Assessment of Localized Muscle Fatigue for Industrial Task Evaluations

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Abstract

Localized muscle fatigue (LMF) has received a growing interest. Local fatigue is associated with an increased risk of musculoskeletal injury. A number of studies have been conducted in this area to investigate the following issues. How can fatigue lead to musculoskeletal disorders? What are the fatigue internal precipitating mechanisms? What factors affect fatigue (individual factors as well as task factors)? How to assess the development of LMF while performing a task? How LMF can be used for industrial task evaluations? From industrial relevance point of view, the last question appears to be interesting. It is true since reports have documented a number of interventions as a result of LMF studies including evaluations of task procedure, working tool, work-rest schedule, working shift, and etc. However, there are some challenges for further interventions pertaining to limitations of current LMF assessment methods. The present paper elaborates several fatigue measures for monitoring development of LMF, and their current limitations. In conclusion, there is an ongoing need to find better fatigue measures. More effective industrial interventions can be expected if more reliable and sensitive measures can be obtained.
Keywords: Localized muscle fatigue, Musculoskeletal disorders, Fatigue measures

1. Introduction

Costs associated with musculoskeletal injuries and disorders at workplace are still high. In an industrialized country such as USA, according to it's Bureau of Labor Statistics, there were over 520 thousands cases of work related musculoskeletal disorders (WMSDs) with days away from work, accounting for about 34% of total number of injuries and illnesses. Annual costs of WMSDs in this country were estimated to be $45.8 billion, or nearly $1 billion per week (Liberty Mutual Research News, 2003). Much higher figures are predicted in developing countries, including Indonesia. This fact should remain as a main concern for Indonesian ergonomist.

WMSDs appear to result from complex interactions among numerous causal mechanisms. Based on epidemiological studies, physical workload, repetitiveness, and static effort are among the main risk factors mentioned for several disorders. Since these biomechanical factors are closely related to fatigue, localized muscle fatigue (LMF) has been used as a surrogate measure of WMSDs. Reports have documented that workers performing fatiguing tasks have a variety of adverse outcomes, such as chronic rotator cuff tendonitis, trapezius myalgia, and cervicobrachical disorder. Though remained exactly unknown, several theories have also been mentioned that describe causal role of fatigue in WMSDs, including myalgia, increased pressure around peripheral nerves leading to chronic nerve compression, ischemia-reperfusion injury, and overload in "Cinderella" motor units that can occur along with or subsequent to fatigue.

2. Concept of LMF

Physical fatigue is a common phenomenon. We feel fatigue physically while performing a work or an exercise or any daily activity, more specifically for that with demanding or prolonged efforts. There are two types of physical fatigue, which are whole body or localized. The latter is the focus of this present paper, due to its effects localized to a specific group of muscles. The term of "localized muscle fatigue (LMF)" has been introduced by Chaffin in 1973. Several definitions have also been proposed by him and other investigators that can be concluded as association of LMF with a decrement in muscle generating capacity.

Fatigue should be differentiated from endurance. Fatigue is a gradual process, while the latter is associated with a capability limit to maintain a certain effort. Since fatigue gradually develops, investigators have interested in observing physiological, biomechanical, and biochemical changes associated with fatigue. A number of studies have been directed toward understanding its internal mechanisms, factors affecting fatigue, fatigue measures and etc. Imagine that if fatigue process and its magnitude can be well predicted as well as its impacts on human performance. This should be part of our interest as ergonomist. Such information can then be used for industrial task design and evaluation.

Author's previous studies have touched two research issues in the area of LMF, which are 1) effects of personal factors (more specifically, aging and gender) as well as task parameters on fatigue during static and intermittent-dynamic efforts, 2) fatigue measures during low-level contraction (Yassierli et al. 2007; Yassierli and Nussbaum, 2007; 2008a; 2008b). Low-level effort and dynamic contractions were chosen due to its relevancy to industrial settings, including office works, assembly works, and etc.

Localized muscle fatigue may develop even during low level efforts (Yassierli and Nussbaum, 2008a). A number of studies have observed the occurrence of muscle fatigue (measured via muscle activities, strength reduction, and subjective assessment) during low level contraction, though the muscle was found to have adequate blood flow supply, for example. From a neuromuscular perspective, fatigue at low-level effort seems to be more affected by a failure in peripheral processes than by central failure system. Note that central fatigue is characterized by a reduction in voluntary muscle activation due to a lack of adequate central nervous system (CNS) drive to the motoneuron pool. Regardless of the adequacy of excitatory impulses, peripheral fatigue is accompanied with a failure in the contractile ability within a muscle. The peripheral process involves activation of the surface membrane, propagation of action potential along the t-tubular system, release of calcium (Ca^{2+}), and activation of the contractile elements. Peripheral failure in the latter process, at the level of excitation-contraction (E-C) coupling, has been hypothesized as a main cause of fatigue during isometric contractions at low level efforts that can be associated with a reduction in Ca^{2+} release and an increase in intracellular Ca^{2+}.

3. Measures of LMF

Simply, fatigue is commonly associated with tiredness as its symptoms. It is also sometimes accompanied by declines in awareness and alertness. Biomechanically, the existence of fatigue can be predicted by capacity declines in certain muscles. Physiologically, fatigue is also associated with increases in heart rate, body temperature, and oxygen uptake. All of these symptoms have become simple measures of fatigue. In addition, several equipment have also been used to monitor fatigue such electromyography (EMG), mechanomyography (MMG), near-infrared spectroscopy (NIRS). Each has its own limitations and some of commonly used methods are discussed below.

Subjective Measure

Borg's CR-10 scale is one of the commonly used subjective measures in LMF study. Using the scale, an individual's perception of muscle fatigue or discomfort resulting from an exercise can be assessed. The score lies between 0 and 10. This is a simple, interesting measure. Some studies have found that the measure is highly correlated with objective measures, such as EMG or reduction in muscular strength (e.g. Yassierli and Nussbaum, 2008a). It should be noted that pain or other muscular discomfort may not necessarily correlate with the development of fatigue. In addition, due to its self-assessment method, this measure may be biased. In an experimental situation this limitation could be treated by carefully choosing participants (motivational aspect) and experimental protocols.

Strength decline

One of a widely used objective measure for fatigue, which is mentioned as a gold standard, is the time-dependent decline of an individual's maximum strength. Two similar terminologies have been used here, which are maximum voluntary exertion (MVE) or maximum voluntary contraction (MVC). To measure the MVE or MVC, a set of standard procedures have to be used, and a set of fixtures may be needed to strap certain parts of body and to make sure that only the target muscle exerted. However, this method may interrupt task being studied. Figure 1 shows an example of a fixture built to measure MVE of the middle deltoid muscle during arm abduction while lower and upper arms are horizontal (Muslim, 2007). The test was performed before, after, and at certain time interval while performing the task.

Surface EMG

To date, surface EMG has been used extensively in examining localized muscle fatigue. Though precise relationships between EMG and physiological changes within the muscles are still being debated, changes in the EMG signals are typically associated with fatigue development. The changes include an increase in the EMG amplitude and a shift in spectral measure. The former is probably an indication of increased motor unit recruitment and/or firing rate, while the latter is claimed, in part, to result from a decline in the muscle fiber conduction velocity (MFCV) due to a decrease in intracellular pH and accumulation of extracellular potassium.

It is worth noting that applications of EMG have resulted in a number of valuable interventions. EMG has been applied as a parameter for better design of hand tools and posture and workstation design. EMG has also been used to determine acceptance criteria of muscular loads for job design and to estimate time-to-fatigue while working. In the clinical setting, EMG-fatigue analysis has been used in physical rehabilitation, monitoring muscular strain and fatigue on surgeons, diagnosis of muscle impairment, and prediction of functional and endurance deficits.

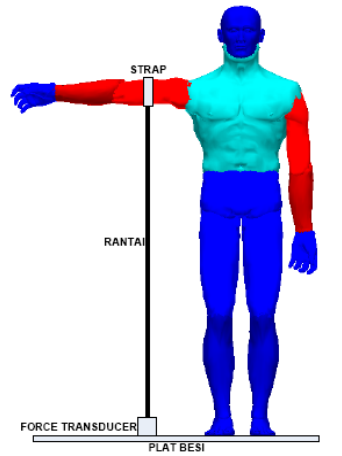

Figure 1. Example of a fixture built to conduct MVC test in measuring fatigue while performing a simulated knitting works

The utility of EMG-based measures, however, seems to be affected by the type of contractions performed. The two mentioned measures have shown inconsistent changes for dynamic efforts and during low level efforts. The reason is that stationarity, a requirement for standard spectral analysis (i.e. fast-Fourier transform, FFT), has been questioned for dynamic EMG due to modulations of muscle force, length, and velocity during movement.

Yassierli and Nussbaum (2008a) proposed a different approach in analyzing EMG data. It was argued that one possible reason for less effective use of existing EMG measures to indicate fatigue is that the measures seem to inadequately characterize EMG signals. Therefore, a non-linear method (i.e. fractal analysis) was used. Mandelbrot coined fractal from the Latin adjective fractus meaning irregular, fragment or fraction. The essential characteristic of fractals is ‘self-similarity’, meaning that the properties of the pieces are similar to those of the whole. Many biological structures can be regarded as natural fractals such as the vascular tree, the bronchial tree, and the renal glomerulus. The results showed that this method seems to be promising as an alternative EMG-based fatigue measure, even though further study is still need to apply this method in different task conditions. Figure 2 and 3 illustrate fractal characteristics of EMG signals and their time-dependent changes due to fatigue.

a. b.

Figure 2. EMG signal taken from an isometric exertion shows fractal characteristics (similarity at different scales) a) original EMG signal, and b) averaged signal of 10-consecutive data points

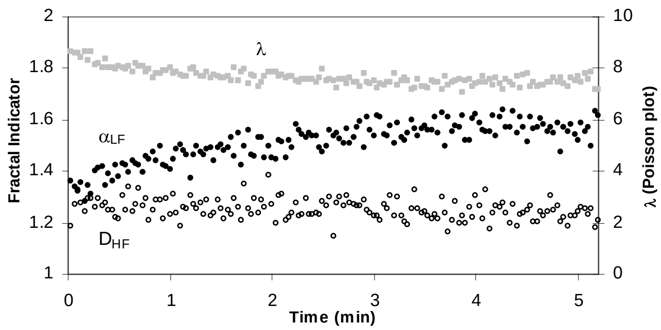

Figure 3. Sample time-dependent changes of different fractal-based EMG indices

4. LMF and Industrial Task Evaluation

How a LMF study can benefit to industries? Fatigue should be considered as an important factor in task design and evaluation. Fatigue is accompanied with declines in work capacity as well as alertness, awareness, and willingness to work. After working in a certain period of time during a fatiguing task, decreases in productivity and quality of work should be expected. The industrial designer should then decide at what level the fatigue is acceptable and when it happens (called as time to fatigue). This issue continues to be interesting.

LMF study can be used for determining work-rest schedule. Muslim (2007) and Yassierli and Nussbaum (2008b), for example, investigated two different work-rest conditions (shorter and longer cycle durations) during knitting tasks and back flexion-extensions, respectively. Results of the study suggested that shorter cycle durations result in slower fatigue development. Of course, this guideline is unique for different task situations.

LMF study can also be used to quantify workers' capacities. Yassierli et al. (2007) and Yassierli and Nussbaum (2007; 2008b) compare muscle capacities of younger and older individuals, in terms of strength, fatigability, endurance, and ability to fully recovered. The studies also recommended some guidelines for task design. For example, effort level at 30% of maximum strength seems to be the limit for intermittent lifting works at duration of up to one-hour. Additional 10% load above this level would reduce the endurance time about 30-40%

Finally, LMF can be used as justification for ergonomic interventions. This approach is much better than using only subjective feedback such as Nordic Questionnaire. Comparing two different tasks (before and after intervention for example), one with slower fatigue development can simply be justified better. Better means more ergonomic, more efficient, and more productive.

5. Conclusions

Studies on localized muscle fatigue have resulted in a number of interventions that provide benefits for industries. The key for further intervention depends upon ability of investigators to come up with better fatigue measures that should be applicative, reliable, and sensitive to fatigue at different task conditions. Industrial tasks are characterized by complex contractions. Among commonly used measures, subjective measures such as the Borg scale seem to be simple, but could be biased. MVE test requires a specific target group of muscles, and may interrupt task being investigated. EMG-based fatigue measures seem to be promising, though need for further investigation. Further studies are needed to improve the existing fatigue assessment methods.

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