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Abstract- Myoelectric signal remains the gold standard to objectively monitor muscular activities despite the tedious task of separating cross talk from contractions. This work evaluated the signal characteristics during FES-evoked contractions in muscle force and fatigue assessment to reiterate its inherent setbacks despite overwhelming research efforts to improve its signal to noise ratio. It was observed that researchers often had to tradeoff either i) aesthetic and compact design for complex electrical circuit to remove noise and ii) transcutaneous for invasive percutaneous stimulation to eliminate stimulus artifact in order for characteristic M-wave of evoked EMG to be significant in FES evoked contraction analysis. We aim to stimulate researchers’ interest to investigate alternative and robust paradigms myoelectric signal analysis and future applications of FES system to gain expected acceptance in clinical settings and outdoor activities.

I. INTRODUCTION
According to De Luca; “myoelectric signal-EMG is an electrical manifestation of the neuromuscular activities associated with a contracting muscle. It is an exceedingly complicated signal which is affected by the anatomical and physiological properties of muscle, the control scheme of the peripheral nervous system, as well as the characteristics of the instrumentation used to detect and observe it.” [1]. No matter the source, typical myoelectric signal is inherently embedded in noise of large amplitude and low frequency thus hindering attempts to quantitatively estimate muscle activities despite the wide research attention on the signal [2]. The signal is rich in muscle activation information that is essential in understanding normal muscle activities and neuromuscular abnormalities [3]. The myoelectric signal obtained during FES evoked exercise with characteristic waveform termed M-wave from the muscle is called evoked electromyogram (eEMG) [4].

II. APPLICATION OF MYOELECTRIC SIGNAL
A. Muscle Force Assessment
Myoelectric signal is used to analyze muscle force production/torque relationship with onset of fatigue during voluntary muscle contractions and restoration of functional movement in paraplegic patients through FES evoked muscle contraction. Understanding the initiation of movement in animals and central role of muscle forces is necessary to enhance our understanding of muscle activity during functional movement [5].

Due to the importance of muscle force quantification, Lippold, in 1952, hypothesized that some muscles supporting load isometrically showed a linear and quantitative relationship between applied force and amplitude of electromyogram under a certain limited condition of muscle voluntary contraction. He suggested that future studies should verify other conditions of muscle at which the relationship observed will hold [6]. Earlier before Lippold’s observation, Adrian & Bronk in 1928 [7] had reported that such linear relationship was lacking in the motor nerve of muscle elicited artificially by supramaximal stimulation because all motor units are active and produce a constant electrical signal output. Contraction muscle strength may also vary with other factors like frequency of stimulation, initial tension of the muscle, etc. More recently, Dideriksen and colleagues in 2010 verified EMG inability to predict muscle force once the contraction shows indication of fatigue [8].

Muscle force quantification is of paramount importance in FES application. Currently, the quantification of muscle strength using EMG signal parameters is well appraised, although not yet fully evolved [5] due to particular unresolved issues of overwhelming artifact and cross talk from different sources, as well as the inability to adequately detect synergistic muscle involved in force generation [5]. Lack of consensus regarding the pattern of relationship between EMG and muscle strength is said to be due to inherent limitations of EMG. Furthermore, muscle contraction force originates from the global activity of the underlying muscle fibers whereas surface electromyogram (EMG) only registers information about the electrical activities of motor units located around the site of the detection electrode, and as such, the site of electrode does not covers sufficiently the entire muscle area and thus unable to detect the whole generated signal [9].

B. Muscle Fatigue Assessment
Another area of applications of myoelectric signal is the detection of fatigue. Muscle is said to be fatigued once it
cannot keep the contraction, and may even lead to muscle failure [10]. The first initiative to study the relationship between EMG and muscle fatigue was taken by Piper in 1912 [11] when he noted that the frequency component of surface EMG decreased once the muscle contraction is sustained. Other researchers then built their research around Piper’s observation and noticed the shift in frequency of EMG waveform with fatigue development and also observed steady increase in EMG amplitude recorded with surface electrode [12]. In 1981, Edwards defined fatigue as the incapability of muscle to sustained a required force [13]. Consequently, some researchers have used power, force as direct measurement of muscle fatigue, while some have explored, fatigue detection using the aforementioned variables and electromyogram [14]. However, Miriam and co-researchers stated that a model which combines changes in surface electromyogram variables and power loss failed to map muscle fatigue, especially after the strength training exercise. They also suggesting a better performance with a paradigm that is unaffected by ambulation [14].

I. OBSERVATIONS

The clear evidence of small percentage of individual with neurological impairment that are using FES despite its well appraised application in assistive technology shows that the technology has not gained expected acceptance [15]. Accurate prediction and estimation of electrically evoked muscle force that is currently lacking in the conventional design is pertinent to the efficient control of a FES assistive scheme [15]. M-Wave, which was first observed by Stefancic et al., (1986) [16], often called compound action potential, has been studied to be the characteristic repetitive waveform emanating from synchronous firing rate of all the motor units in response to electrical stimulation when myoelectric signal during FES application is analyzed [17]. In effect, stimulation of paralyzed muscle by FES is reflected by the appearance of M-wave and can be detected as evoked EMG, although, it is often preceded by stimulation artifact [18], thus making subsequent analysis with the resulting signal more challenging.

A. Transcutaneous versus Percutaneous stimulation electrode

In 1992, Merletti and his group observed that; once the surface stimulation and detection technique are used in FES analysis, then stimulation artifact becomes a major issue but when the implanted stimulation electrodes are used for stimulation the artifact effects will be minimal [17, 19] and easier to eliminate [19, 20]. Accordingly, other researchers subsequently conducted fatigue induced protocol on SCI patients, and they were able to verified that; implanted stimulation (percutaneous) has a stimulation parameters and output torque relationship with better stability when compared with external stimulation i.e. transcutaneous due to the variability of surface electrode placement on muscle belly in external stimulation [21] and EMG signal contamination by stimulation artifact due to FES stimulation current that is wrongly recorded by EMG amplifier [22]. In addition, the magnitude of current produced by stimulation is more than that of motor unit action potentials; the stimulation artifact will therefore overwhelm the EMG signal during recording [20]. Equally, in neural stimulation; there is no stimulation artifact as we have in surface stimulation since the site of stimulation and target muscle are far apart [21]. However, another issue to contend with in some implanted stimulation scheme is the issue of radio frequency (RF) which is the means of communication between the stimulator and the implanted electrode. RF can readily interfere with desire eEMG signal (being electrical in nature) and this will necessitate an arrangement of artifact removal circuit as verified by Chesler & Durfee [23]. Another weakness of eEMG observed by Qin and co-researcher was that; the eEMG and torque trend change differently for different subjects. Although there are no explanations so far in the literature for this observation [24].

B. Efforts into Assessment of Electrically Evoked Contractions

Electrical stimulation is drawing increasing attention due to its ability to enhance muscle function through activation of paralyzed muscles [25], to reduce the complications of secondary ailment [26], among others. The potential of electrical stimulation to activate fast motor unit even at relatively low force level makes it relevant in clinical applications [27]. The major difference between electrically evoked and voluntary contraction is rapid fatigue in the former [28] and the critical need to remove stimulation artifact in the evoked EMG signal of electrically evoked contractions [37]. Table I below summarizes the relationship between evoked EMG with muscle force/torque and fatigue development. It shows clearly that for stimulation artifact to be minimal, stimulation approach has to be invasive. It is also an evidence to support the view that more research efforts is required to correlate muscle contractions to force and fatigue development to detect muscle fatigue indices accurately and non-invasively.
Table I: Summary of relationship between EMG (voluntary and evoked) with muscle force and fatigue development.

<table>
<thead>
<tr>
<th>Author, Year</th>
<th>Objective</th>
<th>Nature of Subject: Sample Size</th>
<th>Method of FES Stimulation</th>
<th>EMG Electrode Placement</th>
<th>Methodology</th>
<th>Conclusion</th>
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<tr>
<td>Chesler &amp; William, 1997 [29]</td>
<td>To apply EMG as an indicator of fatigue in an electrically evoked muscle contraction.</td>
<td>HV: 20, SCI: 3</td>
<td>Transcutaneous</td>
<td>Surface</td>
<td>Isometric fatigue experiment with the adoption of (Khaflitz et al., 1988) stimulation approach of quadriceps. Intramuscular stimulation of vastus lateralis was adopted. Cybex II dynamometer was employed to measure isometric knee torque, while the Subject was sitting with hip flexed at approx.90° and thigh was secured with a retraining strap.</td>
<td>Authors indicated that EMG could not be used as practical FES control signal due to the ambiguity in stimulation artifact suppression. Due to different site of stimulation and signal detection, artifact was controlled with the aid of a special artifact balancing. The approach is only viable if intramuscular electrode is used for stimulation and careful placement of surface electrode is ensured. However, the approach is invasive. Stimulation parameter and output torque in implanted stimulation was shown to be more stable than that of transcutaneous stimulation where quality of recruitment was affected by electrode location. Neutral stimulation was said to be more selective and poses much less stimulation artifact. Authors suggested future investigation of adaptive closed loop muscle force control application in implanted systems. The approach is through a surgical intervention. Despite eEMG signal (M-Wave) was carefully acquired by blanking window technique to avoid stimulation artifact. The authors were unable to explain the reason for the different eEMG-torque trends observed for different Subjects. They further proposed that future studies should explore their approach for real time identification and adaptive control of FES. Authors concluded that eEMG could not predict muscle fatigue during FES-cycling. Although, they suggest further investigations due to consistency observed between M-waves and time-curve.</td>
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<td>Erfanian et al., 1998 [30]</td>
<td>To apply evoked EMG as a force sensor to electrically stimulated muscle.</td>
<td>HV: Nil SCI: 2</td>
<td>Percutaneous</td>
<td>Surface</td>
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<td>Mitsuhiro et al., 2011 [21]</td>
<td>To monitor muscle state and access its response to improve the conventional FES system to have an adaptive force-torque control to manage muscle fatigue.</td>
<td>HV: Nil SCI: 1</td>
<td>Implanted (Neural and Epimysial) electrode</td>
<td>Surface</td>
<td>Isometric ankle dorsiflexion torque was measured with a calibrated dynamometer. Evoked EMG signal was recorded by surface electrode placed on the muscle belly of quadriceps.</td>
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<tr>
<td>Qin et al., 2010 [24]</td>
<td>To predict ankle planter flexion torque by exploiting stimulus eEMG during different muscle fatigue states to verify the feasibility of using eEMG as a synthetic force sensor when force measurement is lacking naturally.</td>
<td>HV: Nil SCI: 5</td>
<td>Transcutaneous</td>
<td>Surface</td>
<td>Surface electrode was used to stimulate right triceps surae muscle under isometric muscle condition. The experiment consisted of three (3) sessions: (fatigue inducing test, fatigue recovery test and random test).</td>
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<td>Eduardo et al., 2011 [4]</td>
<td>To investigate if muscle fatigue during FES induced isokinetic cycling is associated with changes observed in evoked EMG signal in SCI subject.</td>
<td>HV: Nil SCI: 8</td>
<td>Transcutaneous</td>
<td>Surface</td>
<td>The quadriceps muscle of each SCI subject was electrically stimulated to enable cycling. Each subject performed FES cycling of 15 minutes with recovery time of 5 minutes.</td>
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<tr>
<td>Erfanian et al., 1996 [31]</td>
<td>To use evoked EMG signal to track changes in the torque generated at the knee</td>
<td>HV: Nil SCI: 1</td>
<td>Percutaneous</td>
<td>Surface</td>
<td>The experiment was carried out under isometric condition where the percutaneous intramuscular electrode is used to stimulate vastus lateralis muscle of a paraplegic patient. The knee was securely fixed at flexion angle of 30° and full extension angle 0°. Quadriceps muscle of each four spinal cord patients was selected for this study due to its role in standing and working, due to easy accessibility for stimulation and or measurement [18]. All measurement began from an unfatigued state, and for each subject and test; mechanical and myoelectric output response of the muscle were measure during an isometric condition.</td>
<td>The finding showed that fatigue analysis demonstrated high correlation between excitation fatigue and contraction fatigue of electrically stimulated muscle. The author concluded that: the linear and quasi-linear eEMG representation of muscle fatigue may be inadequate. However, the approach was also invasive. They concluded that; since fatigue in evoked muscle contraction is due to temporary changes within the myofilbers and thus eEMG amplitude may not be able to reflect force response. Accordingly, despite a separate circuit designed to suppress stimulation artifact which also led to another form of noise called (electrode offset potential of higher magnitude than M-Wave), the design could still not be applied for patient’s ambulation FES control. The authors suggested that future studies should consider other paradigm that could correlate force with fatigue development accurately.</td>
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<td>Mizrachi et al., 1994 [18]</td>
<td>To study the relationship between muscle force and EMG activity during evoked muscle contraction, in effect to verify the condition at which surface EMG can be used as noninvasive predictor of muscle fatigue.</td>
<td>HV: Nil SCI: 4</td>
<td>Transcutaneous</td>
<td>Surface</td>
<td></td>
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Note: HV: Healthy Volunteer, SCI: Spinal Cord Injury Patient
CONCLUSION

The need to investigate alternative signal to access muscle force and fatigue is highlighted. There is an agreement on the efficacy of the implanted stimulation over surface stimulation if significant output is expected in FES applications. Quantitative monitoring of fatigue is essential to FES application for individuals without sensory feedback to delay fatigue naturally. Concerted effort is recommended for mechanical signal alternative paradigm such as mechanomyogram and tensiomyogram as against electrical artifact inherent in eEMG signal. If achieved it can be integrated into the conventional FES system to serve as the modulating signal to set the stimulation parameters to delay muscle fatigue for patients' beneficial ambulation and applications in geriatric medicine and sports.

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