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Review

EMG amplitude, fatigue threshold, and time to task failure: A meta-analysis

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ABSTRACT

Objectives: Electromyographic (EMG) fatigue threshold (EMG_{FT}) is utilised as a correlate of critical power, torque, and force thresholds that establishes a theoretical exercise intensity—the power, torque, or force at which the rate of change of EMG amplitude ($\Delta\overline{EMG}$) is zero—below which neuromuscular fatigue is negligible and unpredictable. Recent studies demonstrating neuromuscular fatigue below critical thresholds raise questions about the construct validity of EMG_{FT}. The purpose of this analysis is to evaluate the construct validity of EMGFT by aggregating $\Delta\overline{EMG}$ and time to task failure (T_{lim}) data.

Design: Meta-analysis.

Methods: Database search of MEDLINE, SPORTDiscus, Web of Science, and Cochrane (inception – September 2016) conducted using terms relevant to EMG and muscle fatigue. Inclusion criteria were studies reporting agonist muscle EMG amplitude data during constant force voluntary isometric contractions taken to task failure. Linear and nonlinear regression models were used to relate $\Delta\overline{EMG}$ and T_{lim} data extracted from included studies.

Results: Regression analyses included data from 837 healthy adults from 43 studies. Relationships between $\Delta\overline{EMG}$ and T_{lim} were strong in both nonlinear ($R2 = 0.65$) and linear ($R^2 = 0.82$) models. $\Delta\overline{EMG}$ at EMG_{FT} was significantly nonzero overall and in 3 of 5 cohorts in the nonlinear model ($p < 0.01$) and in 2 of 5 cohorts in the linear model.

Conclusions: EMG_{FT} lacks face validity as currently calculated; models for more precise EMG_{FT} calculation are proposed. A new framework for prediction of task failure using EMG amplitude data alone is presented. The $\Delta\overline{EMG}$ vs. Tlim relationship remains consistent across sexes and force vs. position tasks.

1. Introduction

Performance fatigability, commonly referred to as 'muscle fatigue,' is defined as a reversible decline in an objective measure of performance (i.e. maximum voluntary contraction) that occurs as a result of both submaximal and maximal exercise.[1] According to the recently updated fatigue-related taxonomy proposed to by Enoka and Duchateau, performance fatigability interacts with 'perceived fatigability' – changes in sensations which impact performance – to produce 'fatigue', a disabling symptom characterised by reduced physical and cognitive function.[1] In submaximal tasks, performance fatigability can lead to an inability to further sustain a task at a given intensity, termed 'task failure'.[2]

The critical power, force, and torque thresholds (referred to as 'critical thresholds' for brevity) demarcate domains of exercise and contractile intensity related to differential mechanisms of fatigability. Above these critical thresholds, fatigability is associated with non-steady-state physiological behaviour (e.g. increase in pH, [PCr], and $\dot{V}O_2$; decrease in [P_i]), while physiological steady states are possible during fatiguing exercise at and below critical thresholds.[3–6] A hyperbolic relationship between power, force, or torque and time to task failure (T_{lim}) exists for exercise performed above these critical thresholds.[7,8]

Numerous reviews have been published on critical thresholds to date, with the current state of knowledge detailed most recently in reviews by Poole, Burnley[3] and Burnley and Jones.[4] Critical thresholds vary with individual characteristics such as training and disease status, but typically occur at 25–35% maximum power output,[9] ~15% maximum voluntary contraction (MVC) for sustained isometric contractions,[10] and 30–40%MVC for inter-

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mittent isometric contraction protocols (i.e. repeated cycles of 6 s contraction, 4 s rest).[11] Exercise across multiple modalities (i.e. single-muscle isometric, whole body dynamic) can be sustained above critical thresholds for a maximum of ~30 min in healthy populations.[3] Given that the principles related to critical thresholds apply across exercise modes,[12] study of single agonist muscle groups during isometric contractions allows for controlled experimental study of fatigability with direct applications to whole body dynamic exercise. Accordingly, to maximize homogeneity of data and simplify results interpretation, this meta-analysis is focused on fatigability during isometric muscle contractions and the critical force threshold.

Electromyographic (EMG) amplitude has been observed to be inversely correlated with the decrement in maximal voluntary muscle force occurring as a result of fatiguing exercise, with increases in EMG amplitude accompanying decreases in maximum muscle force both above and below critical force.[11] This increase in EMG amplitude has been shown to occur at a constant rate (ΔEMG/Δt, abbreviated as '$\Delta\bar{\text{EMG}}$' in this manuscript) proportional to exercise intensity.[13] In physiological terms, a positive $\Delta\bar{\text{EMG}}$ reflects the increased discharge rate and the progressive recruitment of additional motor units over time (see Merletti and Farina[14] for a comprehensive overview of EMG signalling during fatiguing muscle contractions).

The EMG fatigue threshold (EMG_{FT}) represents the maximum force or power which produces an EMG amplitude without trend, slope, or rate of change ($\Delta\bar{\text{EMG}} = 0\%\text{EMG}_{\text{max}} \cdot \text{min}^{-1}$). EMG_{FT} has been proposed and utilised as a reliable[15] correlate of anaerobic and critical thresholds,[16–19] primary outcome for nutrition and training studies,[20–22] and training tool for elite athletes.[23] Similar to the calculation methodology for critical force, the force output at EMG_{FT} is estimated by extrapolation based on empirically determined $\Delta\bar{\text{EMG}}$ from at least two fatiguing exercise bouts at efforts exceeding the EMG_{FT}[13,19] (Supplementary Fig. 1).

Although EMG_{FT} methodology is reliable, prior research has questioned the validity of EMG_{FT} as a correlate of critical thresholds, with studies reporting substantial estimation errors of up to 40%.[13,18] Considering prior research demonstrating that $\Delta\bar{\text{EMG}}$ is positive and nonzero at intensities both above and below critical torque,[11,24] the questionable validity of EMG_{FT} is perhaps unsurprising; EMG_{FT} as currently defined (assuming $\Delta\bar{\text{EMG}} = 0\%\text{EMG}_{\text{max}} \cdot \text{min}^{-1}$) lacks face validity as it describes a scenario – the absence of EMG amplitude increase during exercise – that does not typically occur in vivo.

The authors hypothesize that EMG_{FT} occurs at a positive value of $\Delta\bar{\text{EMG}}$, and thus propose that a nonzero 'threshold' value of $\Delta\bar{\text{EMG}}$ corresponding to critical force may exist. Additionally, it is proposed that determination of this threshold $\Delta\bar{\text{EMG}}$ value may increase the precision of using EMG_{FT} to estimate critical force. As such, the aim of this systematic review and meta-analysis is to evaluate the validity of EMG_{FT} as currently calculated by determining $\Delta\bar{\text{EMG}}$ at EMG_{FT} using empirical data from fatiguing isometric contraction protocols.

2. Methods

This review was prospectively registered in the PROSPERO register (protocol # 42015024368).

The literature search strategy was developed in consultation with a medical librarian from the University of Sydney. The following databases were searched: Medline (1946–8 September 2016), SPORTDiscus (1985–8 September 2016), Web of Science (1980–8 September 2016), and Cochrane (1966–8 September 2016). The search queries used were as follows: (torque* OR force* OR power) AND (muscle* OR contraction* OR MVC OR 'maximum voluntary contraction' OR electromyography OR EMG) AND fatigue. Searches included all relevant subject headings where possible. Human subjects and English language limiters were applied to all searches. A 'life sciences biomedicine' subject limiter was also applied to Web of Science searches.

Inclusion criteria were peer-reviewed journal articles written in the English language and reporting agonist muscle surface or indwelling EMG amplitude data during constant force voluntary isometric submaximal contraction protocols taken to task failure. Inclusion criteria were restricted to isometric contractions to control for EMG variability induced by geometric changes in the muscle during dynamic activities.[25] All healthy adult populations were considered. Protocols must have been conducted under normal conditions (i.e. without prior experimentally induced fatigue or delayed onset muscle soreness) and report at least data from the start and end points of the fatiguing protocol. EMG data must have been sampled according to International Society of Electrophysiology and Kinesiology standards and normalised to valid maximum value (e.g. all EMG levels $\leq$100% EMG_{max}).[26] Given that the primary risk of bias in this meta-analysis is the variable quality of EMG data collection and reporting, the inclusion criterion requiring sampling and reporting of EMG data according to International Society of Electrophysiology and Kinesiology standards acts in lieu of a bias assessment related to main study outcomes.

Relevant studies were identified through initial screening of titles and abstracts from database search results, followed by full-text review of potentially relevant articles. The following data were extracted from studies meeting inclusion criteria: subject numbers and demographics; agonist muscle(s); task type (e.g. force, position); contraction force (%MVC); initial and final EMG levels (%EMG_{max}); T_{lim} (s). For clarity, a 'force task' defines task failure as an inability to maintain a given force output, while a 'position task' defines task failure as an inability to maintain a given joint position while resisting a constant force; prior research has noted significant effects of task type on T_{lim} in isometric contractions.[27–32] Given that EMG_{FT} calculations do not depend on the use of a particular primary agonist muscle,[18,33] all available data from primary agonist muscles were included. EMG data averaged from multiple primary agonist muscles were only included when no data from single agonist muscles were available.

EMG amplitude vs. time plots were inspected when graphic data were available and it was found that increases in EMG amplitude were homogenously linear across studies. In cases where only numerical data at start and failure were available[29,34–39] linearity was, therefore, assumed. As a result, the average rate of change of EMG amplitude ($\Delta\bar{\text{EMG}}$ (%$\text{EMG}_{\text{max}} \cdot \text{min}^{-1}$)) was approximated for all included studies using the formula:

$$\Delta\bar{\text{EMG}} = \frac{\text{EMG}_{\text{final}} - \text{EMG}_{\text{initial}}}{T_{lim}} \qquad (1)$$

As a basis for calculation of critical force, Monod and Scherrer[8] established the following definition of the 'limit work' (W_{lim})(%MVC · min), an isometric analogue of mechanical work representing the maximum isometric 'work' possible before failure. Force is represented by the symbol F, with units of %MVC.

$$W_{\text{lim}} = F \times T_{lim} \qquad (2)$$

This relationship is shown in the context of critical force (CF)(%MVC) in Eq. (3), with W′ representing the maximum isometric 'work' that can be performed above critical force (%MVC · min):

$$W_{lim} = W' + CF\,(T_{lim}) \qquad (3)$$

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