EMG recordings from the bipolar textile electrodes in the left and right front thigh. The recordings were considered a failure if there were blackouts, cutting or major baseline drifting in the signal.

2.5. Statistics and calculations
The method of Bland and Altman (1986) was used to compare the agreement i.e. validity between the two methods of measuring ARV of the EMG signal. In this method the difference against the average of the traditional EMG and textile EMG ARV is plotted. A data sample in the plot represents one 60 % MVC trial, thus there are either 30 (validation A) or 50 (validation B) data points in the plot. We expect that the differences within ±2SD are not practically or clinically important, and that the 2SD is considered as the “limit of agreement” indicating that the two methods can be used with similar accuracy to measure ARV EMG. Correlations and linear regression analysis were also performed between the selected variables. Standard deviations (SD), coefficient of variation (CV%) are reported. For within-session variability CV% was calculated by taking SD of each individual’s five repetitions and then calculating the root-mean-square (RMS) average of individual SD values (RMS SD) and dividing it by the group mean (CV% = RMS SD/mean*100%) (Lu and Glüer 1999). For day-to-day variability, the CV% was calculated the same way separately for three different torque levels: SD of each individual’s repetition at given torque level on five consecutive days was first calculated, then RMS SD was calculated for the entire group and it was divided by the group mean value. Due to the variation in torque even in predetermined levels of effort, the EMG signals were divided by torque to remove the effect of variable torque on the EMG signals (i.e. EMG was normalized to torque). All subjects and performances have been included in the results without removing any outliers.

3. Results

3.1. Validation

Bland-Altman plots from the Validation A protocol showed good agreement between the textile and traditional electrode ARV (Fig. 4). Although there are either one or two samples out of the 2SD range, these represented less than 5 % of the cases. The mean value in the Bland-Altman plots was positive demonstrating that the amplitude of the traditional EMG signal was greater that that of the textile electrodes.

Bland-Altman plots from the Validation B protocol also showed good agreement between the two types of EMG measurements (Fig. 5). In this setting, five samples fell outside the 2SD range but still 95 % of the cases were within the limits of agreement. Only in one comparison the agreement was not acceptable (Fig. 5, C). Contrary to Validation A protocol, the mean value of Bland-Altman plots in the Validation B protocol was negative.

All of the Bland-Altman plots contained heteroscedasticity expressed as significant correlation (0.21<r<0.62, 0.05<p<0.001).

3.2. Repeatability
Textile electrodes had similar CV with and without normalization to torque compared to traditional electrodes within one session (Table 1). In both cases, when the EMG was normalized to torque, CV% became slightly lower but still remained over 10% for both electrode types. Day-to-day variation was between 8% and 11% for the textile electrode signals. When the EMG signal was normalized to torque, the mean CV% for textile electrodes varied from 5-11% at different force levels (Table 2).

3.3. Feasibility

The recordings with textile electrodes during maximal oxygen uptake test provided signals that were increasing with the treadmill speed and VO₂ uptake (Fig. 6). We did not encounter any problems in 64.3% of the recordings. We experienced some problems and missed part of the signals in 28.6% of the recordings due to contact problems between skin and the electrode. The data was unusable in 7.1% of the subjects mainly due to contact problems between the skin and the electrode.

3.4. Correlations between muscle strength, subcutaneous fat thickness and EMG

EMG-torque relationships for textile (A, B) and traditional electrodes (C, D) at 60% of the MVC using setup A are given in figure 7. Muscle activity recorded by the textile electrodes explained 44-53% while the traditional electrodes explained 38-54% of the variance in muscle strength (Fig. 7). The correlations between the textile and traditional EMG signals were not aligned to the line of identity, thus causing low r² values (0.103< r²<0.589, slope 1.3-4).

There were significant negative correlations between subcutaneous fat thickness and traditional EMG amplitude in four of the six muscles (right leg RF: r=-0.70, p<0.001, VL: r=-0.51, p<0.001, VM: r=-0.530, p<0.001, left leg VM: r=-0.43, p<0.01). Significant correlation between subcutaneous fat thickness and EMG from the textile electrodes were found only in the left leg (r=0.43, p<0.05).

4. Discussion

The novel textile electrodes embedded into shorts to measure averaged rectified EMG has been developed specifically for an easy use and real-time monitoring in the field and in clinical settings. Accurate assessment of muscle activity is not only important for research, but also for sports and clinical work. Since the textile electrodes embedded into shorts is a new technology, it was essential to establish its reliability and feasibility. The results of this study showed that the signals from the textile electrodes are in good agreement with the traditionally measured surface EMG signal. Both methods have similar within-session repeatability, and the day-to-day variability of less than 11% for the textile electrode signal. The relationship between muscle strength and EMG was similar for both traditional and textile electrodes. The results suggest that the new textile electrodes embedded into shorts is a valid and feasible method for assessing muscle activity in real-time.
The signal conditioning in the textile electrodes was optimized for the economy of data storage and transmission, and it was constraint of the product. Thus, it was quite different from the SENIAM recommendations. Most importantly, it need be considered that the lower cut-off frequency of 50 Hz used in the present study be decreased to 20 Hz. This change is technically possible without increasing movement artefacts in the signal because of the secure connections between the electrodes and wires. In the shorts, the only connector interface is in the electronics module that is tightly attached to the module connector. As compared to traditional electrodes with loose wires, and especially electrodes with snaps, the presented new technology may to be more insensitive to movement artefacts arising from wires and connectors.

In our validation part of the study, the Bland-Altman plots were used to evaluate the agreement of ARV EMG between the textile electrodes and traditional bipolar surface electrodes. The Bland-Altman plots demonstrated heteroscedasticity with $r^2$ values between 0.21 and 0.62. The heteroscedasticity refers to the relationship between the difference in the two methods and the size of the measured variable. Thus, the greater the ARV, the greater is the difference in the results of the traditional and textile electrodes. We observed that there was one subject with extreme values who contributed to the heteroscedasticity but could not find any reason to classify those samples as outliers; thus we considered them to describe a naturally greater variation in the ARV. We found the mean value of Bland-Altman plots in Validation A protocol was positive demonstrating that the traditional electrodes yielded slightly higher values. Nevertheless, 95% of the data points were within the 2SD confidence interval showing that the two methods are in good agreement whether absolute or relative values are examined (Fig. 4). In Validation B protocol, the mean value was negative indicating that the textile electrodes gave higher ARV than the traditional electrodes. The difference in the mean value between Validation A and B protocols may be partly due to the differences in the inter-electrode distance. In Validation A protocol the distance was 50 mm giving a greater signal amplitude, while in the Validation B protocol the inter-electrode distance was only 20 mm.

The textile and traditional electrodes showed similar CV% (Table 1). The CV% of ARV decreased when the signal was normalized to torque. This was expected because in spite of the predetermined torque levels, the actual produced torque varied approximately 5%. The remaining variation is due to the measurement error and the natural variation in the motor unit discharge. Partly, the variation may also be due to some degree of fatigue cumulated from previous contractions (Rainoldi et al 1999). Both sensors produced similar relationship between EMG and torque (Fig. 7). The rather high correlations were somewhat surprising because the data was measured only at 60% of the MVC reflecting that there is a relationship between EMG and torque when measured in different individuals and not only across wide range of force levels.

The day-to-day repeatability of the textile electrodes was slightly lower compared to that of within session repeatability. The test-retest CV% in the amplitude of bipolar surface EMG has been reported in a recent study by Clark et al (2007). They found that using RMS EMG signals during MVC from four lower leg muscles separated by four weeks that the mean CV varied between 13 and 20%. These values were
somewhat higher to those found in the present study for the textile electrodes in submaximal contractions (CV 8-11 %, Table 2). When the EMG amplitude was normalized to torque, the CV was 5-11 %. The lower CV in day-to-day than in within-session repeatability tests may be because putting on the shorts again on different days do not add much to the variability that exists in one measurement session. A factor could also be the different skin conditioning. In within-session tests when traditional electrodes were used the skin was shaved, abraded and cleansed that can cause irritation. On the other hand, in day-to-day comparison the skin was not conditioned in any way. In the textile electrodes the shape and size of the conductive area, and the interelectrode distance are different and much larger than in the typical bipolar sEMG electrodes. It is possible that the larger conductive area is not so sensitive to slight differences in electrode positioning in longitudinal studies as compared to the traditional electrodes. On the other hand, the larger area is not muscle specific but collects data from entire muscle groups, which can be an advantage in conditions where information of the precise motor control is not required. Further, the textile electrode is placed directly on the skin surface without any conductive medium (gel) in-between. This fact eliminates the possible effect of compression that can approximate the conductive area of the electrode to the signal source. These results indicate that the EMG measurement with the textile electrodes embedded in shorts may have advantage over traditional electrodes in terms of skin preparation. This provides support for the use of the textile electrode technique in the field conditions since it allows fast and easy preparation; wet the electrodes and put on the shorts as any normal sportswear.

In the feasibility test, we applied commonly used protocol for runners and for ordinary individuals during VO$_2$ test. The textile EMG signal increased during the VO$_2$ max test. The same phenomenon has been reported for the VO$_2$ max test during cycling (Hug et al 2004) but no EMG changes were reported during running (Avogadro et al 2003). We found a linear increase in EMG in most subjects while some showed an initial decrease followed by increase until the end of the test. These individual patterns are due to differences running technique that alter the EMG patterns during running (Finni et al 2003). Overall, our assessment of the feasibility of textile electrodes in field conditions was promising as long as the garment worn is sized properly to fit the subject. Majority of the problems observed were due to loss of contact between skin and the electrode during the VO$_2$ max test. Clearly, majority of the measurement errors came from the individual differences in the thigh size. We noticed that even the small size shorts were not tight enough for some lean, tall distance runners and the electrode could move in relation to the skin, even though we wrapped tape around the thigh on top of the shorts. On the other hand, the medium size shorts were too tight for some subjects and we left the zipper in the hem open and wrapped the tape around the thigh. Further, it is essential that the electrodes are wet during the measurements to ensure proper conduction. The proper shorts size and large electrode area with sufficient moisture provides friction which prevents the electrode movements on the skin surface, thus minimizing the motion artifacts between the skin and the electrode.

Studies have reported that individual variance in EMG is due to anatomical and physiological factors of the muscle (e.g. fiber length and orientation, motor unit size, type and synchronization), thickness of the
subcutaneous tissues and characteristics of the detection system such as inter-electrode distance and electrode shape, size and location on the muscle (Farina et al 2004). In this study significant correlations were found with ARV from traditional electrodes and subcutaneous fat thickness in four muscles. This may suggest that the EMG amplitude tends to be greater in leaner subjects. Conversely, in the left side the textile electrode signal amplitude and fat thickness had a positive relationship. However, it must be noted that none of these correlations were strong and the fat thickness could explain only 11-50 % of the variation in EMG amplitude. It may be that the different location of the electrodes affected the appearance of correlations; the traditional electrodes were placed over the muscle bellies (positioning B) while the textile electrodes located in the distal muscles.

Finally, it is important to notice that this study analyzed the ARV EMG only. While the present application seems proper to monitor the EMG signal amplitude, other parameters such as frequency spectrum and conduction velocity are not appropriate to look at with the present setting.

5. Conclusions
The shorts with embedded textile electrodes is a promising method to measure rectified, averaged EMG. The textile electrode signal amplitude lies within 2SD of the signal measured with traditional bipolar surface electrodes. The textile electrodes provide similar or even better reproducibility as the traditional bipolar surface electrodes with CV between 5 and 17 %. The textile electrodes embedded into cloths can be easily and safely used with a module that wirelessly transmits data to a wrist top computer to be visualized in real-time for athletes and patients in the field conditions.

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References


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Tables

**Table 1.** Coefficient of variation (CV%) of within-session repeatability measurements. The electrode position was according to SENIAM (see Fig. 1b). Logic for the abbreviations: Torque right Trad = torque in the right leg when recording EMG with traditional electrodes, EMG right Trad = mean EMG signal from 3 muscles in the right leg recorded with traditional surface electrodes, EMG/T right Textile = EMG-Torque relationship when EMG was recorded with textile electrodes from the right leg.

<table>
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<th>Torque right Trad</th>
<th>Torque left Trad</th>
<th>Torque right Textile</th>
<th>Torque left Textile</th>
<th>EMG right Trad</th>
<th>EMG left Trad</th>
<th>EMG right Textile</th>
<th>EMG left Textile</th>
<th>EMG/T right Trad</th>
<th>EMG/T left Trad</th>
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<td>15,9</td>
<td>21,3</td>
<td>17,4</td>
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</tbody>
</table>
Table 2. Coefficient of variation (CV%) of day-to-day repeatability measurements of the textile electrodes.

The three absolute force levels (1-3) with two repetitions have been averaged across a day within individuals. Because the torque itself had some variation, EMG was divided by torque to produce CV of textile EMG independent of variation in torque (two right hand columns).

<table>
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<th>Force level</th>
<th>Torque right</th>
<th>Torque left</th>
<th>Textile EMG right</th>
<th>Textile EMG left</th>
<th>Textile EMG /T right</th>
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Captions to illustrations

Figure 1. Summary of study design and the electrode positioning used in the different protocols. Setup A: Four pairs of traditional electrodes (filled circles) were placed on the exact location of the textile electrodes (rectangular shape). The measurements were performed twice so that first the traditional electrodes were in the right leg and textile electrodes in the left leg. In the second measurement their places were switched. Setup B: The traditional electrodes were placed to the locations defined by SENIAM for vastus lateralis (VL), rectus femoris (RF) and vastus medialis (VM). Similarly, the measurements were performed twice as in the setup A.

Figure 2. Example of raw recordings during 60% of the MVC knee extension of torque (top panel), textile electrodes (middle) and traditional electrodes (bottom) as placed in the setup A (see Fig.1). The average EMG and torque values used for analysis were taken from a 1 s window (vertical bar).

Figure 3. Picture of the shorts with embedded textile electrodes, wires and electronics module attachment point. The shorts viewed from front (A) and the front side viewed inside out (B).

Figure 4. Bland-Altman plots for rectified, average EMG (A,B) and EMG-torque ratios (C,D) from Validation A protocol. A and C) Comparisons in the left leg (filled squares) and the right leg (open squares). The solid line represents mean and dashed lines 2SD range. B and D) Comparisons during the same performance but textile and traditional electrodes in different legs. Open squares: textile electrodes in the right leg and traditional electrodes in the left leg. Filled squares: textile electrodes in the left and traditional electrodes in the right leg. Two samples correspond to 3% of the cases.

Figure 5. Bland-Altman plots for rectified, average EMG (A,B) and EMG-torque ratios (C,D) from Validation B protocol. A and C) Comparisons in the left leg (filled squares) and in the right leg (open squares). The solid line represents mean and dashed lines 2SD range. B and D) Comparisons during the same performance with textile and traditional electrodes in different legs. Open squares: textile electrodes in the right leg and traditional electrodes in the left leg. Filled squares: textile electrodes in the left and traditional electrodes in the right leg. Five samples correspond to 5% of the cases.

Figure 6. Example from recordings of textile EMG signals from the right (A) and the left leg (B) during the treadmill test. C) Example of heart rate (HR), oxygen uptake (VO2), EMG and lactate (LA) during the test. D) A 5 s window of the EMG data shown in A and B showing that the individual contacts can be distinguished from the data.
Figure 7. EMG-torque relationships for textile (A, B) and traditional electrodes (C, D) at 60% of the MVC using setup A (see Fig. 1).
Measurement of EMG activity with textile electrodes embedded into clothing
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**Study design**

**Validity**
- Validation A – Electrode positioning A (n=10)
- Validation B – Electrode positioning B (n=10)

**Reliability**
- Within session – Electrode positioning B (n=10)
- Day-to-day – Textile electrodes only (n=8)

**Feasibility**
- VO2 max test (n=28) running on treadmill - Textile electrodes only

**Electrode positioning**

**A**
- Right
  - Traditional electrodes
- Left
  - Textile electrodes

**B**
- Right
  - RF
  - VM
  - Traditional electrodes
- Left
  - Textile electrodes
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A B

Module connector

Module connector

Wire

Ground electrode

Electrode

Electrode

Zipper
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A  
Mean EMG (trad – textile)

B  
Mean EMG (trad – textile)

C  
Mean EMG/T (trad – textile)

D  
Mean EMG/T (trad – textile)
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A

Textile EMG left leg (µV)

Torque left leg (Nm)

R² = 0.4375

B

Textile EMG right leg (µV)

Torque right leg (Nm)

R² = 0.5275

C

Traditional EMG left (µV)

Torque left leg (Nm)

R² = 0.4972

D

Traditional EMG right (µV)

Torque right leg (Nm)

R² = 0.5302