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Effect of fatigue on the stationarity of surface electromyography signals

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ABSTRACT

The estimation of muscle fatigue using surface electromyography (SEMG) is of high relevance to evaluate ergonomic risk factors in the occupational settings. Signal stationarity plays an important role while selecting appropriate SEMG signal processing method for fatigue evaluation. The Fourier algorithm based signal processing methods (mean or median frequency of power spectrum) rely on the assumption that the signal under investigation is stationary. Stationarity of SEMG signals and its association with fatigue is rarely studied in the ergonomics literature. Therefore, this study was aimed at understanding the effect of fatigue on the stationarity of the SEMG data. Ten participants performed 40 min of fatiguing upper extremity exertions and SEMG data were recorded from the right upper trapezius muscle. The SEMG data recorded under static and dynamic conditions at the beginning and at the end of fatiguing exertions were used in the analysis. The stationarity analysis was performed for five window sizes of 128, 256, 512, 768 and 1024 ms using modified reverse arrangement test. The results showed that the muscle fatigue reduced the stationarity of the SEMG signal under static and dynamic conditions. The relationship between the muscle fatigue and the stationarity of the SEMG signal was found to be significant at the window size of 512 ms. A significantly higher fatigue related decrease in the stationarity was observed during dynamic exertions compared to the static exertions.

Relevance to industry: The findings from the current study illustrate that the stationarity of SEMG signals could be used to quantify muscle fatigue under static and dynamic task conditions. These findings are useful to the ergonomic practitioners in conducting muscle fatigue estimation using SEMG.

1. Introduction

Neuromuscular fatigue is believed to be one of the precursors of work-related musculoskeletal disorders (MSDs) (Armstrong et al., 1993) and therefore precise fatigue estimation methods are essential for MSD prevention. Among various methods that are used to estimate the neuromuscular fatigue, surface electromyography (SEMG) is a preferred method by many ergonomists.

The changes in the frequency spectrum of the SEMG signal, i.e., a shift in the mean or median frequencies toward lower values or a change in the power of the low and high frequency components, are used as the common indicators of muscle fatigue (Chowdhury et al., 2013; Shankar et al., 1989; Kumar and Narayan, 1999; Pau et al., 2014; Nussbaum, 2009).

The fast Fourier transform (FFT) or discrete Fourier transform (DFT) (Beck et al., 2006) algorithms are used to study the frequency spectrum of SEMG signals. These algorithms assume that the signal under investigation is stationary (Oppenheim et al., 1989; Bilodeau et al., 1997). A SEMG signal is said to be stationary if the average, variance, and frequency contents of the signal do not alter over time (Oppenheim et al., 1989; Blanco et al., 1995; Bendat and Piersol, 2000). In the case of non-stationary SEMG signals, the set of samples are statistically dependent and the mean, variance and frequency content of the signals change over time (Shwedyk et al., 1977; Beck et al., 2005).

Literature on the stationarity of SEMG signal is limited to how it is affected by selection of different window sizes. Cho and Kim (2012) reported that the stationarity level of the SEMG signal is significantly affected by the choice of window size. The authors observed a higher stationary level at a window size of 750 ms compared to the window sizes of 250, 500, 1000 and 2000 ms for

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the erector spinae muscles during 0%, 25% and 50% MVC levels. In another study, Waly et al. (2003). investigated the effect of window sizes (64, 128, 256, 512, 1024, 2048, and 4096 ms) on the frequency characteristics of the SEMG signal during sustained isometric exertions performed at 25%, 50%, and 100% MVC levels. The authors recommended that a window size smaller than 250 ms should be avoided in order to eliminate high variability in the spectral estimation of the SEMG data. For the window size of 500–1000 ms, the SEMG signal recorded from the bicep-brachii muscle during isometric exertions at 50% MVC was reported to be stationary by Inbar and Noujaim (1984).

In addition to the window size, fatigue, can also affect signal stationarity due to the time-dependent variation in the SEMG produced by altered motor unit recruitment pattern. However, no previous study has evaluated relationship between SEMG signal stationarity and muscle fatigue due to work-related exertions. This study was aimed at understanding the effect of muscle fatigue on the stationarity of the SEMG signal. It was hypothesized that the fatigue would affect the stationarity of the SEMG signal. The reverse arrangement test, and modified reverse arrangement test have been used in the past to evaluate the stationarity of the SEMG signals (Beck et al., 2006; Cho and Kim, 2012). Cho and Kim (2012) suggested that modified reverse arrangement test as the modified type of reverse arrangement test, was more conservative method in judging SEMG signal stationarity. Thus, the modified reverse arrangement test was used to study the stationarity of the SEMG signals in this study.

2. Methods

2.1. Approach

A lab-based experiment was performed to generate neuromuscular fatigue by simulating arm exertions. The exertions involved repetitive transferring of small loads from fingertip height to eye-height while the subject was in a standing position. These exertions required repetitive elevation and abduction of the right shoulder and arm. The SEMG data were recorded from the right upper trapezius muscle.

2.2. Participants

Ten healthy male subjects were recruited for the data collection. The average age, mass, and height of the subjects were 27 (±4.8) years, 71.1 (±9.3) kg, and 170.2 (±11.1) cm, respectively. The subjects were free from any type of musculoskeletal disorders and had no history of neck and shoulder injury. Before data collection, the experimental procedures were explained to the subjects, and their signatures were obtained on the consent forms approved by the local institutional review board.

2.3. Apparatus/tools

2.3.1. Electromyography (EMG) system

The EMG system used in this study consist of a 16-channel wireless transmitter (Telemyo 2400T), pre-amplified lead wires (CMRR>100 dB and input impedance > 100 MΩ), and disposable, self-adhesive Ag/AgCl snap electrodes (1 cm diameter, inter-electrode distance is 2 cm) (Noraxon, 2011). The bipolar electrodes connect to one end of the pre-amplified lead wires and the other end of the lead wires connect with the wireless transmitter. The SEMG data was sampled at a frequency of 1500 Hz.

2.3.2. Workstation

A custom-built workstation was used to perform repetitive arm exertions. This workstation consists of two adjustable work surfaces placed orthogonally with respect to the participant (Fig. 1). Thirty small cylindrical containers (diameter = 3.0 cm; height = 5.08 cm; weight = 50 g) were used to perform the repetitive exertions.

2.4. Experimental design

A two-factor experimental design was used. Factor 1, fatigue was treated at two fixed levels (non-fatigued and fatigued). As noted, repetitive exertions were used to induce fatigue. The muscle activity data recorded prior to or at the beginning of the physical exertions were treated as "non-fatigued" condition. The muscle activity data recorded at the end of the physical exertions were treated as "fatigued" condition. Factor 2, type of exertion was also treated at two fixed levels (static and dynamic). The SEMG data recorded during a static T-pose (90 degrees of arm abduction in frontal plane) prior to and after the completion of physical exertions were treated as the "static or isometric" condition. The muscle activity data recorded during repetitive arm exertions at the beginning and at the end of repetitive arm exertion were treated as the "dynamic" condition (Fig. 2).

2.5. Data collection

First, the experimental set-up, equipment, and data collection procedures were explained to the participants. Subsequently, the following stepwise procedure was used to collect the experimental data.

2.5.1. SEMG data collection preparation

The SEMG data from the right upper trapezius muscle were recorded by placing an electrode along a line joining the acromion and C7, at 1/3 the distance from the acromion process. Prior to the placement of the SEMG electrodes, the skin of the anatomical landmarks was shaved, abraded and cleaned with 70% alcohol.

2.5.2. Experimental procedure

Once the participants were instrumented with the surface electrodes, they performed three 10 s isometric reference exertions (90 degrees of arm abduction in frontal plane) (Fig. 2). Next, the participants performed repetitive stocking and un-stocking operations using the custom-built workstation (Figs. 1 and 2). The participant stood at a comfortable distance from the surface 1 and 2. The heights of the surface 1 and 2 were adjusted to the participant's fingertip and eye heights, respectively. During stocking operation, the participants manually transferred 30 cylindrical containers from surface 1 to surface 2 (Figs. 1 and 2). During unstocking operation, the containers were transferred back to surface 1. The stocking and unstocking operations were performed continuously for 20 min (session 1) followed by a rest period of 5 min. After the rest period, participants continued the same stocking and un-stocking operations for another 20 min (session 2). The SEMG data were recorded continuously during sessions 1 and 2. At the end of session 2, three repetitions of isometric reference exertions were collected. The participants were provided at least 1.5 min of rest period between any two isometric reference exertions as well as prior to the repetitive dynamic exertions. In addition, at the end of each session, subjective discomfort data in the right shoulder region were recorded using Borg's scale (Borg, 1982).

2.6. Data processing

The SEMG signals were processed using a custom-built Matlab script in MATLAB (R2011a, The Math Works Inc.) software. The

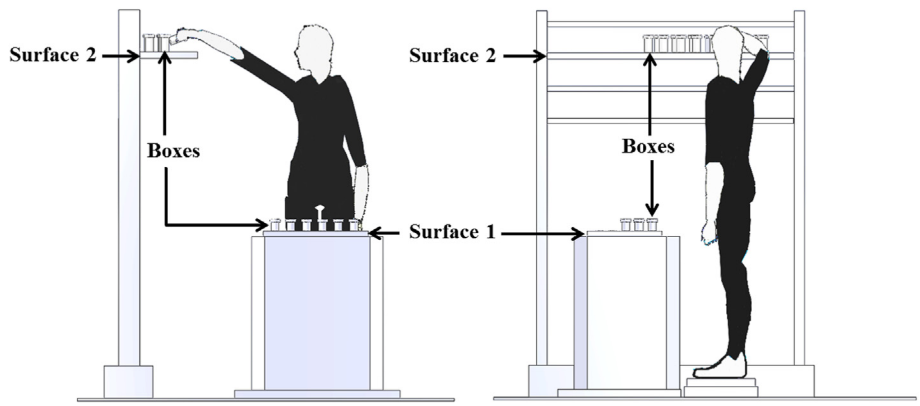

Fig. 1. The custom-built workstation used for the repetitive exertions.

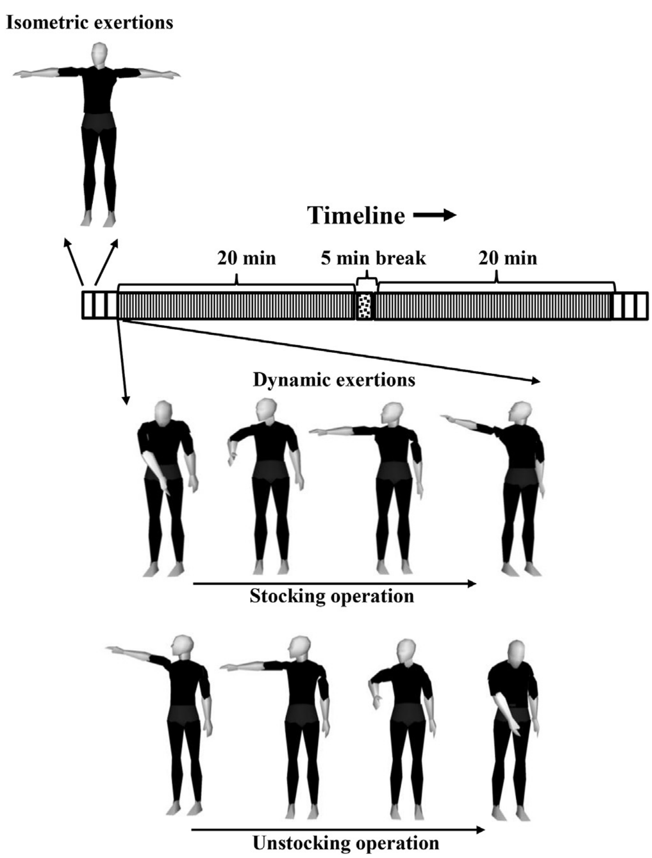

Fig. 2. Experimental timeline and type of exertions. Static exertions were performed prior to and after the completion of repetitive arm exertions.

SEMG data were filtered with a cut off frequency between 10 Hz and 400 Hz. The 60 Hz equipment noise and its harmonics were also attenuated. The SEMG data during isometric reference exertions recorded before session 1 were categorized as non-fatigued data. For dynamic exertions, data recorded during stocking operations performed in the 1st minute of session 1 were categorized as non-fatigued data. Similarly the SEMG data recorded at the end of session 2 (isometric reference exertions and the 20th minute of session 2) were categorized as fatigued data.

The SEMG data were further segmented into equal and non-overlapping segments using five window sizes: 128 ms (192 data points), 256 ms (384 data points), 512 ms (768 data points), 768 ms (1152 data points), and 1024 ms (1536 data points). The length of signal during each isometric reference exertion was approximately 15000 data points (10 s). The first 9216 data points (multiple of each window size) were selected for further analysis (Fig. 3). Three isometric reference exertions were treated as separate repetitions. During the repetitive dynamic exertions, the length of each stocking operation was approximately 2 s (3000 data points). The SEMG data during 9 consecutive stocking exertions (28,500 data points) were used for further analysis. Using a length of 9216 data points, this data was further divided into three segments, each treated as a separate repetition (Fig. 3).

Then, the modified reverse arrangement test was performed on the selected signal length using a custom-built Matlab script (R2011a, MathWorks, Inc.). The window sizes of 128, 256, 512, 768 and 1024 ms divided each segment of 9216 data points into 48, 24, 12, 8 and 6 sub-segments, respectively. Each sub-segment contains n data points $(x_1, x_2, \ldots x_n)$. The sub-segment was further divided into equal, non-overlapping intervals of 32 ms (48 observations) sub-windows $(x_1, \ldots, x_{48}; x_{49}, \ldots, x_{96}; \ldots \ldots; \ldots; x_{n-48}, \ldots, x_n)$. For each sub-window the mean square value (μ) was calculated. The reverse arrangement (A_i) was calculated by counting the total number of inequalities: $\mu_j > \mu_i$ for $j < i, where\, j = 1, 2, 3, \ldots, l-1$; $i = j+1, 2, 3, \ldots, l$; l = number of sub-windows.

The total number of reverse arrangement (A) of a sub-segment was computed by using the following equation:

$$A = \sum_{i=1}^{l} A_i. \tag{1}$$

The test statistics (z-score) was then calculated using Equation (2) (Kendall and Alan, 1961; Chau et al., 2005):

$$z = \frac{A - \left\lfloor \frac{l(l-1)}{4} \right\rfloor}{\sqrt{\frac{2l^3 + 3l^2 - 5l}{72}}} \tag{2}$$

Signal segment was considered stationary if the absolute value of test statistics were less than 1.96 $(\alpha = 0.05)$.

2.7. Statistical analysis

The percent stationarity was estimated using Equation (3).

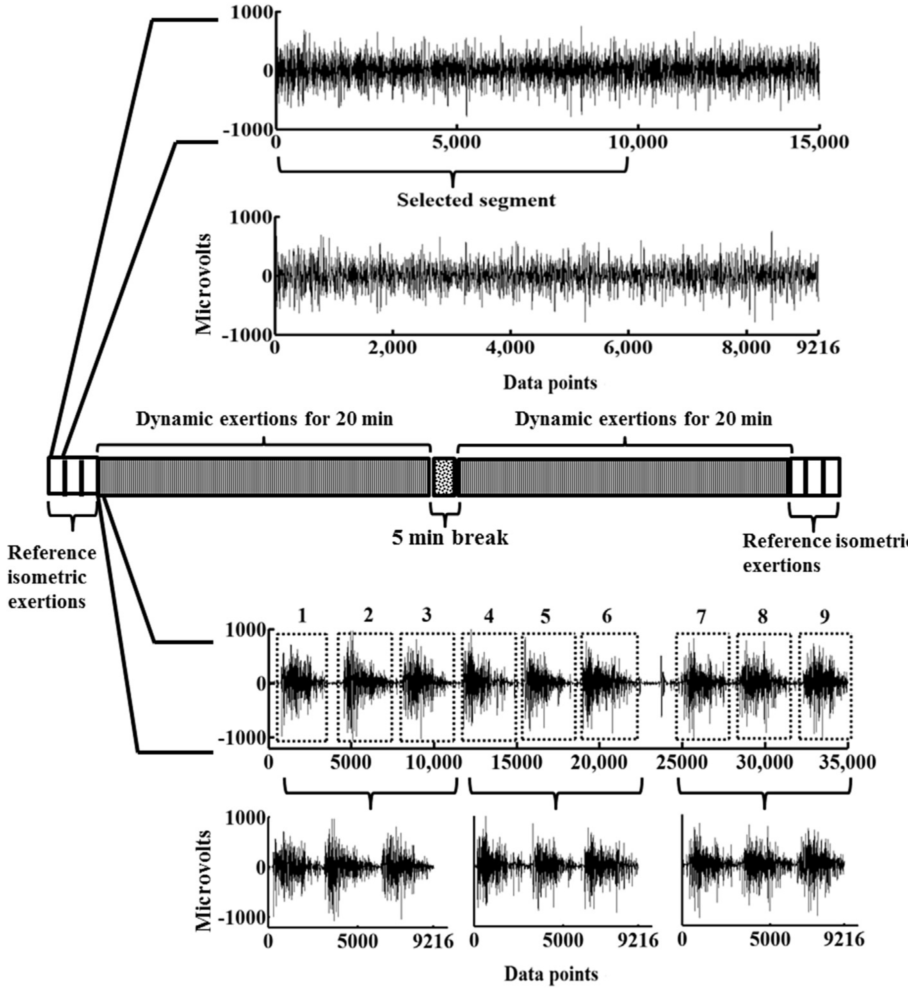

Fig. 3. Schematic representation of SEMG data segmentation.

$$\%Stationarity = \left(\frac{Number\ of\ stationary\ sub-segments}{Total\ number\ of\ sub-segments}\right) \times 100\% \quad (3)$$

The equality of variance and normality test for percent stationarity data demonstrated that the assumption of the homoscedasticity and normal distribution were true. Therefore, a general linear ANOVA was performed to evaluate the effect of fatigue and exertion on the stationarity of the SEMG signal. The fatigue and exertion were treated as fixed effects and the participants were treated as randomized block. Separate analysis was performed for different window sizes. The hypothesis was tested at a 95% confidence level in Statistical Analysis System version 9.2 (SAS Institute Inc.).

3. Results

The mean durations of stocking and unstocking operation for session 1 and 2 were 61.61(±2.32) s and 60.69(±2.39) s, respectively. On average, participants completed 19.5(0.71) and 19.8(0.79) stocking and unstocking operations during sessions 1 and 2, respectively.

3.1. Discomfort ratings

All the participants reported a baseline discomfort of 1 (= nothing at all) at the beginning of session 1. At the end of session 1, a mean discomfort of 5 (1.2) (= moderate discomfort) was reported by the participants; and at the end of session 2, a mean discomfort of 7 (0.6) (= some complicated discomfort) was reported by the participants.

3.2. Stationarity test result

A significantly higher stationarity of SEMG data was observed for isometric exertions compared to dynamic exertions for all window sizes ($p < 0.01$) (Table 1 & Fig. 4). Signal stationarity decreased with the increase in the window sizes. It was more prominently observed for the dynamic exertion signals. A higher stationarity was observed for non-fatigued SEMG signals compared to fatigued SEMG signals during both isometric and dynamic exertions for all window sizes (Table 1 & Fig. 4). The significant differences in the stationarity of the SEMG signals due to muscle fatigue were observed for window sizes of 256 and 512 ms (Table 1). The interaction between the type of exertion and the muscle condition was only significant ($p < 0.01$) for window size of 512 ms. At this window size, the muscle fatigue decreased the

Table 1
Mean and standard deviation of the percent stationarity for the effect of exertion type and muscle condition. Statistically significant values are marked with asterisks (*).

Window size	Type of exertion		p-value	Muscle condition		p-value
	Isometric	Dynamic		Non-fatigued	Fatigued	
128	91.47 (1.75)	89.85 (2.42)	0.054	90.95 (1.66)	90.78 (2.41)	0.781
256	92.52 (2.11)	84.10 (4.57)	<0.001*	89.58 (3.26)	87.04 (3.85)	0.046*
512	92.59 (5.38)	59.57 (9.48)	<0.001*	80.25 (6.39)	71.91 (7.79)	0.002*
768	89.58 (5.80)	48.38 (11.73)	<0.001*	71.53 (7.22)	66.44 (6.46)	0.073
1024	88.89 (9.62)	43.83 (7.05)	<0.001*	67.28 (6.18)	65.43 (7.87)	0.633

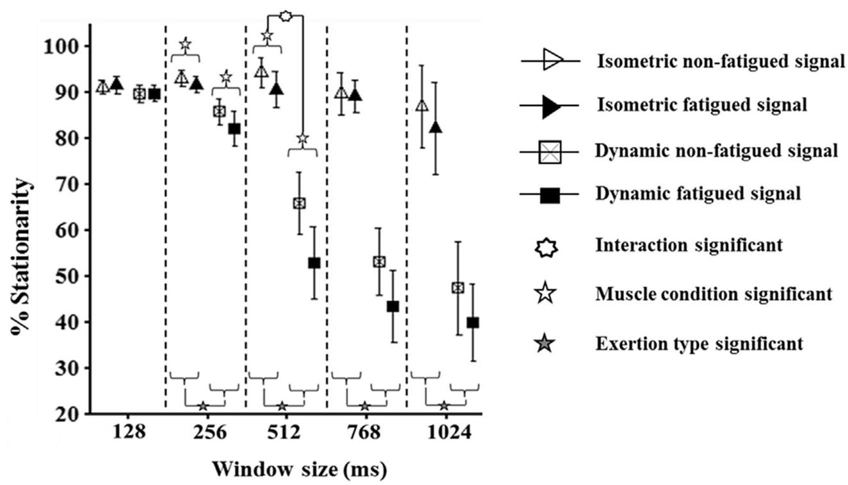

Fig. 4. The stationarity behavior of SEMG data for different window sizes, exertion type, and muscle condition. Error bar represents 95% confidence interval. Asterisks (*) represents a significant effect (P < 0.01).

stationarity by 3.92% during isometric exertion compared to 19.63% during dynamics exertion (Table 1 & Fig. 4).

4. Discussion

In this study, the relationship between muscle fatigue and the signal stationarity were tested using five different window sizes. Modified reverse arrangement test was used to study signal stationarity. The results demonstrated that muscle fatigue affected the stationarity properties of the SEMG signals. A decreased stationarity was observed under fatigued condition for both the exertions. Under fatigued condition, changes in the concentrations of calcium ions (Ca^{2+}) and lactic acid negatively impact muscle fiber excitation-contraction coupling (Kurebayashi and Ogawa, 2001; Allen, 2004). Increased motor unit firing rate is therefore required to maintain similar force exertion levels (Vukova et al., 2008). This induces higher time-dependent variation in the amplitude of the SEMG signal resulting in larger reverse arrangements and thus reduced stationarity. During dynamic exertions, the motor unit recruitment is further augmented by the increased conduction velocity under fatigued condition and therefore a higher decline was observed for the dynamic exertions.

The stationarity of the SEMG data were also affected by the type of exertion. Higher non-stationarity was observed for the dynamic exertions compared to the isometric exertions. It is likely that SEMG signals of isometric exertions would be stationary since the physiology of the neuromuscular system such as the neural input and blood or oxygen supply to the muscle remains relatively stable (Hefftner et al., 1988). On contrary, the muscle force, length, and velocity change continuously during dynamic exertions. These changes alter the motor unit recruitment pattern to trigger time-dependent variation in the amplitude of the SEMG signal. The stationarity test method measures these variations in terms of larger reverse arrangements and thus showed a reduced stationarity for the dynamic exertions compared to the isometric exertions.

It was also observed that the variability associated with the percent stationarity was dependent on the window size. A much higher variability was observed for a window size of 1024 ms compared to smaller window sizes of 128 and 256 ms. A longer window size (record length) may incorporate more force fluctuation than shorter window sizes contributing to the variability in the signal stationarity. A shorter window size (record length) can overcome such force fluctuation causing less variability. However, shorter window size may not sufficiently capture the spatiotemporal trend in the SEMG data for accurate or complete assessment of the muscle fatigue during isometric and dynamic muscle exertions (Bendat and Piersol, 2000; Inbar and Noujaim, 1984). Thus, a choice/selection of window size is critical for stationarity and SEMG based fatigue estimation.

At the window sizes of 256 and 512 ms, a significant reduction in the stationarity was observed due to muscle fatigue for both isometric and dynamic exertions. A window size of 512 ms differentiated the muscle conditions (type of exertion, fatigue) more precisely in terms of SEMG signal stationarity than other window sizes. A significant interaction was observed between the type of exertion and fatigue at the window size of 512 ms. At the other smaller (128 ms) or larger (768, 1024 ms) window sizes studied in this paper, the SEMG signal stationarity was different between the type of exertion without any effect of muscle fatigue. Thus, a window size of 512 ms could be a reasonable window size to measure signal stationarity to investigate muscle fatigue development. In a study by Waly et al. (2003), a similar observation was made about the window sizes. The authors (Waly et al.) recommended that a window size of 512 ms should be used to estimate the effect of muscle fatigue when longer records are used to estimate the power spectrum.

There are several limitations which should be considered while interpreting the findings of this study. First, only male participants were used in this study. Females have higher fatigue resistant type I fibers (slow twitch) compared to males and therefore it is possible that the females may exhibit different post fatigue SEMG signal patterns. Accordingly, for the females the stationarity behavior may not follow the trend observed in this study. Future studies should include both male and female populations. Second, physical motion during the repetitive task was not studied. It is possible that the participants may have altered their posture or lifting style due to the fatigue. A study of postural kinematic may provide additional cues regarding the influence of postural factors on the stationarity of the SEMG signals. Future studies should also evaluate the stationarity behaviour as a possible measure of muscle fatigue under different task conditions for different muscle groups.

5. Conclusions

In conclusion, fatigue was found to affect the stationarity of the SEMG signal. A reduction in the stationarity was observed with the development of fatigue. Higher stationarity was observed during isometric exertions compared to the dynamic exertions. A window size of 512 ms displayed better signal stationarity trends compared to other window sizes. Overall the study findings conclude that stationarity of SEMG signal could be used as a possible fatigue quantification method.

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