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Wearable Embroidered Muscle Activity Sensing Device for the Human Upper Leg

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***Abstract*— Within the last decade, running has become one of the most popular physical activities in the world. Although the benefits of running are numerous, there is a risk of Running Related Injuries (RRIs) of the lower extremities. Electromyography (EMG) techniques have previously been used to study causes of RRIs, but the complexity of this technology limits its use to a laboratory setting. As running is primarily an outdoors activity, this lack of technology acts as a barrier to the study of RRIs in natural environments. This study presents a minimally invasive wearable muscle sensing device consisting of jogging leggings with embroidered surface EMG (sEMG) electrodes capable of recording muscle activity data of the quadriceps group. To test the use of the device, a proof of concept study consisting of $N = 2$ runners performing a set of $5\,\mathrm{km}$ running trials is presented in which the effect of running surfaces on muscle fatigue, a potential cause of RRIs, is evaluated. Results show that muscle fatigue can be analysed from the sEMG data obtained through the wearable device, and that running on soft surfaces (such as sand) may increase the likelihood of suffering from RRIs.**

***Keywords* - running related injuries, running surfaces, electromyography, wearables.**

I. Introduction

Today, running is one of the most popular physical activities, as of Spring 2014 there were 65.58 million runners in the USA accounting for a 20.53% of the American population. Moreover, during the last decade, the number of runners has grown considerably [1]. The benefits of running are numerous, ranging from increased life expectancy to preventing chronic diseases or conditions (*e.g.,* type-2 diabetes, cardiovascular disease, and obesity) [2].

However, the practice of running also gives rise to Running Related Injuries (RRI) of the lower extremities (*e.g.,* aquiles tendinopathy, plantar fascitis, and patellar tendinopathy) [3]. The causes of RRIs are heterogeneous, and changes in the biomechanical factors of the runner (*e.g.,* contact time, stride length) have previously been investigated [4]. However, research is still lacking in determining what role running surfaces have of changing these biomechanical factors and hence causing RRIs. Particularly, how running surfaces influence the fatigue levels of the leg muscles as a result of a running activity is not clear.

The most common method for estimating muscle fatigue, namely electromyography (EMG), is based on examining the electrical activity of the skeletal muscles. However, it is difficult to perform in natural running settings since it requires not only delicate expensive equipment, but specialised anatomical knowledge for sensor placement and interpretation of results.

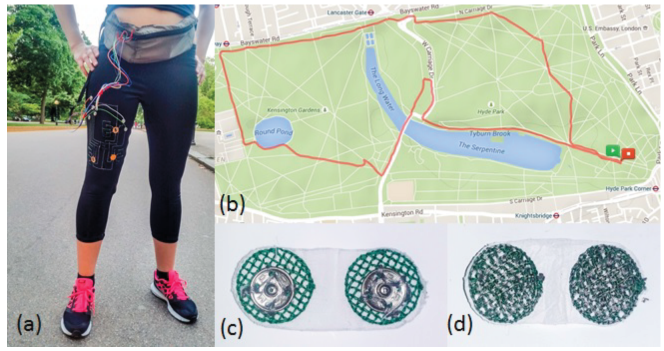

Fig. 1: (a) Participant wearing the jogging leggings with embroidered sEMG electrodes made for this study. (b) Asphalt track route for participant 1. (c), (d) Top and bottom view of the embroidered sEMG electrodes, respectively.

To overcome these problems, this study presents a new wearable muscle sensing device consisting of jogging leggings with custom embroidered surface EMG (sEMG) electrodes capable of recording muscle activity data of the quadriceps group (*i.e.,* Vastus Medialis, Vastus Lateralis, and Rectus Femoris) in a non-laboratory setting, see Fig. 1. The wearable sEMG device allows collecting long term EMG data in a great variety of environments due to its compact design. Furthermore, the use of the device does not require extensive prior anatomical knowledge, as the sensing electrodes are embroidered into the garment at the correct locations, following standards set by the SENIAM project [5]. Thus, the user does not need to be concerned about sensor placement, and can simply pull the leggings on just like ordinary clothing.

In this paper, the device is demonstrated as a platform for monitoring muscle fatigue during endurance-based long distance ($5\,\mathrm{km}$) running tests on different surfaces (asphalt, sand and an athletics track). Using data from the device, the dependency between running surface and muscle fatigue is identified, whereby running on compliant surfaces with greater damping (*e.g.,* sand) leads to the highest levels of muscle fatigue, followed by very stiff surfaces with little damping features (*e.g.,* asphalt). These results highlight the use of the proposed device for long term observation of behaviour.

II. Background and Related Work

This section provides a brief overview of the functioning of electromyography, and its use in measuring muscle fatigue. It also reviews related literature from laboratory based biomechanical studies on risk factors for RRIs.

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A. Methods for Electromyography

Electromyography enables the force generated by the skeletal muscles to be estimated by measuring their electrical stimulation from the central nervous system (CNS) [6], via either invasive or non-invasive techniques. In regards to the former, *intramuscular EMG* records activity by inserting a fine wire into the muscle and measuring muscle signals. However, whilst this results in a high quality signal its invasiveness makes it unsuitable for many applications, especially in wearable sensing devices.

A more suitable method is *surface EMG* (sEMG) where electrodes are placed on the skin surface above the target muscle. When following a bipolar configuration, pairs of electrodes are placed on top of the belly of the muscle with a $1\,\mathrm{cm}$ to $2\,\mathrm{cm}$ separation between the electrodes, and a reference electrode is placed on top of electrically neutral tissue. The difference between the signals collected by each of the two electrodes is amplified.

Current commercial systems such as BTS Surface EMG (Vandrico, North Vancouver, Canada), and Tringo Wireless EMG (DelSys, Massachusetts, USA) offer wireless EMG solutions. However, these present several disadvantages since they (i) are expensive (ranging from €448.00 to €15,675.00), (ii) are bulky (reducing their portability and affecting natural user motion), and (iii) rely on gel-based sEMG electrodes requiring anatomical knowledge for their placement and limiting their re-usability.

B. Measuring Muscle Fatigue with EMG

Due to the inherent issues with collecting sEMG data with standard sensors (§II-A) the study of estimating and monitoring *muscle fatigue* has been limited. Muscle fatigue is a consequence of muscle activity, to prevent cellular or organ failure [7].

Fatiguing of the muscles influences both the amplitude and the frequency properties of EMG signals [8], and during fatigue, further muscle fibres need to be recruited (activated) in order to sustain the desired performance. This is shown as an increase of the amplitude of the EMG signal. Regarding the spectral features of the EMG signal, changes in the the firing behaviour of the motor units and the shape of the Motor Unit Action Potential (MUAP) result in a left-shifting of the power spectrum of the EMG signal [8].

A number of different approaches have been proposed in the literature in order to elucidate muscle fatigue. These include (i) amplitude based parameters analysis, (ii) spectral analysis, and (iii) time-frequency analysis (*i.e.,* wavelets ratios). In amplitude based analysis, the presence of muscle fatigue increases the instantaneous value of the EMG signal with time [7]. Regarding the spectral analysis, muscle fatigue results in a left-shifting of the power spectrum of the EMG signal and hence a decrement of the instantaneous mean and median frequencies is seen. Finally, for time-frequency analysis, the wavelets ratios increase their value as the muscles get fatigued. Due to the isotonic nature of running, the collected sEMG signals cannot be considered as stationary and hence only amplitude based parameters and time-frequency techniques are suitable, the *instantaneous Average Rectified Value* (iARV) signal being the most common parameter used in the literature [7].

C. Muscle Fatigue as a Cause of RRIs

Amongst a number of other biomechanical factors, muscle fatigue has been shown to significantly increase the likelihood of injury in dynamic behaviour such as running [9]. To date, several studies have examined a number of factors in relation to this, including (i) training characteristics (*e.g.,* running volume), (ii) anthropometric factors (*e.g.,* foot strike), (iii) biomechanical factors (*e.g.,* contact time), (iv) physiological variables (*e.g.,* lactose level), and (v) running-related medical history [4]. However, largely due to the technological barrier of taking measurement equipment out of the laboratory, few have examined these factors in ordinary environments, as may be used by the general running population [10]. This limits such studies to simulating the running conditions, ignoring possible contributing factors. Previous research in this area has mainly focused on how these might affect the biomechanical factors of the runner, using short ($< 20\,m$) tracks [11]. However, this is unsatisfactory when studying many factors. For example, the effect of the *running surface* on fatigue cannot easily be simulated in laboratory studies. The presented system is a first step in taking such studies into the real world.

To summarise, despite the great amount of work in studying the biomechanics of running, and the causes of musculoskeletal injuries, there is an apparent technological barrier in taking these studies into real world environments. In the next section, the implementation of a new textile-based EMG system is presented along with the signal processing techniques necessary for its use in estimating muscle fatigue.

III. Implementation

To overcome the limitations of collecting EMG data outside the laboratory (as discussed in §II), this paper presents a new, textile-based acquisition system. Specifically, the system consists of a pair of jogging leggings with integrated custom sEMG electrodes, made from conductive yarns, directly embroidered into the fabric.

A. Design and Fabrication of the Jogging Leggings

The leggings overcome many of the technical and user-specific limitations of current sEMG monitoring devices. They include built-in electrodes at appropriate locations such that anatomical knowledge of optimal sensor locations is not required when using the device. They are also designed in mind of portability for use in multiple environments, with built-in flexible low-weight printed circuit boards (PCBs) to acquire raw sEMG signals in conjunction with an Arduino micro-controller to digitise and store the collected data.

1) Embroidered electrodes: The leggings make use of state-of-the-art *textile sEMG sensors*, recently developed at the Centre for Robotics Research (CORE) at King's College London, for measuring muscle activity in the legs [12]. As a precursor to the present study, experiments were performed to elucidate the best electrode design and fabrication process, and characterise their behaviour for sEMG signal acquisition. Results show that similar sEMG measurements can be obtained by using conductive textile electrodes in place of gel-based disposable electrodes [12]. Comparisons between the developed stainless-steel thread-based sEMG electrodes (using conductive thread Sparkfun DEV-11791, $3.28\,\Omega\,\mathrm{m}^{-1}$) and standard gel-based electrodes (Covidien Kendall Arbo H124SG) show that, while there is greater noise presence when using textile-based electrodes, muscle

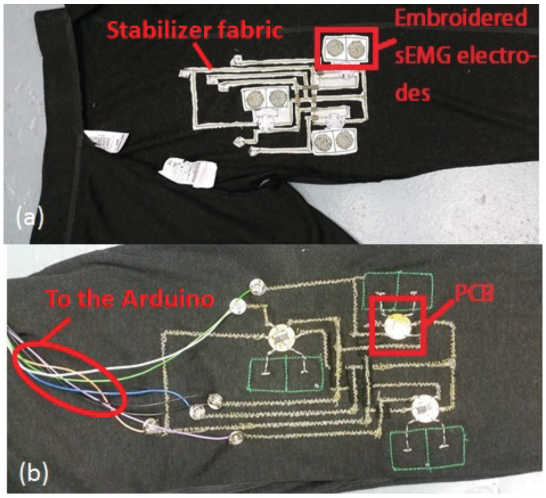

Fig. 2: (a) The interior of the leggings. Notice how the connection lines are first sewn on top of stabiliser fabric (white). This type of fabric prevents the fabric of the leggings stretching during the sewing process. (b) The exterior of the leggings. Note that, the conductive thread of the connection lines is sewn on top of the exterior face of the leggings in order to isolate them from the skin.

activity can still be observed and different levels of muscle engagement distinguished [12]. Note that, the electrodes are multi-use, and the materials used can withstand washing. For this paper, this technology is exploited to enable long term wearable measurement of muscle activity through an integrated textile device recording sEMG of the quadriceps muscles.

2) Circuitry and sensor placement: In the presented system, three pairs of electrodes are embroidered onto a pair of jogging leggings using a Pfaff Creative 3.0 (Pfaff, Kaiserslautern, Germany) sewing machine based on the design variables obtained in [12] and according to the indications of the SENIAM project. The placement area is tightened using extra thick felt fabric to enhance the contact with the skin tissue. European medium (M) leggings size is selected and participants were selected such that their inside leg measurement ensures the sensor locations to be in accordance with SENIAM recommendations. The stretchability of the fabric means that at rest there is a $1\,\mathrm{cm}$ inter-electrode distance, and this never goes beyond a $2\,\mathrm{cm}$ upper bound in running. The tightness of the leggings means that motion artefacts are negligible in this study (where present they can be addressed through signal processing [13]).

To prevent voltage loss due to the high resistance of the conductive thread, the length of the connection lines is limited to $20\,\mathrm{cm}$ for which voltage losses are negligible. A double stitching pattern along with a zig-zag pattern ensured robust and stretchable connection lines. The leggings are powered at $\pm 3.75\,\mathrm{V}$ using a single rechargeable battery of $7.5\,\mathrm{V}$. Fig. 2 shows the final stages of the fabrication process. Silicone sealant (102 RTV, Hylomar) is used to isolate the connections of the power unit. Finally, a waterproof bag around the waist is used to carry the batteries whilst running.

3) Data acquisition: Three custom PCBs were created to acquire the sEMG signal through each pair of electrodes. Each PCB includes an instrumentation amplifier with adjustable gain according to $G = 1 + (49.4k\Omega)/R_G$, a first order active high pass filter (HPF), a first order active low pass filter (LPF), and a full-wave rectifier connected in cascade. The instrumentation amplifier computes the difference between the two collected signals and amplifies it. The cut-off frequencies of the HPF and the LPF are $20\,\mathrm{Hz}$ and $450\,\mathrm{Hz}$ respectively. The final PCB is flexible, with a thickness of $1.65\,\mathrm{mm}$ and weight of $0.25\,\mathrm{g}$. An Arduino micro-controller is used to sample the signal from each PCB with a sampling frequency of $1\,\mathrm{kHz}$ and an SD shield (Adafruit, NY, USA) is used to store the collected data in a text file with a `.csv` format.

B. Signal Processing for Muscle Fatigue

To quantify muscle fatigue from the sEMG data collected using the sensor-embedded jogging leggings, the presented system includes a signal analysis script written in MATLAB which implements the fatigue analysis methods outlined in §II-B. The script includes the computation of the iARV signal from the *average rectified value* (ARV) value for a $0.2\,\mathrm{s}$ window, where the ARV is computed as $\frac{1}{n}\sum_n |x_n|$. Here, x_n are the digitised values of the sEMG signal and n the number of samples. The non-stationary properties of the EMG signal stem from the isotonic nature of the running activity which limits the study of muscle fatigue to amplitude and time-frequency based analysis.

IV. Experiments

In this section, two evaluations are described. Firstly, an assessment of the wearable sEMG monitoring jogging leggings outlined in §III is made, with the aim to investigate its suitability for natural environment motion experiments. Secondly, the sEMG data collected is analysed using the custom scripts in §III-B to evaluate how the fatigue of the quadriceps group varies depending on the running surface.

The experimental procedure is as follows. sEMG data is collected from $N = 2$ participants (mean weight $75 \pm 2.83\,\mathrm{kg}$, and mean height $177 \pm 5.66\,\mathrm{cm}$). For each participant, data is collected from three running trials (each of $5\,\mathrm{km}$ in length) on sand, asphalt, and an athletics track, where participants run at their normal training speed. There is a minimum $24\,\mathrm{h}$ resting period between trials, to allow for muscles to recover. Note that, as described in §III, placement of the electrodes requires no prior anatomical knowledge for the participants, since they are sewn into the leggings at the correct locations.

Before beginning the experiments, participant data was collected, including fitness level, age, height, weight, sex and running gear. A pre-screening test was performed to ascertain whether the participants were eligible for the experiments or not (PAR-Q&U questionnaire approved by the Canadian Society for Exercise Physiology). Ethical approval for the study was obtained from the King's College London Research Ethics office.[1]

Fig. 3 shows the iARV for participant 1 whilst running on the three different surfaces. As explained in §II, the amplitude of the sEMG signal increases in presence of muscle fatigue as more muscle fibres are recruited. This phenomenon is observed for the three surfaces with varying rates of increase, as the iARV value of the sEMG signal increases with time. Table 1 summarises the percentage increase of

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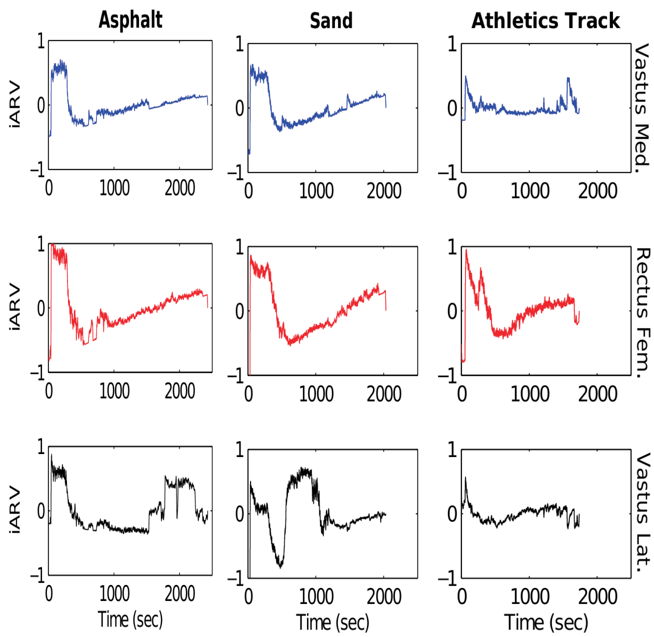

Fig. 3: iARV of the quadriceps muscles whilst running on asphalt (first column), sand (second column), and the athletics track (third column). Note that the iARV signal increases with time due to the effect of muscle fatigue.

Muscle	Asphalt	Sand	Athletics Track
Vastus Medialis	100.04%	127.71%	54.90%
Rectus Femoris	100.02%	126.75%	121.22%
Vastus Lateralis	99.14%	100.07%	35.90%

TABLE I: Percentage increase of the iARV signal for each muscle whilst running on asphalt, sand and the athletics track surfaces between the beginning and end of the running trials.

the iARV signal for each muscle whilst running on each surface between the beginning and end of the running trials. It can be seen that, running on the sand surface leads to the maximum amplitude increment of the iARV signal for the three muscles, whereas the athletics track led to the minimum increase after the $5\,\mathrm{km}$ trials. Similar results are observed for participant 2, indicating that running on sand increases the likelihood of suffering from RRIs when compared to asphalt or athletics track surfaces.

A potentially confounding issue in these results is the factor of subjects sweating during the course of physical activity. The conductivity of the skin varies in proportion to the number of active sweating glands, so that increased perspiration causes the offset value at the output of the PCBs to increase, thereby increasing the iARV. However, note that, the outdoor temperature recorded when collecting data on the athletics track was greater than that for the sand, so a greater increase in iARV would be expected for the form. This is not seen in the data (ref. Table I), suggesting that this effect, if present, does not play a significant role.

V. Conclusion

In this study, the design of a new minimally invasive muscle sensing device capable of recording muscle activity data in natural environments is created. The device offers wearable capabilities that allow long-term collection of data by inexperienced users.

The experiments presented here show that wearable sEMG technology is feasible and that it has practical research applications. The wearable sEMG device is cheap, robust, easy to build and suitable for the every day user. As a proof of concept, $N = 2$ runners took part in three $5\,\mathrm{km}$ running trials on three different surfaces (asphalt, sand and athletics track) and with sEMG data recorded using reusable fabric-based electrodes. The results showed that different levels of muscle fatigue could be detected when running on different surfaces. They matched the expectations that running on the athletics track leads to the lowest levels of muscle fatigue, followed by the asphalt track and finally by the sand track as a direct consequence of muscle activity as outlined in [4]. This, in turn, suggests that running on sand increases the likelihood of suffering from RRIs when compared to the asphalt and athletics track surfaces.

Future work will consider the possibility of a multi-sensor device capable of recording kinematic and kinetic data such as the impact peak, loading rate and contact time that would support and enhance the measurement of muscle fatigue.

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