Effect of oral glucose supplementation on surface EMG during fatiguing dynamic exercise

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Abstract—The aim of this study was to examine the effect of oral glucose supplementation on the surface electromyographic (sEMG) signal recorded during a dynamic, fatiguing exercise protocol. Five healthy subjects participated in the study. Blood glucose concentration and sEMG signals from five upper leg muscles were recorded during a cycling exercise performed at 70% $\dot{V}O_{2peak}$ until task failure, on two separate occasions. Glucose was consumed at 15 minute intervals throughout one trial. The median frequency of the sEMG was observed to increase progressively throughout the exercise, with a greater increase in the with glucose condition. This is in direct contrast to the typical decrease in median frequency known to occur during a fatiguing isometric contraction. The result may indicate an increase in $Na^+ - K^+ - ATPase$ activity during fatiguing dynamic exercise resulting in an increase in muscle fiber membrane excitability due to membrane hyperpolarization.

Index Terms—Surface electromyography, fatigue, time-frequency analysis

I. Introduction

MUSCLE fatigue - the underlying cellular mechanisms and the effect it has on performance are pertinent topics in the areas of sports performance and rehabilitation. Fatigue may be defined as any exercise induced reduction in the force generating capacity of a muscle [1]. It is multifactorial in nature, encompassing a range of processes within the central and peripheral neuromuscular system, including perturbations of both intra- and extra-cellular ionic concentrations, in particular of Na^+ and K^+. These fluxes in the ionic concentrations affect the excitability of the membrane, which is a critical regulatory step in skeletal muscle contraction [2].

Monitoring of fatigue during isometric muscle contraction using surface electromyography (sEMG) is well documented. A progressive decrease in the median frequency (F_{med}) of the electromyographic signal occurs with local muscle fatigue during sustained isometric contractions. This is caused by a reduction in muscle fiber excitability and the consequent reduction in muscle fiber action potential conduction velocity.

The relationship between sEMG parameters and muscle fatigue during dynamic exercise is less clear. Studies implementing a high-intensity fatiguing protocol have shown a reduction in F_{med} of the sEMG signal occurring, similar to that observed in sEMG of an isometric contraction [3], [4]. In contrast, studies which have employed a low or medium intensity, dynamic fatiguing protocol have observed either no change, or an increase in F_{med} of the sEMG [5], [6].

Glucose ingestion during exercise is believed to contribute to the maintenance of the muscle-energy balance. However, its effect on exercise capacity may depend on the intensity of the exercise. Glucose ingestion during an intense endurance exercise performed at 83% $\dot{V}O_{2peak}$ had no effect on time to exhaustion [7], whereas ingestion of glucose during 120 min of steady state cycling at 63% $\dot{V}O_{2peak}$ was observed to improve subsequent time trial performance [8]. The aim of this study is to analyze and compare the changes in the F_{med} of sEMG signals recorded during fatiguing, sub-maximal, dynamic exercise to exhaustion performed both with and without oral glucose supplementation.

II. Methods

A. Subjects

Five healthy, moderately active subjects (one female), mean age 25.4 (±4.9) years, participated in the study. All subjects were free from any cardiovascular/respiratory disease, and had no lower limb injuries. Prior to attending the laboratory for testing, subjects were requested to refrain from strenuous exercise for a period of 24 hours, and abstain from caffeine and alcohol for a period of 12 hours. Approval for the study was obtained from the Human Research Ethics Committee, University College Dublin. The study was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants prior to inclusion. A medical history questionnaire was also completed by each subject.

B. Familiarization

Prior to testing, each subject attended the laboratory for a familiarization session and an incremental, sub-maximal cycle ergometry test using a Lode Corival (Lode B.V. Medical Technology, Groningen, The Netherlands) constant-load (cadence independent) cycle ergometer. The sub-maximal test followed the original YMCA protocol [9]. The saddle height was adjusted to obtain a slight flexion of the knee joint with the pedal at the lowest position. A three lead ECG setup was used to monitor the heart rate of the subject. The subject cycled at a cadence of 50 rev/min (rpm) at an initial work load of 25

W for 3 min. The heart rate during the last 5 s of the first workload was used to determine the subsequent workloads. The test was terminated when two workloads were completed with heart rates between 110 and 150 beats/min. The results of the YMCA sub-maximal test were used to establish the work rate for the experimental protocol.

C. Experimental protocol

The experimental protocol consisted of attendance at the laboratory on two separate days, with at least five days between them. The order of the two sessions was randomized, with three of the subjects completing session A first. For both session A and B, participants were instructed to cycle to fatigue at a work rate of 161 (±17) W (70% of the estimated

VO_{2peak}) maintaining a steady cadence between 50 and 60 rpm. Task failure was defined as the time point at which the rate of cycling fell below the established steady state by 10%, and remained below it for 10 s, despite strong verbal encouragement being given to the subject. During session A, the subject received glucose (0.25g/kg body-weight (BW)) dissolved in water (4ml/kg BW) at 15 minute intervals for the duration of the task. Prior to session B, subjects fasted for a minimum of 12 hours, and received water (4ml/kg BW) at 15 minute intervals for the duration of the task. The warm-up period was standardized for all subjects: 2 minutes of cycling at 25%, 50% and 75% of the work rate prescribed for the session.

D. Blood glucose

Prior to starting the test session, and at 10 minute intervals for the duration of the task, fingertip glucose measurements were taken using the One Touch Ultra glucometer, and One Touch Ultra test strips, in conjunction with a One Touch UltraSoft lancing device (LifeScan, Inc., Milpitas, CA). At each time point, two blood samples from the same lance were used to obtain two blood glucose readings. The mean of the two readings was used as the value for blood glucose concentration at that time point. Excess sweat was removed from the fingertip prior to obtaining the blood sample.

E. Data recording

Surface electromyography (EMG) was recorded from the rectus femoris, vastus medialis, vastus lateralis, semitendinosus and biceps femoris muscles of the dominant leg using wireless bipolar electrodes (Delsys Trigno® Wireless EMG System, Boston, MA). This system consists of small (27 x 37 x 15 mm, < 15 g) sensors each with four silver bar contacts, which are attached to the skin using the Delsys Adhesive Sensor Interface (Delsys, Boston, MA). EMG signals were amplified, band-pass filtered (20 Hz to 450 Hz) and sampled at 1515 Hz. The electrodes were placed in accordance with the SENIAM guidelines by a qualified physiotherapist. The skin was shaved if necessary, lightly abraded and cleaned with 70% isopropyl alcohol. EMG data were recorded continuously throughout the experimental session. The Trigno® Wireless EMG system was used in conjunction with a
Micro1401-2 Data Acquisition unit (Cambridge Electronic Design Ltd., UK), Spike2 software (Cambridge Electronic Design Ltd., UK), and a custom built interface.

An accelerometer (Delsys Trigno® Wireless EMG System, Boston, MA) was attached to the posterior side of the lateral malleolus of the dominant leg. The accelerometry data were collected using the same setup as the EMG, detailed above, and sampled at 49.95 Hz.

F. Data analysis

All data analysis was performed off-line. The data were processed using the Teager-Kaiser energy (TKE) operator, which takes both the amplitude and frequency of the signal into consideration [10], [11]. A threshold based algorithm, developed in [12] to identify the onset of muscle activity using the TKE operator, was utilized to determine the activity for each pedal revolution. The root mean square (RMS) amplitude and median frequency (F_{med}) of a 100ms section centered at the peak of each EMG burst was calculated for each muscle. F_{med} was calculated using the continuous wavelet transform with an analytic Morlet wavelet [13]. The data were then divided into bins, each corresponding to 5% of the time to exhaustion, where 0% represents the start point of the exercise and 100%, task failure. A single average value of RMS amplitude and F_{med} were calculated for each bin. These were then normalized with respect to the initial average value.

To identify an arbitrary start point of each pedal revolution, the recorded accelerometry data were smoothed with a 1 Hz, low pass, FIR filter. The peaks of the data were identified, and the frequency of the cycling obtained. The point of task failure was defined as the time after which the frequency of cycling had fallen by 10% or more from the original steady-state frequency for a period of at least 10 s. The time point was confirmed by manual inspection of the raw data.

III. RESULTS

A. Task failure

The frequency of steady-state cycling was 55 (±2) rpm for session A and 54 (±3) rpm for session B. The time to task failure was 4598 ± 1554 s and 4069 ± 1535s in sessions A and B respectively. The raw EMG signal for a single pedal revolution is presented in Fig. 1 for the five upper leg muscles. The smoothed accelerometry signal together with the identified start and end point of the revolution are also indicated.

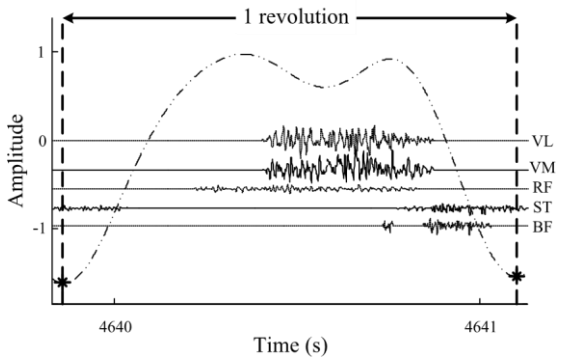

Figure 1. Sample raw EMG data recorded from the vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), semitendinosus (ST) and biceps femoris (BF) of one subject, shown for a single pedal revolution of the fatiguing dynamic cycling task. The smoothed accelerometry signal and the identified peaks indicating the start and end point of the revolution are also shown.

B. Blood glucose

The mean blood glucose concentration values at each time point for all subjects for both session A (with glucose) and session B (no glucose) is presented in Fig. 2.

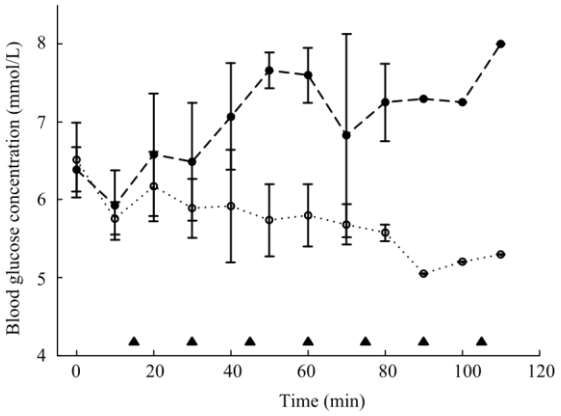

Figure 2. Mean (±std. dev.) blood glucose concentrations for five subjects recorded during a fatiguing dynamic cycling task performed under two conditions; A in which oral glucose was given at 15 minute intervals throughout the exercise, and B, in which the subject fasted prior to the session, and was given water throughout the task. The solid triangular markers show the time point at which a drink was given. Each data point shows the mean (failure at that time point. The solid circles are the mean blood glucose± std. dev.) of all subjects that had not reached task concentrations recorded during the glucose condition, and the unfilled circles are the mean blood glucose concentrations during the no glucose condition. The last three data points in both conditions are for one subject only.

C. EMG

The RMS and F_{med} values of the sEMG signal are presented in Fig. 3 as mean values (±std. dev.). These are shown for each of the five muscles in the upper leg; rectus femoris, vastus medialis, vastus lateralis, semitendinosus and biceps femoris. In the with glucose condition, the mean F_{med} values (± std. dev.) of the five muscles are 1.20 (±0.14), 1.07 (±0.09), 1.16 (±0.05), 1.15 (±0.09) and 1.08 (±0.06) respectively. In the without glucose condition, these values are 1.11 (±0.07), 1.05 (±0.08), 1.11 (±0.07), 1.01 (±0.18) and 1.03 (±0.11).

A total of 25 recordings were analyzed (5 muscles in each of 5 subjects). In the glucose condition, the mean value of F_{med} at the point of task failure increased in 24 out of 25 of these recordings when compared to the initial F_{med}. In the without glucose condition, no increase of F_{med} was observed in a total of 8 recordings. The EMG recorded from the rectus femoris of one subject was omitted as a problem occurred on that channel during data collection.

IV. Discussion

The main finding of this study is that the median frequency of the sEMG signal increased progressively throughout the dynamic exercise protocol, with a greater increase observed when glucose was consumed throughout the exercise when compared with the fasted protocol. This result is in contrast to the progressive reduction in F_{med} of sEMG that is typically observed during a fatiguing isometric contraction.

Previous studies of the sEMG signal during dynamic exercise have revealed less pronounced and less consistent changes in the F_{med} when compared to those recorded during isometric contraction. Analysis of sEMG during high intensity dynamic exercise yield a decrease in F_{med} resembling that found in isometric contractions with fatigue [4]. The changes to the F_{med} of the sEMG recorded during protocols employing a lower exercise intensity are less pronounced and less consistent, with some showing a slight increase [6], and others no change [5], in F_{med}. The slight increase observed in the F_{med} of the vastus lateralis in most (8 out of 12) subjects studied in [6] was during an incremental, dynamic cycling protocol, but the endurance time of their protocol was substantially less than that observed in the present study.

An increase in F_{med} of sEMG is observed during repeated, isometric exercise, with the increase proportional to the increase in baseline muscle fiber conduction velocity (MFCV) [14], [15]. An increase in MFCV above baseline levels has also been noted during the recovery period immediately following sustained isometric contraction [16]. One hypothesis is that this could reflect an increase in motor unit recruitment, although in [17] motor unit recruitment was found to have little effect on EMG spectral variables during cycling. Therefore, this is unlikely to contribute to the changes observed in F_{med} in the present study.

Several other hypotheses have been proposed to explain an increase in F_{med} in sEMG during a fatiguing protocol, including muscle fiber swelling, increased muscle temperature and activation of $Na^{+}\text{–}K^{+}\text{–}ATPase$. Activation of the ion pump results in hyperpolarization of the sarcolemmal membrane, which in turn facilitates faster propagation of action potentials [15], higher MVC (maximum voluntary contraction) and

therefore an increase in the median frequency of the EMG signal. The hypothesis that the increase in MFCV

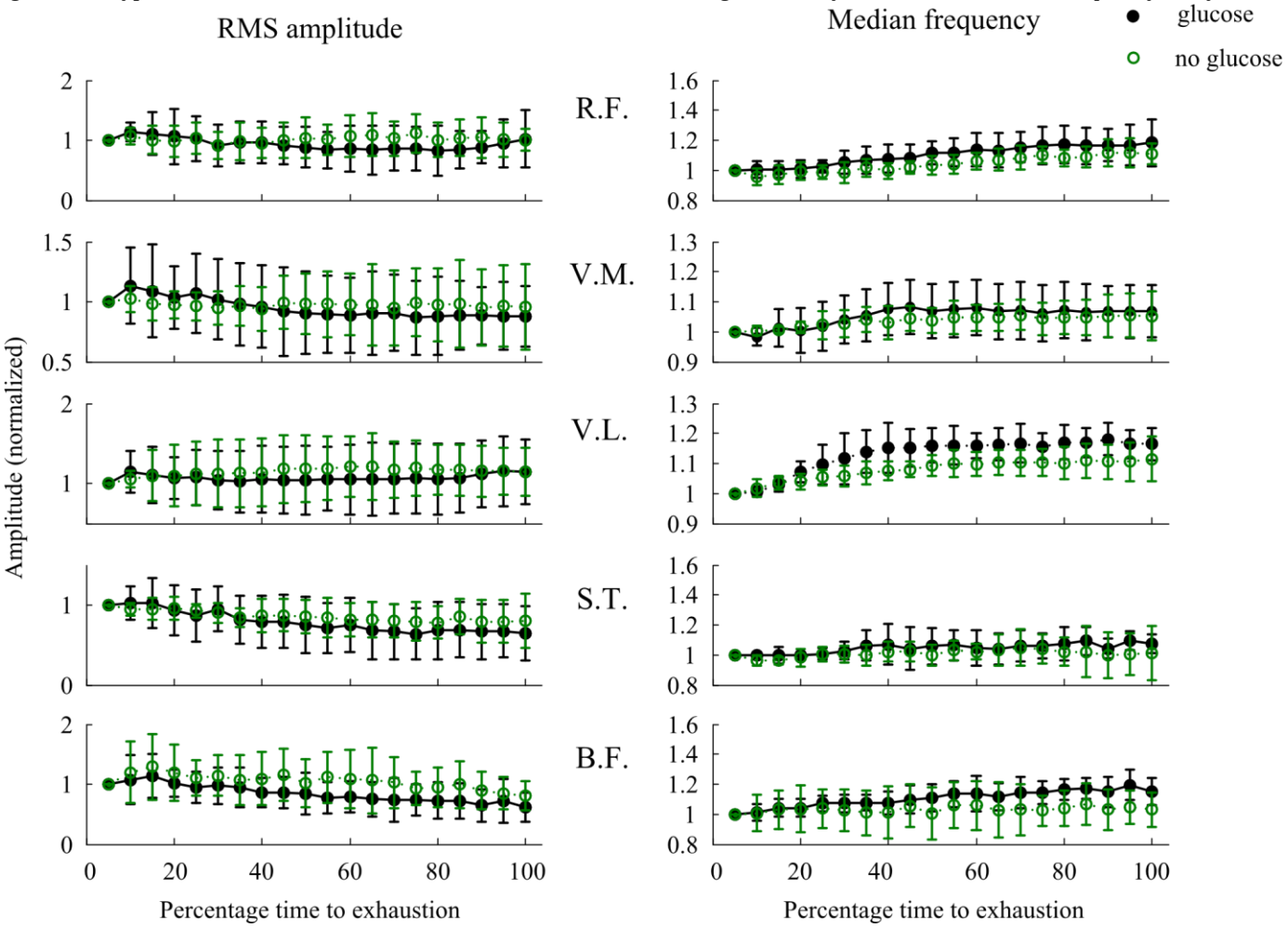

Figure 3. Normalized root mean square (RMS) amplitude and median frequency (F_{med}) values of the surface electromyographic (sEMG) signal recorded during a fatiguing dynamic cycling task for each of five muscles; rectus femoris (R.F.), vastus medialis (V.M.), vastus lateralis (V.L.), semitendinosus (S.T.) and biceps femoris (B.F.). Values shown are the mean values±standard deviation for five subjects, and are given as the mean for each 5% bin of time to task failure. The solid data points indicate the with glucose condition, and the open points are the no glucose condition. 0% (time to exhaustion) represents the start point of the exercise and 100%, task failure.

is caused by rapid activation of $Na^+ - K^+ - ATPase$ is supported by results presented in [15], where ouabain (a specific inhibitor of $Na^+ - K^+ - ATPase$) was observed to completely prevent the increase in MFCV during repeated isometric contractions [15]. Oral glucose supplementation has been shown to increase $Na^+ - K^+ - ATPase$ during prolonged cycling exercise at 57 % of $\dot{V}O_{2peak}$ [18], during a similar intensity and protocol to that used here. These results support the hypothesis that changes in the activity of $Na^+ - K^+ - ATPase$ may be the mechanism underlying the increase in F_{med} of the sEMG in the present study. Glucose supplementation may further increase $Na^+ - K^+ - ATPase$ activity resulting in the more pronounced increase in the F_{med} observed.

A recognized limitation of this study is that only F_{med} of the sEMG signal is analyzed. Alternative time-frequency analysis methods, and techniques such as fractal analysis [19] and recurrence quantification analysis (RQA) [20], [21] have been shown to quantify fatigue in sEMG. This limitation will be addressed in a follow-up study with a larger sample population.

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