

# Endurance Time is Joint-Specific: A Modeling and Meta-Analysis Investigation

<sup>1</sup> Keith Avin, <sup>2</sup> Laura Frey Law

Graduate Program in Physical Therapy and Rehabilitation Science  
The University of Iowa, Iowa City, IA

## INTRODUCTION

Muscle fatigue is defined as “any exercise-induced reduction in the ability to exert muscle force or power, regardless of whether or not the task can be sustained” (1). This highly complex phenomenon has been the focus of countless investigations over several decades. However, little attention has been given to whether fatigue varies systematically between muscles about a given joint.

As contraction intensity increases, often standardized to maximum voluntary contraction (%MVC), endurance time (ET) decreases in a curvilinear fashion. This intensity-ET relationship is frequently referred to as Rohmert’s curve (2). Despite the plethora of research on ETs for a static muscle contraction, this vast array of data has not been systematically analyzed to investigate 1) between-joint differences or 2) validate static intensity-ET models. Thus, the goals of this study were to: 1) perform a thorough systematic review of the literature to obtain all data related to sustained static contractions and their associated ET; 2) calculate empirically-derived models that demonstrate the negative decay which best fit the static fatigue ET and contraction intensity data; and 3) use these models to make joint-level comparisons, validated using traditional statistical meta-analysis comparisons. This information may prove beneficial for future applied fatigue research, ergonomic applications of digital human modeling, as well as clinical interventions of appropriate therapeutic dosing parameters.

## METHODS

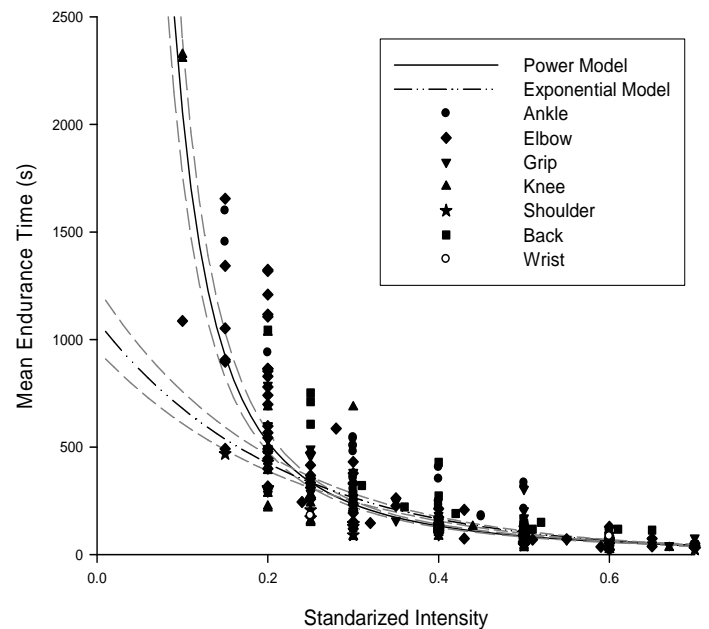
The authors performed a two-stage systematic review of literature pertaining to sustain static contraction until volitional failure in healthy, human subjects with a mean reported age between 18-50 years. Power and exponential functions were fit with their respective 95% Confidence Interval to the entire data set (generalized model), for each of the specific joints (i.e., ankle, back, grip, elbow, knee,

and shoulder), and for specific joint torque directions (e.g. ankle plantar- and dorsi-flexion).

## RESULTS AND DISCUSSION

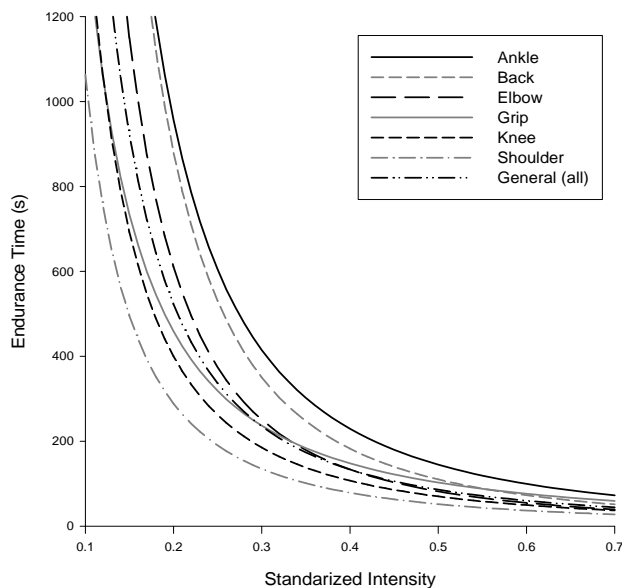
The literature search resulted 180 articles meeting the inclusion criteria from a total of 15,210 potential publications. The numbers of studies per joint are as follows: Ankle (17), Back (20), Hand/Grip (38), Elbow (52), Knee (54), and Shoulder (11). The total sample sizes for each joint range from 32 to 834, and mean sample sizes ranged from 10.4 to 22.8 subjects per study, with a total of 349 data points.

The power function explained a greater portion of the data variance in all of the 7 models ( $R^2 > 0.73$ )(Fig.1). All 15 pairwise joint model comparisons were significant (standardized overlap  $< 0.59$  between 95% CIs for joint-specific models, Fig 2).



**Figure 1:** The general power ( $R^2 = 0.81$ ) and exponential ( $R^2 = 0.78$ ) static fatigue models are shown with their 95% confidence intervals (CIs) along with the entire data set (N=180 studies, 349 task intensities).

Although ET differences varied with intensity, the ankle was most fatigue-resistant, followed by the back, elbow, knee, and finally the shoulder was the most fatigable (Fig 2). Large effect sizes ( $> 0.8$ ) were observed across 11 joint pairs, in particular for comparisons with the ankle (the most fatigue-resistant) and the shoulder (least fatigue-resistant). Ankle dorsiflexion and plantarflexion were not significantly different throughout the intensity range. Elbow flexion and extension models were only significantly different below 28% MVC, with flexion more fatigue resistant than extension. No other within-joint comparisons were performed due to lack of data available.



**Figure 2.** Each joint-specific power fatigue model is plotted to demonstrate relative differences in fatigue resistance (ET) between each joint model as a function of contraction intensity (% MVC):

This is the first study to systematically compile data related to sustained static contractions to determine ET models as a function of intensity level, and compare them across joints and torque directions. The primary findings of this investigation are: 1) the compilation of studies reporting ETs for static contractions resulted in the power function being best able to predict 74-91% of the variance in the reported fatigue data across all intensities; 2) the joint-specific models indicate ET varies significantly between joints (e.g. ankle, back, elbow, grip, knee, and shoulder) as a function of

contraction intensity; 3) statistical between-joint comparisons of the pooled fatigue data generally validate these model conclusions; and 4) the within-joint antagonist comparisons (e.g. elbow flexion vs extension) were not able to consistently show significant differences in fatigue-resistance.

Future studies are warranted to better characterize model differences with specific population categories, such as males versus females, young versus old, and endurance-trained versus untrained individuals. Although these characterizations were beyond the scope of this work, they may have influenced the final models, as the distribution between each potential population category was not necessarily balanced (with the exception of no older adult populations included). For example, of the 115 fatigue data points for the elbow, 60 involved only men, 1 involved solely women, and 54 were mixed, including both men and women. Thus the resulting fatigue curves are likely to be influenced to a greater extent by men than women.

## CONCLUSIONS

In summary, the power curves resulted in consistently higher  $R^2$  values and a single generalized fatigue model does not adequately represent most individual joints. The underlying mechanisms contributing to these differences are not clear, but likely multifactorial. These findings may impact applied sciences such as rehabilitation and ergonomics, as well as future investigations of muscle fatigue. Indeed, fatigue development at one joint may not be representative of fatigue across all joints. Future studies on specific fatigue mechanisms may benefit from replication at multiple joints.

## REFERENCES

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2. Rohmert W. *Int Z angew Physiol einsch Arbeitsphysiol* **18**: 123-164, 1960.

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