INTRODUCTION
Muscle fatigue has been defined as “any reduction in the ability to exert force in response to voluntary effort”[1]. The reduction in force due to static muscle contractions was first quantified by Walter Rohmert [2]. The relationship between intensity and endurance time (ET) have been coined “Rohmert Curves”, and have been studied by many other researchers [2-8].

Recently, we compiled a large meta-analysis to “update” the “Rohmert curves” for each joint region (ankle, knee, trunk, shoulder, elbow, and hand/grip) [9]. The updated “Rohmert curves” provide more up to date and accurate versions of the static isometric intensity-ET curves for each joint region, however these curves only represent static muscle contractions. Unfortunately, there are few muscle fatigue models that represent the development of fatigue for more complex contractions (i.e. intermittent work rest cycles) that are observed in the work force. Although ET has historically been the main outcome variable for empirical muscle fatigue models [2, 6], it could be problematic for intermittent tasks due to the long ETs that are associated with low intensity and low duty cycle (DC) tasks. Whereas, the decline in peak torque over time provides a metric of fatigue that can be assessed at multiple time points.

Thus the goal of this study was to create localized muscle fatigue models, akin to “Rohmert curves” for intermittent tasks, considering task intensity and DC. This was accomplished by 1) conducting a comprehensive review of literature to extract relevant fatigue data 2) developing a statistical model of percent torque decline as a function of task intensity and DC for individual joint regions (ankle, knee, trunk, shoulder, elbow, and hand/grip).

METHODS
Systematic Review of Literature
A systematic review of localized muscle fatigue was performed using the following databases: PubMed, Cumulative Index to Nursing and Allied Health Literature (CINAHL), Web of Knowledge, and Google Scholar. The search criteria used strategies previously described [9], using search term combinations that would elicit relevant articles reporting torque decline during intermittent tasks.

Inclusion and Exclusion Criteria
The inclusion criteria included: studies with healthy human subjects, ages between 18-55 years old, intermittent/static tasks with force/torque data, a task time of at least 30 seconds, and published in English. Exclusion criteria included: dynamic contractions, simultaneous multi-joint testing (e.g. squat lifts), functional tasks, body/limb weight as primary resistance, and electrically stimulated contractions. Data that involved patient populations or interventions (i.e. creatine supplementation) were not used for the analysis, but any control subjects’ data were included [9].

Data Analysis
The authors, number of subjects, sex, and task intensity (% effort) were compiled in the Excel database as previously described [9]; additionally the duty cycle and percent decline at discrete time points (30, 60, 90, and 120 seconds) of the MVC (mean and SD) were recorded. The four discrete time points were chosen based on the available data. When appropriate, graphical data was obtained using pixel analysis (Adobe Photoshop, San Jose, CA) [9]. Only joints with a minimum of 3 (i.e. three points are needed to define a plane) data points at different combination of MVCs and DCs were further analyzed at each time point.

Based on the power relationship observed in the intensity-ET curves for sustained contractions (i.e., 100% DC) [9], a log transform was performed across each data set. The log transformed data set was then plotted in TableCurve3D (SYSTAT
Software Inc, Richmond, CA) and fit to a plane in the form of Equation 1. An exponential transform was then applied to the plane equation in order to transform the plane to a power relationship as previously described [9], where a, b, and c are the model coefficients (Equation 2).

1) \( \ln(\%TD) = \ln(a)+b*\ln(DC)+c*\ln(MVC) \)
2) \( \%TD = a \cdot (DC)^b \cdot (MVC)^c \)

RESULTS AND DISCUSSION

Figure 1: Example of the general empirical torque decline model at 120s. The 95% CI is shown by the colored planes.

69 publications (194 data points) were found, enabling surfaces to be created for 4 joint regions (ankle, knee, elbow, and hand/grip) and a general surface for each of the 4 time points (Figure 1). Based on the power relationship observed in the intensity-ET curves for sustained contractions (i.e. 100% DC) [9], the data points were fit to nonlinear, 3-parameter, power equation (Equation 1). The 3D surface fits varied across joints and times, with median \( R^2 = 0.500 \) (range 0.036 to 0.990) (see Table 1). Overall, the joint-specific fits were superior to the general model, indicating heterogeneity between joints.

Table 1: \( R^2 \) (n data points) values for 3D torque decline-intensity-DC models

<table>
<thead>
<tr>
<th>Joint</th>
<th>30 seconds</th>
<th>60 seconds</th>
<th>90 seconds</th>
<th>120 seconds</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle</td>
<td>0.597 (7)</td>
<td>0.673 (20)</td>
<td>0.535 (7)</td>
<td>0.832 (24)</td>
<td>0.655</td>
</tr>
<tr>
<td>Knee</td>
<td>0.465 (19)</td>
<td>0.258 (23)</td>
<td>0.462 (16)</td>
<td>0.416 (15)</td>
<td>0.439</td>
</tr>
<tr>
<td>Elbow</td>
<td>0.794 (7)</td>
<td>0.941 (11)</td>
<td>0.990 (6)</td>
<td>0.990 (7)</td>
<td>0.966</td>
</tr>
<tr>
<td>Hand/Grip</td>
<td>0.628 (11)</td>
<td>0.036 (21)</td>
<td>0.968 (8)</td>
<td>0.182 (22)</td>
<td>0.405</td>
</tr>
<tr>
<td>General</td>
<td>0.222 (44)</td>
<td>0.216 (75)</td>
<td>0.207 (37)</td>
<td>0.410 (68)</td>
<td>0.219</td>
</tr>
<tr>
<td>Median</td>
<td>0.597</td>
<td>0.258</td>
<td>0.535</td>
<td>0.416</td>
<td>0.500</td>
</tr>
</tbody>
</table>

CONCLUSIONS

This research focused on developing models of muscle fatigue involving intermittent tasks. Overall, model fits were reasonable, suggesting this 3D empirical approach has merit, but the lack of available data and the non-uniformity of the data make deriving firm conclusions challenging. While additional studies are needed to validate and advance the current models, these results suggest 3D fatigue models have merit. These novel approaches could have significant impacts in the ergonomics field to maximize worker effectiveness while minimizing the risks for musculoskeletal disorders.

REFERENCES


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