33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Repeatability of surface EMG-based Single Parameter Muscle Fatigue Assessment Strategies in Static and Cyclic Contractions

Sabeer A. Zaman, *Junior Member, IEEE,* Dawn T. MacIsaac, *Senior Member, IEEE*, and Philip A. Parker, *Senior Member, IEEE*

***Abstract*—The repeatability of a spectral surface electromyography-based fatigue assessment strategy was evaluated. Variability of two fatigue-trend tracking parameters was used as an indicator for repeatability. The parameters were the natural logarithm of the slope of linear mean frequency decline $lnMF_S$ and the percent drop in mean frequency MF_D. The coefficient of variation *CoV* was used as the metric for repeatability, representing the ratio of the standard deviation to the mean of repeated measures from the same individual. Five weekly fatigue tests on the right biceps brachii were conducted on 11 participants with a fatiguing regime comprising of alternating static and cyclic segments, collecting seven channels of differential EMG. The resulting 95% confidence intervals of the CoV were: 15.38-24.87% (Static $lnMF_S$), 12.21-23.36% (Cyclic $lnMF_S$), 13.18-21.85% (Static MF_D), and 12.37-24.39% (Cyclic MF_D). There was no statistically significant difference in repeatability between any combination of parameter and types of motion.**

I. Introduction

TRACKING the surface myoelectric signal with electromyography is a noninvasive approach for studying the fatiguing process in muscle and can potentially be implemented in clinical settings. Based on the two primary myoelectric manifestations of fatigue – increase in amplitude of the surface electromyographic signal (sEMG) and power spectral shifts towards lower frequencies [1] – various muscle fatigue assessment strategies have been proposed [2]. While these strategies have been demonstrated to be sensitive to the underlying fatiguing process, the repeatability of such strategies has not been thoroughly investigated. This work evaluates the repeatability of two univariate spectral fatigue assessment parameters under static and cyclic conditions.

For fatigue assessment, spectral parameters are preferred over time domain parameters since it has been shown that amplitude features often exhibit changes opposing fatigue manifestations [1], due to greater sensitivity to non-fatiguing factors such as time-dependent characteristics of the skin-electrode interface. The most popular spectral measures are the median frequency and mean frequency (MF) [2]. Most research has focused on static contractions, where the sEMG can be divided into wide sense stationary segments, allowing for accurate spectral estimation. Under dynamic conditions, variations in muscle length and/or force are factors that influence characteristic frequencies in addition to fatigue. For instance, the resulting change in muscle geometry varies the relative position of active and detectable motor units. While there is ongoing research into use of advanced time-frequency signal analysis [3] and multi-feature mapping techniques [4] to overcome such non-stationarities, MacIsaac et al. [5] demonstrated that the Short Time Fourier Transform (STFT) could be effective in tracking fatigue trends under constrained dynamic conditions by simply tracking an average characteristic frequency in the signal. The present study further investigates this possibility by evaluating and comparing repeatability of MF trends with fatigue, under static versus cyclic (periodically repeated change in muscle length and force) conditions.

Repeatability of sEMG parameters have been investigated, mostly focusing on static contractions. Though contradictions and exceptions exist in the literature, most studies conclude that initial values of spectral parameters are repeatable, while trend values (slope of line of best fit) are not [6] - [9]. The metrics most commonly used to evaluate repeatability in these studies are the Intraclass Correlation Coefficient (ICC) and the Standard Error of Measure (SEM). The ICC is a relative measure of repeatability that quantifies the proportion of total variance attributable to intersubject differences – thus it measures how well the measurement can differentiate between subjects and is directly influenced by the heterogeneity of the sample. SEM is the expected degree of error in measurement, stated in the units of measurement being evaluated. This study is interested in quantifying the precision of the fatigue assessment strategies – instead of focusing on intersubject differences like the ICC, the work focused on the degree of variation across trials for a particular individual. While this is similar to what SEM measures, SEM has two major disadvantages: it cannot be used to compare strategies with different units of measurement, nor does it indicate the degree of impact the imprecision has on measured values. A dimensionless metric known as the coefficient of variation (*CoV*) was used in this work to overcome these deficiencies. The *CoV* measures the standard deviation of measurements relative to the mean.

Manuscript received April 15, 2011. This work was supported in part by grants from the Natural Sciences and Engineering Research Council of Canada (Grant numbers RGPIN261749 and A4445-04).

S. A. Zaman is a graduate student with the Institute of Biomedical Engineering, Department of Electrical and Computer Engineering, University of New Brunswick, Fredericton, NB E3B5A3, Canada (e-mail: sabeer.zaman@unb.ca).

D. T. MacIsaac and P. A. Parker are with the Institute of Biomedical Engineering, Department of Electrical and Computer Engineering, University of New Brunswick, Fredericton, NB E3B5A3, Canada (e-mail: dmac@unb.ca; pap@unb.ca).

II. METHODOLOGY

The coefficient of variation CoV is defined as

$$CoV = \frac{s_{trials}}{|u_{trials}|}, \quad (1)$$

where s_{trials} is the sample standard deviation of scores across repeated measures from a single participant, and u_{trials} is the mean of those measures. As a proportion of measured values, the CoV signifies the relative precision of measurement and its dimensionless nature allows comparisons between different assessment strategies (which may use indices with different units) and/or conditions (such as conditions of motion, experimental setup/protocol).

A. Fatigue Test Protocol

Five healthy males and six healthy females participated in the study, aged 25 ± 4 years old. All participants completed five weekly fatigue tests on the right biceps brachii. Each fatigue test was scheduled during the same hour of each week for a particular participant. No participants engaged in any physical fitness of the upper body during the course of the study. To ensure conditions remained as consistent as possible across trials, the participants were encouraged to maintain the same diet and sleep patterns for the day before and the day of each trial.

The apparatus used during the fatigue tests consisted of a large disc attached to a central pulley at its axis as previously described in [4]. A frame supporting the disc and pulley allowed each participant to rest the upper arm upon a platform while flexing and extending at the elbow, which was aligned with the pulley-disc axis. The apparatus was equipped with an ergometer for monitoring and recording elbow joint angle, and a load cell for assessing maximum voluntary contraction (MVC).

Each fatigue test included a 3-trial MVC assessment, followed by an endurance test after a 20-min break. For the MVC assessment, the disc was fixed to allow only 130° flexion at the elbow. The participant was instructed to pull against the load cell as hard as they could for five seconds, keeping their shoulder in a standard position. Visual feedback was provided on a computer to encourage the participant, and the output was digitally recorded for offline processing. Each MVC trial was repeated 3 times, with a one minute break between each assessment to minimize effects of fatigue. The maximum of the 3 trials was considered the MVC for the fatigue test. During the endurance test, the participants flexed and extended at the elbow to track a target on a computer screen, against a load 40% of the assessed MVC. The endurance test consisted of cyclic contractions periodically interrupted with a static contraction. The cyclic segments constituted repeated cycles of flexion and extension between 50° and 130°, at a constant angular velocity of 32°/s for 25 s. The static segments were 5 s of sustained contraction held at 90° and occurred every 30 seconds. Real-time tracking feedback was provided on a computer screen alongside a target moving in the prescribed fashion. Participants were verbally encouraged to continue the fatiguing protocol. The end of the endurance test was indicated when a participant could not hold a complete static contraction, or could not achieve the full range of a cyclic contraction.

B. Data Acquisition

During the full course of the endurance test during each trial, the sEMG was measured from the right biceps brachii using an eight channel Ag-AgCl linear electrode array with 5mm spacing. The electrode array was positioned such that the first channel was centered at 40% of the humerus length measured from the fossa cubit to the acromion process as recommended by SENIAM guidelines [10] and DeFreitas et al. [11]. During the first trial, this positioning was recorded on an arm-fitted transparency, which was used in future trials to accurately reposition the electrode array. Prior to electrode application, the skin surface was abraded with abrasive skin cleaning paste, cleansed with rubbing alcohol and treated with conducting gel.

After firmly securing the electrode array in position with adhesive tape, it was connected to a Prima EMG 16-channel data acquisition unit, with differential gains of 5000 to 10000 depending on the participant, yielding seven channels of differential sEMG data. The Prima was also connected to an ergometer fitted to the disc that tracked the angular position of motion during the fatiguing exercise. The processed signals from the Prima were routed to a computer for digital recording via a National Instruments 16-bit resolution DAQ-6024E PCMCIA data acquisition card, sampling at 1024 Hz.

C. Data Processing

The electrode array yielding seven channels of data was used to ensure that at least one channel was clear of any end-effects (effects from innervation zone and/or muscle termination). All channels were visually inspected and based on this inspection, channel 3 was selected for analysis in this study.

For every trial, joint angle data collected from the ergometer was used to identify and separate static and cyclic segments of sEMG data. Fatigue trends for the static and cyclic data were then obtained based on MF.

A MF value was estimated for each 5 s static segment, calculated from a periodogram obtained by averaging 0.5s, 50% overlapped Hamming-windowed epochs. The MF values for the static segments of a single fatigue trial formed the *static MF fatigue trend*.

The cyclic data was segmented with one cycle per segment, beginning and ending at the minimum joint angle (50°). Following the procedure from MacIsaac et al. [5], a MF value for each cyclic segment (approximately 5 s long) was also obtained by averaging 0.5s, 50% overlapped Hamming-windowed epochs. While the dynamic factors involved affect the frequency estimates, due to the cyclic nature of motion, the effects are fairly repeatable and manifest as a relatively constant bias across cycles. This still

allows for detection of any trend due to fatiguing factors. Thus, the series of MF values obtained from this procedure formed the *cyclic MF fatigue trend*.

D. Fatigue Assessment Strategies

1) Natural logarithm of MF Slope ($lnMF_S$)

From each static and cyclic MF trend per trial, a line of best fit was obtained via least squares linear regression. Note that the time was *not* normalized and retained its original unit, seconds. The slope MF_S (Hz/s) of the fitted function characterized the linear decline of MF. The sample of MF_S values (one sample per trial per type of motion) had a left-skewed distribution which introduces a bias in s_{trials}. To counter this, MF_S was normalized by taking the natural log of its absolute value, henceforth termed $lnMF_S$. Given that the values of MF_S are strictly negative in MF fatigue trends, there is no loss of information with this transformation. The transformation is not meant to propose an alternative index to MF_S; it is used to calculate an unbiased value for s_{trials}, for use in the computation of *CoV*.

2) Percent Drop in MF (MF_D)

An additional nonparametric fatigue assessment parameter was investigated – the percent drop or decline in MF during the course of the fatigue trial, which is calculated as

$$MF_D = \frac{Initial\ MF - Final\ MF}{Initial\ MF} \times 100\%. \quad (2)$$

MF_D (%), like $lnMF_S$, also represents information about how MF changes with the progression of fatigue. It has a computational advantage in that only the first and last MF data points are required to calculate it.

E. Statistical Analysis

In order to first rule out any systematic trial effect (e.g., a learning effect) a one-way repeated measures ANOVA (blocked by subject) was conducted for each parameter and condition pair, with trials as the factor. Upon ruling out systematic variation, the *CoV* of each parameter was calculated for each subject using (1). The overall variability, as an indicator of parameter repeatability, was expressed as a 95% confidence interval (CI) of each parameter's *CoV*.

Repeatability was compared between both types of motion (static and cyclic) as well as both parameters ($lnMF_S$ and MF_D). This was done by conducting a two-way repeated measures ANOVA (blocked by subject), with condition of motion and parameter as fixed factors with two levels each.

For sampled values of s_{trials} and u_{trials} from normally distributed data, the asymptotic distribution (i.e., distribution of a large sample) of *CoV* values is modeled as a noncentral t-distribution [12]. When this is the case, statistics specific to this distribution should be used to conduct statistical comparisons and compute confidence intervals. However, three tests of normality (Anderson-Darling, Ryan-Joiner and Kolmogorov-Smirnov tests) indicated the sampled *CoV* values in this study were normally distributed. Hence, it was justified to use an ANOVA for comparing repeatability. Nevertheless, we recognize that the normality tests used lack power for small sample sizes. In order to avoid erroneous conclusions from the ANOVA in case the *CoV* is in fact not normal, a Wilcoxon signed rank test was also conducted for each combination of comparisons (static $lnMF_S$ vs. cyclic $lnMF_S$, static MF_D vs. cyclic MF_D, static $lnMF_S$ vs. static MF_D, and cyclic $lnMF_S$ vs. cyclic MF_D). The Wilcoxon test is nonparametric and does not assume the data is from any particular type of distribution.

All tests were interpreted at a 5% significance level.

III. Results

The results of the one-way repeated ANOVA returned p-values > 0.05 for all four pairings of condition and parameter. Table I and II show summary statistics per subject of the values of $lnMF_S$ and MF_D respectively. Fig. 1 depicts the 95% CIs for the *CoV* of all four combinations of assessment parameter and type of contraction.

Results from the two-way repeated measures ANOVA, show that there were no significant effects (p-values > 0.05), thus indicating that there was no statistically significant difference in repeatability for either factors (parameter and type of motion) within each individual. The Wilcoxon signed rank tests per comparison further confirmed these outcomes (p-values > 0.05).

TABLE I
SUMMARY STATISTICS FOR VALUES OF $LNMF_S$

Participant	Static $lnMF_S$			Cyclic $lnMF_S$		
	u_{trials}	s_{trials}	CoV	u_{trials}	s_{trials}	CoV
1	-2.119	0.355	16.77%	-2.164	0.223	10.31%
2	-1.565	0.283	18.09%	-1.602	0.321	20.06%
3	-1.483	0.232	15.65%	-1.547	0.239	15.47%
4	-1.913	0.268	13.99%	-1.841	0.166	9.01%
5	-0.933	0.229	24.58%	-0.852	0.232	27.25%
6	-2.309	0.241	10.44%	-2.373	0.232	9.77%
7	-1.705	0.191	11.19%	-2.060	0.144	6.98%
8	-1.643	0.479	29.18%	-1.726	0.483	27.97%
9	-1.822	0.491	26.96%	-1.812	0.288	15.91%
10	-2.010	0.565	28.12%	-2.251	0.526	23.39%
11	-1.426	0.377	26.40%	-1.457	0.429	29.45%

TABLE II
SUMMARY STATISTICS FOR VALUES OF MF_D

Participant	Static MF_D			Cyclic MF_D		
	u_{trials}	s_{trials}	CoV	u_{trials}	s_{trials}	CoV
1	35.37%	7.04%	19.90%	36.13%	3.17%	8.77%
2	44.61%	8.58%	19.23%	41.81%	7.27%	17.39%
3	45.08%	3.31%	7.35%	45.11%	1.97%	4.37%
4	31.15%	8.99%	28.85%	37.45%	5.22%	13.95%
5	52.69%	9.29%	17.64%	49.13%	7.87%	16.01%
6	21.29%	3.74%	17.55%	26.86%	7.01%	26.12%
7	40.75%	3.46%	8.50%	29.40%	2.71%	9.23%
8	37.08%	9.71%	26.18%	37.85%	10.04%	26.53%
9	45.84%	6.15%	13.42%	38.38%	7.81%	20.34%
10	22.76%	3.62%	15.89%	19.98%	6.45%	32.27%
11	49.58%	9.01%	18.18%	45.30%	12.32%	27.19%

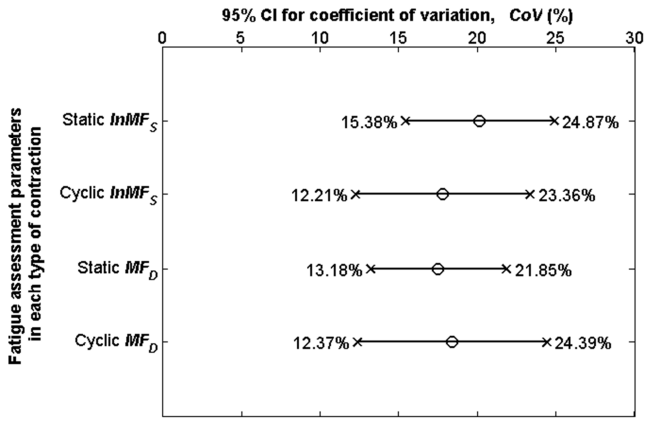

Fig. 1. Two-tailed 95% confidence intervals for *CoV* for each combination parameter and type of motion.

IV. Discussion

Results shown in Fig. 1 represent the bounds of how variable (relative to a mean estimate) we expect our fatigue assessment parameters to be for both kinds of contractions. These values can now be used to evaluate how repeatability may affect observations in different applications of fatigue assessment.

For instance, if a physiotherapist wanted to assess a patient's muscle performance using $lnMF_S$ during a sustained contraction fatigue test, he/she would know the full range within which the true value lies in the best case (±15.38%) or worst case (±24.87%) scenario. The therapist may deem the assessment too imprecise or possibly use the range of values itself for gauging muscle performance. Furthermore, if used in rehabilitation to track improvement in muscle performance, a change of at least 15.38% would be required to consider it a true change, while a change of over 24.87% would definitely be a real improvement.

Note that while the therapist would need to determine error bounds of the measured parameter using $lnMF_S$, the actual assessment parameter could still remain as MF_S. The use of the log transform is required only for calculating precision, since the metric *CoV* is well-defined when the underlying distribution of data is known to be normal. For instance, if the measured value of MF_S is x Hz/s, with a *CoV* of c%, the 68% CI of the value would be $xe^{\frac{\pm c}{100}\ln(x)}$.

The results from this study are readily interpretable across other repeatability studies. *CoV* values are not dependent on homogeneity of the sample they were obtained from like the ICC, and being dimensionless allows comparison with parameters with different units.

A case in point is the comparisons made in this study. Results show that each parameter is equally repeatable under static as well as cyclic contractions. Furthermore, both parameters appear to have the same degree of repeatability.

V. Conclusion

The results here provide further support for using the proposed STFT-based procedure by MacIsaac et al. [6] in cyclic contractions, as it is as repeatable in cyclic contractions as it is in static contractions.

The MF_D is a more attractive alternative to $lnMF_S$ as only two data points need to be obtained and it involves no complicated computation. Since the results indicate it performs equally well as $lnMF_S$, it is an equally plausible fatigue assessment parameter.

Future work with the data collected in this study will involve assessment of the effects of electrode positioning on the repeatability of fatigue assessment parameters, which is a commonly cited potential cause for poor repeatability [7]-[9].

References

[1] C. J. De Luca, "Myoelectrical manifestations of localized muscular fatigue in humans," *Crit. Rev. Biomed. Eng.*, vol. 11, pp. 251-79, 1984.

[2] M. Cifrek, V. Medved, S. Tonković and S. Ostojić, "Surface EMG based muscle fatigue evaluation in biomechanics," *Clin. Biomech.*, vol. 24, pp. 327-340, 2009.

[3] P. Bonato, S. H. Roy, M. Knaflitz and C. J. De Luca, "Time-frequency parameters of the surface myoelectric signal for assessing muscle fatigue during cyclic dynamic contractions," *IEEE Trans. Biomed. Eng.*, vol. 48, pp. 745-53, 2001.

[4] D. T. MacIsaac, P. A. Parker, K. B. Englehart and D. R. Rogers, "Signal Processing - Fatigue Estimation With a Multivariable Myoelectric Mapping Function," *IEEE Trans. Biomed. Eng.*, vol. 53, pp. 694-700, 2006.

[5] D. MacIsaac, P. A. Parker and R. N. Scott, "The short-time Fourier transform and muscle fatigue assessment in dynamic contractions," *J. Electromyogr. Kinesiol.*, vol. 11, pp. 439-449, 2001.

[6] R. Merletti and P. Parker, *Electromyography : Physiology, Engineering, and Noninvasive Applications*. Piscataway, NJ; Hoboken, N.J.: IEEE Press; Wiley-Interscience, 2004, pp. 233-258.

[7] A. Rainoldi, G. Galardi, L. Maderna, G. Comi, L. Lo Conte and R. Merletti, "Repeatability of surface EMG variables during voluntary isometric contractions of the biceps brachii muscle," *J. Electromyogr. Kinesiol.*, vol. 9, pp. 105-119, 1999.

[8] Arnall FA, Koumantakis GA, Oldham JA and Cooper RG, "Between-days reliability of electromyographic measures of paraspinal muscle fatigue at 40, 50 and 60% levels of maximal voluntary contractile force," *Clin. Rehabil.*, vol. 16, pp. 761-71, 2002.

[9] E. Kellis and A. Katis, "Reliability of EMG power-spectrum and amplitude of the semitendinosus and biceps femoris muscles during ramp isometric contractions," *J. Electromyogr. Kinesiol.*, vol. 18, pp. 351-358, 2008.

[10] H. J. Hermens, R. Merletti and B. Freriks, *SENIAM European Recommendations for Surface Electromyography*. Enschede, The Netherlands: Roessingh Research and Development, 1999.

[11] J. M. DeFreitas, P. B. Costa, E. D. Ryan, T. J. Herda, J. T. Cramer and T. W. Beck, "Innervation zone location of the biceps brachii, a comparison between genders and correlation with anthropometric measurements," *J. Electromyogr. Kinesiol.*, vol. 20, pp. 76-80, 2010.

[12] D. B. Owen, "A survey of properties and applications of the noncentral t-distribution," *Technometrics,* vol. 10, no. 3, pp. 445-478, Aug. 1968.