Neuromechanical response to repetitive workloads relative to current upper extremity ergonomics thresholds

Daniel Muller (Abdel-Malek)

CRE-MSD

Centre of Research Expertise for the Prevention of Musculoskeletal Disorders

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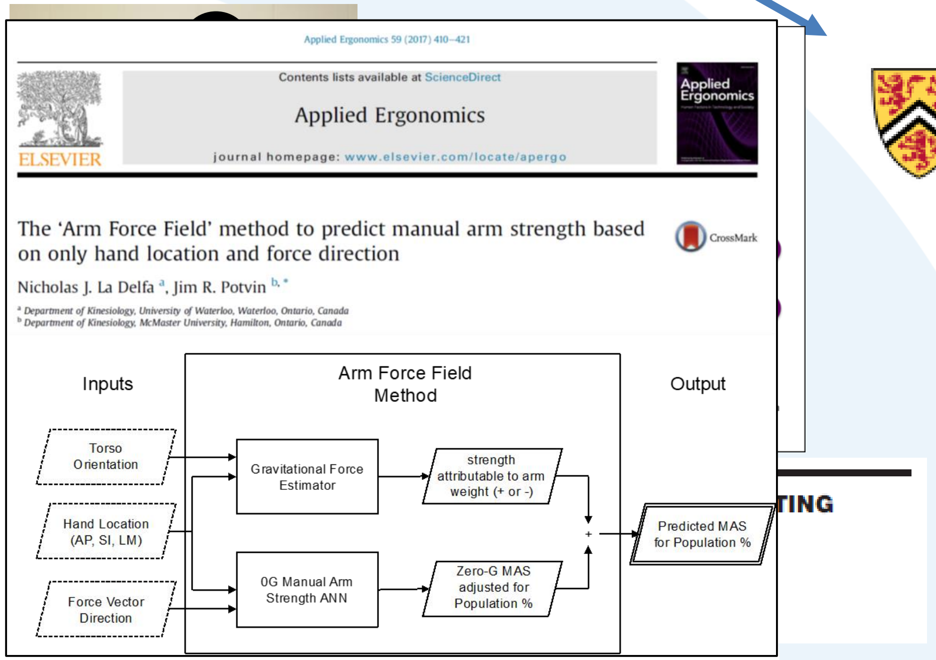
OntarioTech UNIVERSITY

My Timeline

Dr. Jim Potvin



Applied Ergonomics 59 (2017) 410–421

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

The 'Arm Force Field' method to predict manual arm strength based on only hand location and force direction

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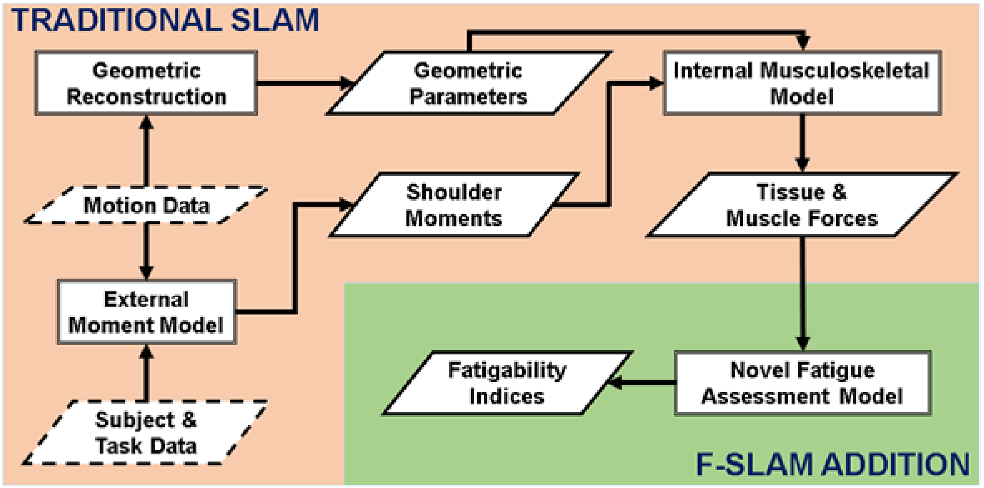
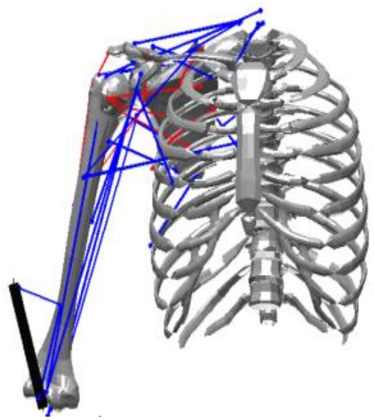
[b] Department of Kinesiology, McMaster University, Hamilton, Ontario, Canada



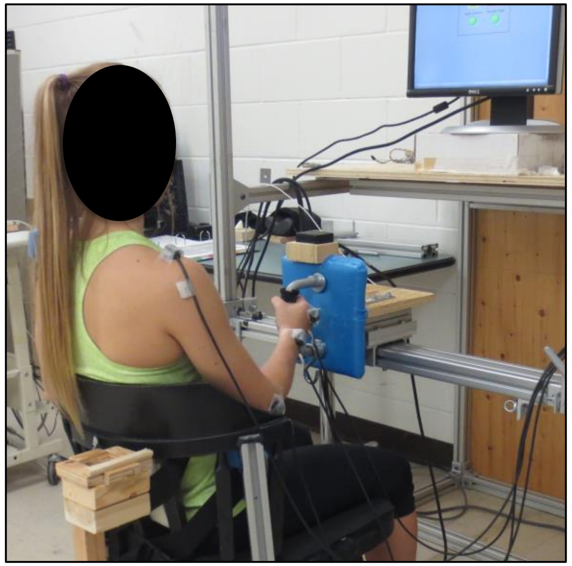
Dr. Clark Dickerson



Research Objective & Themes

The overall **GOAL** of my lab is to reduce musculoskeletal injuries, primarily through the enhancement of ergonomics strength and fatigue assessment tools within DHM work simulation.

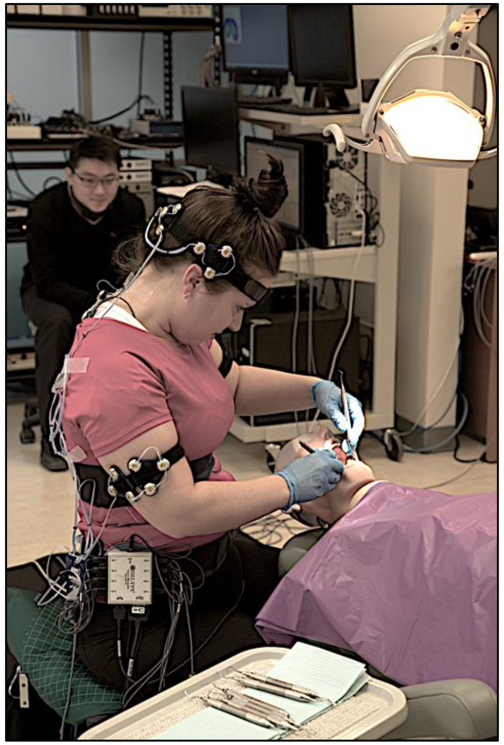
Theme A
Understanding Human Capability And Performance



Theme B
Neuromuscular & Mental Fatigue

Theme C
Digital Human Modeling & Work Simulation

Theme D
Applied Research



Basic Research → Applied Research

How it all goes together (more specifically)

Objective 1:
Factors affecting human strength
e.g. sex & age (1a), linear vs. torque exertion (1b), limb-dominance (1c), static vs. dynamic (1d)

Obj. 3a: Incorporate within DHM

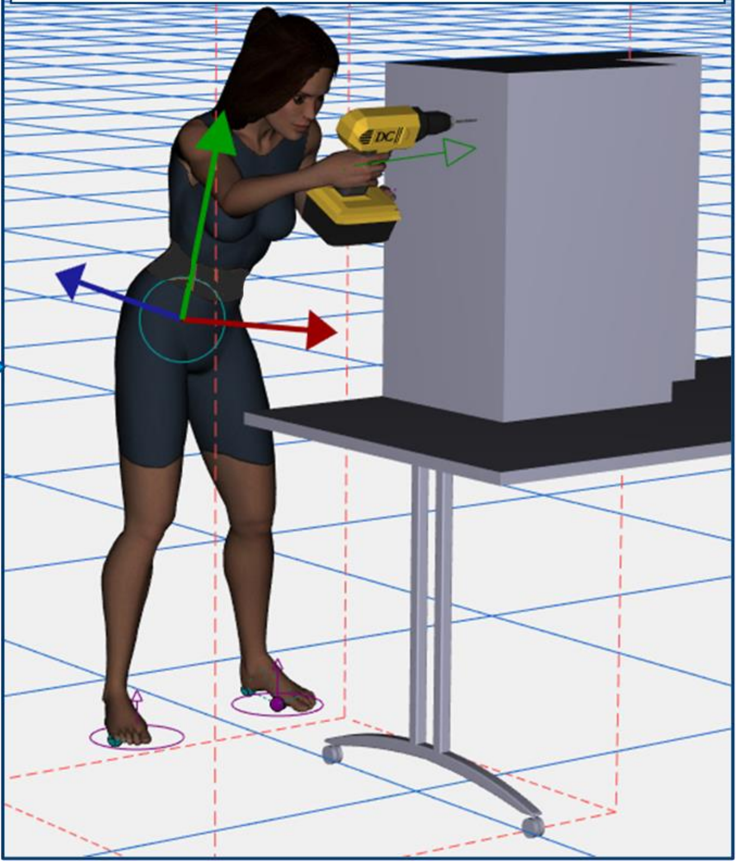
GOAL:
Accurately estimate acceptable manual forces & torques

Obj. 3c: Validate work simulations

Obj. 3b: Incorporate within DHM

Objective 2:
Understanding muscle fatigue & **mental fatigue** as a transient modifier of strength (2a-d)

Proactive Ergonomics Analysis using Work Simulation



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NSERC CRSNG


fatigue
head
depressed
psychology
office
distress
stressful
upset
work
financial
ache
stress
problem
mental
lifestyle
sick
depression
despair
negative
therapist
tired
frustration
anger
failure
headache
business
confused
feeling
medicine
expression
health
loss
stressed
lonely
anxiety
unhappy
career
inspiration
lifestyles
trouble
desperation
grief
overburdened
tense
exhausted
sadness
brain
emotion
migraine
corporate
job
people
thinking
exhaustion
pain
emotional
pressure
worried
tension
anxious
crisis
misery
psychotherapy
misfortune
crying
solution
bad
ill
alone
low
weak
panic
fear
overhead
scream
#2223163

Muscle Fatigue

"*an exercise induced* ***reduction in the ability of the muscle to produce force*** *or power, whether or not the task can be sustained. As a consequence of this definition, fatigue often begins* ***soon after the onset of sustained activity****, even though an individual can continue performing the task*."

Barry & Enoka (2007) in 'The neurobiology of muscle fatigue – 15 years later'

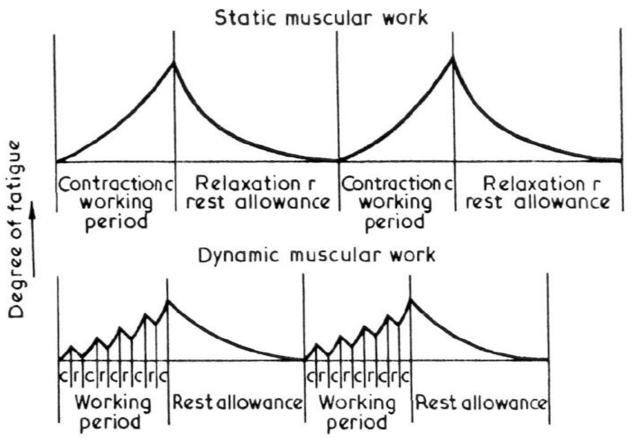
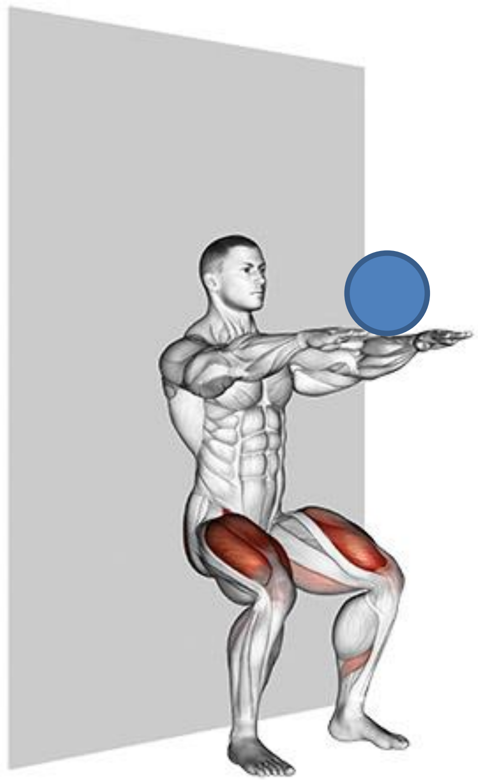


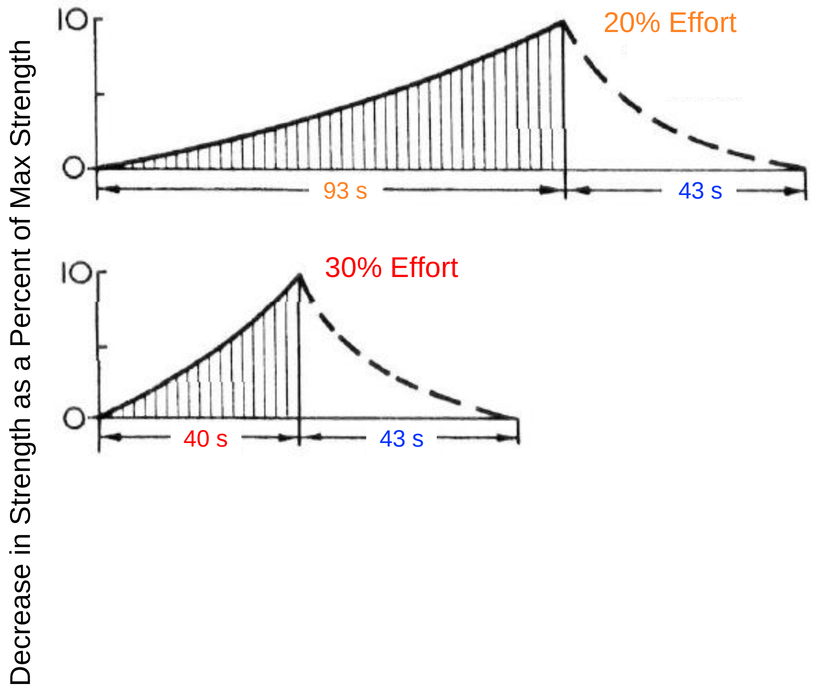
Fig 5 Change of the degree of fatigue in static and dynamic muscular work alternating with rest pauses (schematically)

Rohmert (1973)

"a ***process*** *that results in the impairment of wellbeing, capacity, and/or performance as a result of [work] activity"*

Yung & Wells (2016) in CRE-MSD Position Paper 4164-8





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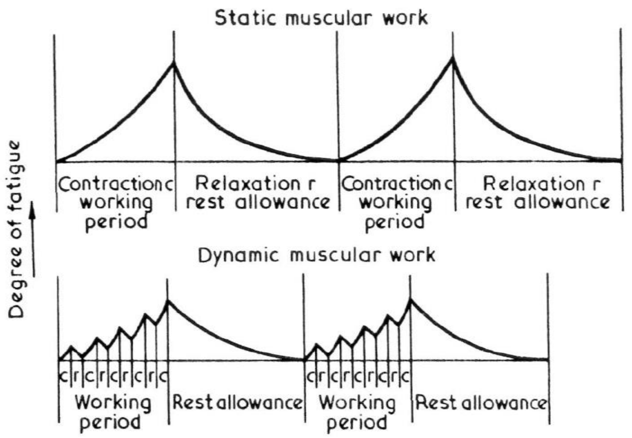

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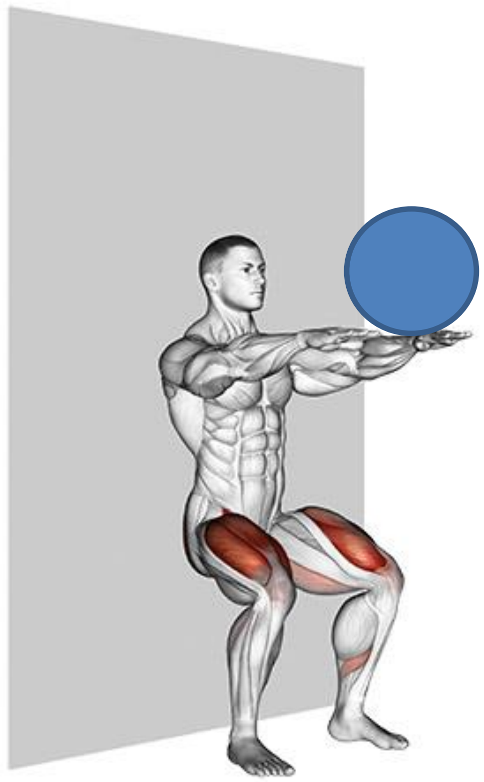

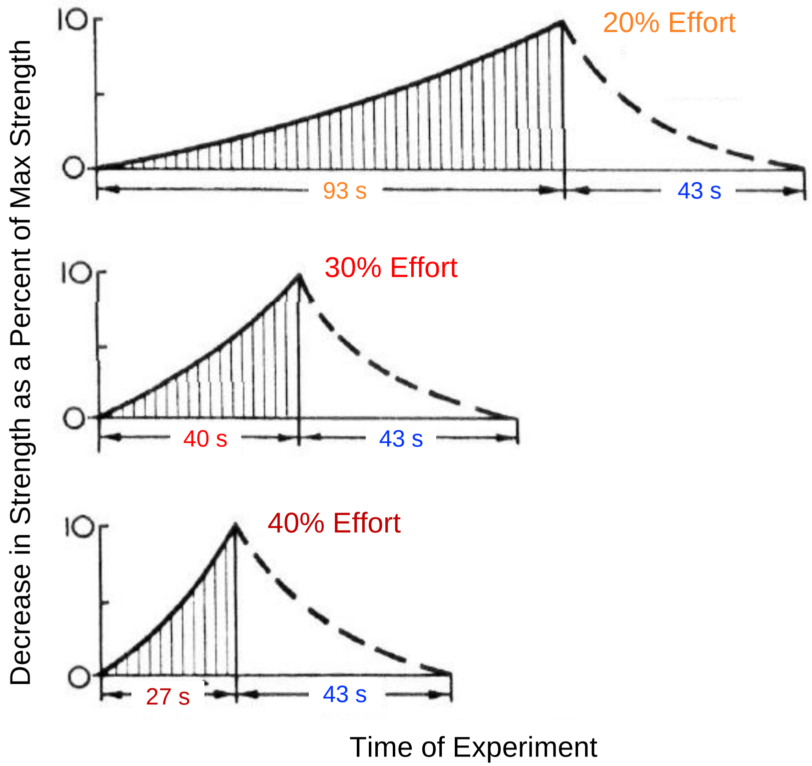

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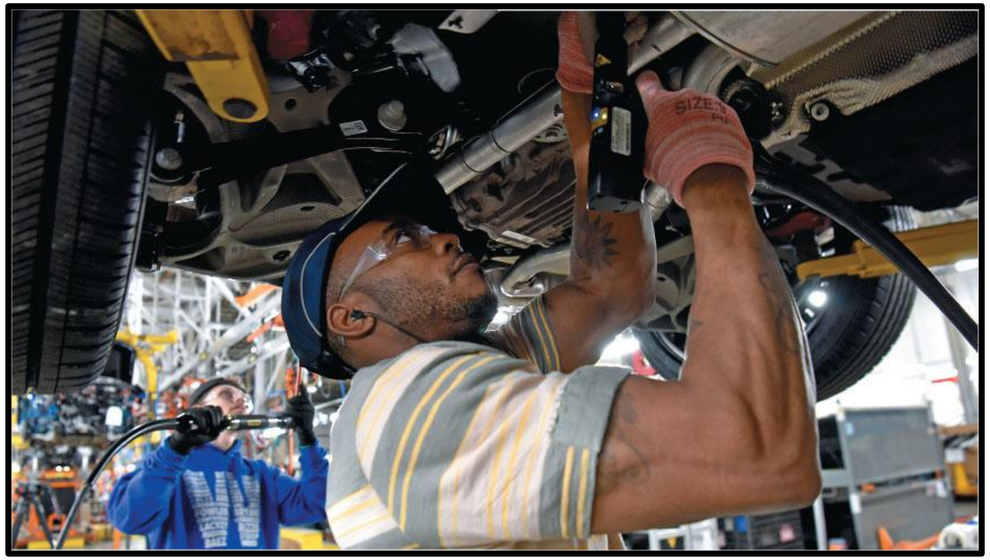
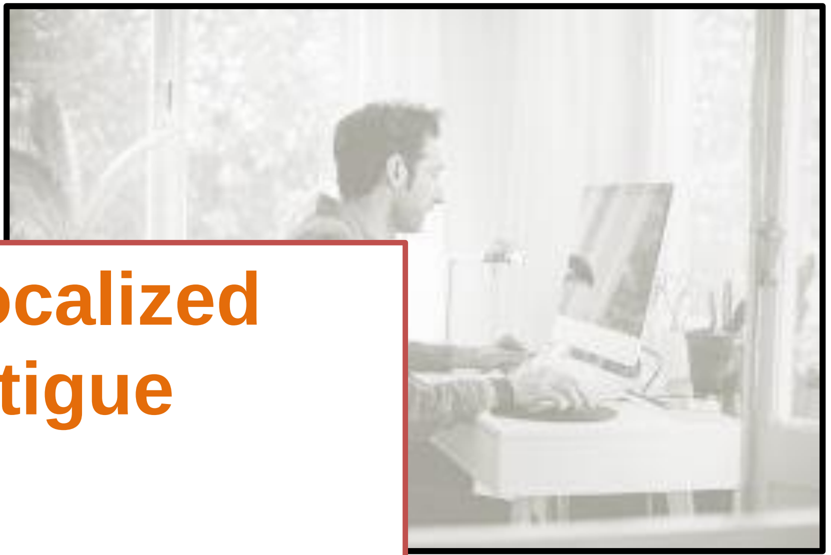




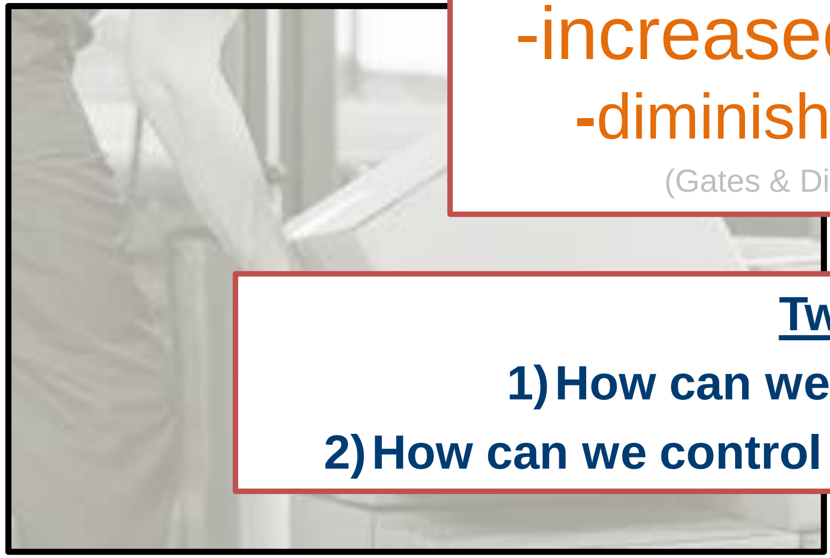
Persistent localized muscle fatigue

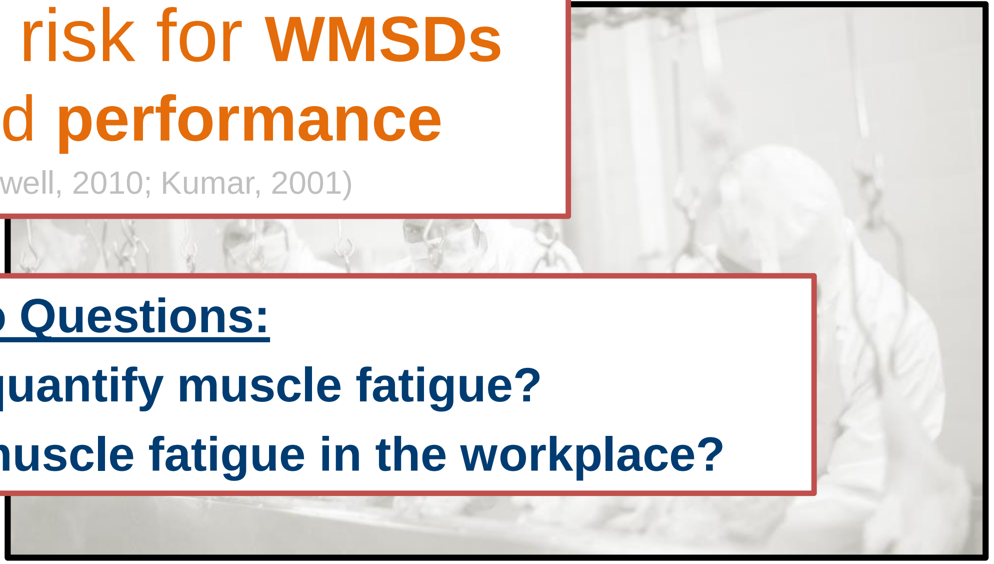
↓

-increased risk for **WMSDs**

-diminished **performance**

(Gates & Dingwell, 2010; Kumar, 2001)





Two Questions:

1) **How can we quantify muscle fatigue?**
2) **How can we control muscle fatigue in the workplace?**

Quantifying localized muscle fatigue

- **Strength** declines (MVC output)
- **Myoelectric** measures (electromyography)
  - Increase in EMG amplitude
  - Decrease in EMG frequency spectrum

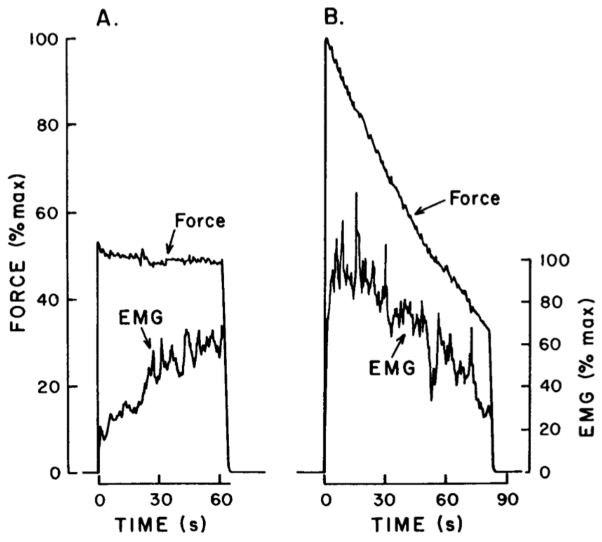
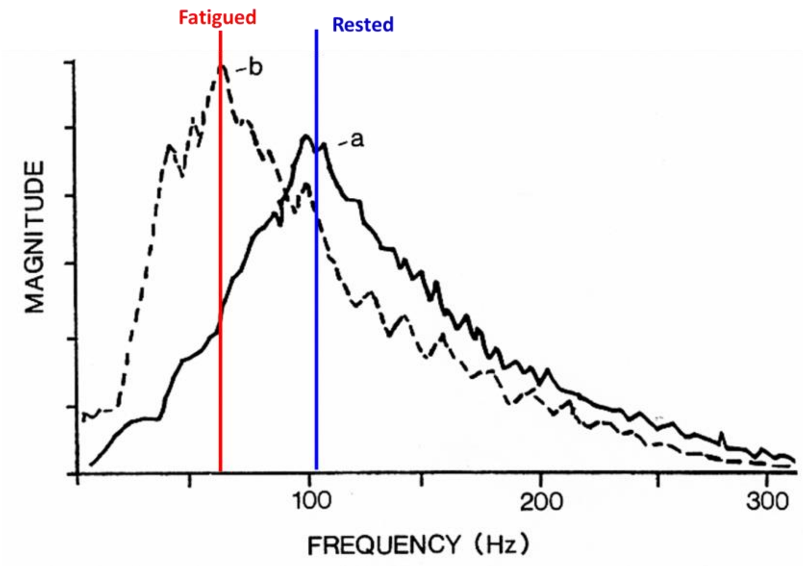
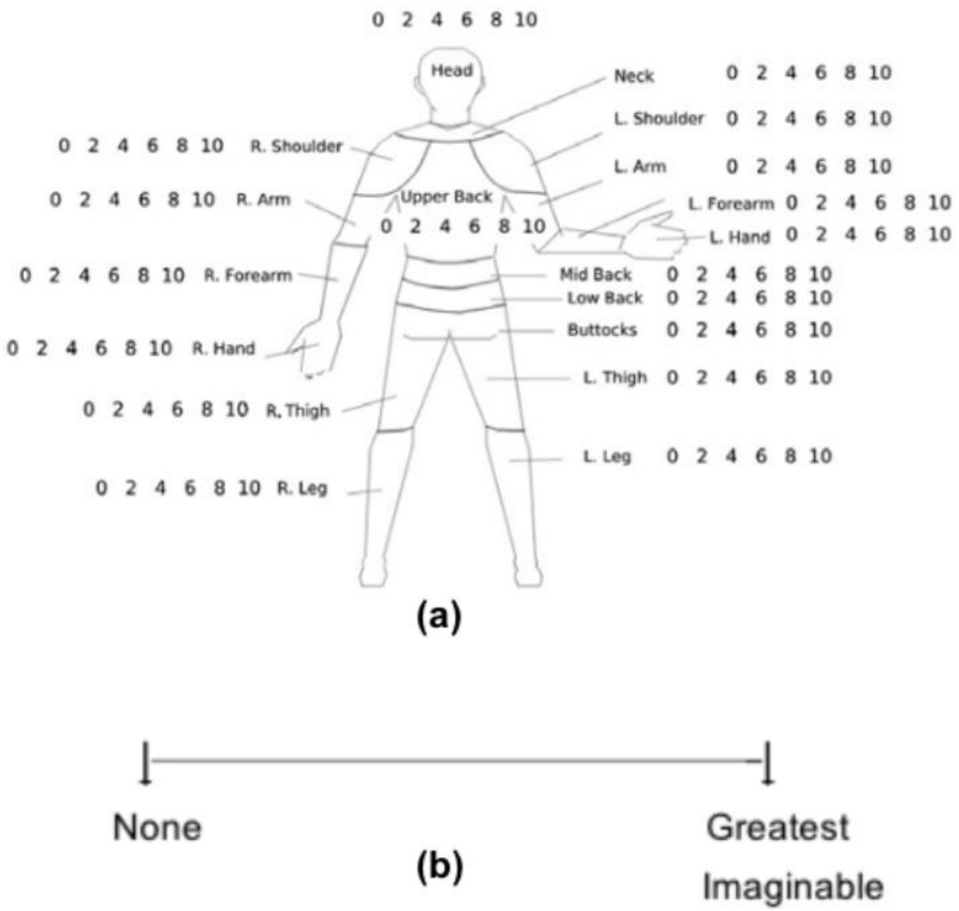


Figure 4. Force and smoothed rectified EMG activity during sustained voluntary isometric contractions of biceps brachii at A) a constant force held at 50% of the maximal initial value; and B) during a sustained maximal contraction.



Quantifying localized muscle fatigue

- **Strength** declines (MVC output)
- **Myoelectric** measures (electromyography)
  - Increase in EMG amplitude
  - Decrease in EMG frequency spectrum
- **Psychophysical ratings** of perceived fatigue or discomfort
  - RPF, RPD via Borg CR-10 or Visual Analog Scales
  - Do raters truly understand what they are rating?



(a)

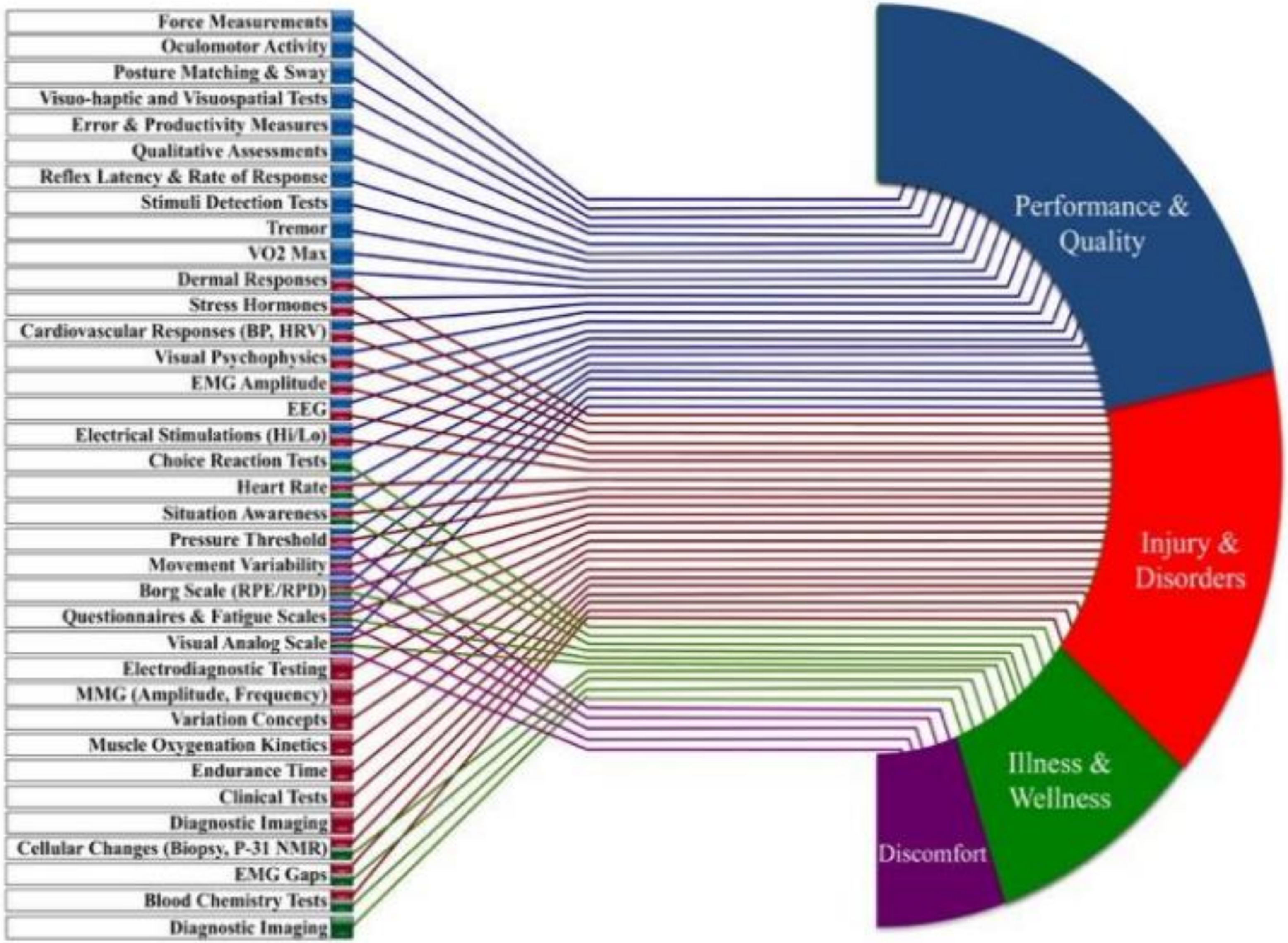
(b)

Position Paper

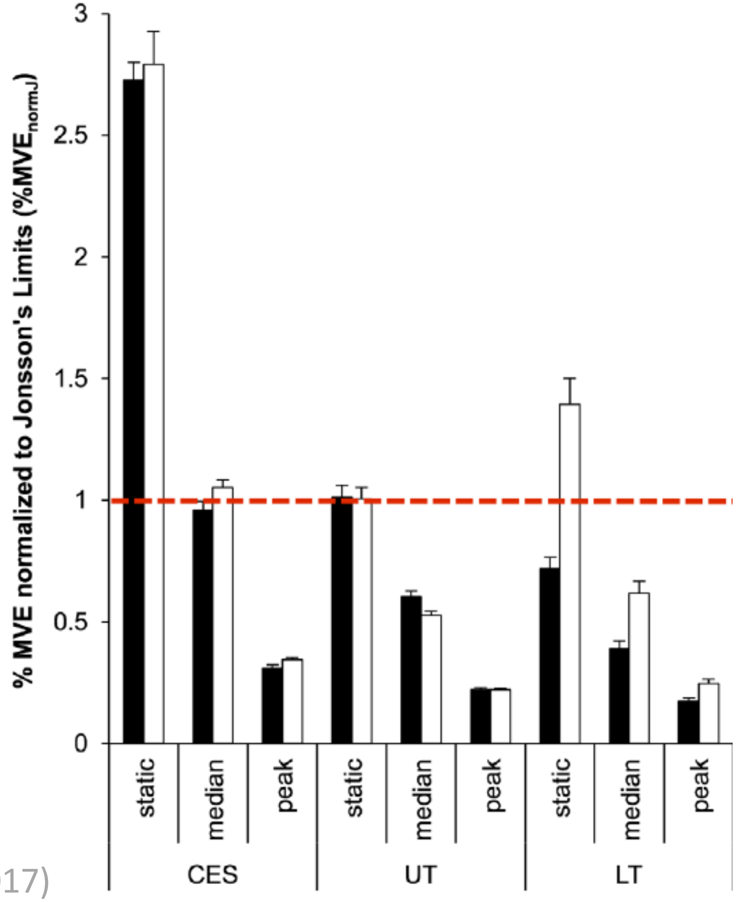
CRE-MSD Centre of Research Expertise for the Prevention of Musculoskeletal Disorders

How Do We Measure Neuromuscular Fatigue at the Workplace? The Toronto CRE-MSD Workshop

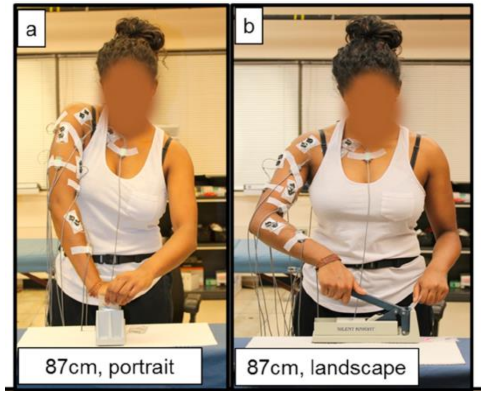
Marcus Yung and Richard Wells

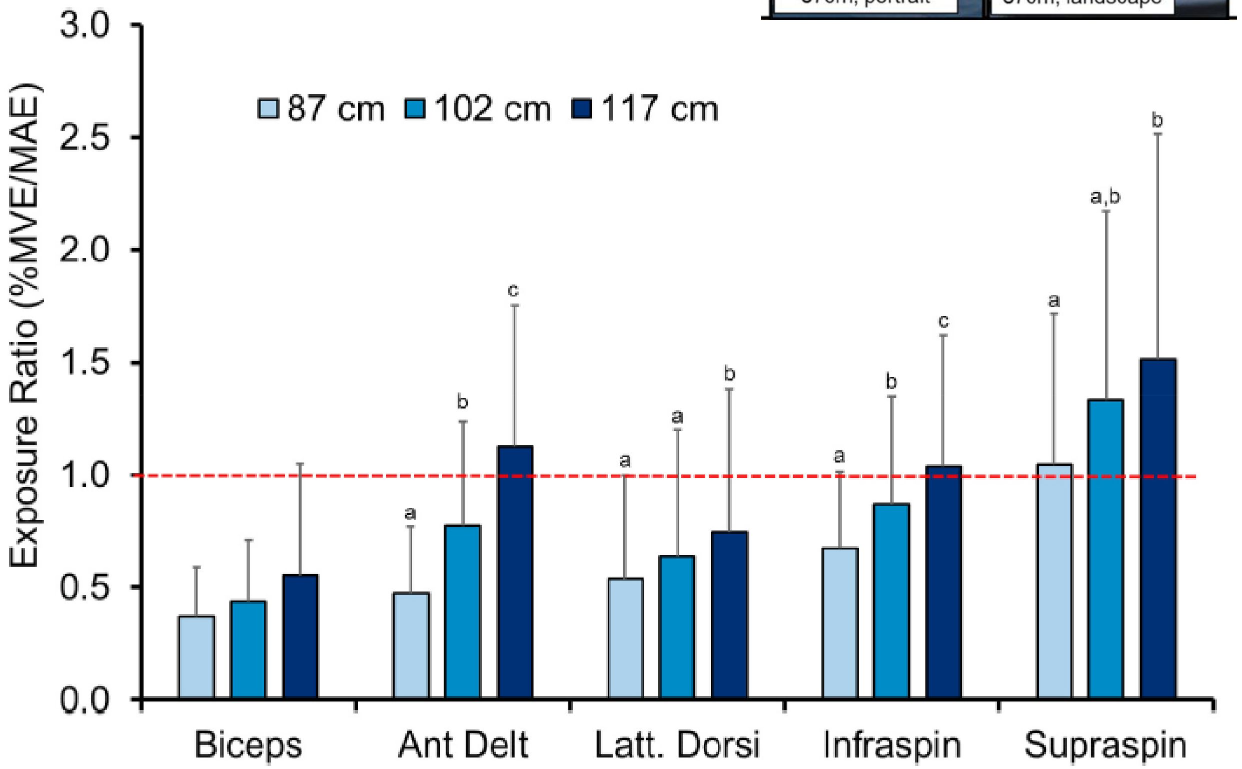


Examples in Research: EMG



La Delfa et al (2017)





La Delfa et al (2021)

Examples in Research: EMG

- Great for comparisons between conditions/factors, quantifying how much fatigue is developing and comparing to standards
  - Can result in recommendations and best practices

- But, we can't do an EMG study on every possible work task
  - How can we proactively prevent or control fatigue?
  - Do work "thresholds" exist?
    - Preferably using more accessible inputs (e.g. force, repetition, duration, etc.)?

How can we control fatigue in the workplace?

Balancing effort and recovery time

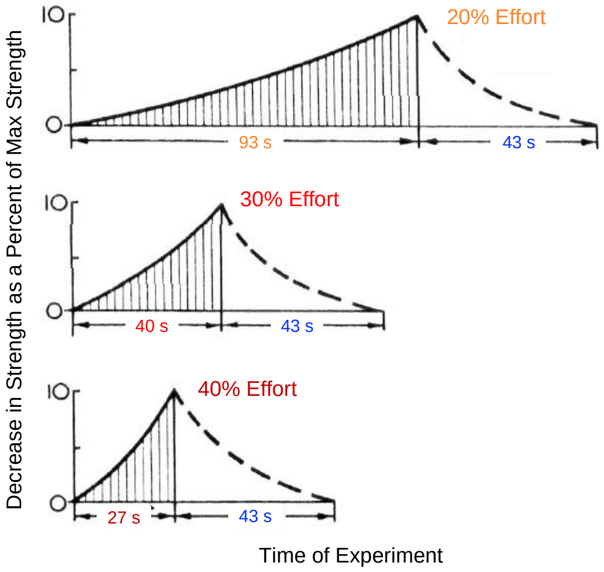
Applied Ergonomics, 4.3, 158–162

Problems of determination of rest allowances

Part 2: Determining rest allowances in different human tasks

Walter Rohmert

Institut für Arbeitswissenschaft, University of Technology, Darmstadt



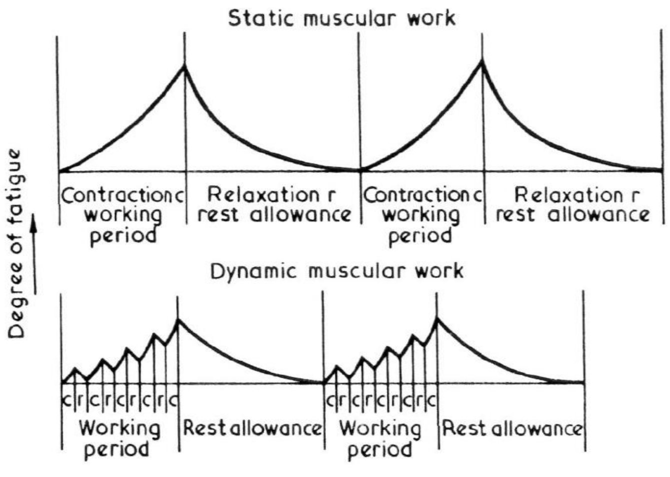


Fig 5 Change of the degree of fatigue in static and dynamic muscular work alternating with rest pauses (schematically)

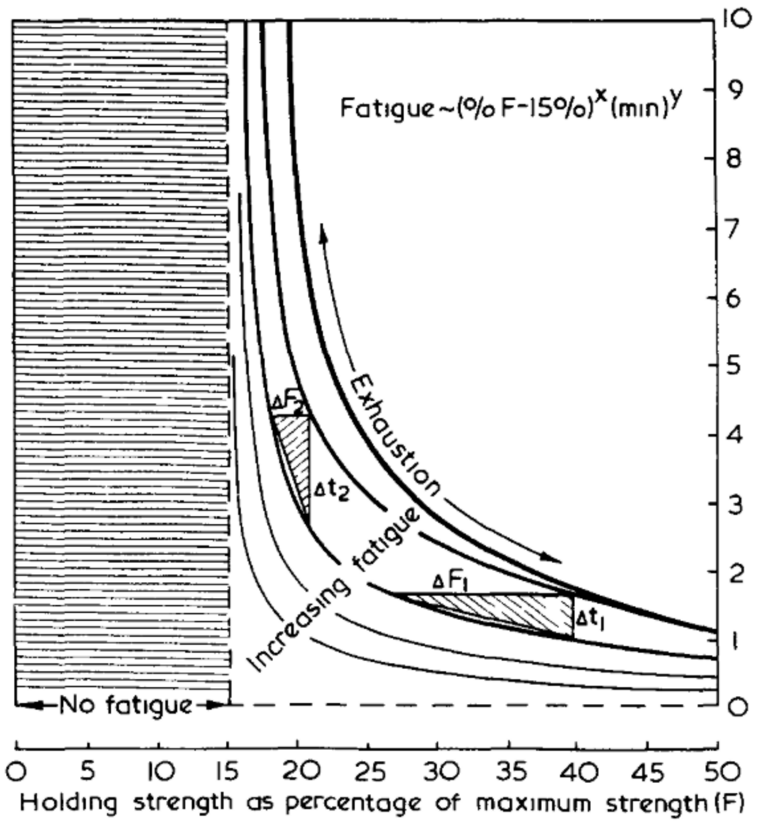
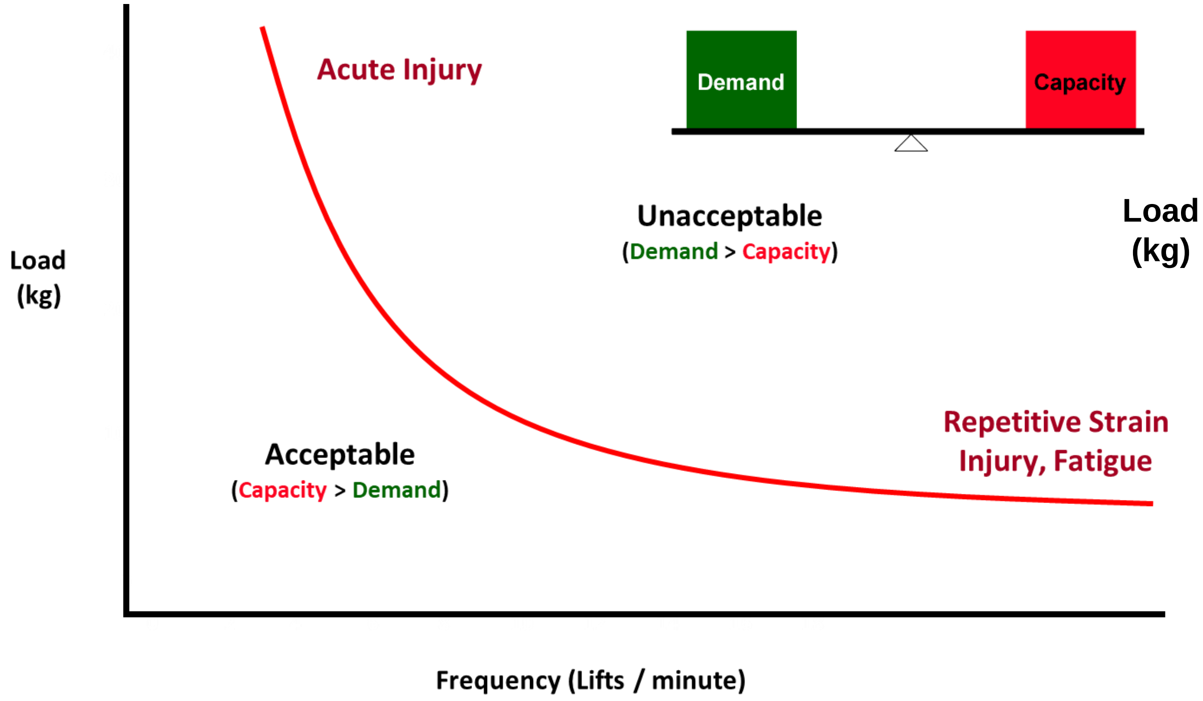
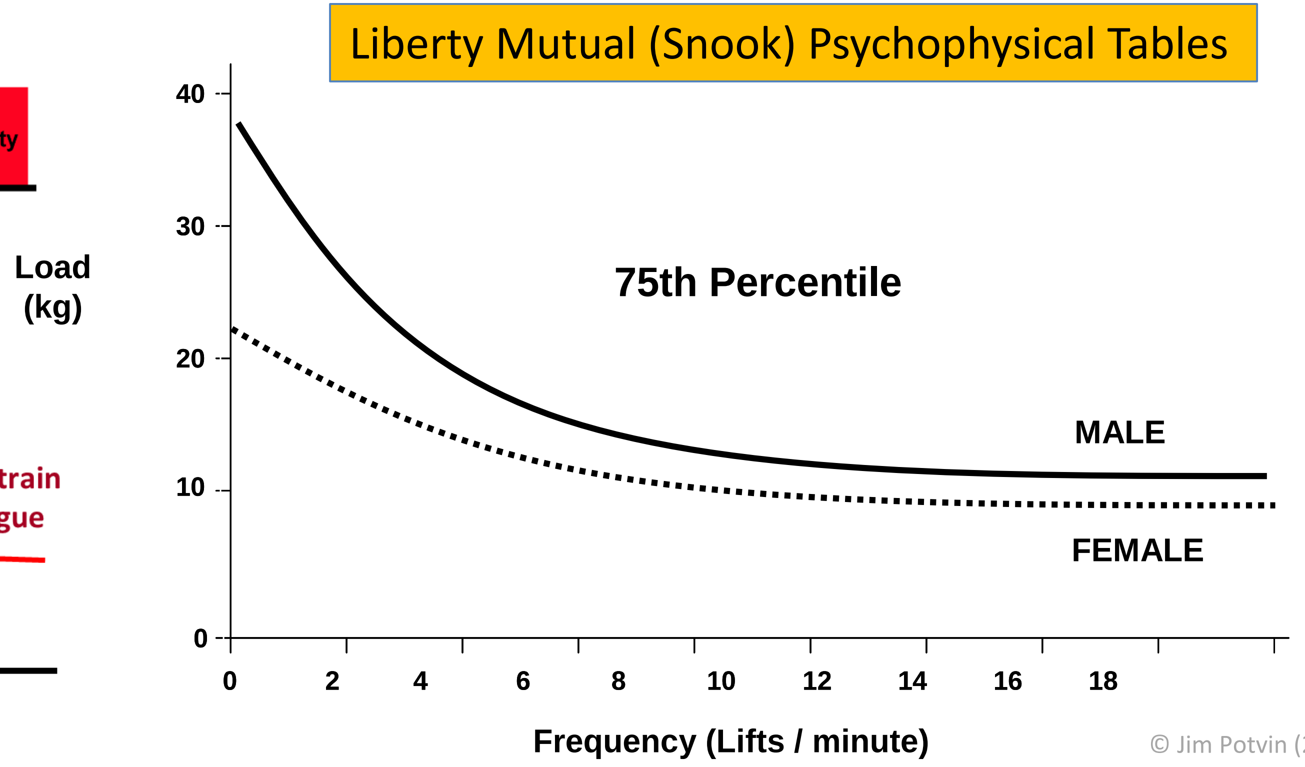


Fig 4. Optimizing fatigue in static muscular work (Δt curtailing duration of working period, ΔF lowering intensity of work)

How can we control fatigue in the workplace?

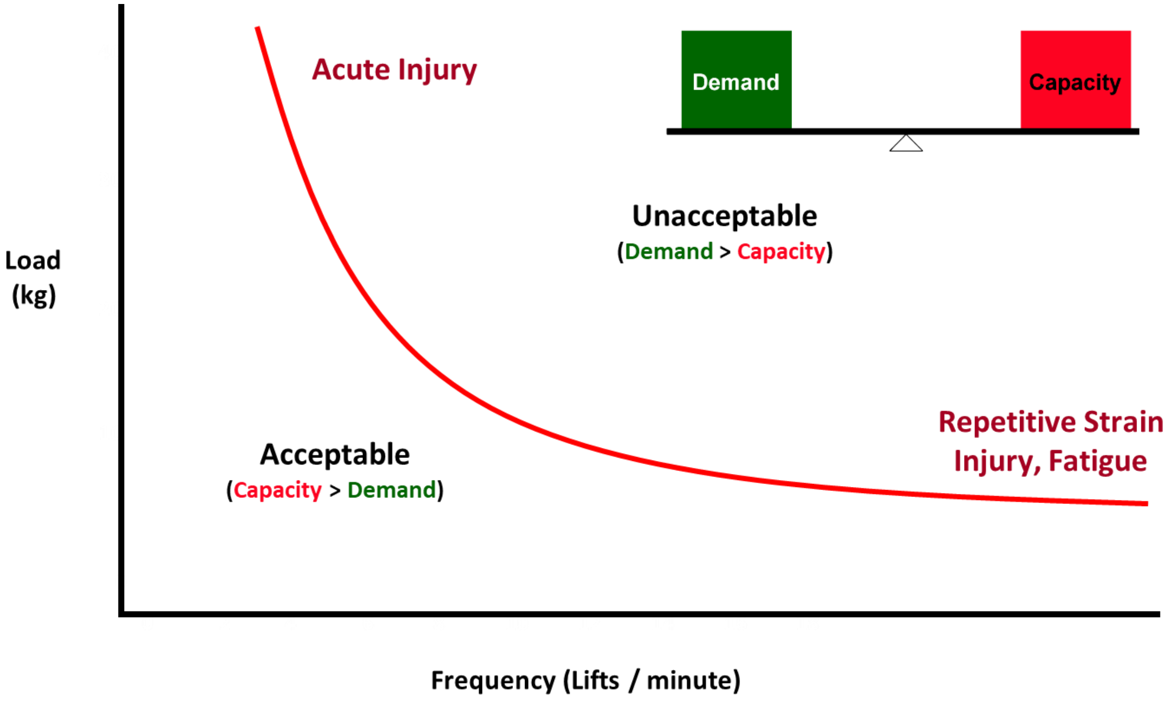
Reducing load based on frequency/repetition





How can we control fatigue in the workplace?

Reducing load based on frequency/repetition



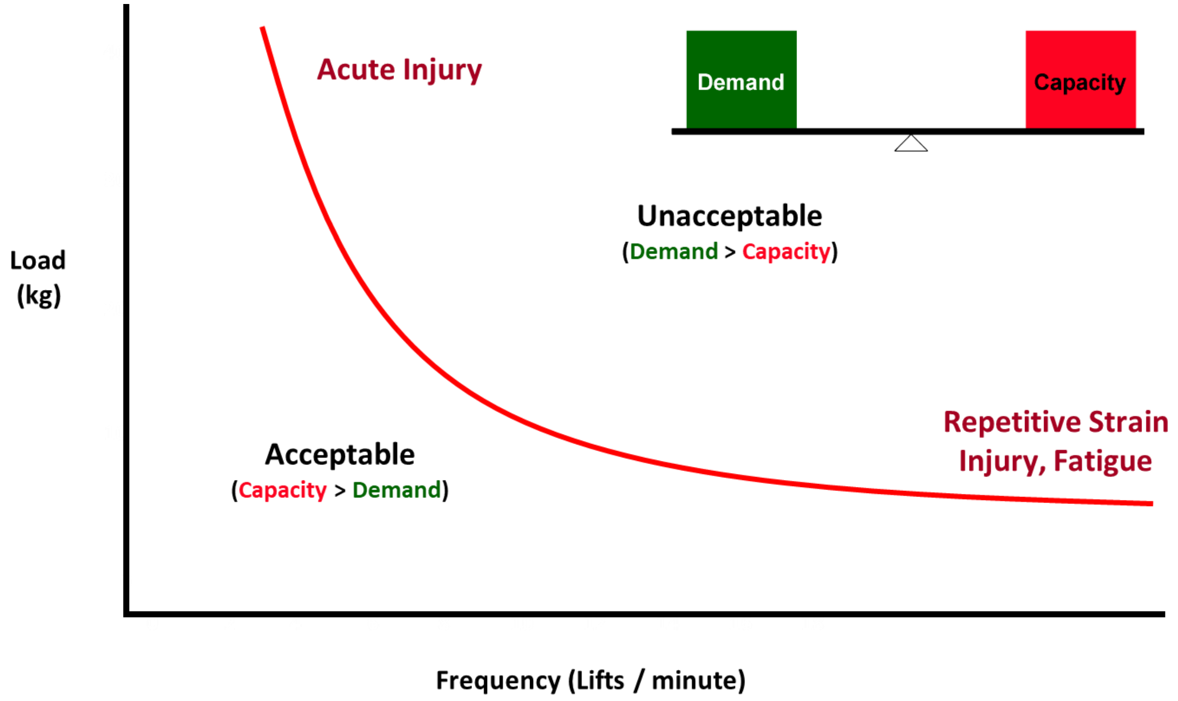
NIOSH Revised Lifting Equation – Waters et al 1993

Table 7. Frequency multiplier (*FM*).

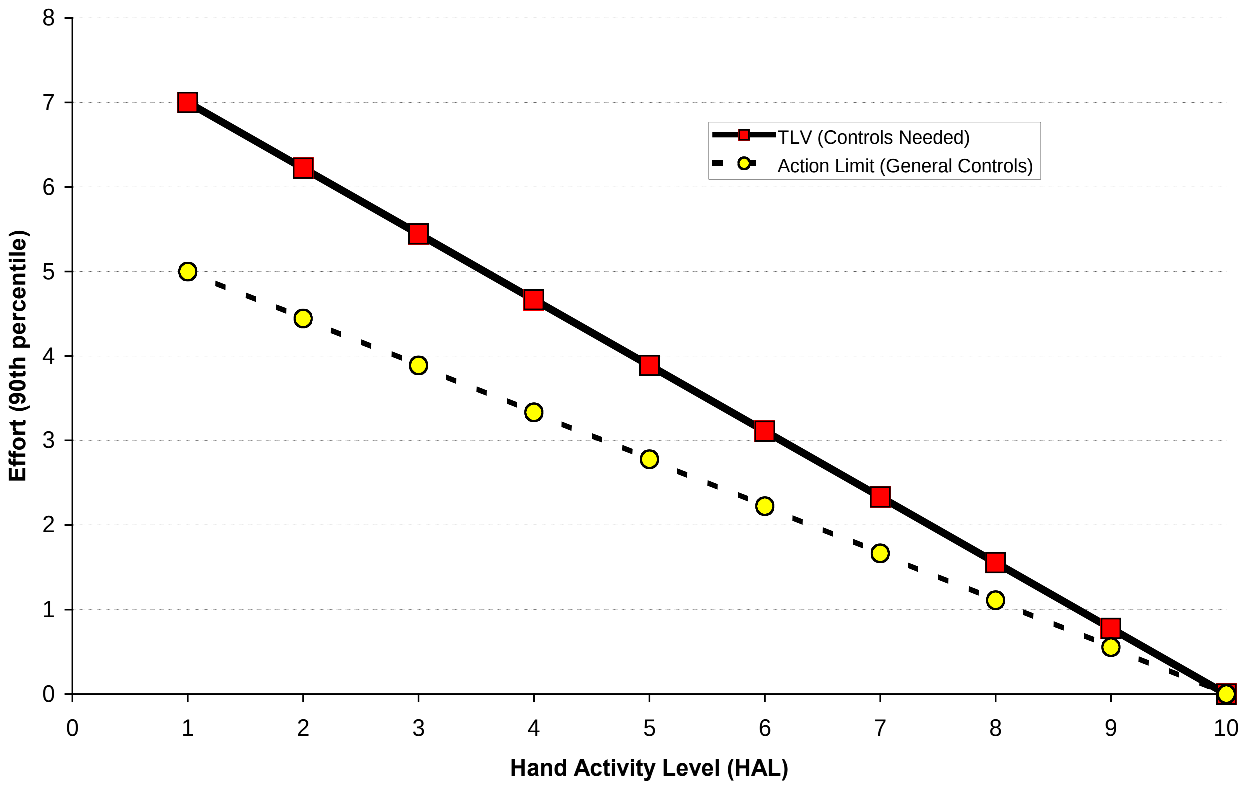
Frequency lifts/min	Work duration ≤ 1 h		Work duration ≤ 2 h		Work duration ≤ 8 h	
	$V < 75$	$V \geq 75$	$V < 75$	$V \geq 75$	$V < 75$	$V \geq 75$
0·2	1·00	1·00	0·95	0·95	0·85	0·85
0·5	0·97	0·97	0·92	0·92	0·81	0·81
1	0·94	0·94	0·88	0·88	0·75	0·75
2	0·91	0·91	0·84	0·84	0·65	0·65
3	0·88	0·88	0·79	0·79	0·55	0·55
4	0·84	0·84	0·72	0·72	0·45	0·45
5	0·80	0·80	0·60	0·60	0·35	0·35
6	0·75	0·75	0·50	0·50	0·27	0·27
7	0·70	0·70	0·42	0·42	0·22	0·22
8	0·60	0·60	0·35	0·35	0·18	0·18
9	0·52	0·52	0·30	0·30	0·00	0·15
10	0·45	0·45	0·26	0·26	0·00	0·13
11	0·41	0·41	0·00	0·23	0·00	0·00
12	0·37	0·37	0·00	0·21	0·00	0·00
13	0·00	0·34	0·00	0·00	0·00	0·00
14	0·00	0·31	0·00	0·00	0·00	0·00
15	0·00	0·28	0·00	0·00	0·00	0·00
>15	0·00	0·00	0·00	0·00	0·00	0·00

How can we control fatigue in the workplace?

Reducing load based on frequency/repetition



ACGIH TLV for Hand Activity Level (1999)

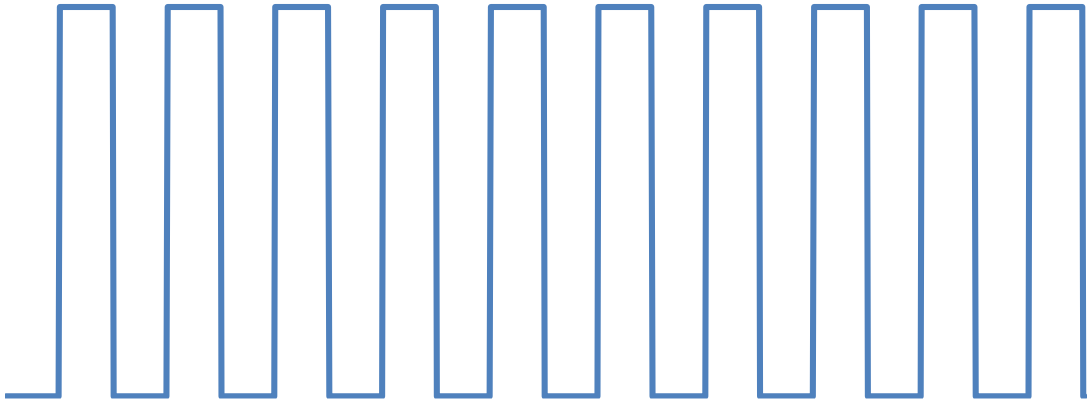


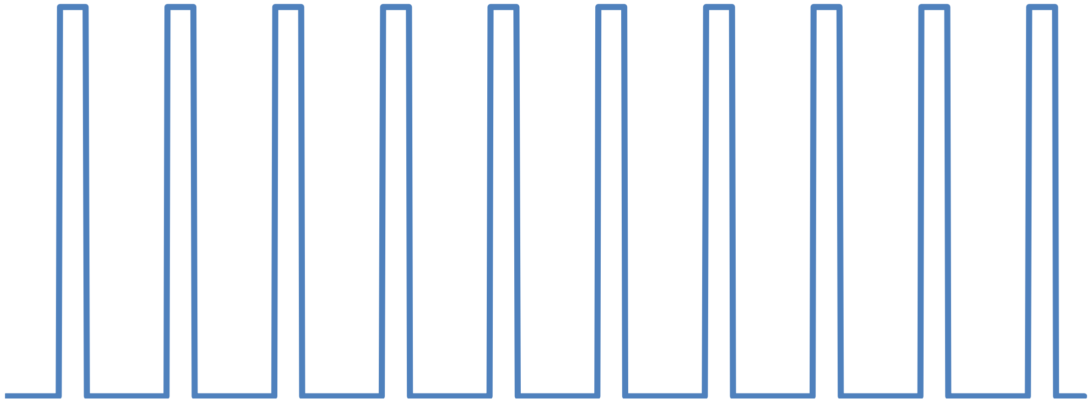
How can we control fatigue in the workplace?

Reducing load based on duty cycle?

10 repetition/min
50% duty cycle

10 repetition/min
25% duty cycle





How can we control fatigue in the workplace?

Reducing load based on duty cycle?

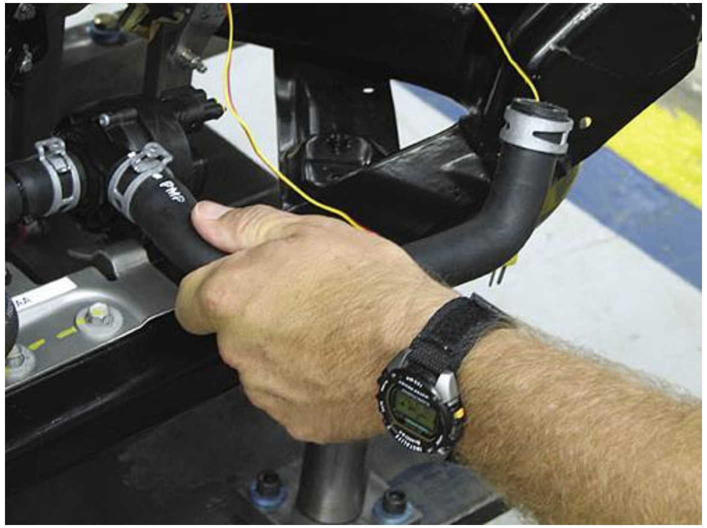
Predicting Maximum Acceptable Efforts for Repetitive Tasks: An Equation Based on Duty Cycle

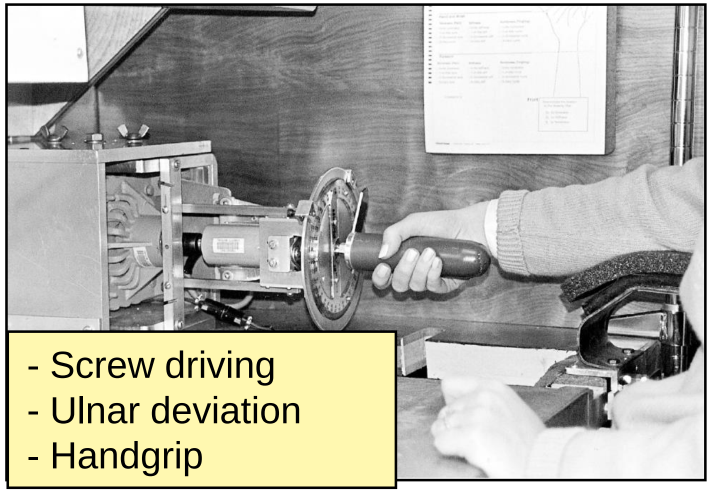
Jim R. Potvin, McMaster University, Hamilton, Ontario, Canada

HUMAN FACTORS
Vol. 54, No. 2, April 2012, pp. 175-188

Maximum Acceptable Effort (MAE) Equation

- Inclusion criteria:
    1. determine some maximum acceptable demand for upper limbs
    2. acceptable for 8 hours
    3. task has no assistive devices or tools
    4. training over multiple days for each task
    5. testing on only one task per day
    6. adjustment period at least 40 mins on testing day
        - Muppasani & Fernandez (1996)
    7. effort durations were provided or could be estimated





- Screw driving
- Ulnar deviation
- Handgrip

FIGURE 3. Subject workstation: screw driving with a 39-mm yoke handle, middle of motion

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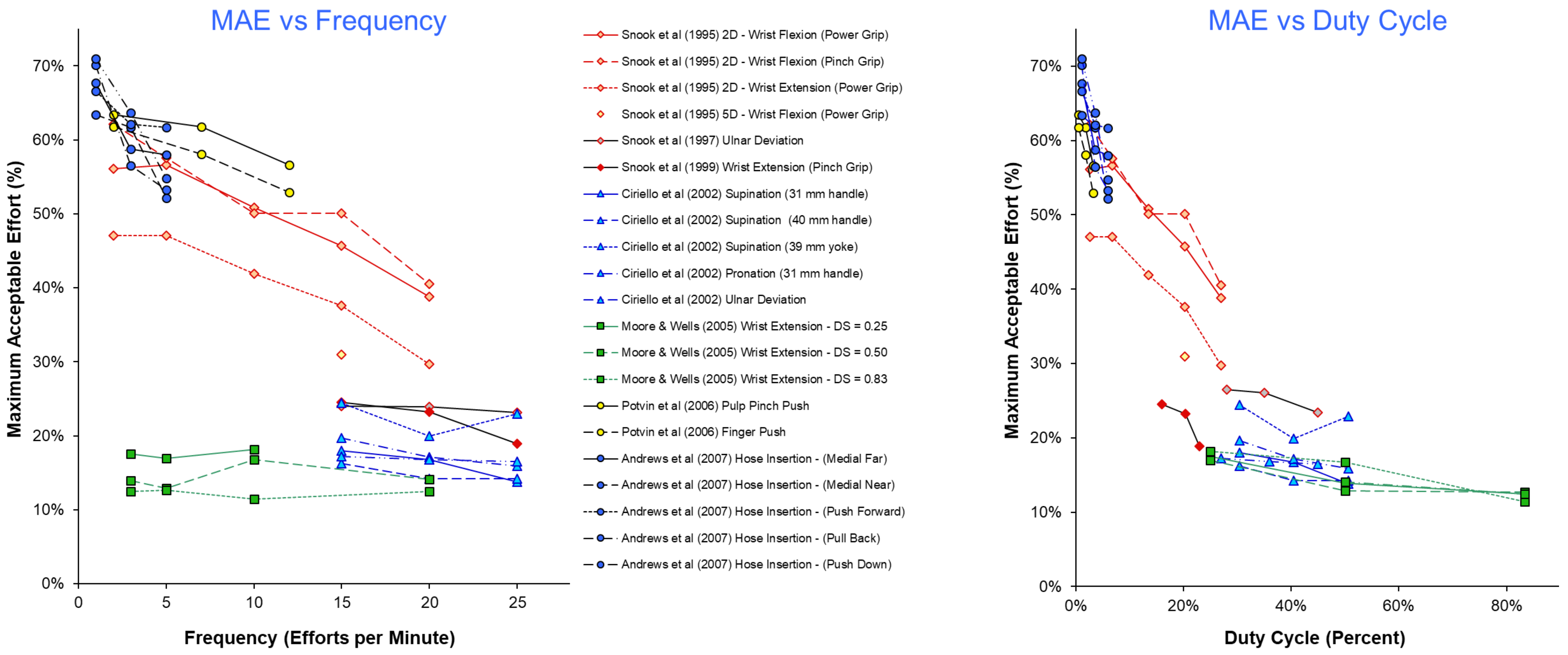
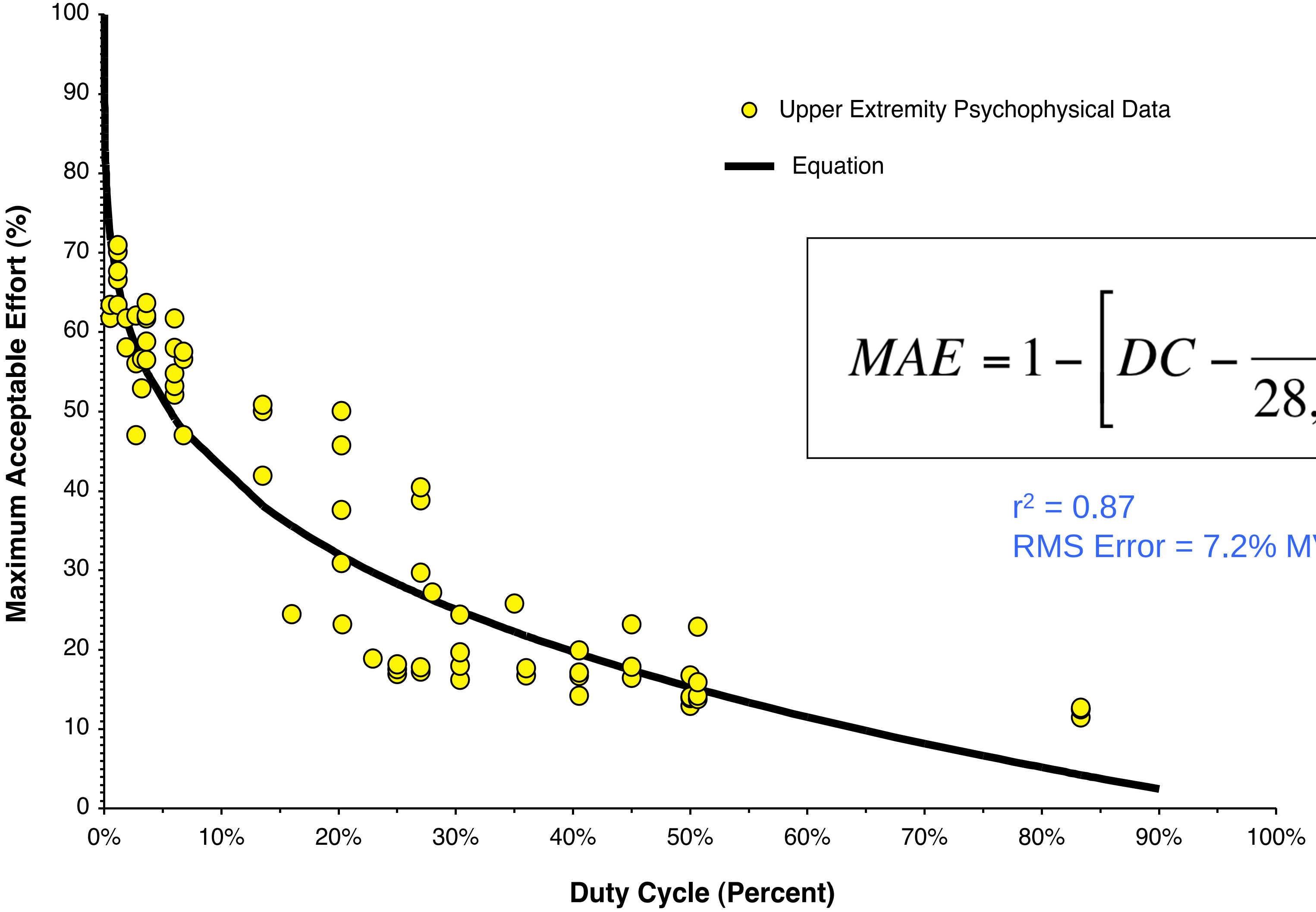
Study		Subjects	Freq (/min)	Duration (s)	Duty Cycle (s/min)	Duty Cycle (%)	Tasks
Snook et al (1995)	2 days/week	15	2	0.810	1.62	2.7%	- Wrist flexion: power grip - Wrist flexion: pinch grip - Wrist extension: power grip (n = Total of 15 tasks)
			5	0.810	4.05	6.8%	
			10	0.810	8.10	13.5%	
			15	0.810	12.15	20.3%	
			20	0.810	16.20	27.0%	
	5 days/week	14	15	0.810	12.15	20.3%	- Wrist flexion: power grip (n = 1)
Snook et al (1997)		11	15	1.120	16.80	28.0%	- Ulnar deviation: power grip (n = 3)
			20	1.050	21.00	35.0%	
			25	1.080	27.00	45.0%	
Snook et al (1999)		20	15	0.640	9.60	16.0%	- Wrist extension: pinch grip (n = 3)
			20	0.610	12.20	20.3%	
			25	0.550	13.75	22.9%	
Ciriello et al (2002)	Ulnar Deviation	10	15	1.080	15.00	27.0%	- Ulnar deviation: power grip (n = 3) - Supination: 31 mm screwdriver - Supination: 40 mm screwdriver - Supination: 39 mm yoke - Pronation: 31 mm screwdriver (n = 12)
			20	1.080	20.00	36.0%	
			25	1.080	25.00	45.0%	
	Pronation & Supination		15	1.215	15.00	30.4%	
			20	1.215	20.00	40.5%	
			25	1.215	25.00	50.6%	
Moore & Wells (2005)	Duty Cycle = 25%	8	3	5.000	15.00	25.0%	- Wrist extension: in-line powered srcrewdriver (n = 11)
			5	3.000	15.00	25.0%	
			10	1.500	15.00	25.0%	
	Duty Cycle = 50%		3	10.000	30.00	50.0%	
			5	6.000	30.00	50.0%	
			10	3.000	30.00	50.0%	
			20	1.500	30.00	50.0%	
	Duty Cycle = 83.3%		3	16.667	50.00	83.3%	
			5	10.000	50.00	83.3%	
			10	5.000	50.00	83.3%	
			20	2.500	50.00	83.3%	
Potvin et al (2006)		24	2	0.160	0.32	0.5%	- Push: pulp pinch - Push: finger tip (n = 6)
			7	0.160	1.12	1.9%	
			12	0.160	1.92	3.2%	
Andrews et al (2008)		15	1	0.685	0.69	1.1%	- Hose insertions: 5 hand locations (n = 15)
			3	0.717	2.15	3.6%	
			5	0.721	3.61	6.0%	

Maximum Acceptable Effort (MAE) Equation



Maximum Acceptable Effort (MAE) Equation



$$MAE = 1 - \left[DC - \frac{1}{28{,}800} \right]^{0.24}$$

$r^2 = 0.87$

RMS Error = 7.2% MVE

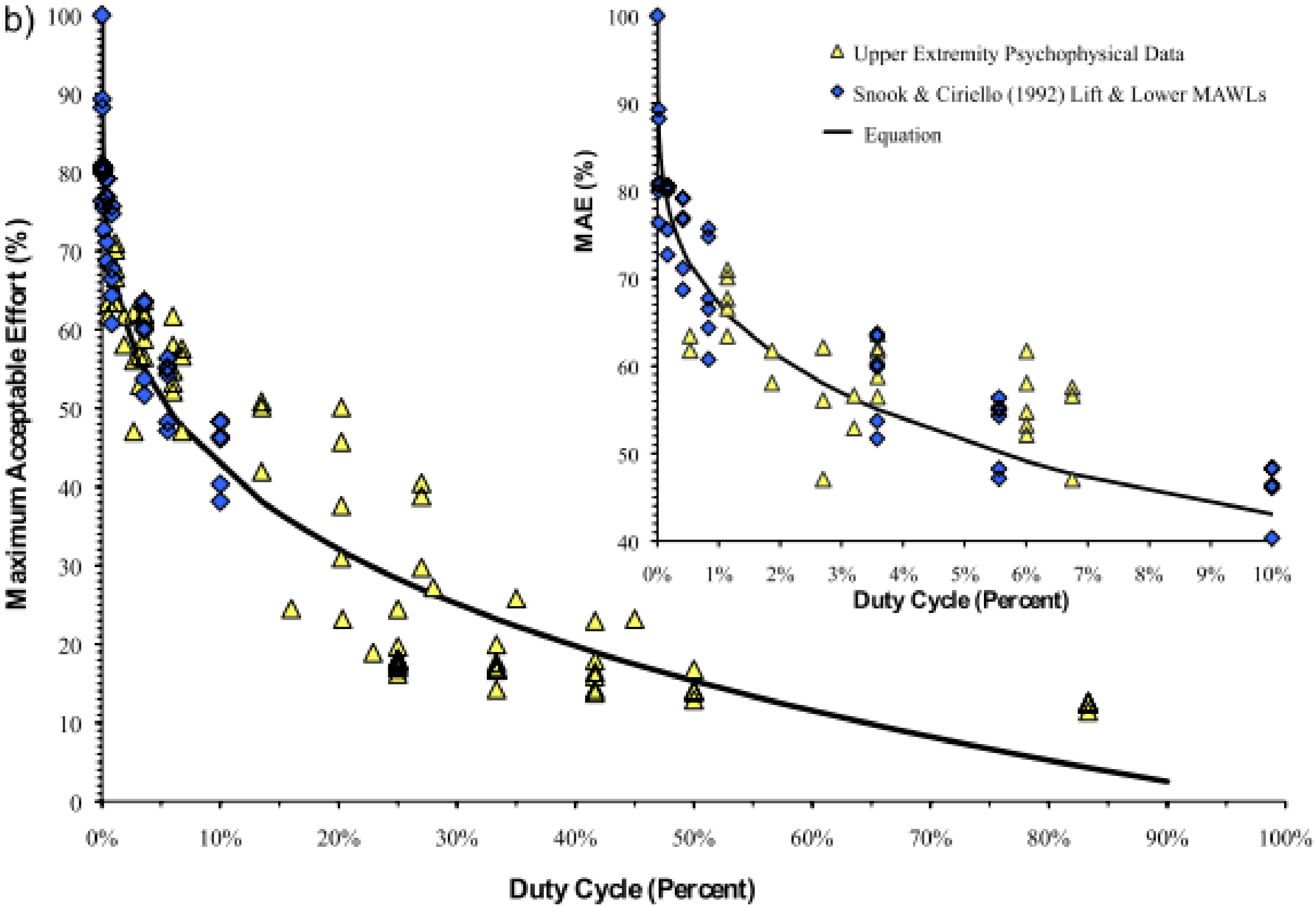
Maximum Acceptable Effort (MAE) Equation

Work 41 (2012) 397-400 397
DOI: 10.3233/WOR-2012-0189-397
IOS Press

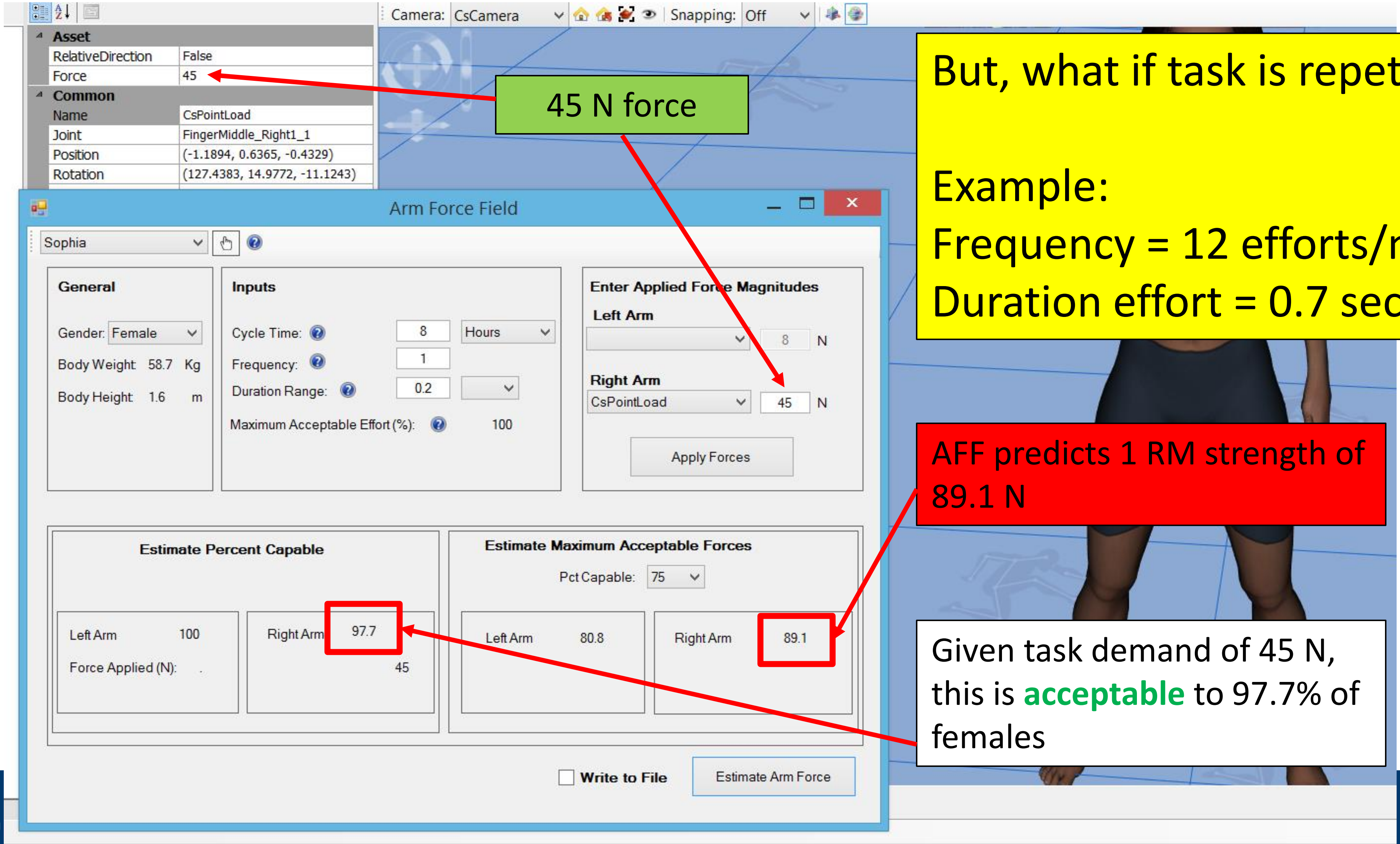
An equation to predict maximum acceptable loads for repetitive tasks based on duty cycle: evaluation with lifting and lowering tasks

Jim R. Potvin[a*]
[a]*Department of Kinesiology, McMaster University, 1280 Main Street West, Hamilton, Ontario, Canada, L8S 4K1*

The shape of the MAE equation also fits lifting/lowering data



How can the MAE be used in practice?



45 N force

But, what if task is repetitive?

Example:

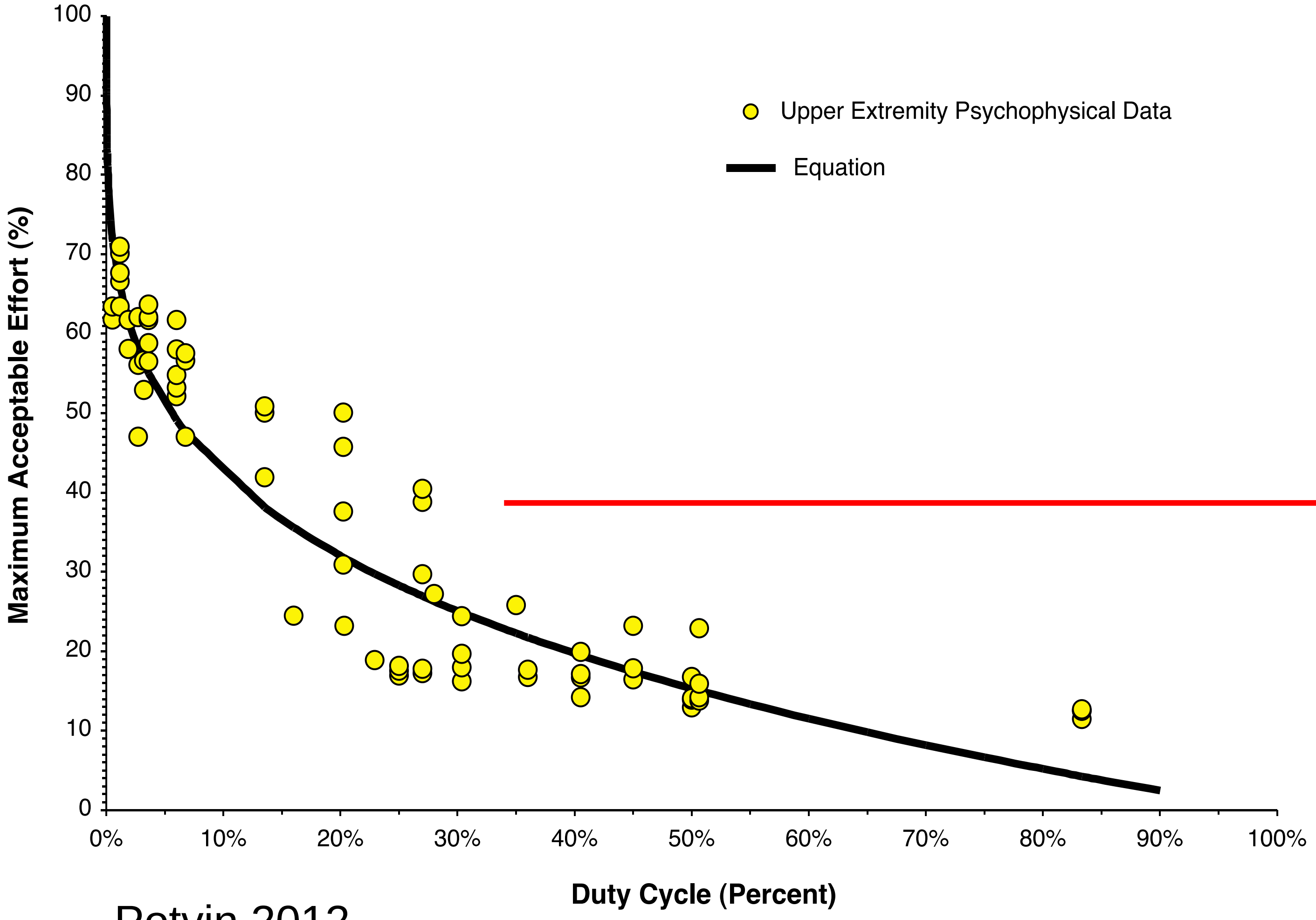
Frequency = 12 efforts/min

Duration effort = 0.7 seconds

AFF predicts 1 RM strength of 89.1 N

Given task demand of 45 N, this is **acceptable** to 97.7% of females

Accounting for duty cycle



Potvin 2012

Arm Force Field (or any strength value)

↓

Determine Strength
1 RM for 75% female
f=0.002/min, low duration

↓

Apply MAE Correction
AFF Strength x MAE correction

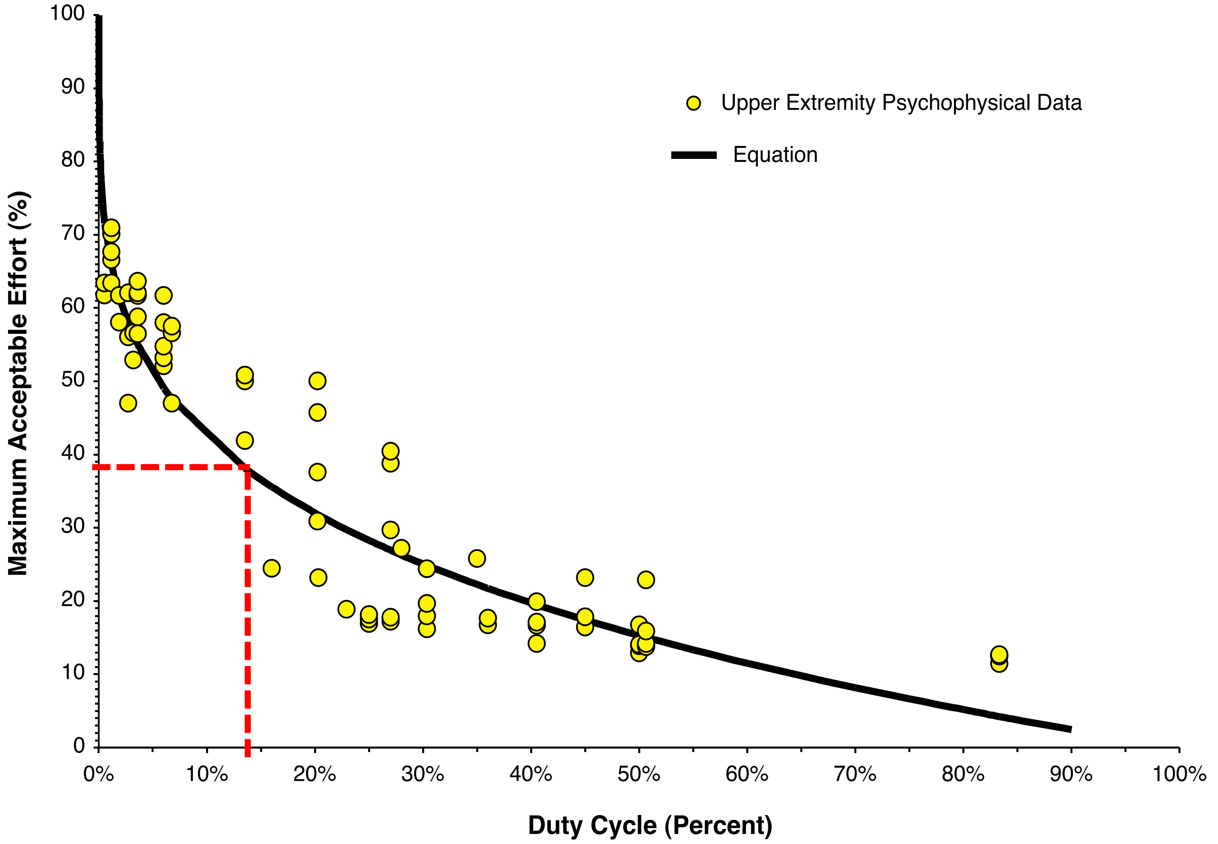
↓

Acceptable force corrected for repetition/duration

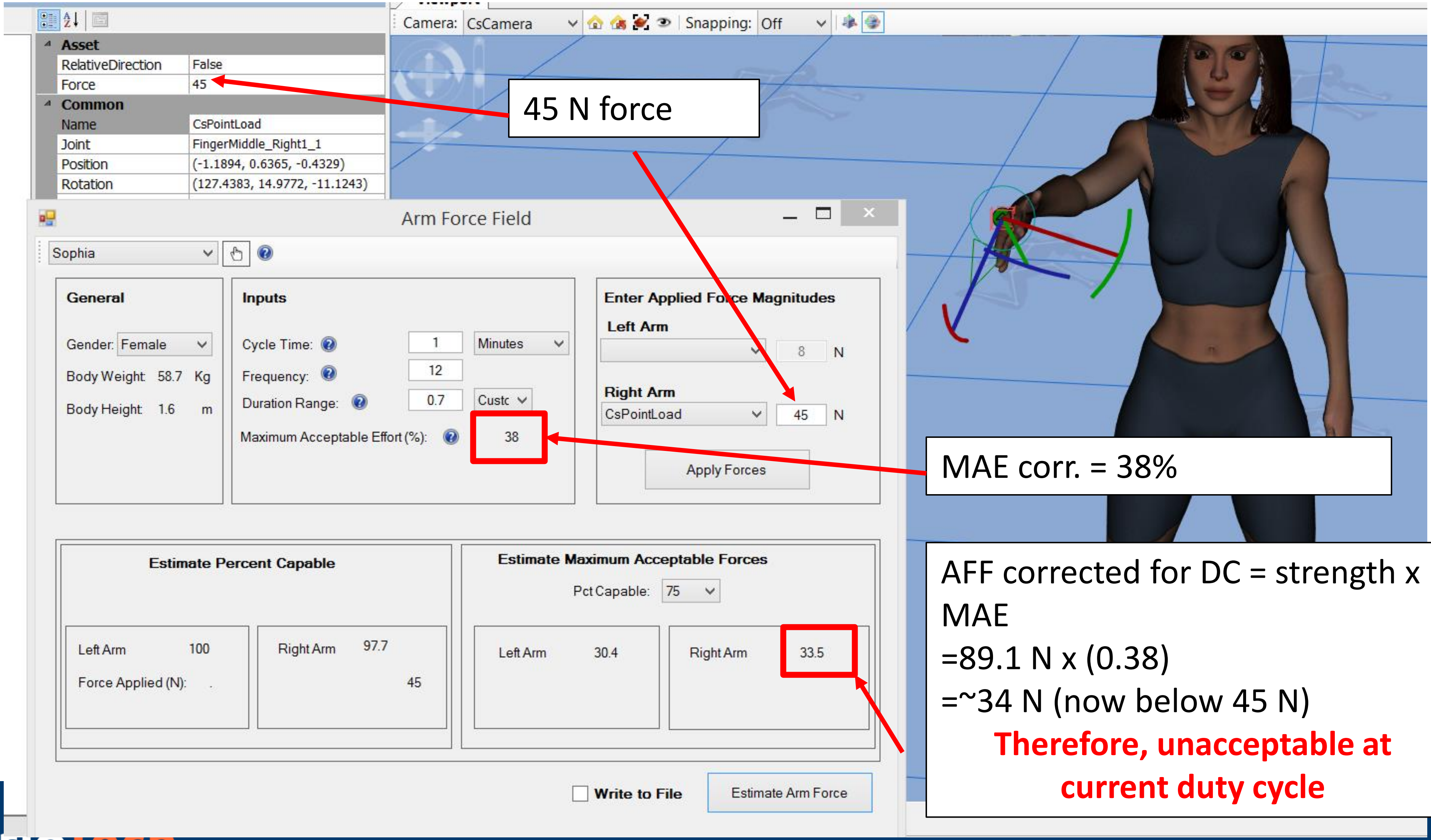
Accounting for duty cycle

- What if task has following parameters:
  - Frequency = 12 efforts/min
  - Duration effort = 0.7 s

- DC = (12 x 0.7)/60 = 0.14 (14%)
- MAE = 1 - $(0.14 - 0.000035)^{0.24}$ = 0.38 (38%)



How can the MAE be used in practice?



45 N force

MAE corr. = 38%

AFF corrected for DC = strength x MAE
=89.1 N x (0.38)
=~34 N (now below 45 N)

Therefore, unacceptable at current duty cycle

ACGIH TLV for Localized Fatigue (2016)

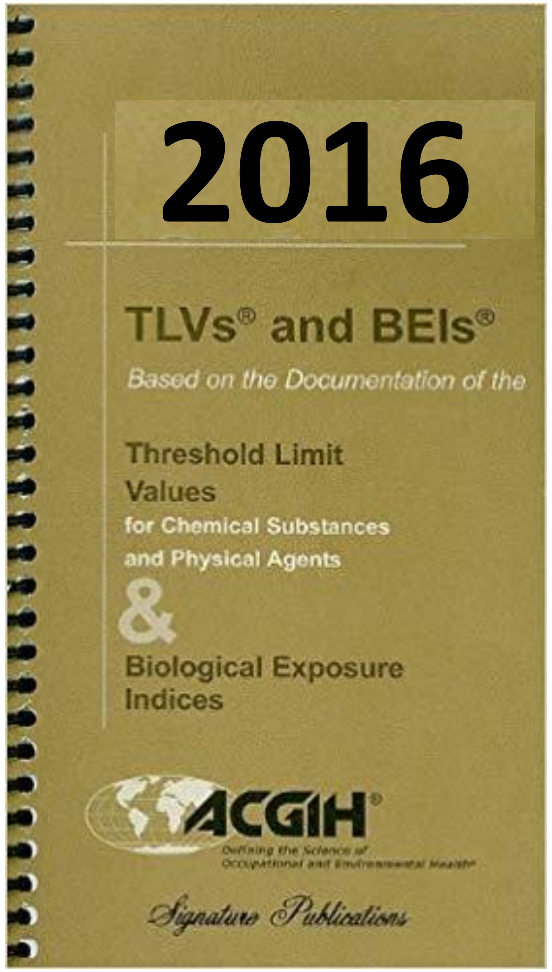
Upper Limb Localized Fatigue: TLV(R) Physical Agents 7th Edition Documentation

ACGIH(R)

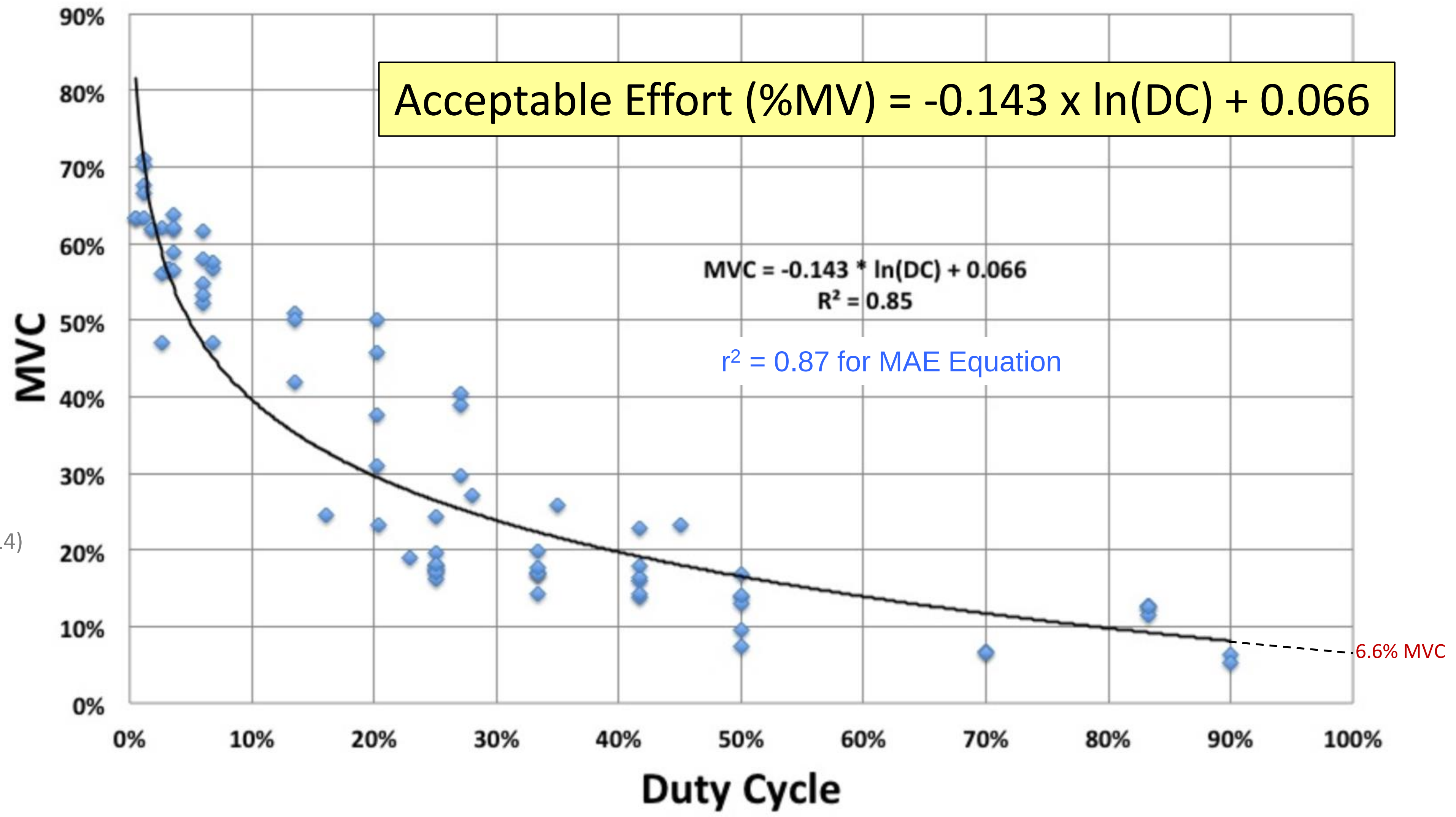
Format:
Electronic (digital download/no shipping)

Member - $48.00
NonMember - $60.00

+ Add to Cart



ACGIH TLV: *Localized Muscle Fatigue*



data from
Potvin (2012)
and
Sonne & Potvin (2014)

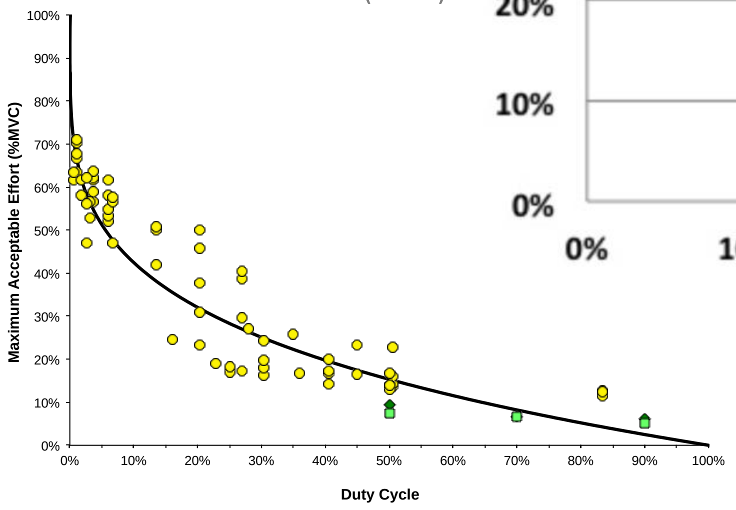


FIGURE 7. TLV® describing maximum voluntary contraction (MVC) versus duty cycle based on data from Potvin (2012, Figure 3) plus Sonne and Potvin (2014). Exponential model fitted to data from 0.5% to 90% duty cycle.

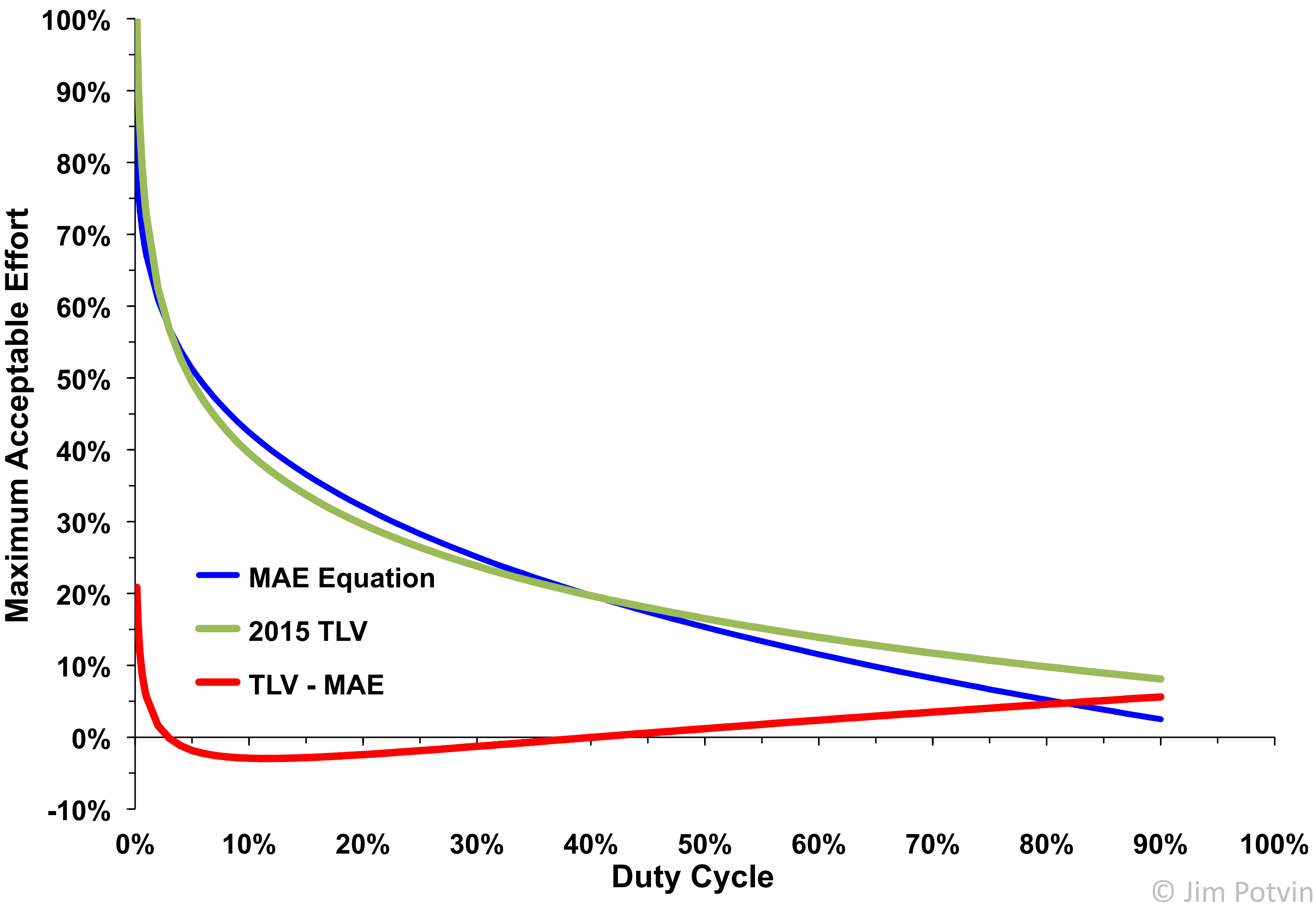
MAE vs ACGIH TLV

TLV = -0.143 x ln(DC) + 0.066

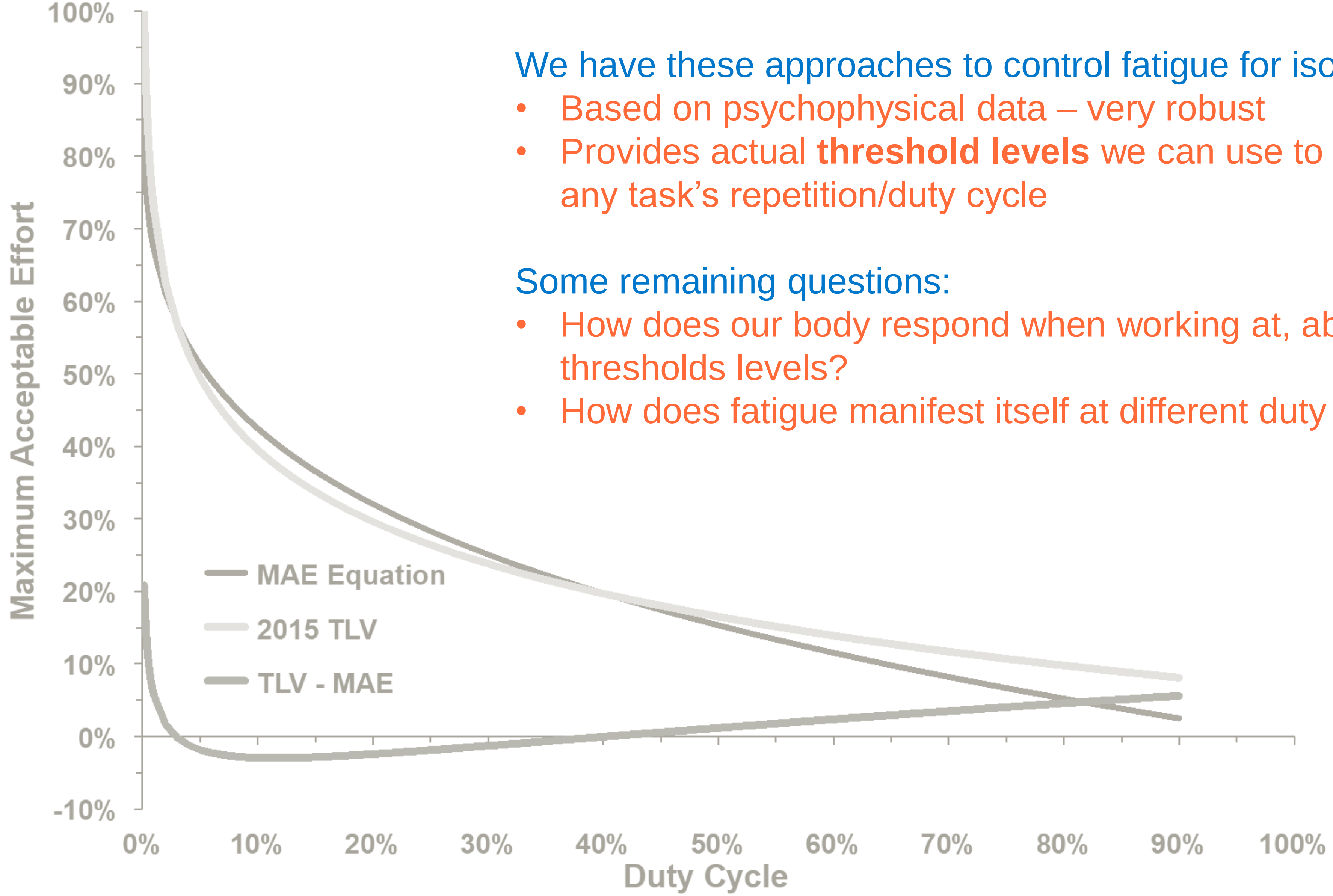
allows: 6.6% MVC at DC = 1.0
100% MVC for 42s/day

MAE = 1 – $DC^{0.24}$

allows: 0% MVC at DC = 1.0
100% MVC for 1s/day



Next Steps: Validation?



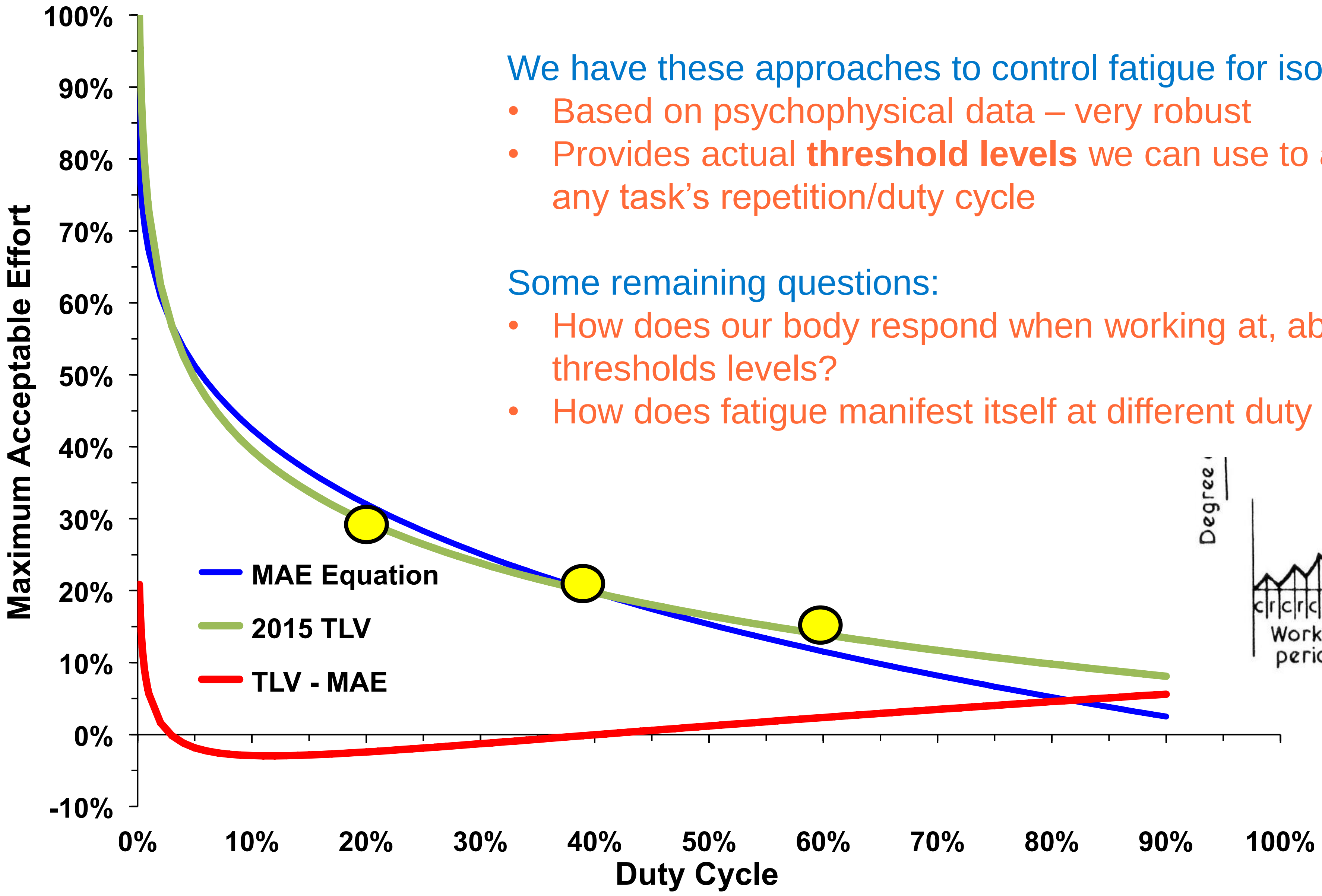
We have these approaches to control fatigue for isolated tasks

- Based on psychophysical data – very robust
- Provides actual **threshold levels** we can use to adjust force levels based on any task's repetition/duty cycle

Some remaining questions:

- How does our body respond when working at, above or below these thresholds levels?
- How does fatigue manifest itself at different duty cycles along the curve?

Next Steps: Validation?



We have these approaches to control fatigue for isolated tasks

- Based on psychophysical data – very robust
- Provides actual **threshold levels** we can use to adjust force levels based on any task's repetition/duty cycle

Some remaining questions:

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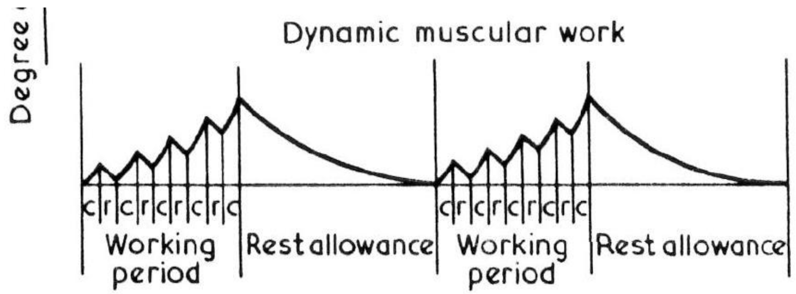
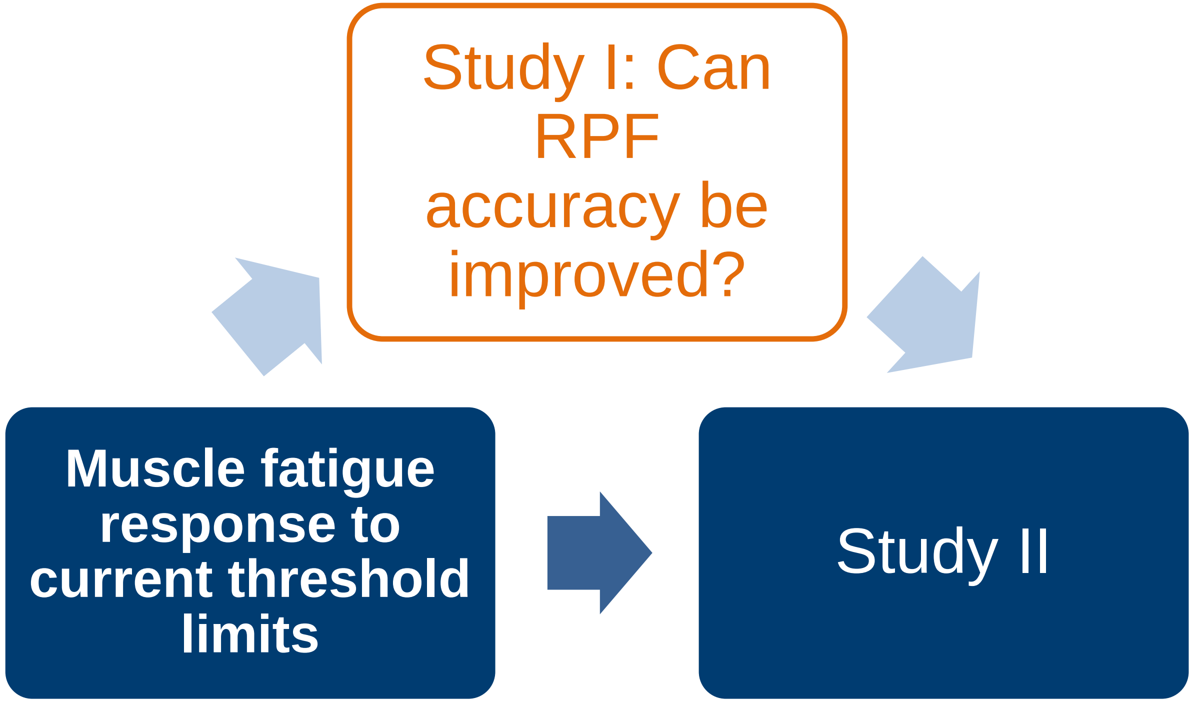


Is the amount of fatigue development the same at different points along this curve?

Goals/Objectives

- Evaluation of current thresholds of exposure for upper extremity work (**Study 2**)
- Improving the quantification of Localized Muscle Fatigue (LMF) (**Study 1**)



RPF – strongly correlated to **force declines** & **EMG measures**

- Inconsistent provision of **scale familiarization**
- **Misunderstood** by participants?

Study 1 Research Question

Does a period of familiarization improve the accuracy of RPF relative to classical measures of LMF (e.g. force output, EMG amplitude & mean power frequency)?

THEORETICAL ISSUES IN ERGONOMICS SCIENCE
https://doi.org/10.1080/1463922X.2020.1827079

Taylor & Francis
Taylor & Francis Group

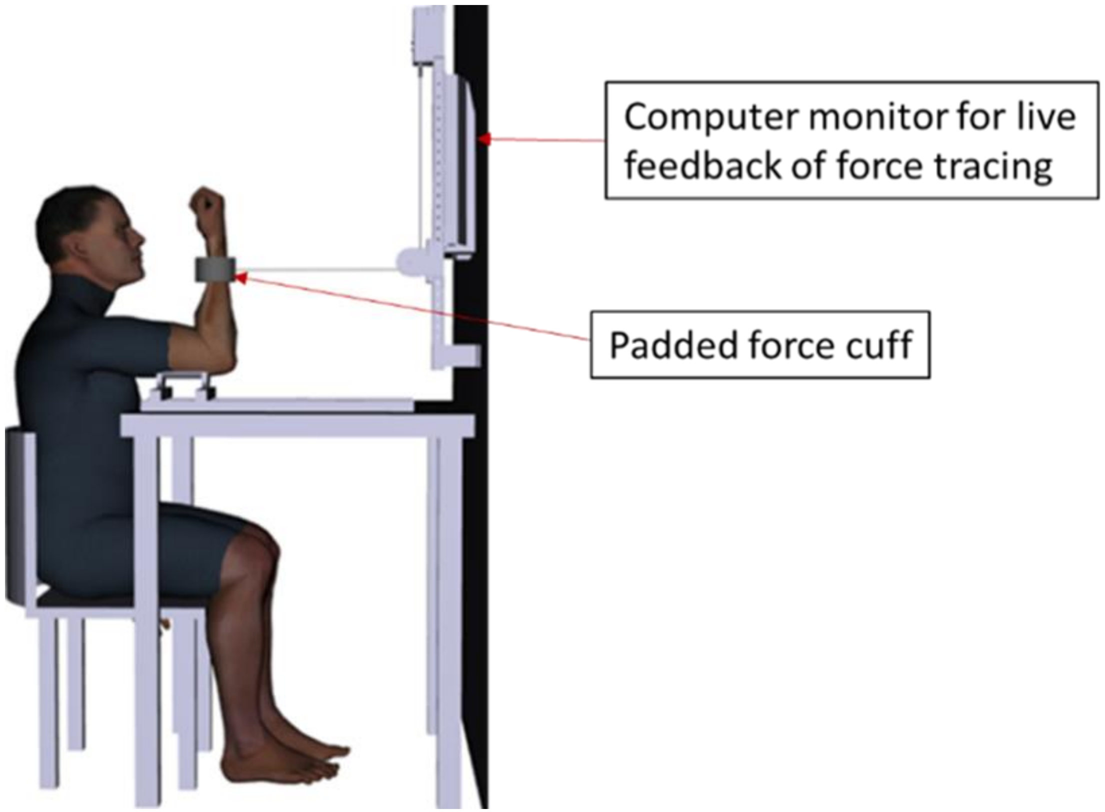
Check for updates

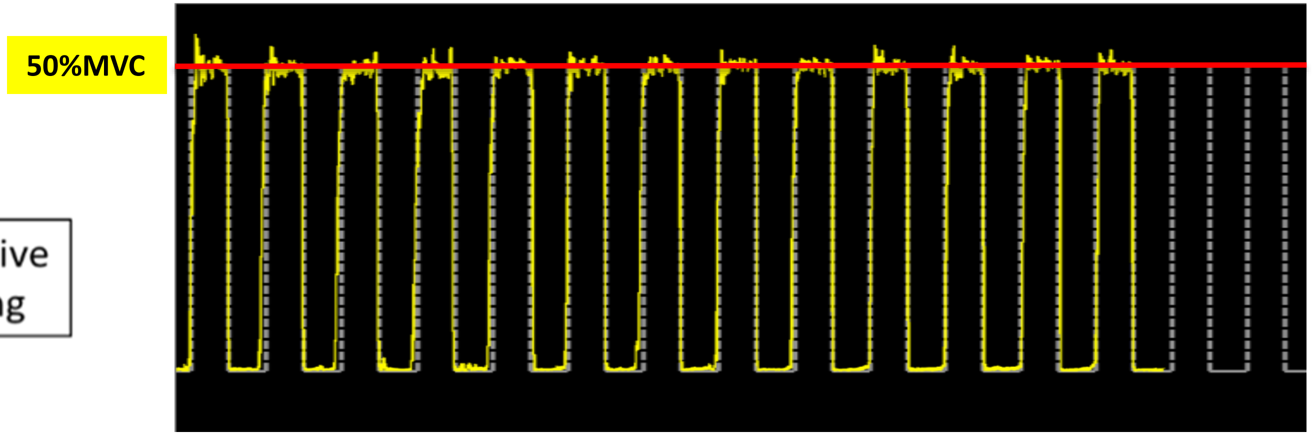
Calibrating ratings of perceived fatigue relative to objective measures of localised muscle fatigue using a feedback-based familiarisation protocol

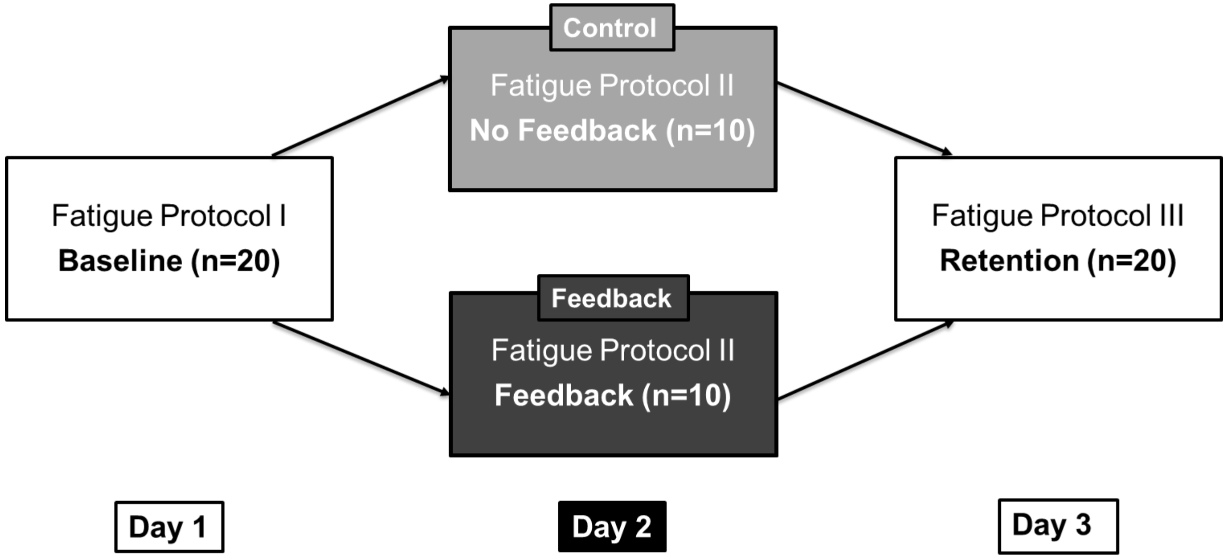
Daniel M. Abdel-Malek[a], Ryan C. A. Foley[a], Fahima Wakeely[a], Jeffrey D. Graham[b] and Nicholas J. La Delfa[a]

[a]Faculty of Health Sciences (Kinesiology), University of Ontario Institute of Technology, Oshawa, Ontario, Canada; [b]Department of Family Medicine, McMaster University, Hamilton, Ontario, Canada

Experimental Procedures & Protocol

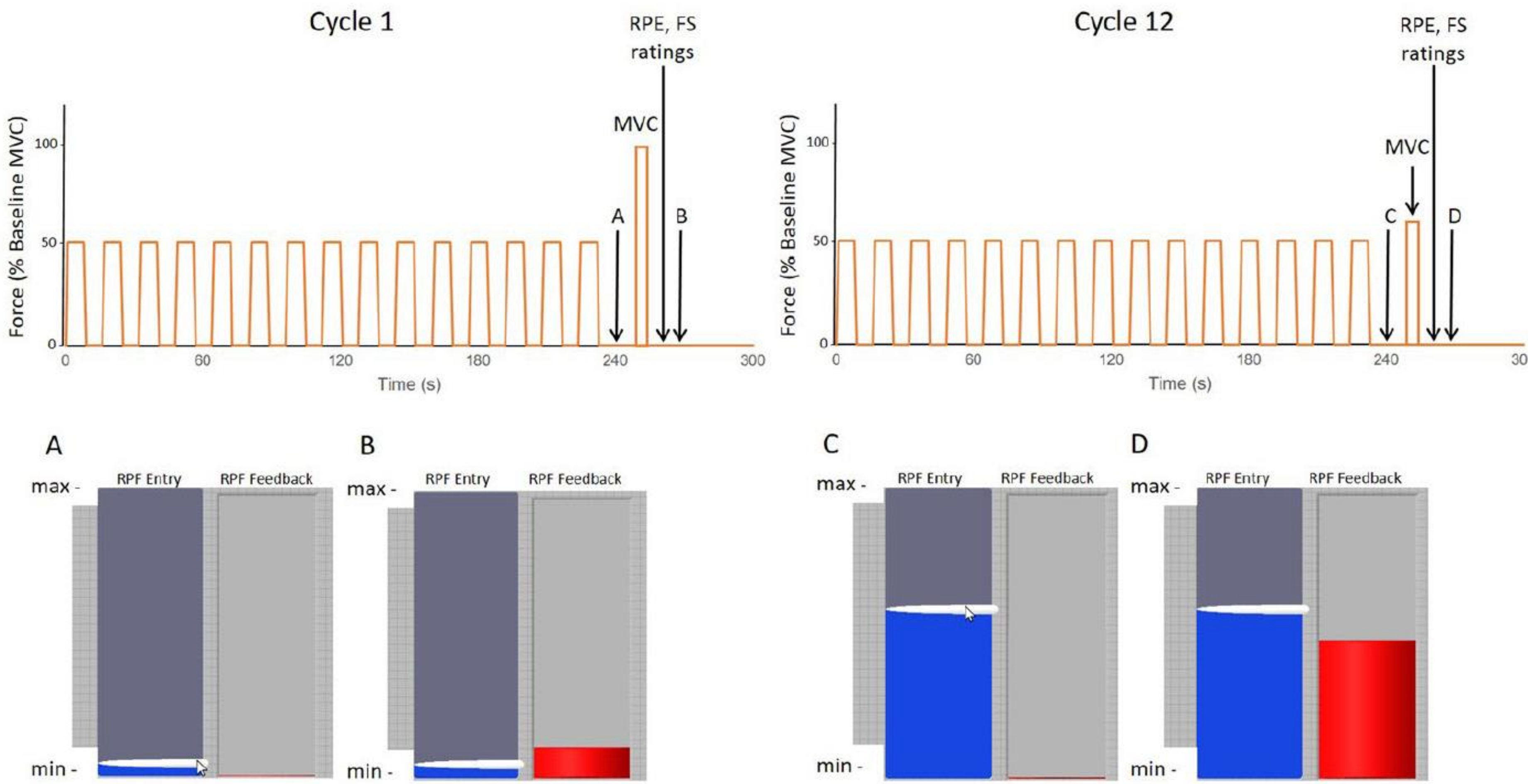






RPF Feedback

Only provided to Feedback group on Day 2

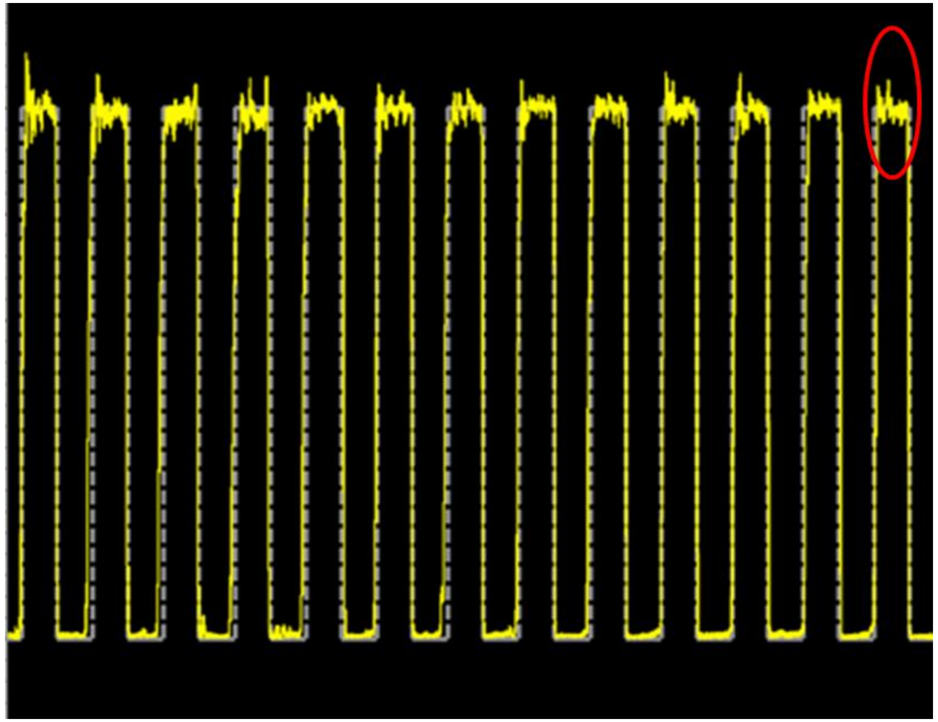


Data Analysis

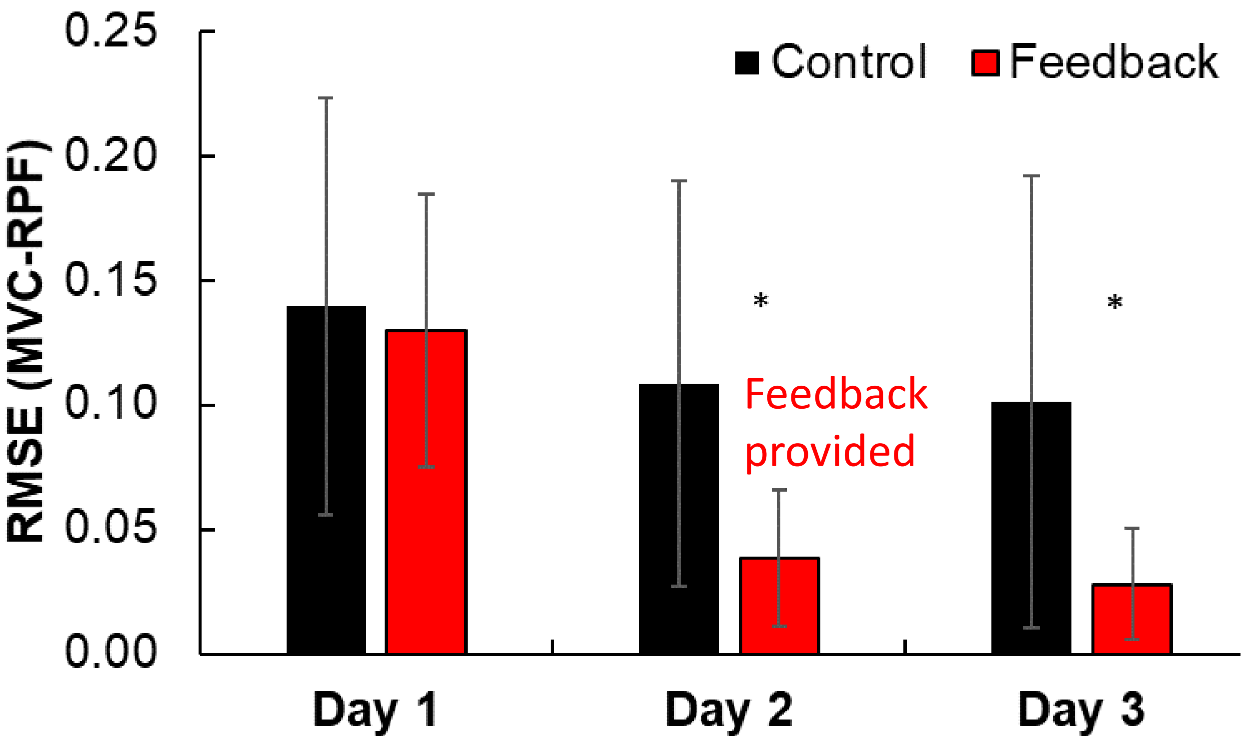
In (or after) final plateau, we obtained:
- EMG amplitude
- EMG Mean Power Frequency (MnPF)
- RPF
- Decline in MVC

All fatigue measures:
- Normalized to baseline
- Time-normalized via rubber-banding
- Fatigue-normalized (-1 multiplier)

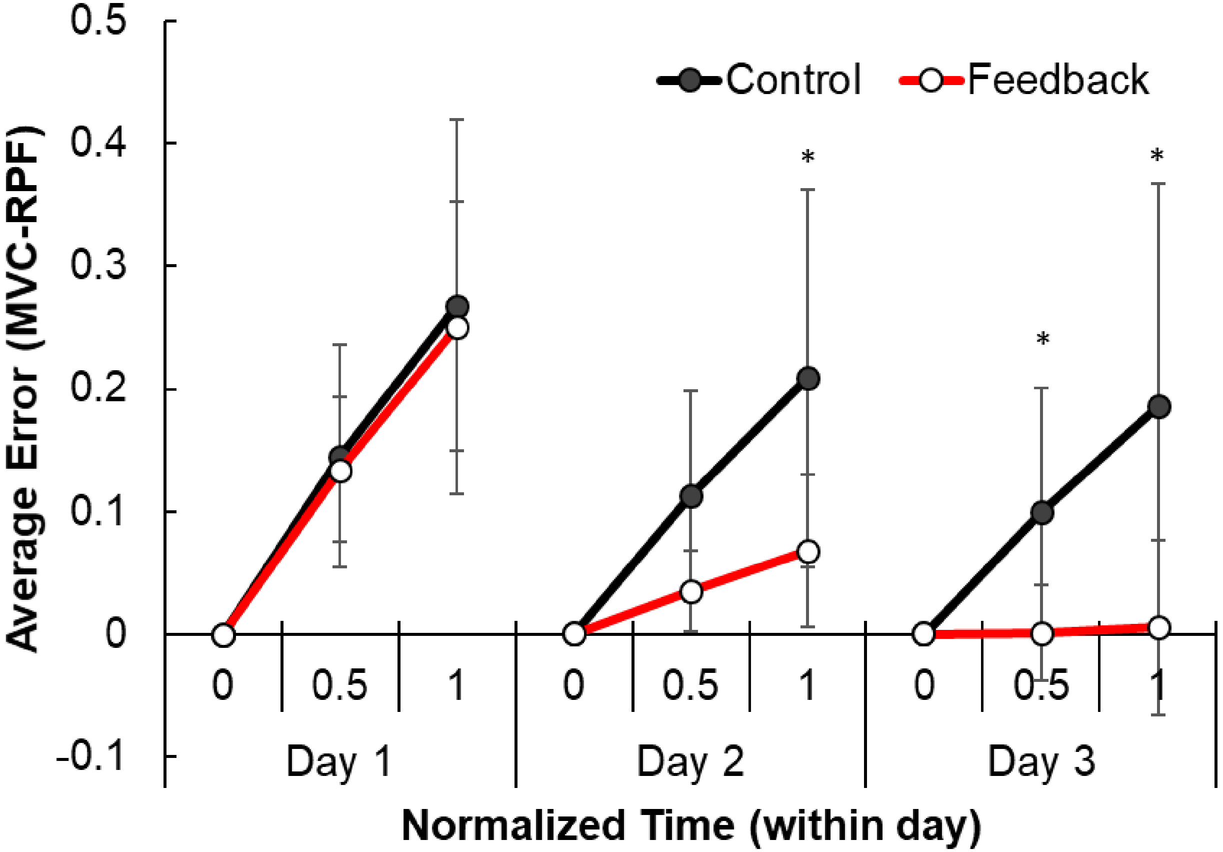
Dependent variables - (1) **average error** and (2) **RMSE** between:
- **RPF-MVC**
- **RPF-aEMG**
- **RPF-MnPF**



Results: RPF-MVC

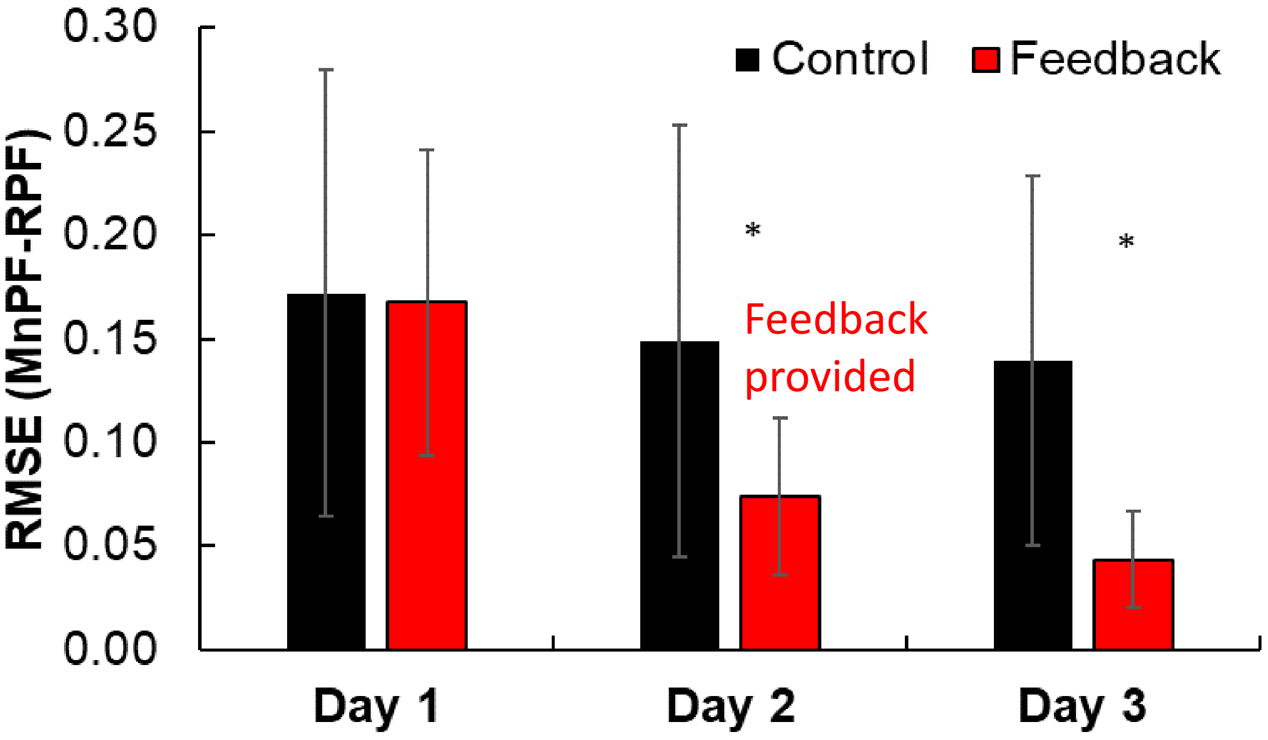


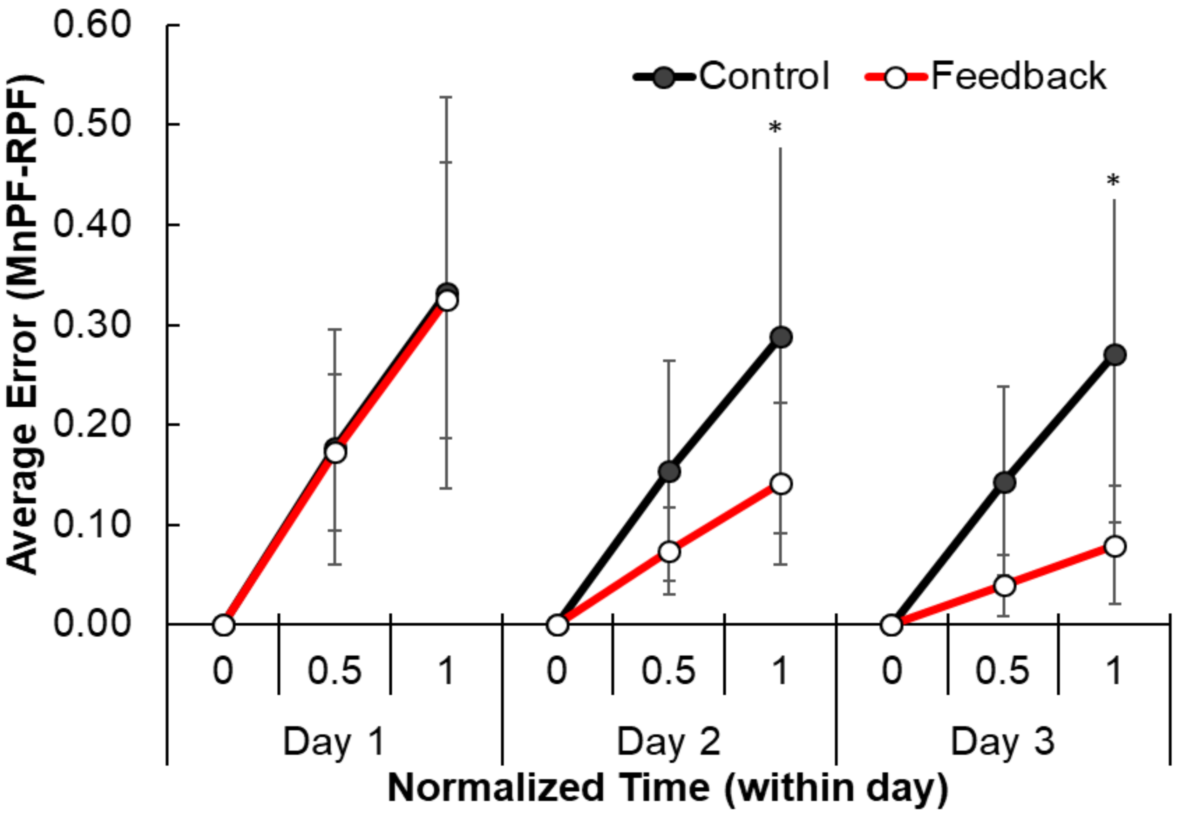
($F= 5.388$, $p < 0.01$, $\eta^2 = 0.230$)



($F = 9.060$, $p < 0.005$, $\eta^2 = 0.335$)

Results: RPF-MnPF





(F= 5.534, $p < 0.01$, $\eta^2 = 0.235$)

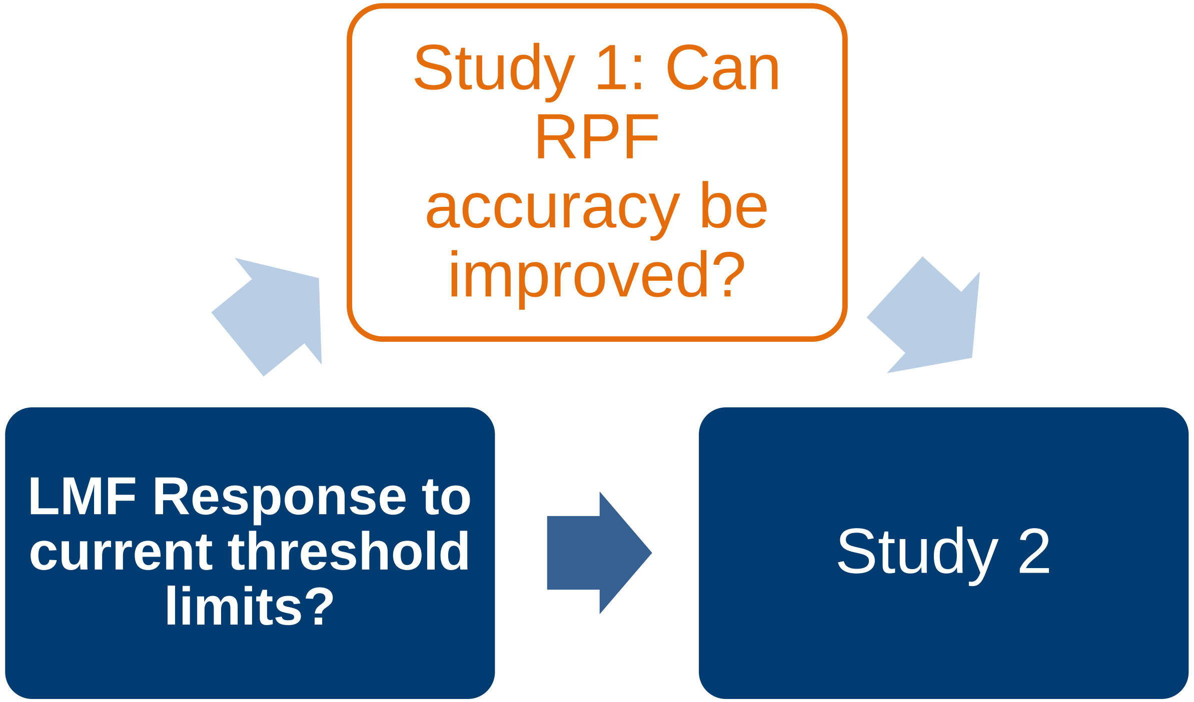
(F= 6.172, $p < 0.05$, $\eta^2 = 0.255$)

Conclusions

- RPF scale familiarization **improved the accuracy** of RPF relative to measures of force output and EMG MnPF
- RPF can be an extremely valuable tool for researchers and practitioners to monitor muscle fatigue
  - Extremely accessible
    - Method for easy field 'familiarization' needed
  - Implications?
    - One of the tricky things about muscle fatigue research is that measurement of the 'gold-standard' metric (i.e. MVC) confounds the fatigue process being studied
      - Accurate RPF ratings could allow us to circumvent this issue

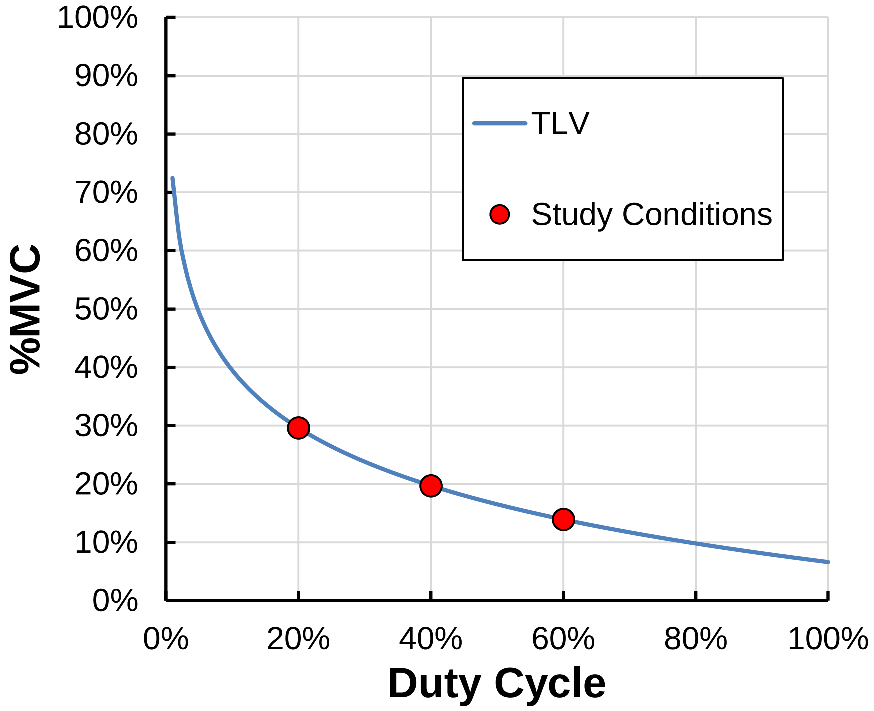
Goals/Objectives

- Improving the quantification of Localized Muscle Fatigue (LMF) (**Study 1**)
- Evaluation of current thresholds of exposure for upper extremity work (**Study 2**)



Study 2 Research Question

To evaluate localized muscle fatigue responses at three workloads along the upper limb TLV



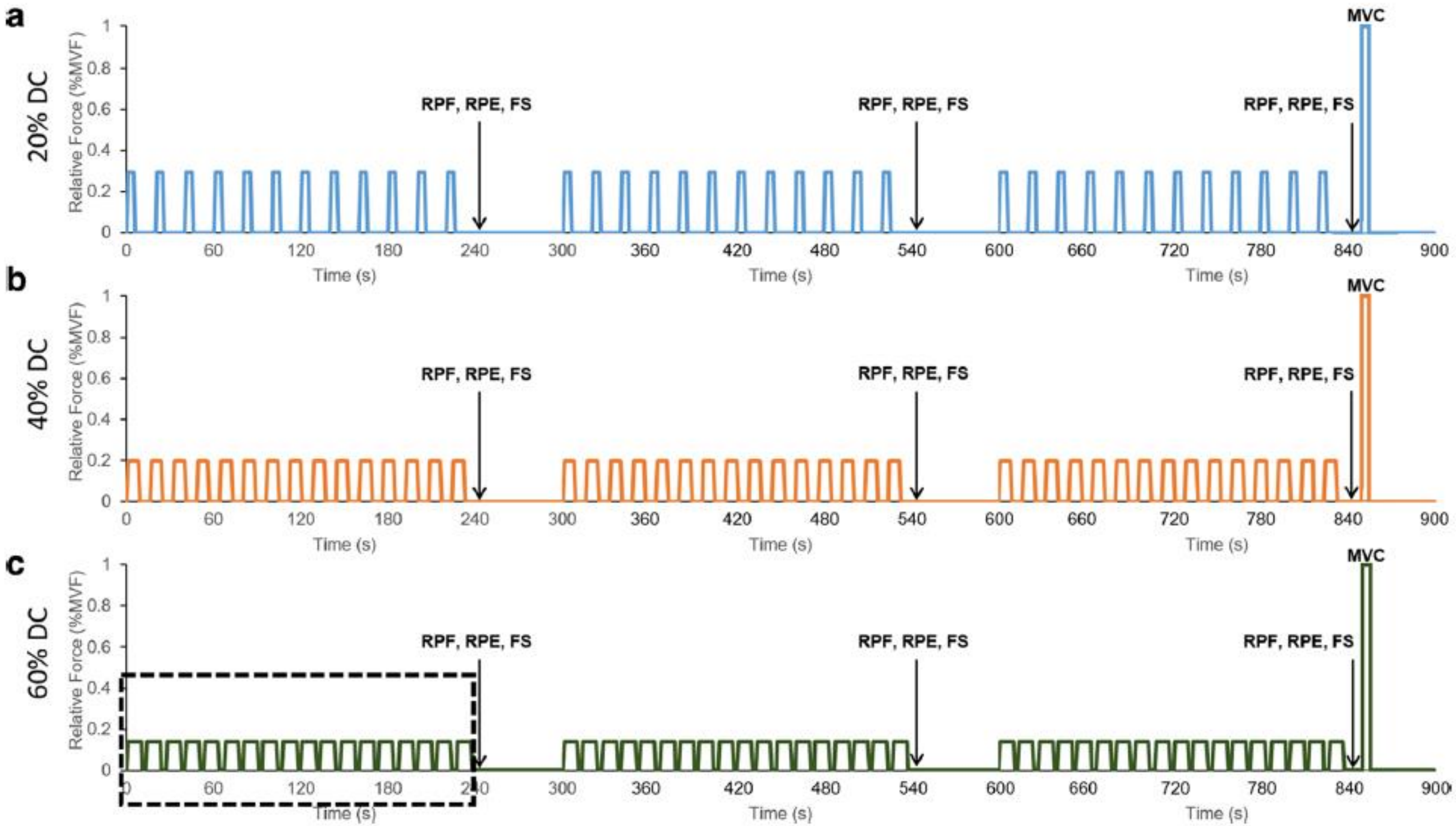
Exploring Localized Muscle Fatigue Responses at Current Upper-Extremity Ergonomics Threshold Limit Values

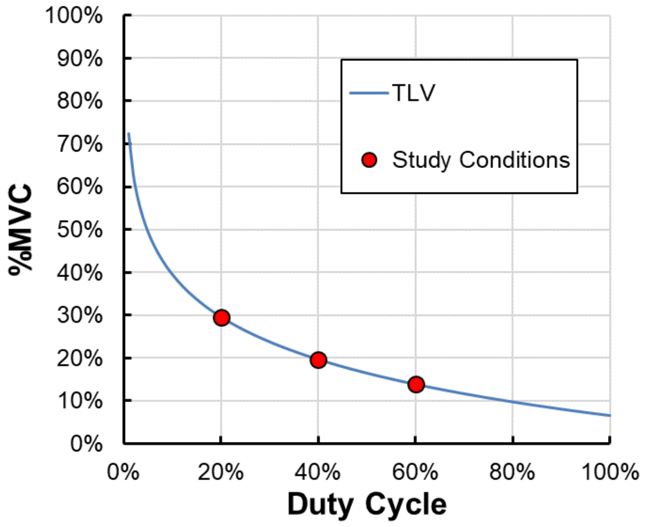
Daniel M. Abdel-Malek, **Ryan C. A. Foley**, **Fahima Wakeely**, Ontario Tech University, Oshawa, Canada, **Jeffrey D. Graham**, McMaster University, Hamilton, Ontario, Canada, and **Nicholas J. La Delfa**, Ontario Tech University, Oshawa, Canada

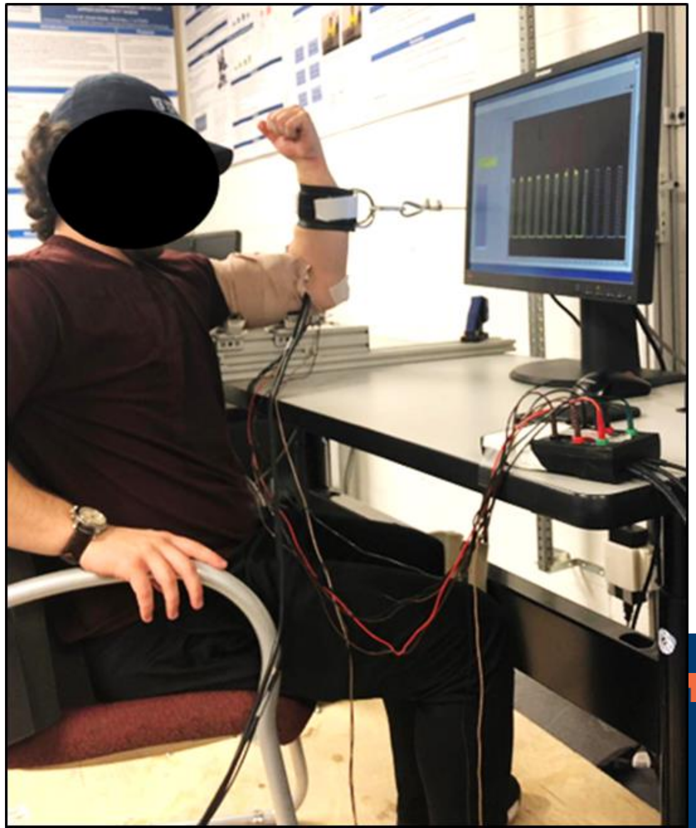
HUMAN FACTORS
Vol. 00, No. 0, Month XXXX, pp. 1-16
DOI:10.1177/0018720820940536

Experimental Procedures & Protocol

Familiarization → Session #1 → Session #2 → Session #3







Data Analysis

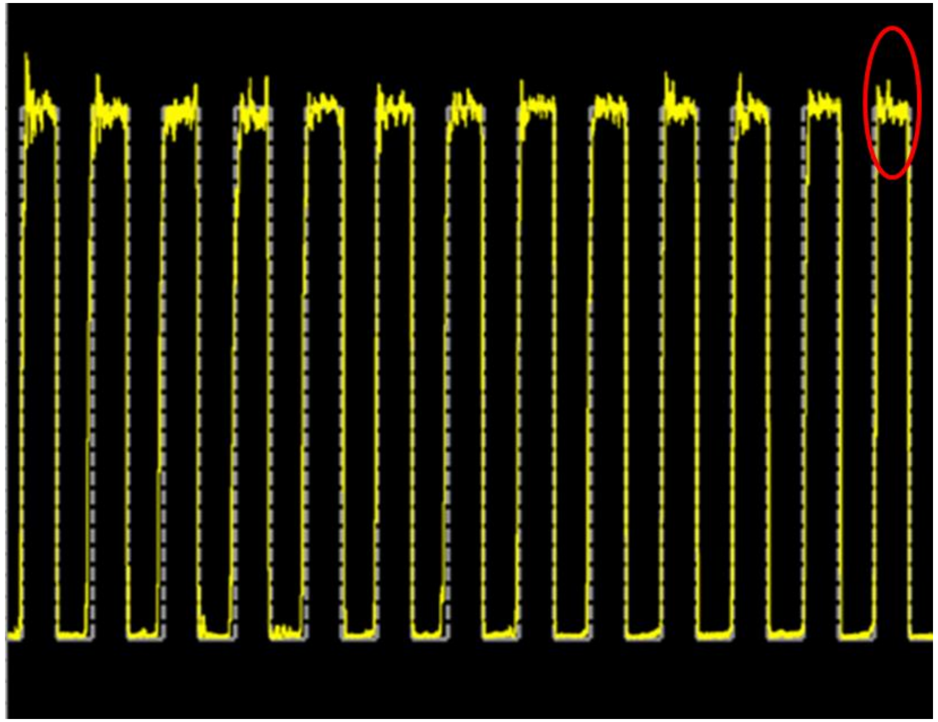
Dependent variables:

- **aEMG, MnPF, MVC, RPF, RPE**

<u>sEMG Processing</u>

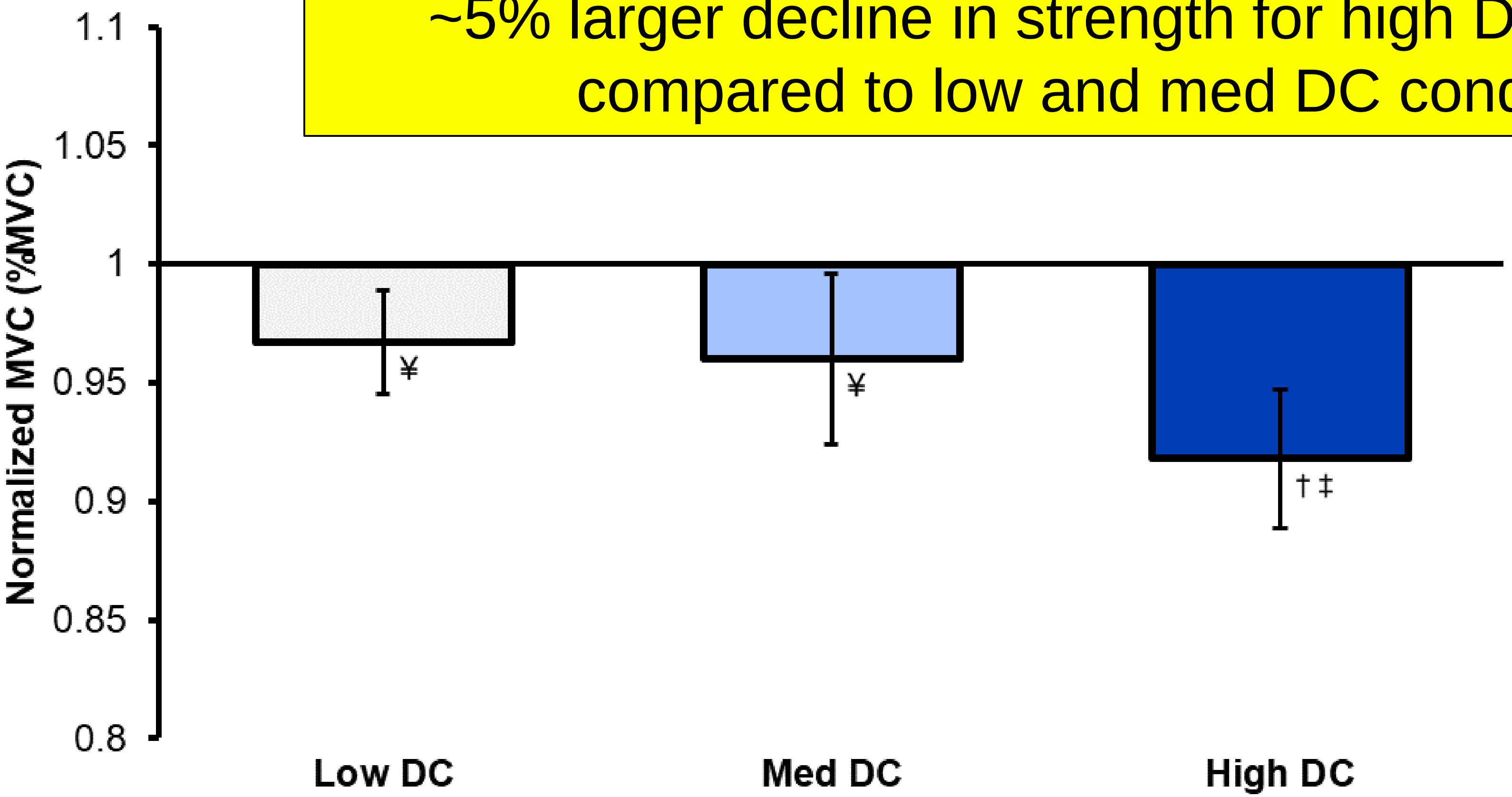
- Root-mean-square (RMS) window of 0.5s
- RMS amp. & MnPF – retrieved from 1s window of final plateau of each cycle

All fatigue measures were normalized to baseline values



Results – Strength (MVC)

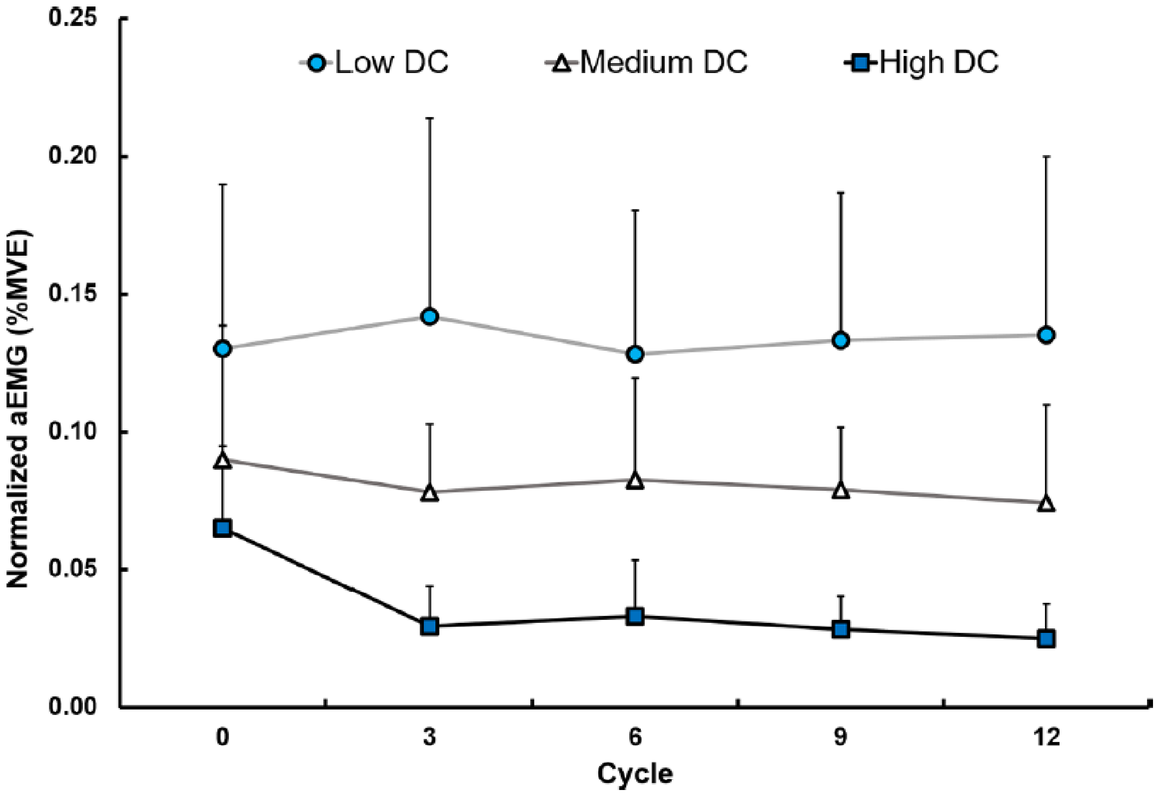
~5% larger decline in strength for high DC condition compared to low and med DC conditions

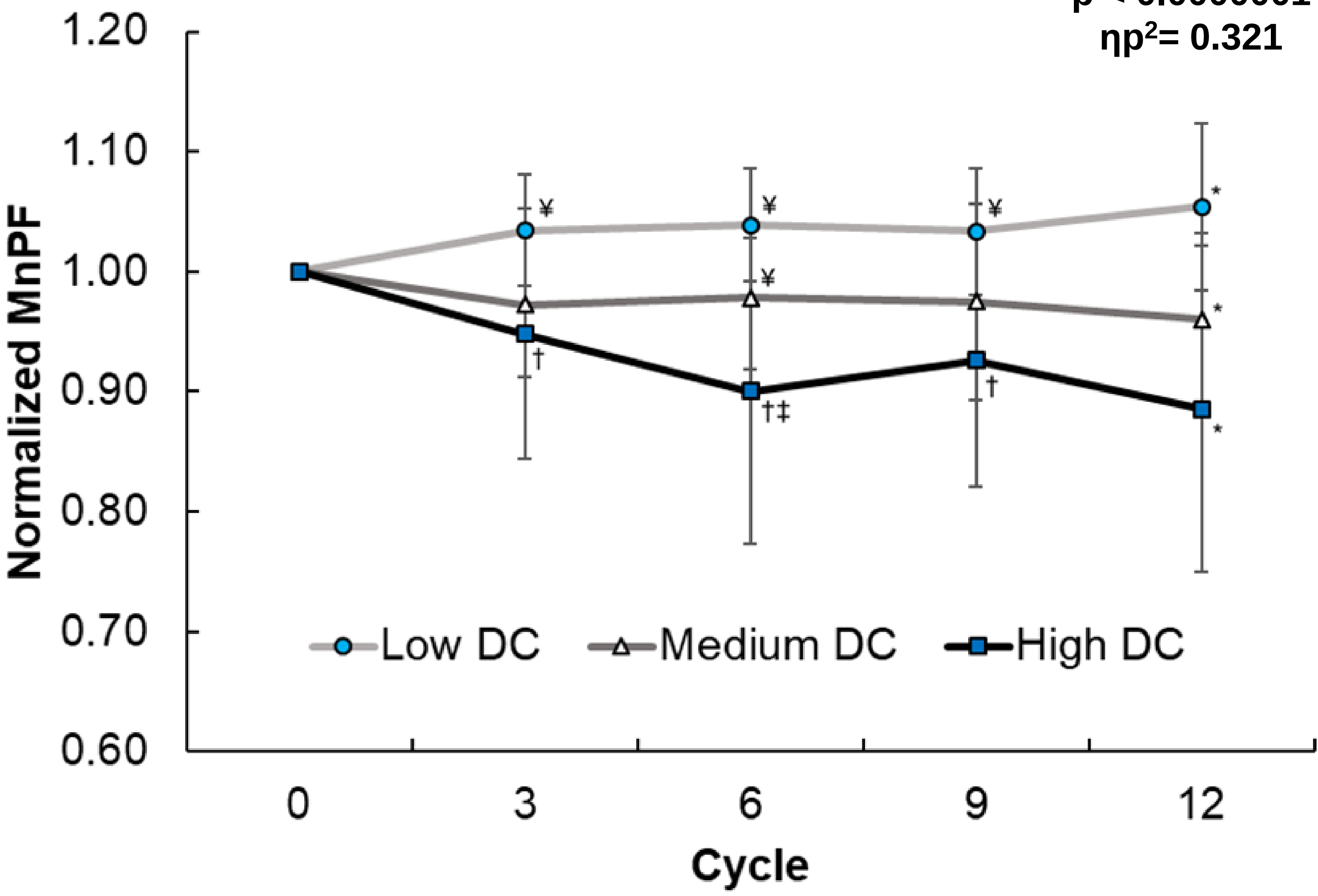


F= 4.277
$p < 0.05$
$\eta p^2 = 0.234$

Significant difference from Low DC (†) Significant difference from Med DC (‡) Significant difference from High DC (¥)

Results – aEMG & MnPF

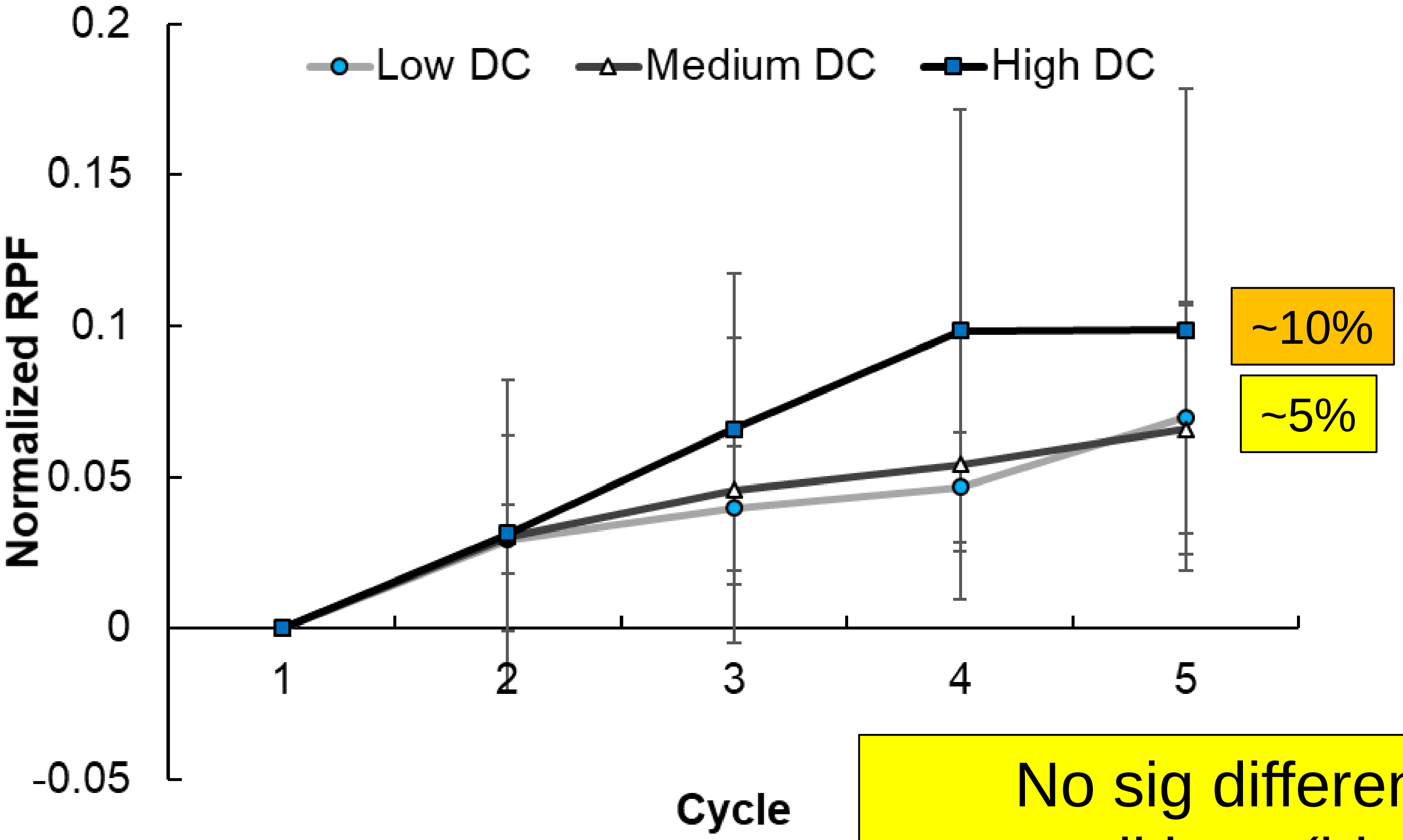


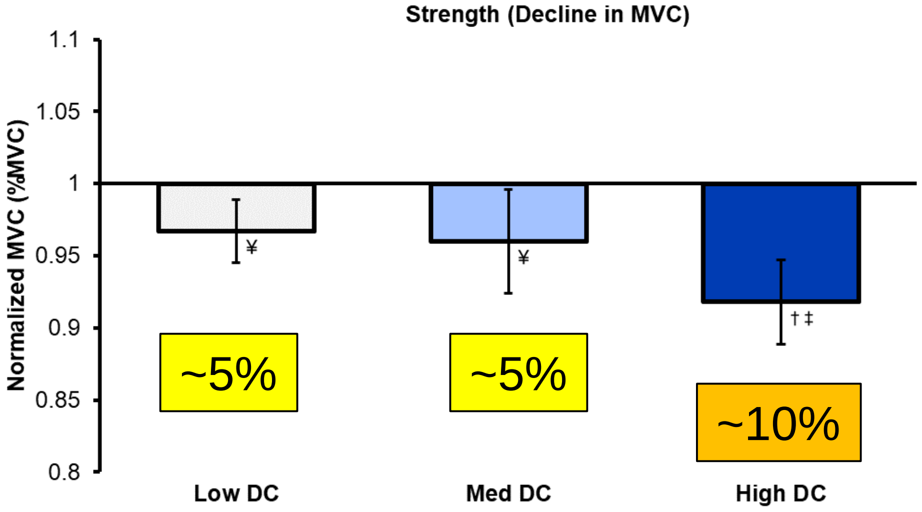


EMG amplitudes scaled with level of force exertion, but no noticeable time effects (other than at start)

High DC showed reduction (i.e. more fatigue) in MnPF
High DC < Med DC < Low DC

Results –RPF



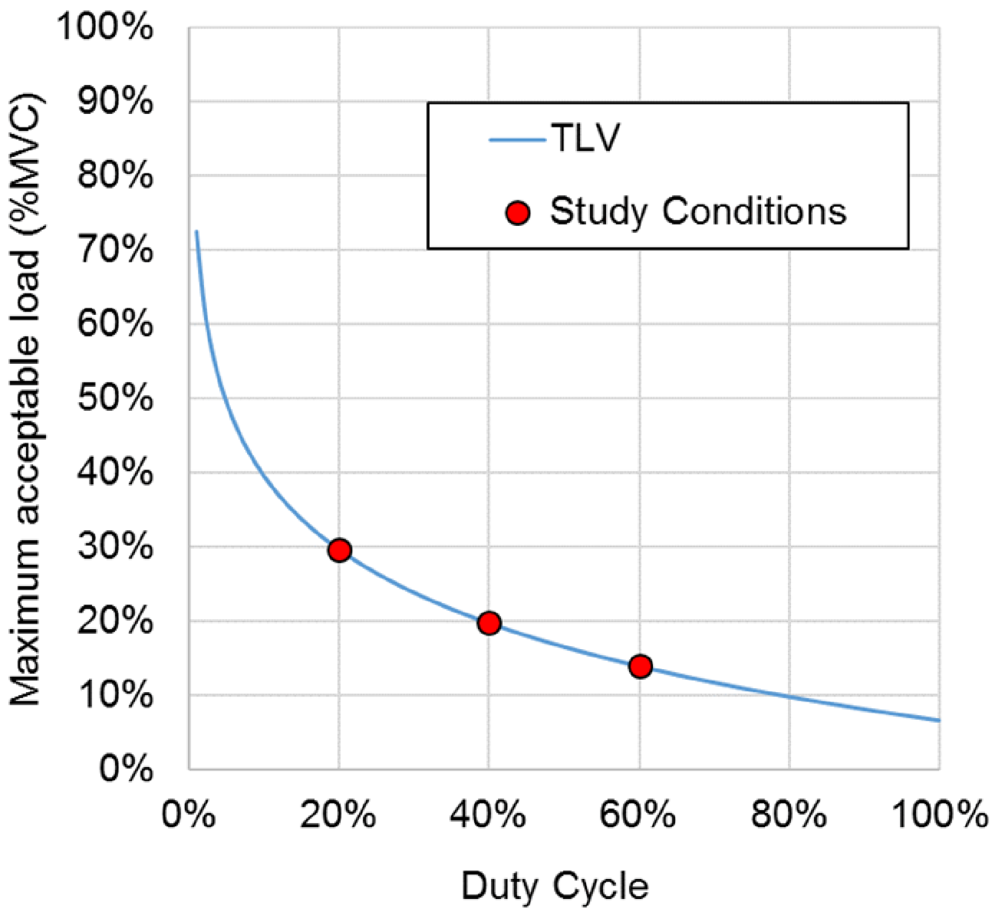


No sig differences between conditions (higher variability)

Discussion

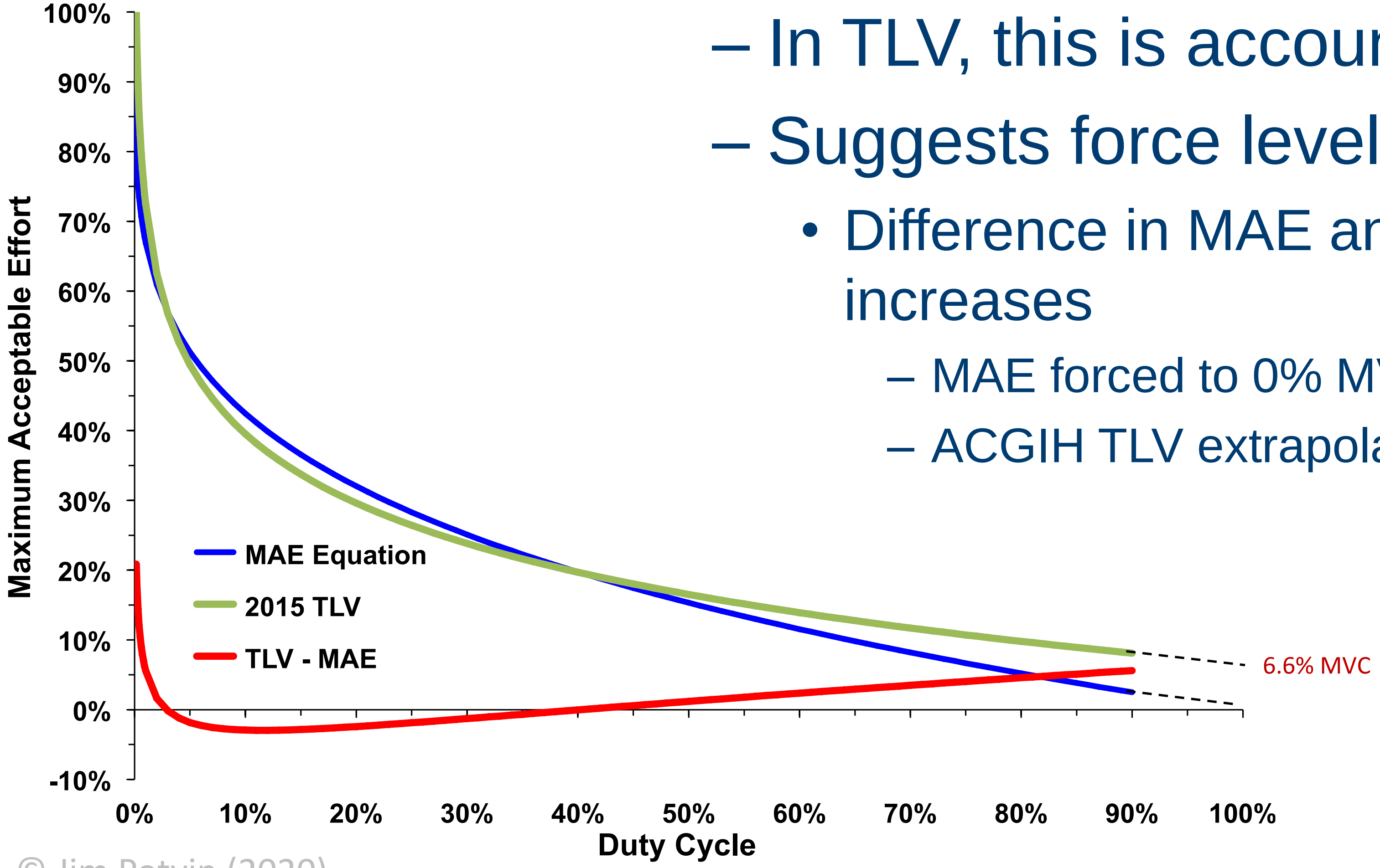
Working at different DCs along the TLV curve produce different fatigue responses

- **High DC** condition – most prominent fatigue response
  - After just 1 hour
    - TLV designed for 8-hours of work



Why?

- Higher duty cycle means less rest
  - In TLV, this is accounted for by lower force level
  - Suggests force level too high at higher DCs
    - Difference in MAE and ACGIH TLV amplifies as DC increases
      - MAE forced to 0% MVC at 100% DC
      - ACGIH TLV extrapolates to 6.6% MVC at 100% DC



"Although some work has suggested that it is possible to sustain low-level isometric contractions indefinitely (Rohmert, 1984), most evidence indicates that activation of the neuromuscular system at any intensity will eventually elicit fatigue (Sjogaard et al, 1986, Ulmer et al, 1989)."

Enoka & Stuart (1992)

Ontario Tech University

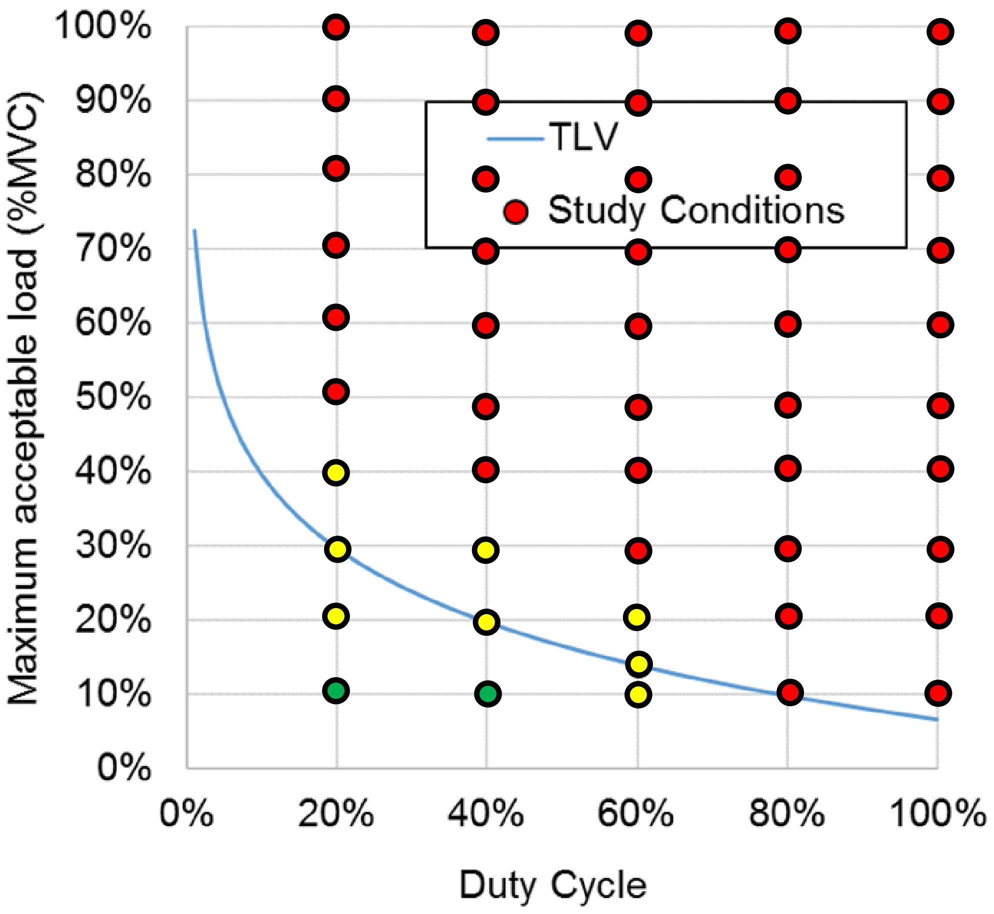
Limitations

- 1-hour protocol vs intended 8-hour threshold limit
  - – still produced differences in fatigue development
- Isolated task
  - – Usually more complex work profiles in reality
- Convenience sample
  - – Experienced workers may develop different strategies over time
- Muscle synergists/antagonists
  - – Only examines biceps brachii

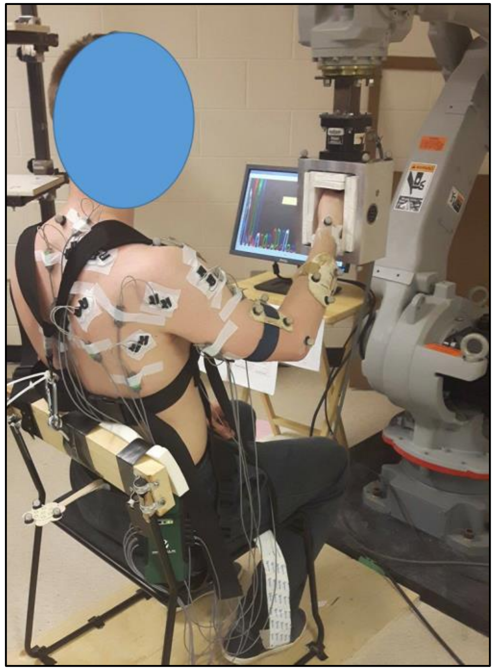
Future Directions

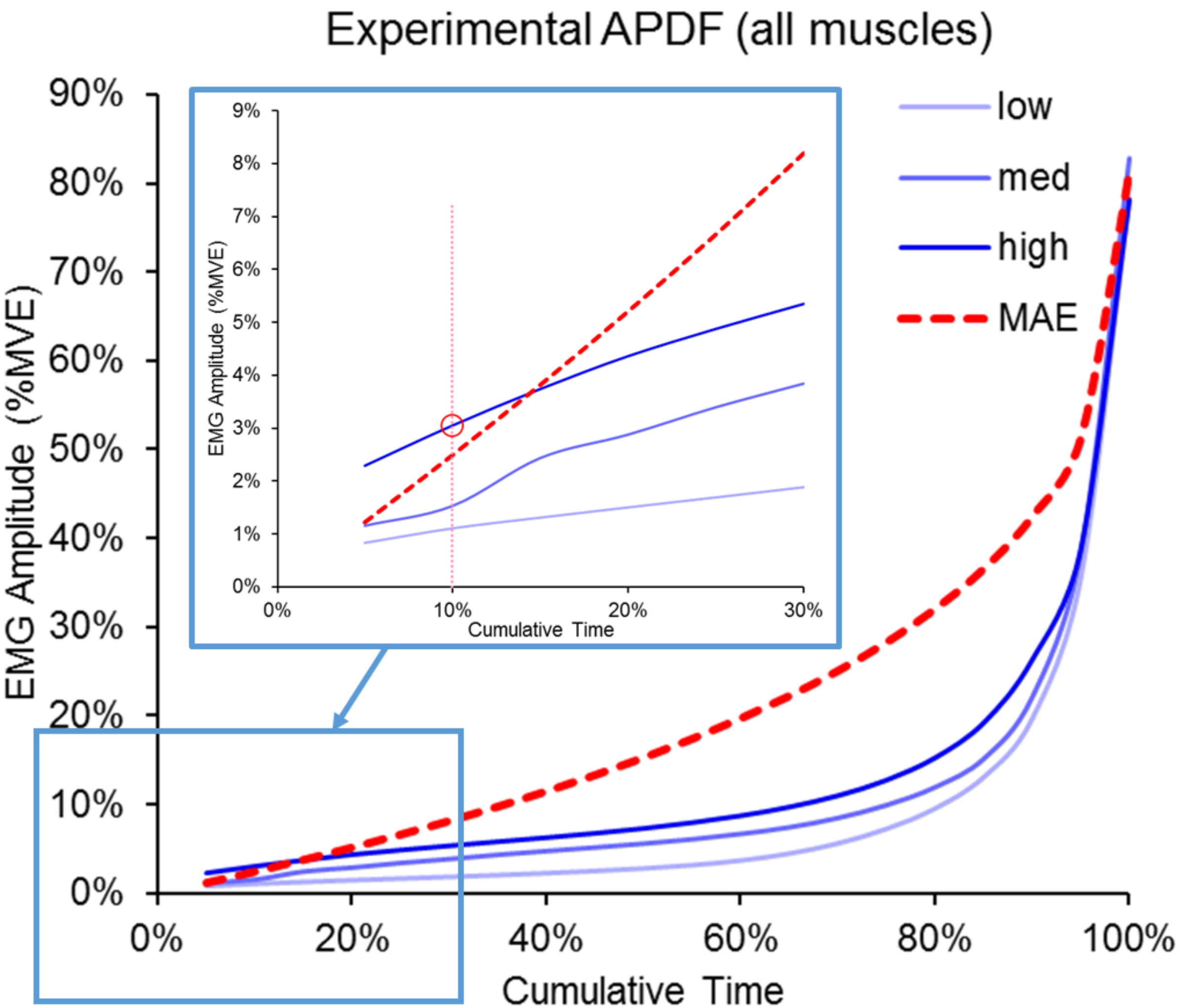
- Further validation using advanced fatigue models to further refine thresholds
  - With enough validation, can we use computational fatigue models to develop similarly easy to implement thresholds?
    - actual TLVs that draw a clear line in the sand

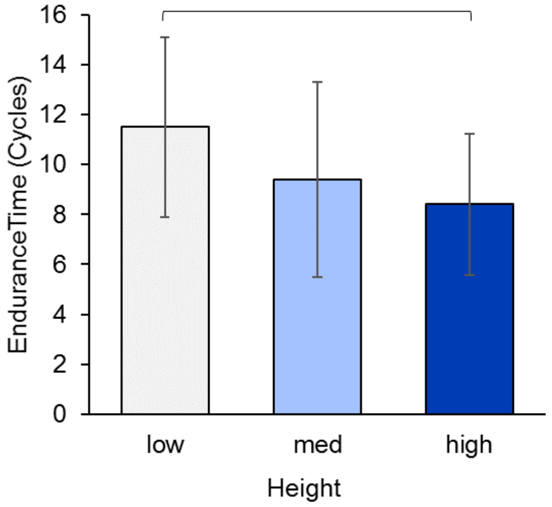
- Evaluation of more complex force profiles and dynamic tasks
  - Can the MAE/TLV equations be used to account for complex force histories?
    - Some initial evidence using Amplitude probability distribution functions (APDFs)
    - Need psychophysical studies comparing dynamic vs static, complex vs constant for same average force levels

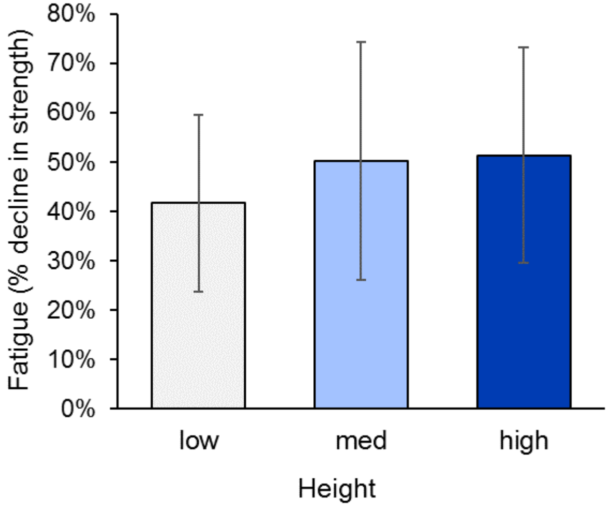


Future Directions



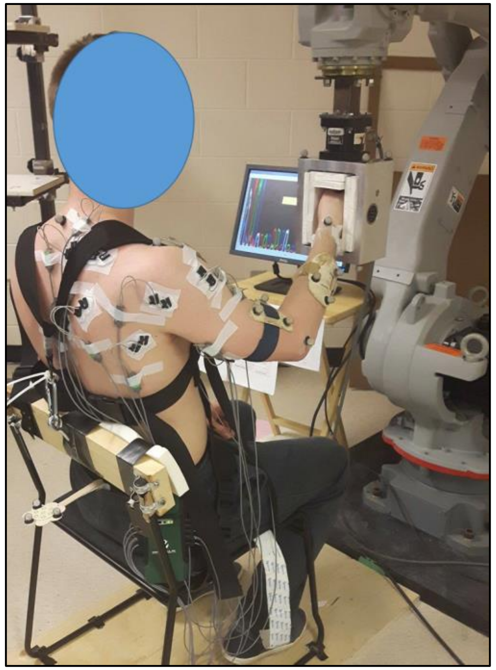


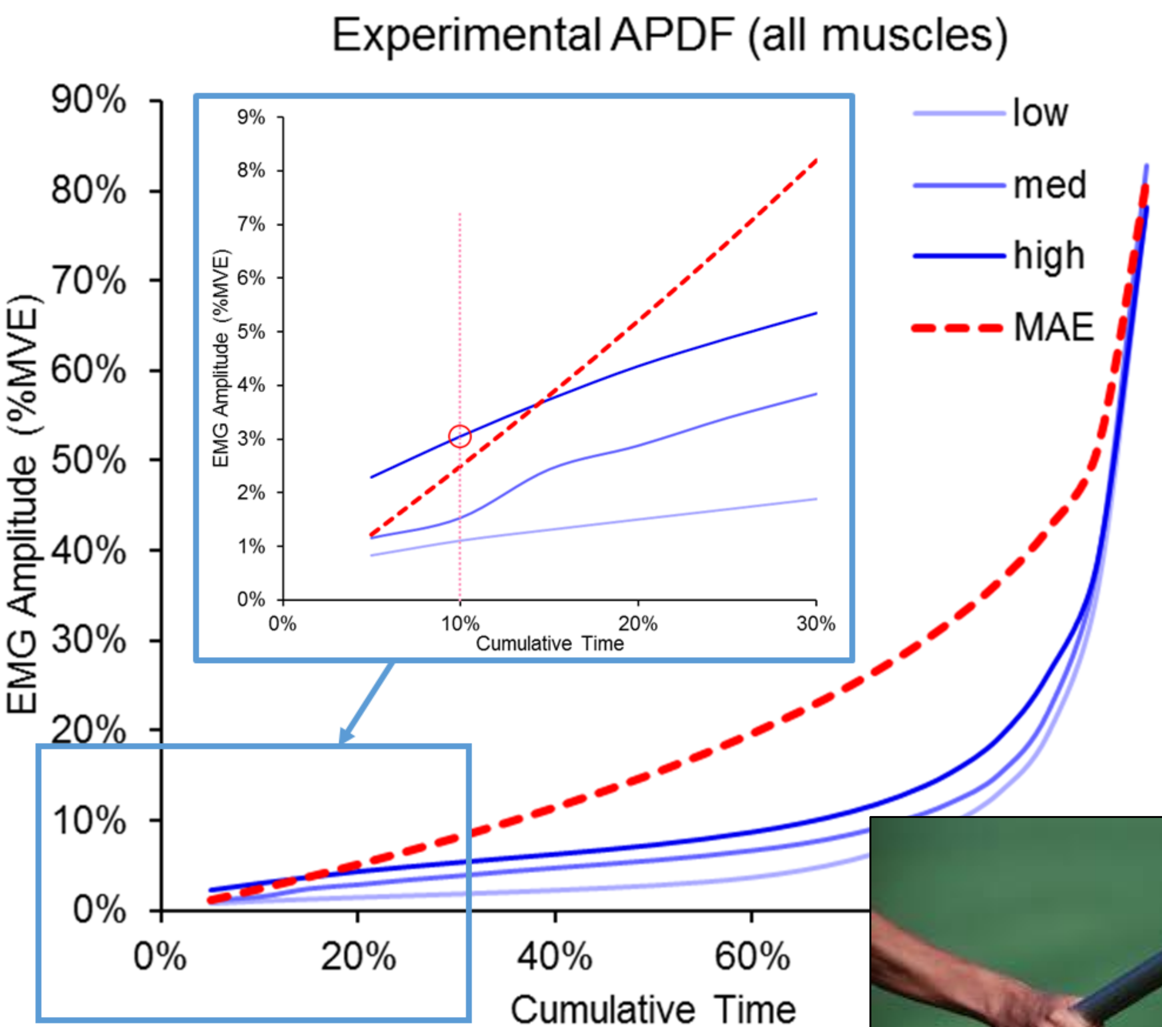


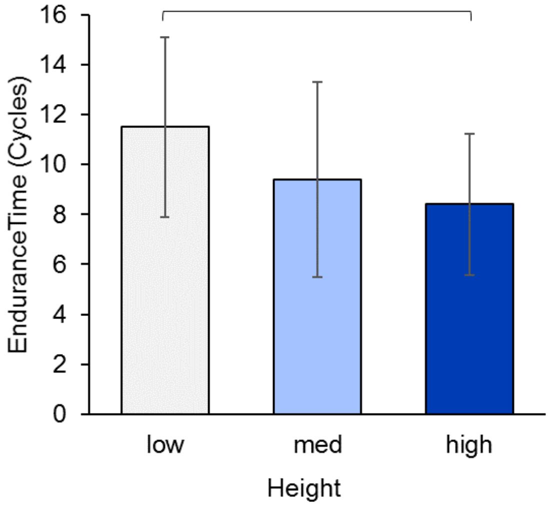


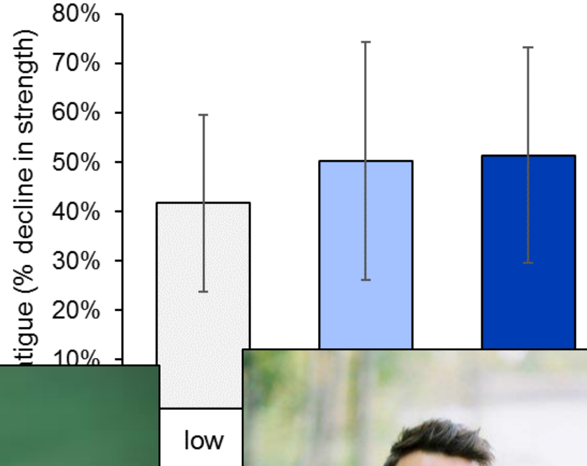
La Delfa & Dickerson (2017)

Future Directions









Final Conclusions

RPF

- Easy to implement by researchers & employers
- Robust & efficient fatigue metric whose accuracy can be improved with some familiarization/training

Current TLVs

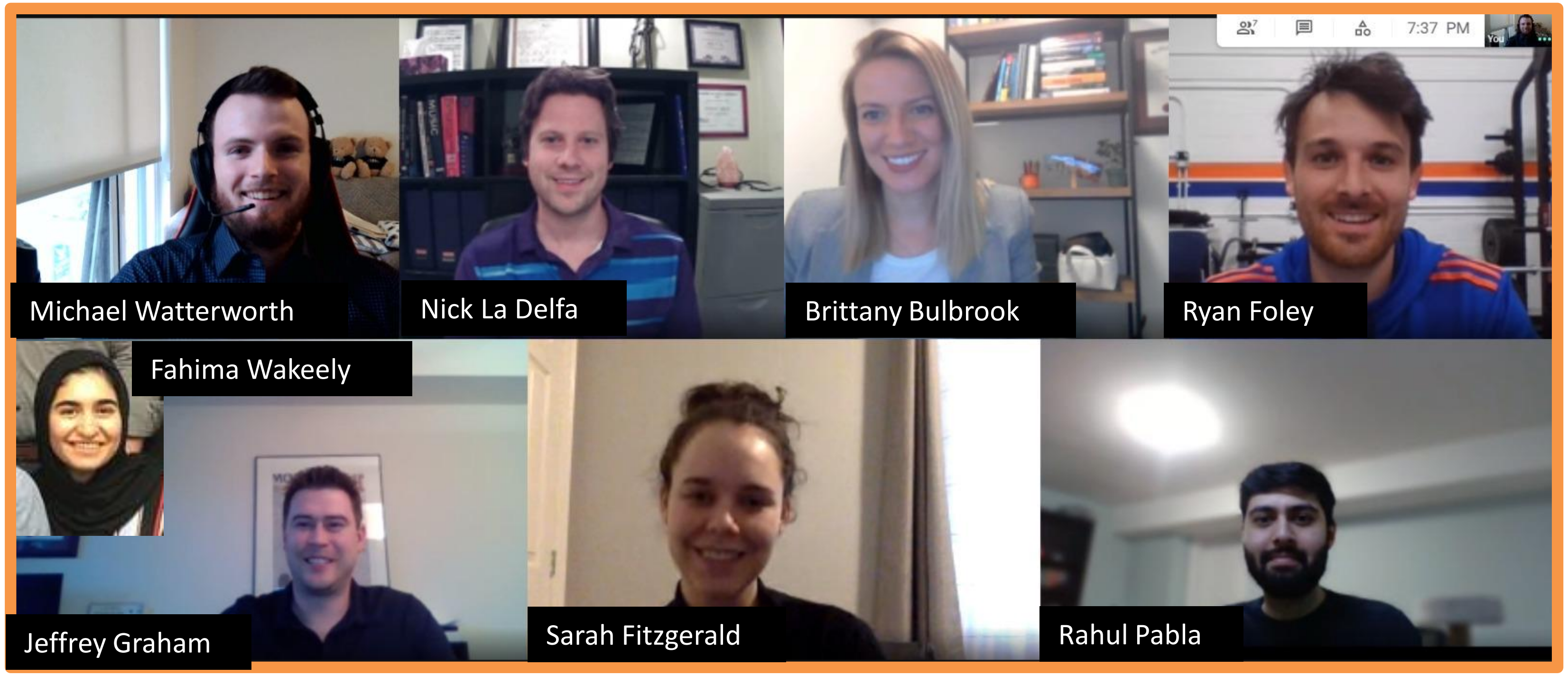
- Not quite equal in avoiding excessive LMF
  - When considering task redesign, reducing DC (or adding more rest time) may be a more potent mechanism to avoid fatigue accumulation than reducing effort/intensity
- Should consider use of Potvin MAE equation in comparison to TLV
  - Especially for higher duty cycles

Thank You!

- **Co-contributors:**
- **Daniel Muller (MD Student)**
- Ryan Foley (PhD Student)
- Dr. Jeff Graham (post doc)
- Fahima Wakeely (MHSc candidate)

Email: nicholas.ladelfa@ontariotechu.ca

Occupational Neuromechanics & Ergonomics Lab



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Centre of Research Expertise for the Prevention of Musculoskeletal Disorders

NSERC CRSNG

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Ontario Research Fund

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- Produced new methodology and/or materials for teaching ergonomics
- Graduated persons who have become outstanding ergonomists

Neuromechanical response to repetitive workloads relative to current upper extremity ergonomics thresholds

CRE-MSD

Centre of Research Expertise for the Prevention of Musculoskeletal Disorders

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