Strategies to Identify Muscle Fatigue from SEMG During Cycling

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Abstract

Detection, quantification and analysis of muscle fatigue are crucial in occupational/rehabilitation and sporting settings. Sports organizations such as Australian Institute of Sports (AIS) currently monitor fatigue by a battery of tests including invasive techniques that require taking blood samples and/or muscle biopsies, the latter of which is highly invasive, painful, time consuming and expensive. SEMG is non-invasive monitoring of the muscle activation and is an indication of localized muscle fatigue based on the observed shift of the power spectral density of the SEMG. But the success of SEMG based techniques is currently limited to isometric contraction and is not acceptable to the human movement community. This paper proposes and tests a simple signal processing technique to identify the onset of muscle fatigue during cyclic activities of muscles such as VL and VM during cycling. Based on experiments conducted with 7 participants, using power output as a measure of fatigue, the technique is able to identify the muscle fatigue with 98% significance.

1. INTRODUCTION

Enhancement of human performance is important for improvement of quality of life, for sports and for industry. For this purpose, it is essential to be able to determine the individual threshold at which the onset of fatigue occurs. Fatigue is the point at which the muscle is no longer able to sustain the required force or power output. Detection, quantification and analysis of muscle fatigue is crucial in occupational/rehabilitation and sporting settings. Undetected muscle fatigue can cause injury to the subject, and besides the pain and suffering that occurs as a consequence of injury, injury and its sequelae are a financial burden to industry and society. Sports organizations such as Australian Institute of Sports (AIS) currently monitor fatigue by a battery of tests including invasive techniques that require taking blood samples and/or muscle biopsies, the latter of which is highly invasive, painful, time consuming and expensive. Coaches and exercise physiologist regularly conduct these laboratory-based tests to detect mechanisms associated with fatigue and to establish exercise protocols to enhance the ability of individuals to resist the onset of fatigue.

Fatigue has been defined as “the point at which the muscle is no longer able to sustain the required force or work output level [14, 15]. Numerous studies have demonstrated that the physiological origins underlying muscle fatigue range from the higher brain centres to the myofilaments of the contracting muscle [16], encompassing central, peripheral and psychological factors

The development of muscle fatigue during exercise is associated with a decrement in performance. Mechanisms of muscle fatigue depend on the exercise conditions (e.g. duration and intensity) and the subject’s level of physical fitness [17]. The decrements in skeletal muscle power output is also related to neural drive reductions may also lead to muscle fatigue in prolonged exercise [18].

Invasive markers of high intensity fatigue include depletion of high-energy phosphates including creatine phosphate, accumulation of metabolic bi products including [lactate], [H^+] and inorganic phosphate [1]. Altered SR Ca^{2+} ATPase and Na^+, K^+-ATPase activity have also been implicated in the fatigue process [3]. Fatigue during prolonged exercise leading to fatigue in 2-3 hours has been associated with depletion of muscle glycogen stores [4]. These measurements are valid and reliable indicators of fatigue but are invasive, and not practical outside the laboratory setting.

Some researchers have attempted to use the electrical activity of muscle and muscle activation to study fatigue, using surface electromyography [5, 6, 7]. These techniques are much less invasive with an obvious appeal to the wider community.

Surface Electromyogram (SEMG) is a bio-signal recorded from the surface of the body and represents the contractile activity of skeletal muscles. It is a result of electrical activity in muscles and is dependent on numerous factors such as the rate of stimulation of the muscle, size of motor units recruited, morphology of the motor units, electrical properties of the tissues and the presence of any synchronisation of the activity of different motor units. The rate of stimulation of the muscle and size of active motor units is dependent on the force of contraction required to be produced by the muscle. It is a complex and non-stationary signal and is a result of summation of number of separate motor unit action potential (MUAP).

Research analysis to date aimed at extracting from the SEMG an indication of localized muscle fatigue has been frequently based on the observed shift of the power spectral density of the SEMG [5, 8, 9]. When the muscle is fatigued, a strengthening of low-frequency components and a reduction in intensity of high-frequency components modifies the spectrum of the SEMG signal. Several parametric measures of SEMG signal have been used as a relative indicator of the muscle fatigue phenomenon for an individual subject. These include the Root Mean Square (RMS), spectrum analysis (instantaneous, mean and median frequency) and zero crossing rates. SEMG is a non-stationary signal and there is a large inter and intra subject variance in the SEMG power spectrum. These variations may occur due to changes in skin and tissue properties, electrode placement, strength of muscle contraction, and muscle fatigue status.

Muscles are the source of SEMG and with a variation of muscle properties with time make SEMG a non- deterministic and non-stationary signal. This makes the process of using SEMG as a reliable measure of muscle fatigue difficult [10]. Methods available to demonstrate fatigue related EMG changes include time domain based measures such as zero crossing counts. Frequency domain characteristics used to measure the spectral changes associated with fatigue include computing the shift in spectral power from higher frequency bands to lower frequency bands, determining the ratio between the high and low frequency contents, and calculating the mean and median frequency within the power spectrum. The authors have used a combination of wavelets and neural networks to reliably classify SEMG with isometric muscle contraction status [11]. The authors have established a wavelet based bio-signal processing techniques that is more reliable for identifying the onset of muscle fatigue [12] and thus established the use SEMG as a reliable indicator for the onset of localised muscle fatigue for isometric middle and high level of muscle contraction that can be automated.

Muscle fatigue may occur due to isometric or non-isometric muscle contraction and may be due to low, high or very high level contraction. When the muscle is contracting to produce motion, the strength of contraction is varying and variation in SEMG is far greater than during isometric contraction. For practical applications, it is important that SEMG be able to identify the onset of muscle fatigue in all such conditions.

The contraction may be due to aerobic or anaerobic origin [1]. The biochemical processes associated with the onset of muscle fatigue changes due to these different causes are believed to be different [13]. This makes the interpretation of SEMG signals from dynamic contractions much more difficult [10]. The success of the current techniques is limited to isometric contraction [12] and is not acceptable to the human movement community. This paper reports a novel technique with the aim at determining the change of SEMG properties due to the onset of localised muscle fatigue during dynamic cyclic motion at high levels of contraction (30 seconds sprint).

Power output by the athlete was monitored and used to identify the onset of muscle fatigue. The paper reports the robustness of our novel technique to identify muscle fatigue during sprint cycling that has been validated with clinical markers and power output measurements. These results suggest that the technique could be utilised in industrial, rehabilitation and sporting situations.

2. THEORY

At the onset of muscle fatigue, there is a steep reduction of the power output. It has been well established that during isometric contraction, there is a shift in the spectrum of the recorded SEMG due to muscle fatigue. Studies by other researchers and experiments conducted by our team have determined that during cycling, the vastus lateralis (VL) and vastus medialis (VM) muscle undergoes cyclic contraction and the properties of SEMG vary cyclically from zero to maximum. Due to such variation in the signal, it is essential to establish a reference in a cycle for the purpose of determining changes.

The peak activity during each cycle represents the maximal contraction and the onset of muscle fatigue will influence this first. Thus the change in SEMG due to muscle fatigue will occur in this section. It thus provides a reference point for comparison of the muscle contraction properties. A window of about 100 milliseconds represents about 10% of the cycle, but over 50% of total work done by the muscle represents a period during which the muscle activity is relatively stationary. This research reports the use of SEMG corresponding to 100-millisecond interval at the peak of muscle contraction. This corresponds to 20 Hz lower end frequency and the duration corresponds to 45 degrees of the cycle and the region of maximal contraction of the muscles and hence was the most suitable compromise.

The aim of this research is to establish a simple technique that will help identify the onset of muscle fatigue during cyclic contracting with movement of muscles such as cycling. Based on the above, the paper proposes a simple signal processing technique to identify the onset of muscle fatigue during cyclic activities of muscles such as VL and VM during cycling. The proposed technique requires computing the envelope of the signal, determining the peak activity during the cycles and computing the spectrum using FFT for a 100 milliseconds window of the signal. To overcome the difficulty due to inter-subject variation, ratio of the median frequency and RMS under pre and post fatigue conditions has been considered to identify the change. This paper also reports the use of markers that determine the angular location in each cycle for correlating the muscle activity with this location. This paper reports the identification of the onset of muscle fatigue by the drop in power output and reduction in speed of cycling and corresponding changes in the frequency spectrum of SEMG.

3. METHODS/RESEARCH PROCEDURE

A. *Subjects*

Seven (7) moderately active male volunteer participants were recruited to undertake this project with age ranging between 18-40 years. Subjects were medically screened and they signed written consent before participating in the study.

A standardised 30 sec cycle test to fatigue on a Lode ergometer with customised software for sprint measurements was conducted. Power output was measured along with SEMG. The subject was termed as 'fatigued' when the power output drops by greater than 33%.

B. Placement of SEMG electrodes

Five sets of Delysis (proprietary) electrodes were placed on the skin of the participant's thigh overlying the muscle under investigation (table 1). Before positioning the electrodes the skin will be cleaned and shaved to remove dead skin, oils and hair from the electrode sites.

TABLE 1: CHANNEL ASSIGNMENT FOR DIFFERENT MUSCLES

Channel 1	Vastus lateralis (outside thigh muscle - front)
Channel 2	Vastus medialis (inside thigh muscle - front)
Channel 3	Rectus femoris (middle thigh muscle - front)
Channel 4	Medial gastrocnemius (inside calf muscle)
Channel 5	Lateral gastrocnemius (outside calf muscle)

The skin was lightly abraded using disposable skin defoliator and then be cleaned with a swab soaked in alcohol with aim to reduce skin impedance to less than 60,000 Ω. Heart-rate was monitored using telemetry (Accurex Plus, Polar Electro OY, Kempele, Finland) to ensure safety of the participant. SEMG was recorded from the five channels (Table 1) using Delysis (Massachusetts, USA) SEMG recording system with fixed inter-electrode distance.

4. SEMG ANALYSIS

RMS of SEMG is related to the force of contraction of the muscles. During cycling, there is cyclic change in muscle contraction. To be able to compare RMS of SEMG during cycling, it is important to select a section of the signal that may be considered stationary over different cycles. This research reports the use of SEMG corresponding to 100-millisecond interval at the peak of muscle contraction. This corresponds to 20 Hz lower end frequency and corresponds to 45 degrees of the cycle and the region of maximal contraction of the muscles and hence was the most suitable compromise. The first and the last cycle of the recordings were discarded because of sudden changes taking place during these segments.

Windowed RMS was computed for the SEMG to identify the envelopes and the bursts of activity. Using these envelopes, three cycles near the start and another three near the end of the exercise, representing pre and post fatigue conditions were considered. The peak of each cycle was identified based on moving root mean square (MRMS), (Figure 2) and a small section (100 milliseconds) of the raw SEMG data were analyzed (figure 1). Signal processing was done using MATLAB software package. (The MathWorks, Natick, Massachusetts, USA).

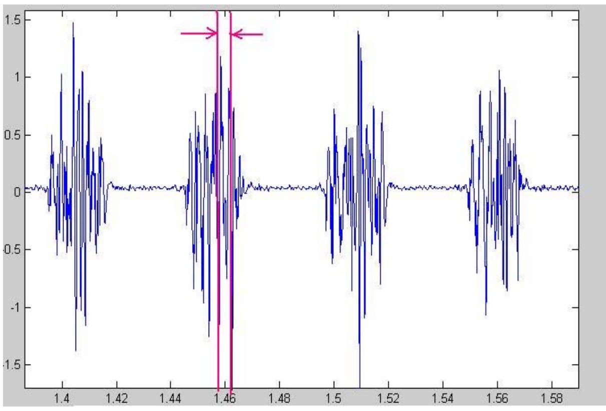

Fig 1: Windowed Raw Signal (Illustration only)

The RMS and median frequency of each of the three envelopes representing the post and pre fatigue conditions were computed. An average was computed for pre and post fatigue condition. Using this, ratio of the pre and post RMS and MF was computed for each subject and for the five channels. A ratio less than one would indicate a decrease due to fatigue. The results were statistically evaluated to determine the significance.

A. *Time Delay*

The variation in angular distance between the reference point and the muscle activation is a useful indication if there was a change in the strategy of the cyclist to deal with muscle fatigue by using different group of muscles. Time delay between the start of each cycle (12- noon) and the peak activation of the muscle was measured to determine the absolute time delay. This was normalized latter with change in speed of rotation to determine the angular delay in the activation of each of the muscles.

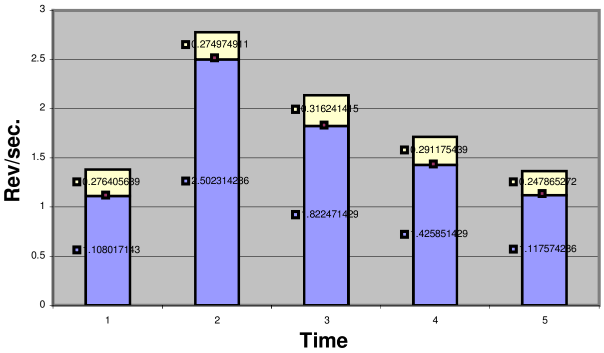

Figure 2. Variation in Speed of Cycling

5. RESULTS

Figure 3 plots the ratio of normalised RMS of the windowed signal under pre and post fatigue conditions while figure 4 plots the ratio of normalised median frequency of the windowed signal under pre and post fatigue conditions. The power output of the athlete at the cycle wheel for the duration of the sprint is plotted in figure 5. Variation of the speed of cycling over the duration of the sprint is plotted in figure 2.

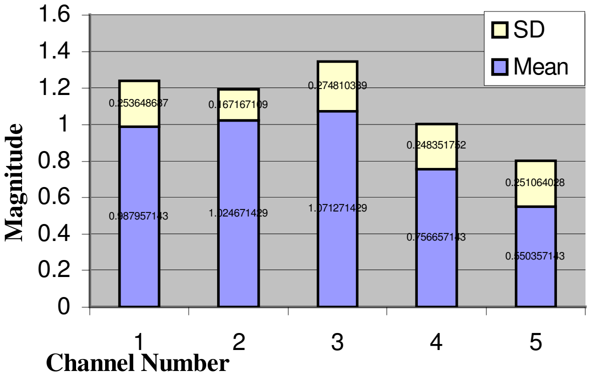

Figure 3. Normalized RMS

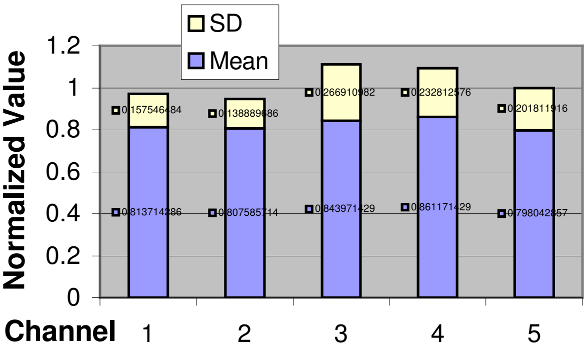

Figure 4: Normalized frequency

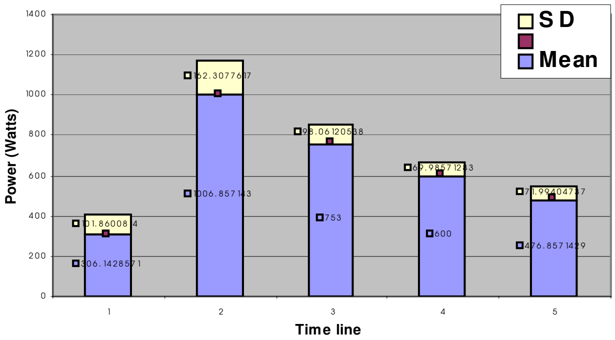

Figure 5 Power Output

TABLE 2: T- TEST FOR MEDIAN FREQUENCY AND RMS

	Median Frequency			RMS		
Channel	t	p	Significance %	t	p	Significance %
1	3.076	0.989	95	0.372	0.639	27.8
2	3.199	0.99	98	0.671	0.263	74
3	2.052	0.957	91	0.494	0.319	69
4	1.907	0.947	90	2.479	0.976	95
5	2.605	0.98	96	2.646	0.981	96

6. OBSERVATIONS AND DISCUSSION

From figure 3, it is observed that for channels 1 to 4, there is little change in RMS of SEMG pre and post muscle fatigue. From figure 4, it is observed that there is a drop of about 20% of median frequency for all the five channels. From figure 5, it is evident that the power maximum occurs at the end of the first quarter followed by a gradual decline and the final power output is approximately half of the power at the start. Similar is the trend in the speed of cycling as this can be noticed from figure 2.

Some of the specific observations and subsequent conclusions are as follows:

1. There is a significant decline in the median frequency of all the five channels by an approximate 20%. From the t-tests (table 2), it is evident that this is significant, with significance ranging from 98% to 90% for different channels. This suggests that the use of median frequency ratio is a useful measure of muscle fatigue during maximal exercise.
2. In general, there is no significant change in the RMS of channel 1, 2 and 3 while there is a small reduction for channels 4 and 5 with T test suggest significance of less than 75%. This suggests that magnitude of SEMG is not significantly affected by the fatiguing of the muscles during dynamic activity.
3. There is a significant reduction of power output by the cyclist with average reduction greater than 50%. This being much more than 33% required determining the muscle fatigue status suggests that in all cases, there was significant muscle fatigue due to the 30 seconds fixed load sprint.
4. The speed curve follows the power output curve. While no statistical evaluation was conducted, visual inspection suggests that the reduction in power is directly related to reduction in speed of cycling.

From the above results, it appears that the peak force produced by the muscles during the sprint does not vary greatly from the start to the end, and this may be an explanation to the observation that there is no significant change in RMS of SEMG for the duration of the sprint. It appears that the muscle fatigue has an effect on the speed of cycling which results in resultant reduction in power output.

There is a significant reduction of median frequency (considered as a ratio) of SEMG with fatigue and this suggests that this may be considered suitable indicator of muscle fatigue.

It is also observed that while RMS of SEMG of three of the muscles do not vary for the duration of the sprint, there is a variation of muscles corresponding to channel 4 and 5. These muscles also have a relatively smaller reduction of median frequency. This suggests that perhaps not all the muscles are equally affected by the sprint.

7. CONCLUSIONS

From this study it is concluded that there is a significant shift of the frequency spectrum of SEMG towards lower frequency when a subject is fatigued during cyclic maximal contraction. The study also demonstrates that there is a significant variation between different muscles suggesting that during the exercise, not all the muscles were equally fatigued. It is also observed that there is no significant change in the RMS of SEMG due to the onset of fatigue.

From the study, it may be concluded that the use of narrow time window at the peal of the activity is sufficient to identify the variation of spectrum of SEMG to identify the onset of muscle fatigue.

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