# REPEATABILITY OF MES-BASED FATIGUE ASSESSMENT IN STATIC AND CYCLIC CONTRACTIONS

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## INTRODUCTION

Local muscle fatigue can be tracked non-invasively by following the correlated changes in signal parameters of the surface myoelectric signal (SMES), widely known as the myoelectric manifestations of muscle fatigue [1]. Based on the two primary manifestations – an increase in amplitude, and power spectral shifts towards lower frequencies - various SMES-based fatigue assessment strategies have been proposed [2]. This work evaluates the repeatability of one such parameter, percent drop in mean frequency, under static and cyclic conditions.

The most popular fatigue tracking spectral parameters are median frequency and mean frequency (MF) [2]. Most studies have concentrated on static contractions – constant muscle force and fiber length – where the SMES can be divided into wide-sense stationary segments, allowing for accurate spectral estimation. Dynamic factors – varying muscle force and/or fiber length – influence characteristic frequencies in addition to fatigue. For instance, the change in muscle geometry will vary the relative positions of active and detectable motor units. Fatigue assessment strategies involving advanced time-frequency signal processing [3] and multi-feature mapping techniques [4] are being investigated to address these additional complexities. However, MacIsaac et al. [5] demonstrated that the short time Fourier transform (STFT) could still be used to track fatigue trends under constrained dynamic conditions by tracking mean frequency as an averaged characteristic frequency across cycles. The present study further explores this possibility by comparing the repeatability under cyclic conditions (periodic changes in force and fiber length) to the repeatability under static conditions.

The repeatability of SMES parameters in general has been investigated in the literature, mostly focusing on static contractions. While contradictions exist, most studies agree that initial values of spectral parameters exhibit moderate to good repeatability, but trend parameters such as slope show poor repeatability [6] – [8].

## METHODS

Using the mean frequency data from Zaman et al. [9], and the percent mean frequency drop, $MF_D$, the focus here was on expressing repeatability in absolute terms in a manner that is useful for practitioners who may use $MF_D$ for fatigue assessment. To this end, standard deviation ($s_{trials}$) across 5 trials for 11 participants is reported, along with standard error of measurement (SEM).

### Setup and data acquisition

The setup, procedure and equipment are described in detail in [9], and the relevant information is summarized here in Table 1 and Figure 1.

Table 1: Summary of experiment

| | |
|---|---|
| **Subjects** | 5 male, 6 female; age: 25±4 years |
| **Trials** | 5 consecutive weekly trials each |
| **Muscle** | Biceps brachii (right arm) |
| **Load** | 40% of maximum voluntary contraction (MVC), where MVC is assessed for every trial |
| **Fatiguing protocol** | Repeated cycles of alternating static (held at 90° for 5s) and cyclic (between 50° and 130° at 32°/s for 25s) contractions until point of failure |
| **Data acquisition** | SMES from 8-channel Ag-AgCl linear electrode array (5mm spacing); elbow angle data from ergometer; both sampled at 1024Hz using Prima EMG 16-channel data acquisition unit |

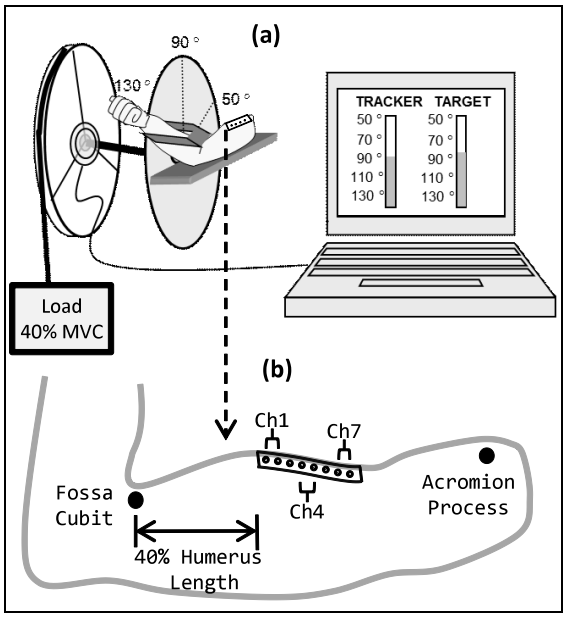


Figure 1: a) Setup with disc-pulley apparatus, attached load, and motion tracking; and b) Electrode placement criteria

Data Processing

SMES from all 7 bipolar channels of data from the electrode array were visually inspected to ensure that at least one channel was clear of any end-effects (effects from innervation zone and/or muscle termination). Data from channel 5 was arbitrarily chosen from amongst the channels that passed inspection, 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 SMES data. Static and cyclic data were processed independently from this point forward to produce a static and cyclic fatigue trend, respectively. The data points in the trend were the computed MF values. In both cases (static and cyclic), following the procedure from MacIsaac et al. [5], a MF value was obtained per segment by averaging 0.5s, 50% overlapped Hamming-windowed epochs. While the dynamic factors involved in the cyclic segments 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.

Percent Drop in MF

Percent drop or decline in MF is a nonparametric fatigue assessment parameter showing the change from the initial to final MF value, calculated as:

$$MF_D = \frac{Initial\ MF - Final\ MF}{Initial\ MF} \times 100\% \quad (1)$$

For each of the 5 trials per subject, two values of $MF_D$ were computed – one for the static fatigue trend and one for the cyclic fatigue trend.

Repeatability Metrics

Repeatability in absolute terms is indicated by an absolute measure of variability. The most intuitive metric for this is the sample standard deviation of scores across trials ($s_{trials}$) for a single subject. The SEM expresses similar information as $s_{trials}$, however is computed from a sum-of-squares (SS) decomposition of the data. The sum-of-squares decomposition allows one to explicitly separate the random and systematic sources of variability. We are interested in quantifying the inherent random variability of fatigue assessment using $MF_D$. Ideally, if the trials are identical, no systematic variation is present and the values of $s_{trials}$ and SEM should coincide. Mathematically, SEM can be computed from the mean squared error (MSE) [10]:

$$SEM = \sqrt{MSE} \quad (1)$$

In a 2-factor general linear model with *n* subjects and *j* trials per subject, the MSE would be computed as:

$$MSE = SSE/[(n-1)(j-1)] \quad (2)$$

where SSE is the sum of squares error, which is the SS term remaining after removing the contributions of subjects and trials from the total SS across all measured scores.

The SEM can be used to compute a third metric, minimum detectable difference (MD), which defines the "difference needed between separate measures for the difference in the measures to be considered real" [10], and can be computed as:

$$MD = SEM \times z_{\alpha/2} \times \sqrt{2} \quad (3)$$

where α is defines the desired confidence level. In this work, we considered a 95% confidence level, thus $z_{\alpha/2}$ is 1.96.

Statistical Analysis

A one-way repeated measures ANOVA (blocked by subject) was conducted on the $MF_D$ values from each condition of motion, with trials as the factor. The ANOVA facilitated the computation of the MSE term to calculate SEM using (1), and was also used to test for the presence of a systematic trial effect (e.g., a learning effect).

A value of $s_{trials}$ was calculated for every subject and condition pair. To compare repeatability between the conditions of motion, a paired t-test was conducted on the pairs of static and cyclic values of $s_{trials}$ from each subject (equivalent to a one-way repeated measures ANOVA on values of $s_{trials}$ with condition of motion as a factor).

All tests were interpreted at a 5% significance level.

## RESULTS

Figure 2 shows the raw data values and mean +/- $s_{trials}$ for $MF_D$ of each subject and condition of motion. Table 2 summarizes the results in terms of the three repeatability metrics for each condition of motion.

Static $MF_D$ showed a significant trial effect (p-value = 0.0149 < 0.05) but cyclic $MF_D$ did not (p-value = 0.4377 > 0.05). However, a post-hoc multiple comparison procedure revealed no significant differences between any pairs of trials for static $MF_D$. Results from the ANOVA comparing static versus cyclic repeatability in terms of $s_{trials}$ also showed no significant difference (p-value = 0.3607 > 0.05).

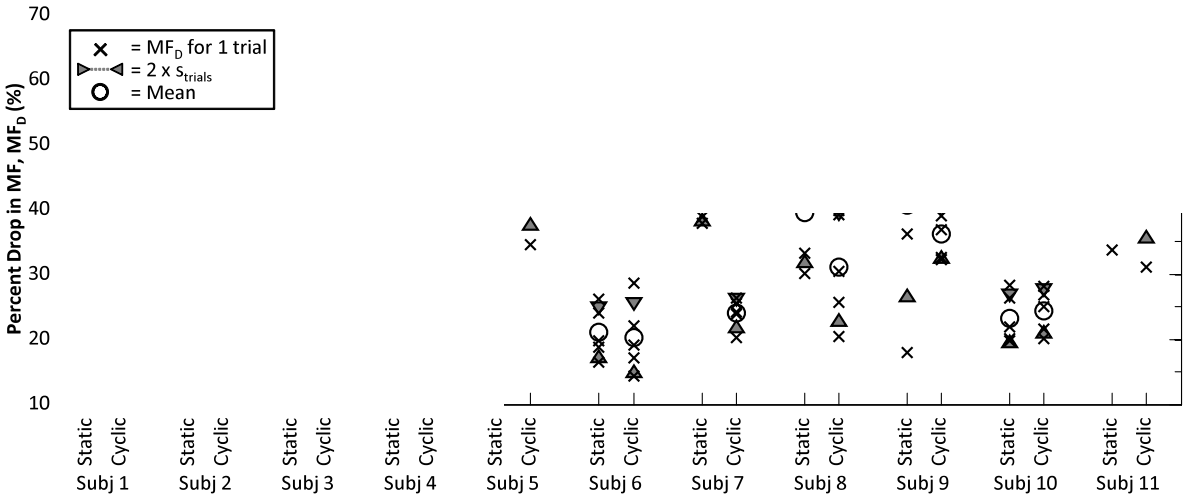


Figure 2: $MF_D$ raw data for static and cyclic conditions, showing mean +/- 1 standard deviation

Table 2: Repeatability of $MF_D$ expressed in 3 absolute metrics

| Repeatability Metric | Static $MF_D$ | Cyclic $MF_D$ |
|---|---|---|
| $s_{trials}$ (as a 95% confidence interval) | [4.26%, 9.09%] (mean = 6.67%) | [3.96%, 7.50%] (mean = 5.73%) |
| SEM | 6.77% | 6.26% |
| MD (95% confidence) | 18.76% | 17.36% |

## DISCUSSION

Results in Figure 2 highlight how variable fatigue assessment results can be from subject-to-subject. The mean $MF_D$ values are different, as expected, but it also appears that the variability within trials is subject-dependent, as indicated by the different sizes of $s_{trials}$.

When visually comparing static to cyclic $MF_D$ for each subject, mean static $MF_D$ appears

higher than mean cyclic $MF_D$ for all subjects except subject 10. However, a visual comparison between each *pair* of static and cyclic results shows very similar $s_{trials}$ – except for subject 9, who had one trial with an unusually low $MF_D$. This observation is confirmed by the paired t-test that indicated no significant difference between $s_{trials}$ for static and $s_{trials}$ for cyclic $MF_D$. This suggests that the (constrained) dynamic factors in cyclic motion do not introduce enough random variation into $MF_D$ values to influence their per cent drop with fatigue, as previously observed by MacIsaac [5].

The ANOVA revealed no systematic trial effect in cyclic $MF_D$, and a possible systematic trial effect in static $MF_D$, which was not confirmed by the pairwise post-hoc test. Likely, this is explained by a type I error in the ANOVA (possibly due to a violation of the homoscedasticity assumption), but regardless, the values of $s_{trials}$ reported represent a conservative estimate – they would be even smaller with all systematic variation removed. SEM is useful in this regard, since it estimates the random variation even in the presence of systematic variation. We see that the SEM of static $MF_D$ (6.77%) is very similar to that of cyclic $MF_D$ (6.26%).

A powerful way to use these results, especially for anyone who wants to practically implement fatigue assessment, is to consider the MD. SEM estimates the amount of expected error in a particular measurement, and MD extends this by defining how different two measurements would have to be for one to be confident that the difference is due to factors other than 'noise' (random error) in the measurements. The MD can help a clinical practitioner to evaluate the repeatability of an assessment strategy within a specific application of interest.

For example, a patient shows a cyclic $MF_D$ of 31% during his initial visit to the physiotherapist. The physiotherapist starts the patient on a particular exercise regimen. After two weeks of the intervention, the therapist conducts another $MF_D$ assessment and the new value is 20%. The obvious interpretation is that this is an 11% decrease in $MF_D$ thus the intervention must be having a positive effect since the rate of fatigue is now lower. However, the MD for cyclic $MF_D$ (at a 95% confidence level) is 17.36%. Since the difference is less than 17.36%, the therapist cannot be sure that the 11% decrease is not simply due to random error in the assessment rather than an improvement in the muscle performance. Note that depending on the situation, the therapist could settle for a lower confidence level, in which case the MD would be lower.

## ACKNOWLEDGEMENTS

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