Joint velocity dependence of fatigue in isokinetic leg extension tasks

Ritwik Rakshit[1], Shuvrodeb Barman[2], Yujiang Xiang[2], and James Yang[1]*

[1]Human-Centric Design Research Lab, Department of Mechanical Engineering, Texas Tech University, Lubbock, TX 79409, USA, *Corresponding Author: james.yang@ttu.edu
[2]School of Mechanical and Aerospace Engineering, Oklahoma State University, Stillwater, OK 74078, USA

Abstract

The ability to predict the decline in muscle strength over the course of an activity (fatigue) can be a crucial aid to task design, injury prevention and rehabilitation efforts. Current models of muscle fatigue have been hitherto validated only for isometric contractions, but most real-world tasks are dynamic in nature involving continuously varying joint velocities. It has previously been proposed that a three-compartment-controller model with enhanced recovery (3CCr) might be used to predict fatigue for such tasks by using it in conjunction with joint- and direction-specific torque-velocity-angle (TVA) surfaces. This allows for the calculation of a time-varying target load parameter that can be used by the 3CCr model, but it increases model complexity considerably and has not been validated by experimental data. The predictions using the 3CCr methods are contrasted against experimental data collected from 10 male participants in a series of isokinetic leg extension tests, covering velocities ranging from 30 to 150 degrees/s. A much lower degree of fatigue is observed for moderate velocities (90 degrees/s) compared to that for lower or higher velocities. The need for a velocity parameter in the 3CCr model is indicated, but further testing with larger sample sizes and more joints is needed before a reliable parameter can be estimated.

Keywords: muscle fatigue, velocity, isokinetic, leg extensors

Introduction

Muscle fatigue is a temporary, exercise-induced decline in muscle strength. It is an inevitable consequence of even the most basic human activities such as lifting weights, running, walking, cycling, driving an automobile, and sitting. Being able to estimate the extent of fatigue can provide crucial input in the fields of ergonomics and task design, where often the goal is to design the task to never require more than the participant's strength at any given time. Its importance is especially amplified in situations where small changes in strength can produce disproportionate outcomes, such as in a dead man's switch or vigilance device. Directly measuring strength, however, is not always feasible—it may be invasive, and always requires specialized equipment, a controlled environment, and, at minimum, task interruption.

Musculoskeletal models can bridge this gap by providing estimates of muscle force or joint torque during the performance of a simulated task using only a computer and no human involvement. At present, however, no musculoskeletal models exist that can account for skeletal muscle fatigue, and the predictions for all such models are therefore only valid for scenarios in which the digital human is unfatigued. Additionally, since high loads cause strength to decline much faster than smaller ones, even these predictions may not be accurate for high-load cases. This underscores the need for musculoskeletal models to incorporate fatigue calculations in their analyses.

Estimations of the extent of fatigue can be made using muscle fatigue models (MFM), which may be either empirical or theoretical. Empirical models provide estimates of strength as a function of time, usually for sustained isometric tasks. They are simple curve fits to experimental data and are easy to implement due to their mathematical simplicity but are limited to the specific cases that the experimental data tested. Theoretical models, on the other hand, are more mathematically complex, but allow for more task parameters than just task intensity and therefore allow the modeling of a wider variety of activities. The 3-compartment controller model (3CC) (Xia & Frey-Law, 2008)—a theoretical MFM—allows the modelling of any task by matching the measured torque output to a reference torque-velocity-angle (TVA) surface to obtain a normalized task intensity, and then using this as the model input. The model was validated for sustained isometric contractions (SIC) (Frey-Law, Looft, et al., 2012), and subsequently adapted for use with intermittent isometric contractions (IIC) by the introduction of an enhanced recovery parameter r in the 3-compartment controller model with enhanced recovery (3CCr) model (Looft et al., 2018). The model has not been validated for any tasks where the joint velocities are non-zero.

In this work, we assess the 3CCr MFM's performance in predicting fatigue for a set of isokinetic contractions and propose the introduction of a velocity parameter to improve prediction accuracy.

Methods

Experiment

Participants

10 male participants—19-32 years of age, with a body-mass index (BMI) between 18.5 and 29.9, and with no history of musculoskeletal or neural disorders or injuries—contributed to the data in this study. All participants gave their informed consent and came in on 6 days, with a minimum of 48 hours separating two consecutive experimental sessions. The first session was used to familiarize the participant

with the experimental protocol and train them to follow the commands. Data from this session was not used for any analysis. On each of the remaining 5 days, an identical protocol was followed.

Protocol

A Biodex System 4 isokinetic dynamometer (Biodex Inc, Shirley, NY, USA) was used for all measurement. The participant was securely strapped into the seat of the dynamometer with the shank of their dominant leg attached to the dynamometer arm. The range of motion (ROM) of the knee was restricted to between 90 and 15 degrees of flexion. The protocol consisted of 5 sets of maximal voluntary isometric contractions (MVIC) interspersed by 4 sets of isokinetic contractions.

The MVICs were measured at 6 joint angles—90, 75, 60, 45, 30, and 15 degrees—in both the extension and flexion directions. This was implemented as 3 seconds of MVIC in the extension direction followed by 2 seconds of rest, and then 3 seconds of MVIC in the flexion direction followed by 2 seconds of rest, before repeating this process for the next joint angle. The entire set of isometric measurements lasted 90 seconds, after which the next phase of the protocol began.

During the isokinetic phase, the participant flexed and extended their leg around the knee joint at a predetermined velocity for a period of 60 seconds. The same velocity was used for both flexion and extension, and the same ROM (90-15 degrees) was used here as for the isometric phase. The participant was instructed to exert maximum effort throughout. The velocity was monitored throughout, and the participant was verbally encouraged to increase their effort if they failed to maintain the velocity for more than one cycle. At the end of the 60 seconds, the participant was instructed to stop, at which point the next isometric phase began.

Only one velocity was used for all 4 isokinetic phases tested on any particular day. This velocity was chosen from 30, 60, 90, 120 or 150 degrees per second, and all participants performed the experiment at all 5 velocities over 5 days. However, the order in which they tested at each velocity was randomized to ensure that experience of a prior velocity did not influence performance in a subsequent session for the group.

Simulation

The 3CCr model and the experimental protocol were recreated in MATLAB (*MATLAB*, 2021). The 5 isometric measurement phases were modelled as IICs with target load (TL)=1. Since extension MVICs were performed for 3 of every 15 seconds devoted to each joint angle, the duty cycle (DC) was set at 3/15=0.2, and cycle time (CT) was set at 15 s. Since the participants were instructed to always exert maximum effort during the isokinetic phase, TL was set at 1. Because the knee extensors were used during the extension phase which made up half of the extension-flexion cycle, DC was set at 0.5. The isokinetic CT (CT) was calculated based on the isokinetic velocity (v) and ROM as:

$$CT = \frac{\times}{} \tag{1}$$

The parameters used to define the two phases of the experimental protocol as IICs are listed in Table 1.

Table 1. Task parameters for the experimental protocol.

Parameter	**Isometric phase**	**Isokinetic phase**
TL	1	1
DC	0.2	0.5
CT	15 s	$\frac{\times}{}$

The ode23 solver was used to solve the 3CCr control equations (Looft et al., 2018) over the entire domain. The parameters used to define the fatigue and recovery properties of the knee extensors were drawn from (Rakshit et al., 2021) and are shown in Table 2.

Table 2. Functional-muscle-group- and sex-specific parameters for the knee extensors (male).

Parameter	**Value**
F	0.01420
R	0.00153
r	12.27

Experimental data processing

The isometric measurements from the experiments were stored as absolute values within a MATLAB data structure. The maximum isometric strength recorded for a particular participant on a particular day for any angle, and at any isometric measurement (ISOM) iteration, was used to linearly scale all the other MVICs down so that all MVICs were expressed as unitless quantities between 0 and 1. This ensured that each participant had at least one reading of strength = 1 at each session. The normalized strength at each ISOM iteration and at each joint angle was averaged across all participants to yield 5 strength-versus-angle (TA) curves—one for each ISOM iteration. The scaled V=0 slice of the TVA surface for the leg extensors from (Frey-Law, Laake, et al., 2012) which best fit the experimental TA curve at each iteration was chosen as the final TA curve. Only 4 of the 6 torque values (corresponding to the 6 joint angles at which strength was measured) in the experiment were used for scaling. The 4 points whose use resulted in the lowest residual error were chosen programmatically for scaling to reduce imperfections in data which might result from a participant absent-mindedly exerting a submaximal force. It was assumed that this would occur at most twice at any ISOM iteration.

Results

Simulation

Since all phases of the protocol are modelled as IICs, the unmodified 3CCr MFM can be used to predict the progress of fatigue. The normalized residual capacity (RC), which is the sum of the fractions of the active motor units (M_A) and the resting motor units (M_R), is depicted in Figure 1 for $v = 30°/s$.

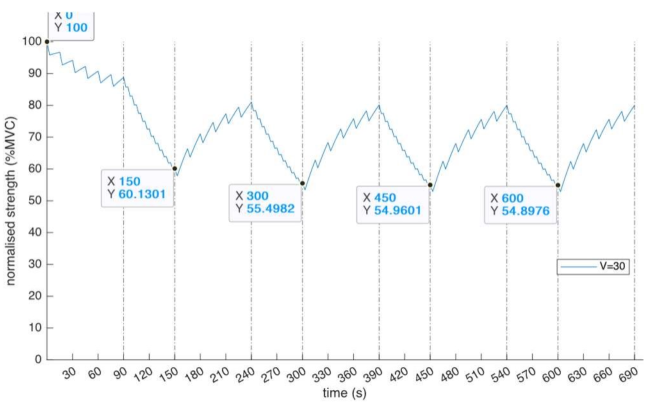


Figure 1. Normalized residual strength prediction from unmodified 3CCr.

While any experimental measurements would reflect only the active compartment size, the sum of active and resting compartment sizes is shown here for clarity. During MVICs, M_R=0 and $M_A \neq 0$. During periods of rest, $M_R \neq 0$ and M_A=0. The 6 dips in RC between 0-90s (and 150-240s, 300-390s, 450-540s, and 600-690s) represent the 6 3-second MVICs at each ISOM iteration. The climb following each dip represents the 12-second recovery period before the next MVIC. It may be noted that the dips represent M_A, while the climbs represent M_R.

It is observed that M_A decreases during the first ISOM iteration (ISOM1), and rises during all subsequent ISOM iterations (ISOM2-ISOM5). M_A always decreases during each isokinetic iteration (ISOK1-ISOK4).

The same predictions are also generated for $v = 90°/s$ and depicted in Figure 2.

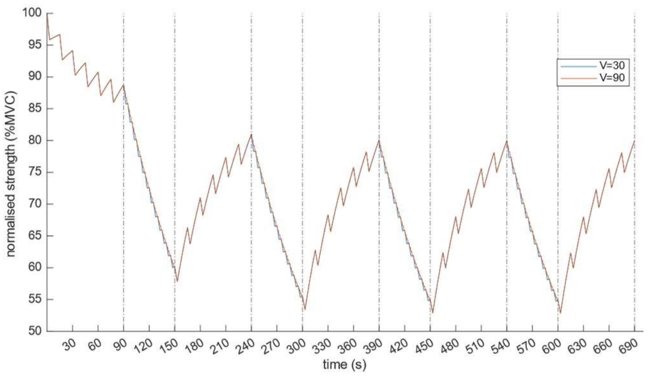


Figure 2. Normalized residual strength prediction using the unmodified 3CCr for two isokinetic velocities.

The two plots are observed to almost overlap, with no discernible difference in the ISOM phases. Even in the ISOK phases, the M_R and M_A values for the two velocities track each other almost exactly, as can be seen in Figure 3.

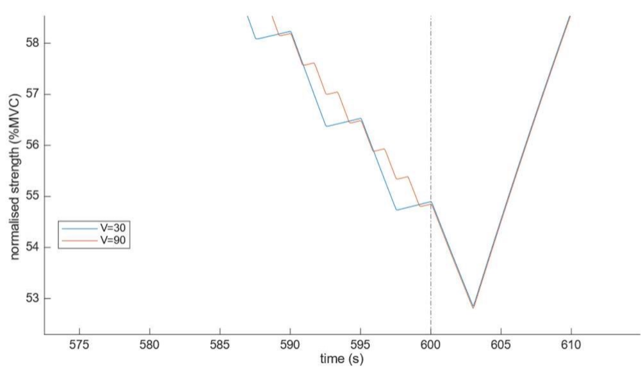


Figure 3. A zoomed-in version of the normalized residual strength for two isokinetic velocities around t=600 s.

Using $v = 30°/s$ but two distinct values of the isokinetic target load ($TL \in \{1, 0.7\}$), two plots are obtained in Figure 4.

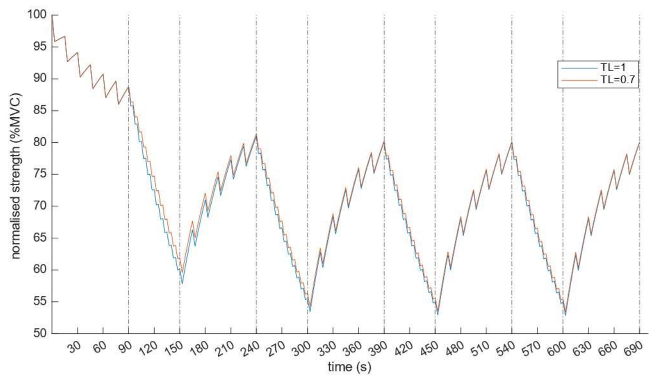
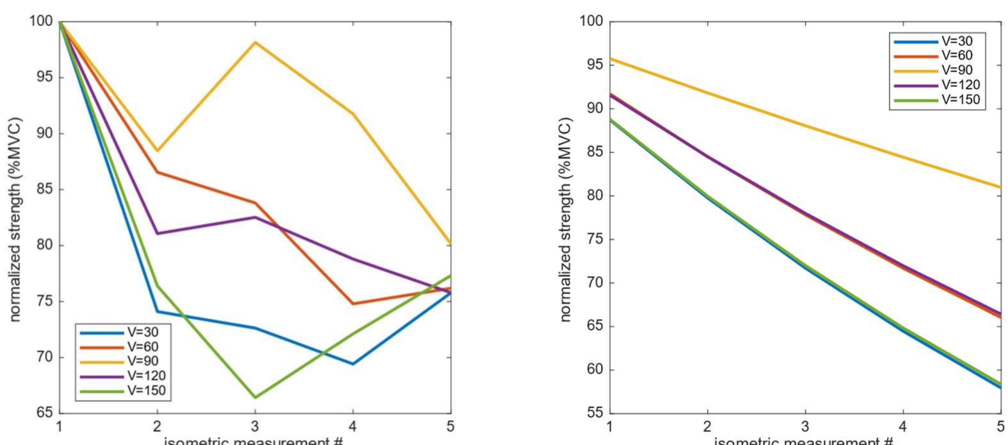


Figure 4. Effect of changing isokinetic target load on the unmodified 3CCr MFM.

There is a small difference (<2% MVC) in the RC between $TL = 1$ and $TL = 0.7$ by the end of ISOK1. However, as the experiment progresses, even this subtle difference diminishes.

Experiment

The averaged normalized strengths measured at 5 stages is plotted for each of the 5 isokinetic velocities in Figure 5 (a). Each curve is scaled up so that it begins at exactly 100% strength. Each plot is then fit to an exponential curve of the form $y = ae$ with a weight vector of [10, 1, 1, 1, 1] to force the fits to assign greater importance to the initial unfatigued torque value. The resulting fits are shown in Figure 5 (b), with the goodness of fit data tabulated in Table 3.



(a) (b)

Figure 5. (a) Scaled variation in fatigue rate with velocity, and (b) exponential fits to variation in fatigue rate data.

Table 3. Goodness of fit data for exponential curve fits to fatigue rate variation.

Velocity	**a**	**b**	**R-square**	**RMSE**
30	0.9869	-0.1065	0.803	0.1176
60	0.9956	-0.0821	0.951	0.0441
90	0.9985	-0.0419	0.736	0.0647
120	0.9921	-0.0803	0.889	0.0672
150	0.9862	-0.1049	0.761	0.1307

From both the scaled and the fit experimental data it is apparent that the rate of fatigue varies with velocity. Faster fatigue is indicated for the extreme velocities (30 and 150 degrees/second), with the rate of fatigue decreasing until it reaches a minimum at a velocity of 90 degrees/second.

Discussion and Conclusions

The present 3CCr model makes almost identical predictions regardless of contraction velocity, as indicated by Figure 2. Yet, limited experimental data shows that the rate of fatigue is indeed affected by velocity. A high rate of fatigue is observed for both extremely low and extremely high velocities, and the fatigue rate is observed to decrease until it reaches its minimum value at a tested velocity of 90 degrees/second. The exponential fits, however, tend to diverge with increasing number of iterations (Figure 5 (b)), whereas the original data initially diverges and then converges (Figure 5(a)). This may indicate that some other function may be better suited to represent the variation in fatigue rates. Additionally, a larger sample size may also help increase model integrity.

The performance of the MVICs themselves causes a certain amount of fatigue or recovery. Within the first isometric test, strength is predicted to decline by about 6%. This occurs because all of the constituent motor units (MU) are initially in the resting state, and after they are recruited into the active state they pass on into the fatigued state. Once a significant fraction of MUs is in the fatigued state, the recovery process dominates in order to move a sufficient fraction of MUs to the resting and subsequently active states to fulfill the target load requirement. This is why RC is observed to rise after it has been sufficiently depleted during the first isokinetic phase. Since every isokinetic phase depletes RC by roughly the same amount, the recovery process dominates every subsequent isometric phase due to the low DC. The current data processing pipeline maps all strengths from an isometric measurement phase to the V=0 slice of an experimentally determined TVA peak strength surface. While only the first strength in each phase (measured at 90 degrees of joint flexion and then scaled) is used to estimate the RC, it may be more robust to compare the strengths at every angle while accounting for fatigue and recovery to obtain an indicative strength after every isokinetic phase.

The protocol currently allows breaks to test isometric strength. A more faithful depiction of the decline in strength with isokinetic activity might be observed if the breaks were less frequent, but pilot experiments revealed that subjects were far less likely to be able to continue maximal effort isokinetic contractions beyond 1 minute. The rest periods allow a measurement of isometric strength and allow the participant to recover so that they may continue with the protocol. A certain unestimated amount of central fatigue was also observed to contribute since most participants reported being unable to continue beyond the 5th isometric measurement, despite the torque readings being not much lower than those at the 4th measurement.

Another source of uncertainty lies in the contribution of the leg extensors during leg flexion. For the purposes of the simulation this contribution has been assumed to be 0. However, antagonistic muscles do serve to stabilize the joint during contractions, so a certain TL might need to be assumed to make the prediction more closely resemble reality.

In conclusion, initial results show that while the 3CCr model is capable of modelling isokinetic tasks as IICs, it likely requires modification to account for the variation in fatigue rates due to different velocities. Fatigue rate decreases with increasing velocity, and then increases again as velocity is increased further. A comfortable mediocre velocity of 90 degrees/second is found to provide the lowest fatigue rate of all the velocities tested. Further testing with a larger number of participants of more joints—elbow, shoulder, hip—for both flexion and extension—should reveal whether the same conclusions hold, and what kind of modifications might be needed to accommodate the effect of varying velocity on the rate of fatigue in the 3CCr model.

Acknowledgments

The authors wish to thank Yvonne Cebe for her invaluable assistance and input during all phases of experimental data collection. This work was partially supported by the National Science Foundation (Award CBET # 1703093 and 1849279; 2014278 and 2014281).

References

Frey-Law, L. A., Laake, A., Avin, K. G., Heitsman, J., Marler, T., & Abdel-Malek, K. (2012). Knee and

Elbow 3D Strength Surfaces: Peak Torque-Angle-Velocity Relationships. *Journal of Applied Biomechanics*, *28*(6), 726–737. https://doi.org/10.1123/jab.28.6.726

Frey-Law, L. A., Looft, J. M., & Heitsman, J. (2012). A three-compartment muscle fatigue model accurately predicts joint-specific maximum endurance times for sustained isometric tasks. *Journal of Biomechanics*, *45*(10), 1803–1808. https://doi.org/10.1016/j.jbiomech.2012.04.018

Looft, J. M., Herkert, N., & Frey-Law, L. A. (2018). Modification of a three-compartment muscle fatigue model to predict peak torque decline during intermittent tasks. *Journal of Biomechanics*, *77*, 16–25. https://doi.org/10.1016/j.jbiomech.2018.06.005

MATLAB (9.10.0.1851785 (R2021a) Update 6). (2021). The Mathworks, Inc.

Rakshit, R., Xiang, Y., & Yang, J. (2021). Functional muscle group- and sex-specific parameters for a three-compartment controller muscle fatigue model applied to isometric contractions. *Journal of Biomechanics*, *127*(August), 110695. https://doi.org/10.1016/j.jbiomech.2021.110695

Xia, T., & Frey-Law, L. A. (2008). A theoretical approach for modeling peripheral muscle fatigue and recovery. *Journal of Biomechanics*, *41*(14), 3046–3052. https://doi.org/10.1016/j.jbiomech.2008.07.013