Modeling Cumulative Arm Fatigue in Mid-Air Interaction based on Perceived Exertion and Kinetics of Arm Motion

Sujin Jang[1], Wolfgang Stuerzlinger[2], Satyajit Ambike[1], Karthik Ramani[1]

1: Purdue University, 2: Simon Fraser University

C DESIGN LAB

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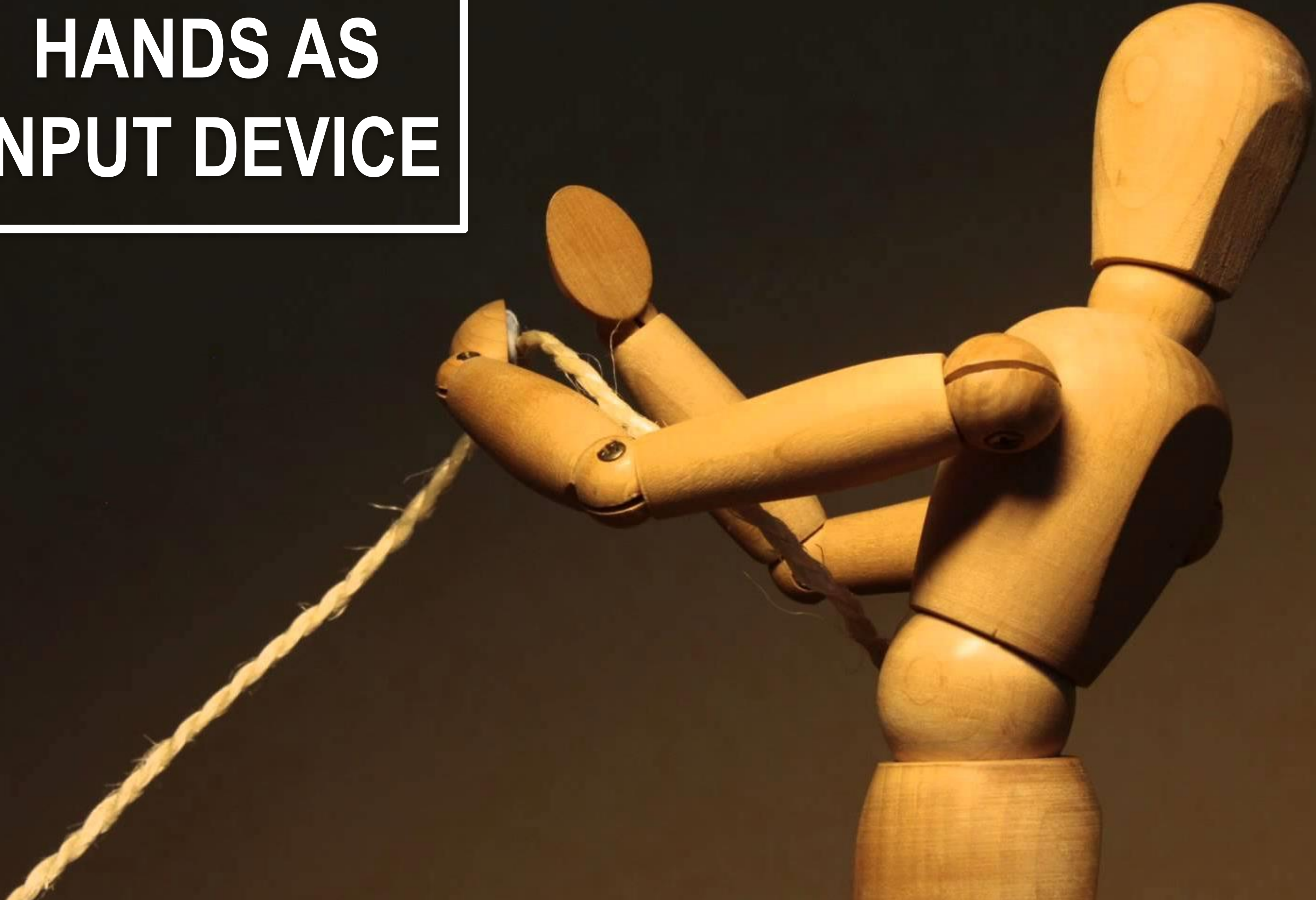
HANDS AS INPUT DEVICE



"Minority Report" directed by Steven Spielberg (2002)

"Iron Man 2" directed by Jon Favreau (2010)

- Strength Required:

15.4% (female), 12.3% (male)

- Endurance Time:

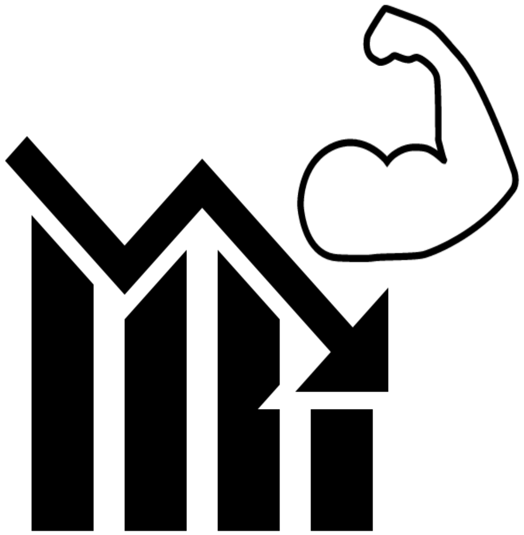
10.5 minutes

- Mathiassen and Ahsberg [1999]

What is *Fatigue*?

Fatigue:
- Decline in maximal force or power capacity of muscle due to a sustained activity

- Physiological and psychological factors Enoka and Stuart [1992]



Cumulative Fatigue involves both active and rest periods

Industrial Ergonomics

http://www.aliexpress.com/w/wholesale-ergonomic-arms.html

https://www.spineuniverse.com/wellness/ergonomics/industrial-ergonomics-prevent-injury-hand-power-tool-use

Sports Medicine

http://www.ifsm.co.in/

Virtual/Augmented Reality

Oculus Rift

HTC VIVE

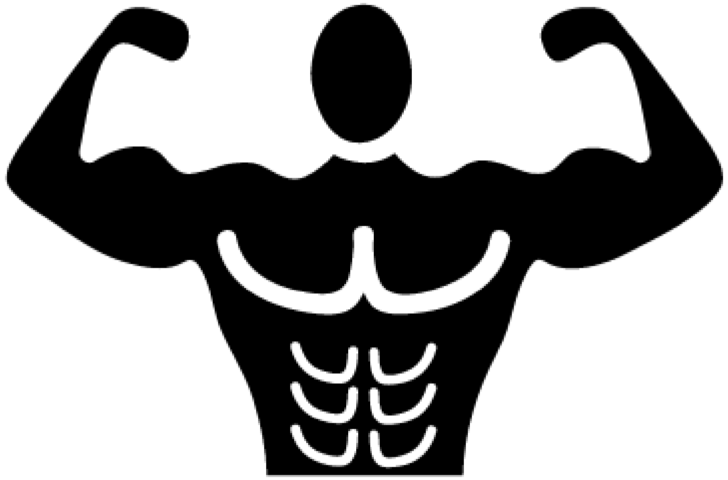
MS HoloLens

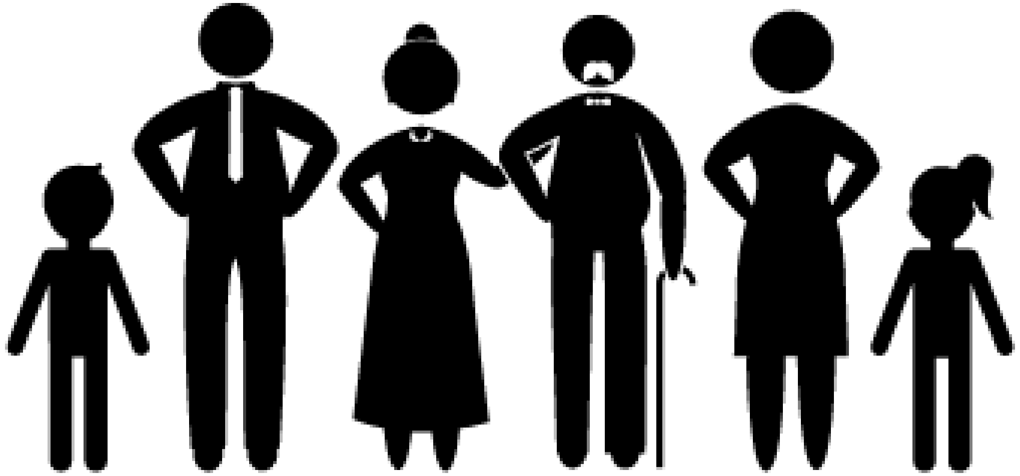
User Interfaces for Aged

http://www.sanctuaryrecruitment.com.au/blog/2016/august/virtual-reality-and-aged-care/

https://www.pinterest.com/pin/326018460495880968/

Fatigue in Mid-Air Interaction Design





- Less-fatiguing interaction design

↓

- Evaluating and optimizing user fatigue

↓

- **Quantifying cumulative fatigue**

HCI concern **“Arm Fatigue”**
(in more than 300 publications)

No good analysis method

Arm Strength Measure

- Fatigue: reduction of arm strength – Enoka and Stuart [1992]

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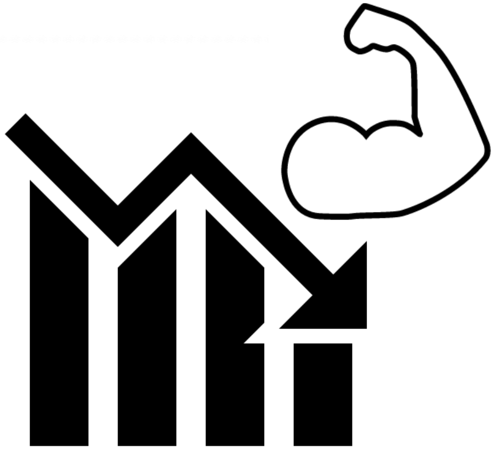
- Measurement of an individual’s max. strength
- **Sensor-based direct measurements**



Biodex Dynamometer

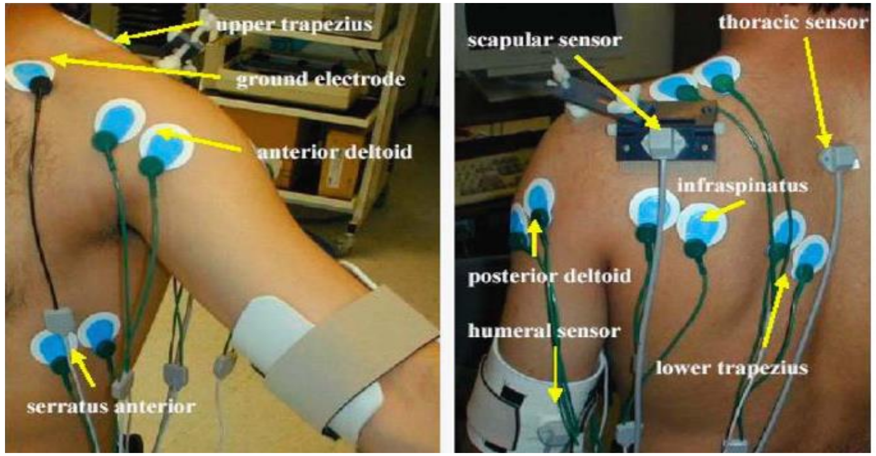
Formica et al. [2012]

Expensive set-up, Impractical, Invasive.

Objective Fatigue Measure

- Muscle activation–Electromyography (EMG) –Cifrek et al. [2009]
- Arterial oxygen – Westerblad et al. [2002]
- Lactic acid accumulation – Westerblad et al. [2002]
- Heart rate – Segerstrom et al. [2007]

Invasive, Impractical, Expensive.



Subjective Fatigue Measure

- Likert scale – Carifio et al. [2007], NASA TLX – Hart et al. [1988]
- **Borg CR-10** – Borg [1982]

Direct verbalization,

Multiple recordings,

Less invasive.

Score	Definition	Note
0	Nothing At All	No arm fatigue
0.5	Very, Very Weak	Just noticeable
1	Very Weak	As taking a short walk
2	Weak	Light
3	Moderate	Somewhat but Not Hard to Go on
4	Somewhat Heavy	
5	Heavy	Tiring, Not Terribly Hard to Go on
6		
7	Very Strong	Strenuous. Really Push Hard to Go on
8		
9		
10	Extremely Strong	Extremely strenuous. Worst ever experienced

Fatigue Measure in HCI

- Consumed Endurance (CE, Hincapié-Ramos et al. [2014])
  - Strong correlation between CE and subject fatigue ratings

$$CE(T, TotalTime) = \frac{TotalTime}{E(T)} * 100$$

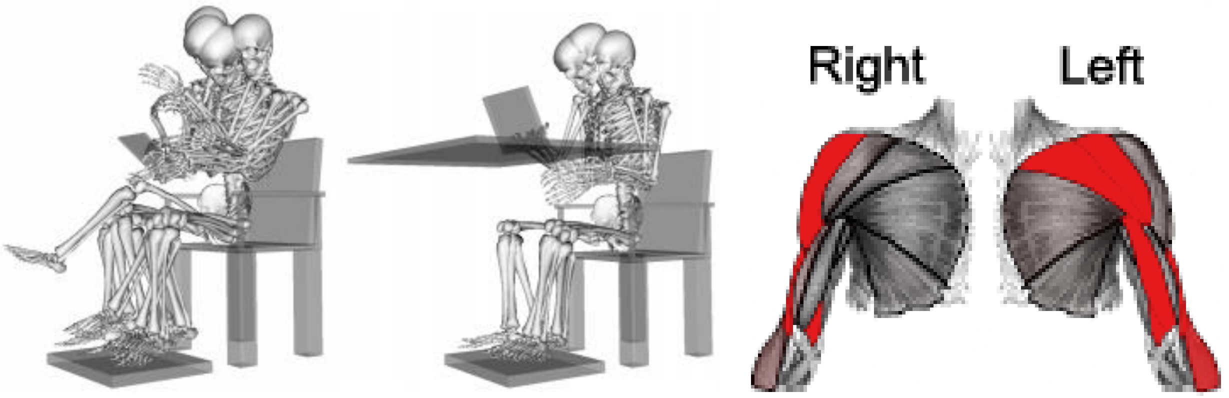
$$E(T_{shoulder}) = \frac{1236.5}{\left(\frac{T_{shoulder}}{T_{max}} * 100 - 15\right)^{0.618}} - 72.5$$

– No consideration of rest

– Zero fatigue below 15% exertion

– No consideration of individual's max. arm strength

- Biomechanical Simulations (Bachynski et al. [2015])
  - Muscle activation simulation using OpenSim
  - No consideration of rest
  - No correlation with subjective fatigue rating
  - Expensive set-up and computing required



Contributions

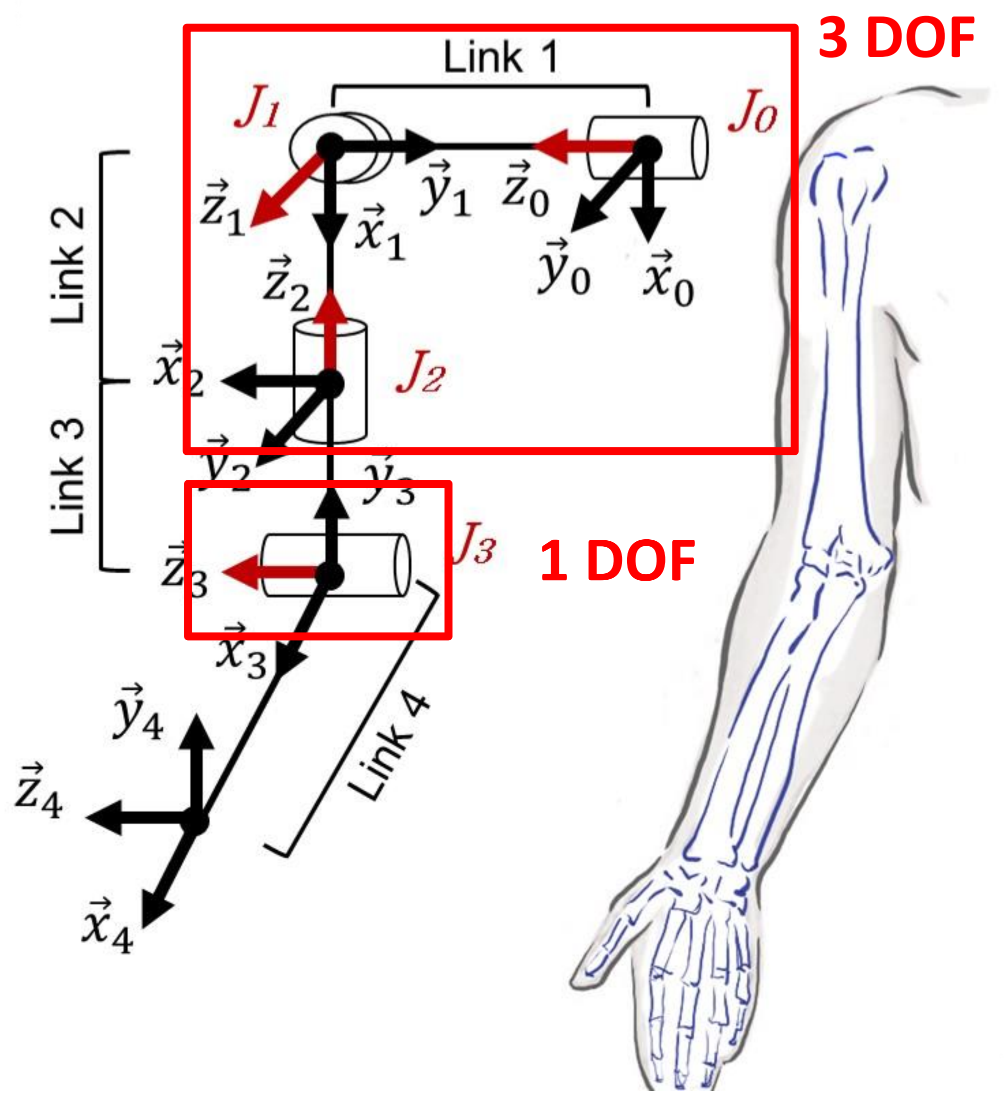
Simple and effective method
to **measure shoulder strength**

Fatigue model predicting
cumulative subjective fatigue

Fatigue model that accounts for both
subjective and biomechanical measure

Biomechanical Arm Model and Analysis

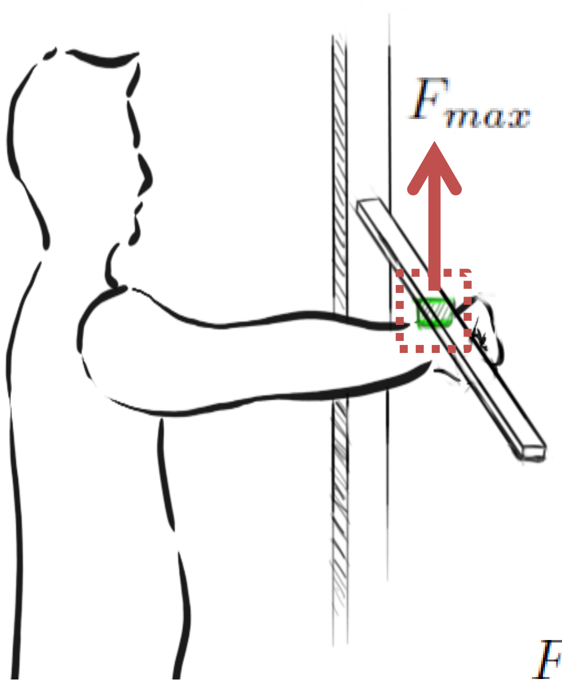
Biomechanical arm model



Arm Movement Data → Newton-Euler Inverse Dynamics → **Shoulder Torque** $T\ (N \cdot m)$

Traditional Direct Arm Strength Measurement

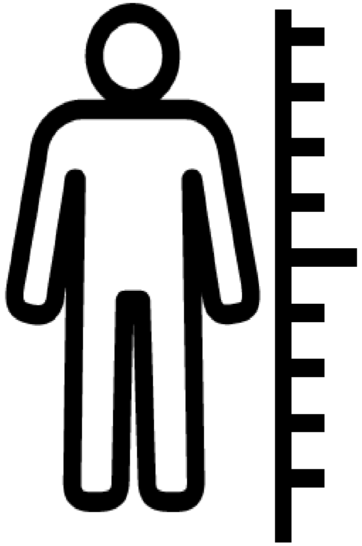
Max. shoulder force measure

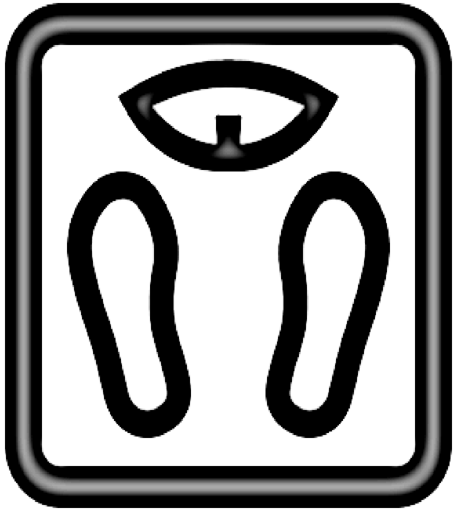


Dynamometer

F_{max} : Max. shoulder force

Body segment parameters





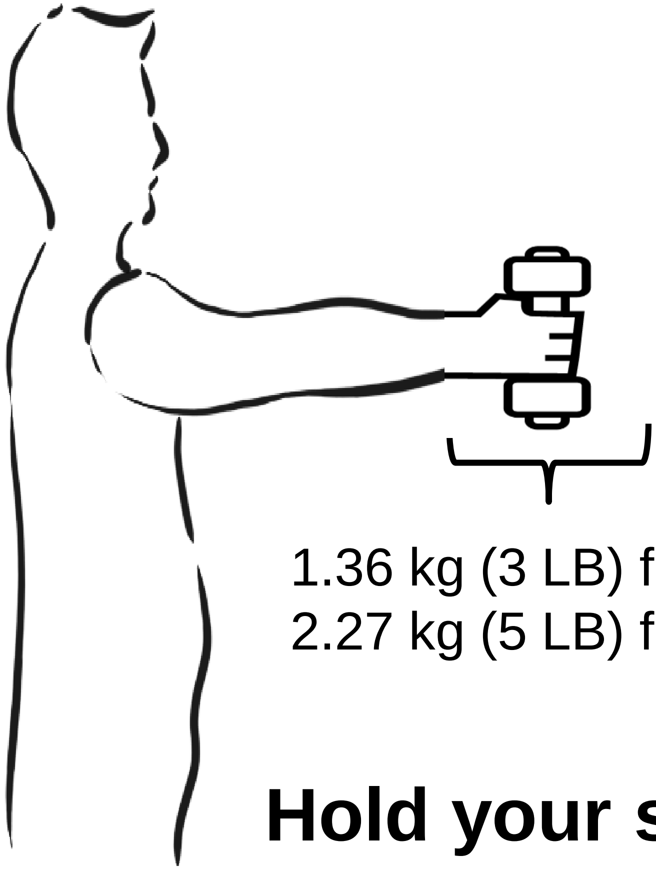
Limb lengths : L_{UA}, L_{LA}

Body segment weights: m_{UA}, m_{LA}, m_H

<u>Max. shoulder torque $(N \cdot m)$</u> $= T_{max,D} = (m_{UA} + m_{LA} + m_H) * G * C + F_{max} * (L_{UA} + L_{LA}),$

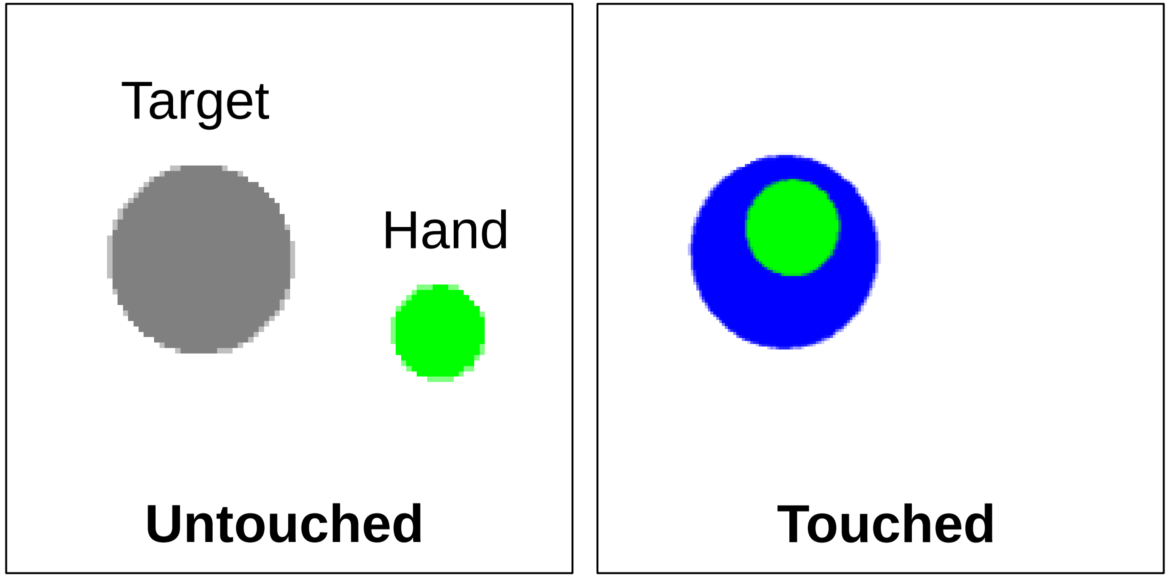
C : distance between C.O.M of arm and shoulder joint, G : gravity (9.8 m/s^2)

Our Indirect Arm Strength Measurement



1.36 kg (3 LB) for female,
2.27 kg (5 LB) for male

MS Kinect 2.0



Hold your stretched arm horizontally with a weight

AS LONG AS YOU CAN!

$T(t)$: shoulder torque → T_{avg}

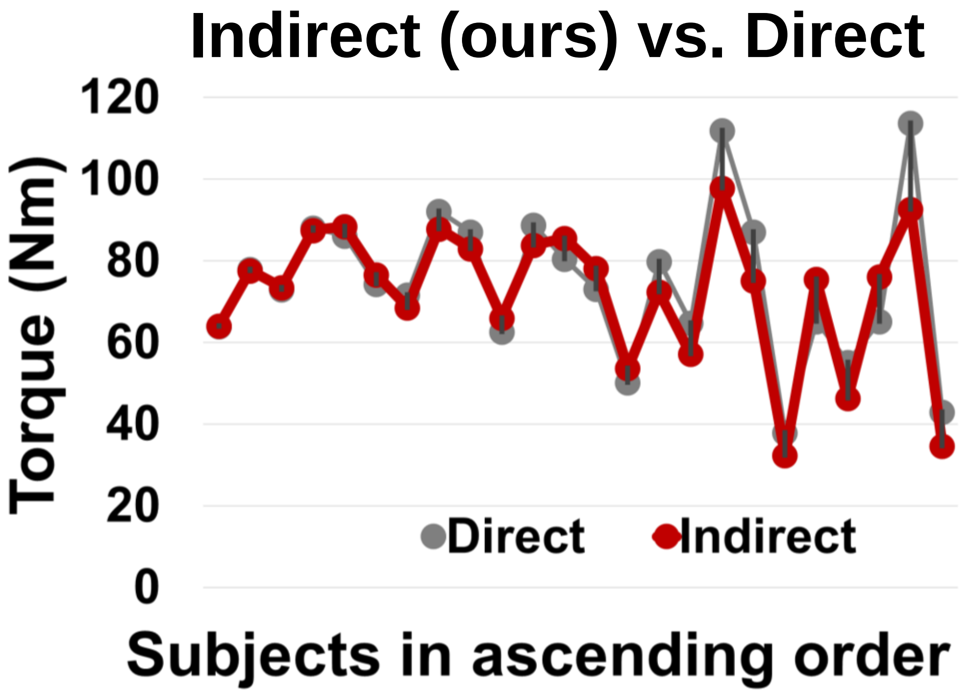
ET : endurance time

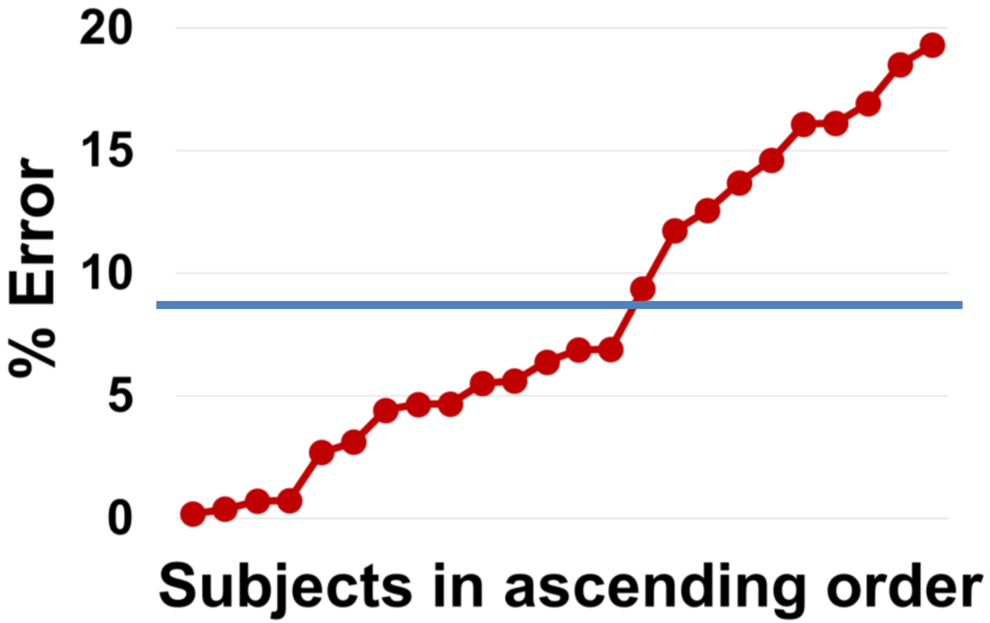
Estimated max. shoulder torque $(N \cdot m)$

$$= T_{max} = \frac{-b * T_{avg}}{\log(ET/a)} \times 100,$$ [Mathiassen et al. 1999]

Comparison Results

- Indirect (ours) vs. Direct (traditional) max. shoulder torque measure
- 24 participants (4 female, 20 male)





Averaged absolute error = **6.1 Nm** (SD=5.0 Nm)

Averaged %Error = **8.4%** (SD=6.21%)

Paired t-Test: **no significant difference between two methods** (p = 0.129)

Cumulative Fatigue Model – Goal

- Target Load (Biomechanical Measure)

$$TL = [T_{current}/T_{max}] * 100(\%)$$

- Estimates Subjective Fatigue Measure (Borg CR10 ratings)

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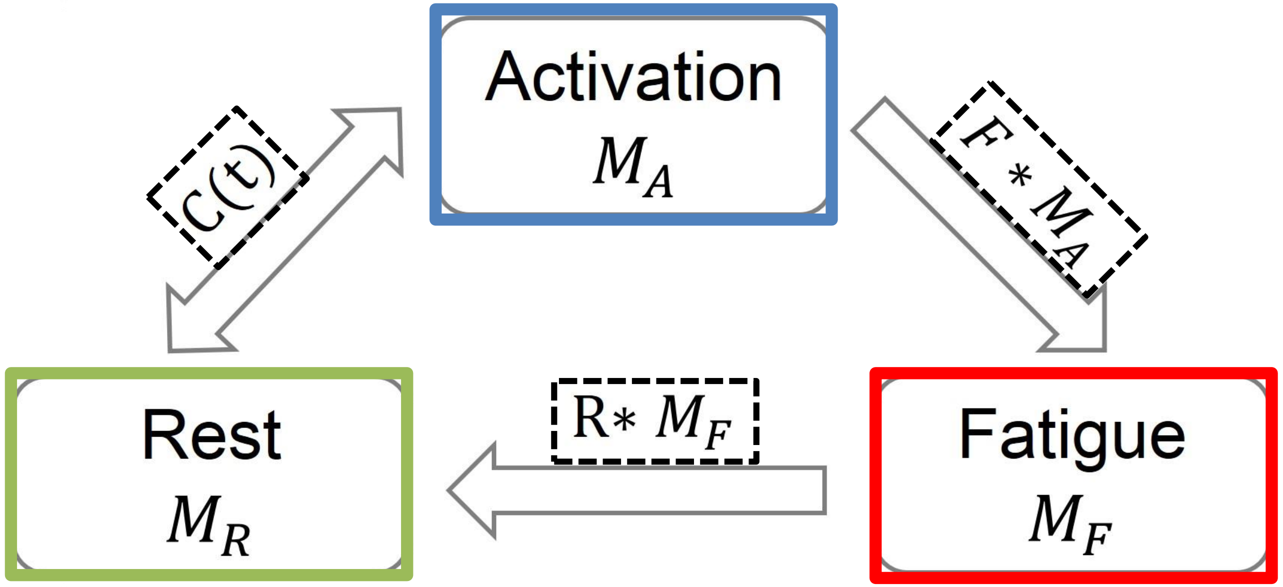
Cumulative Fatigue Model



Three-Compartment Muscle (TCM) Model

-XIa et al. [2008]

$M_R + M_A + M_F = 100\%$ Muscle Units

M_R = Muscle unit (MU) in **Rest** state,

M_A = MU in **Active** state,

M_F = MU in **Fatigued** state (**output**),

$C(t)$ = Muscle activation/deactivation drive

⇧

$TL = [T_{current}/T_{max}] * 100(\%)$ = Target load (**Input**)

Free parameters: F, R

$$\underset{F,R}{\text{minimize}} \sqrt{\frac{1}{n}\sum_{i=1}^{n}[\phi(M_F(i)) - B(i)]^2}$$

$M_F(i)$ = Fatigue estimation

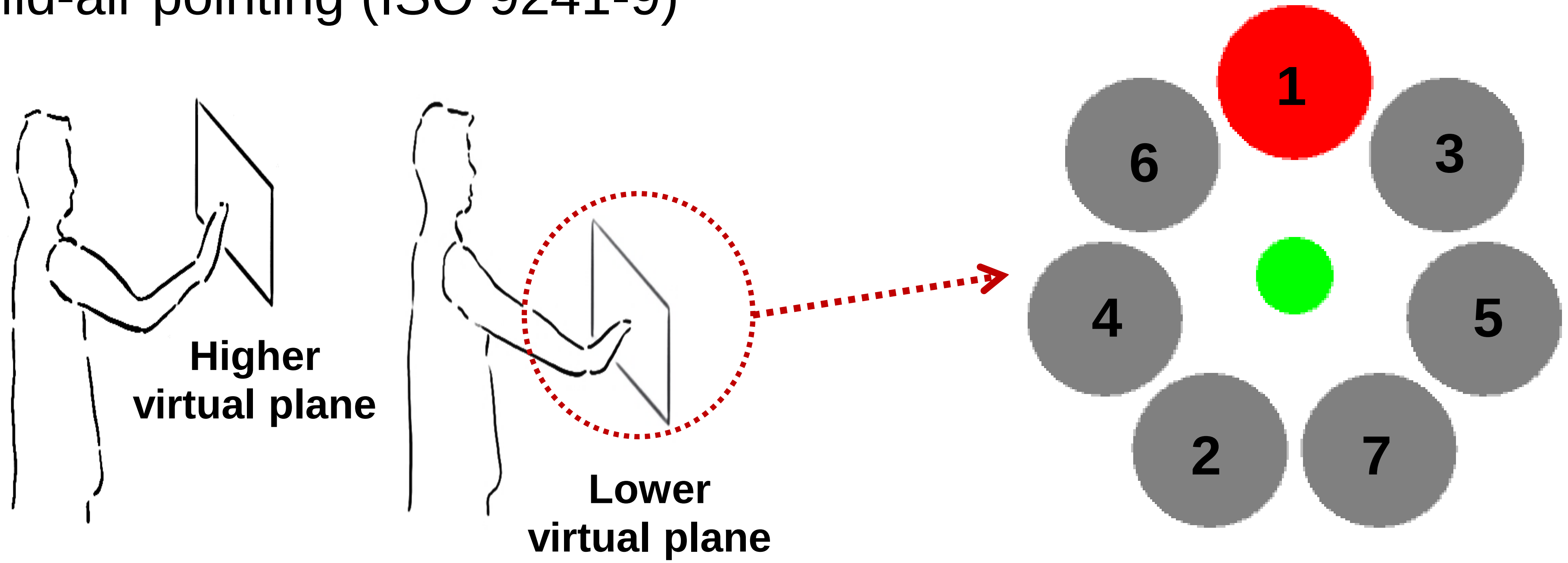
$B(i)$ = Subjective fatigue ratings (Borg CR-10)

$\phi(\cdot)$ = Linear mapping function

Experiments: Mid-Air Pointing Tasks

- **Goal**:
  - Find optimal fatigue model (parameters F and R)
  - Evaluating subjective fatigue estimation performance

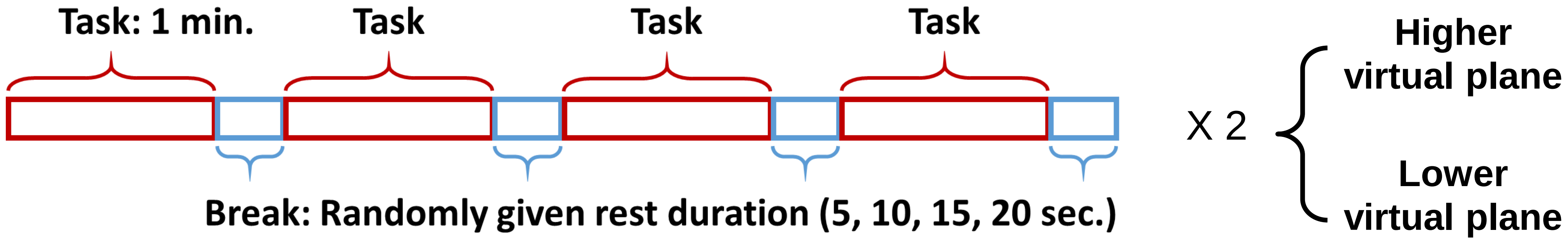
- **Tasks**: Mid-air pointing (ISO 9241-9)



Hit as many targets as you can while keeping good accuracy.

Experiments: Mid-Air Pointing Tasks

- **Procedure:**



- **24 Participants**:

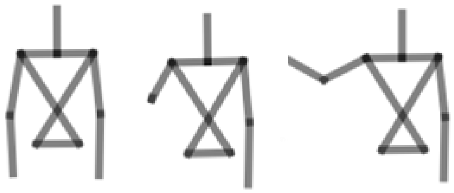
Group 1

Given rest duration: [20s-5s-15s-10s]

Group 2

Given rest duration:[5s-10s-20s-15s]

- **Data recording:**
  - Borg CR10 ratings every 20 seconds and at the start/end of rest
  - Body skeleton tracking using a Kinect 2.0



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1	Very Weak
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5	Heavy
6	
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10	Extremely Strong

Model Performance Analysis

- **Goals:**
  - Evaluate the **model performance** in estimating subjective cumulative fatigue,

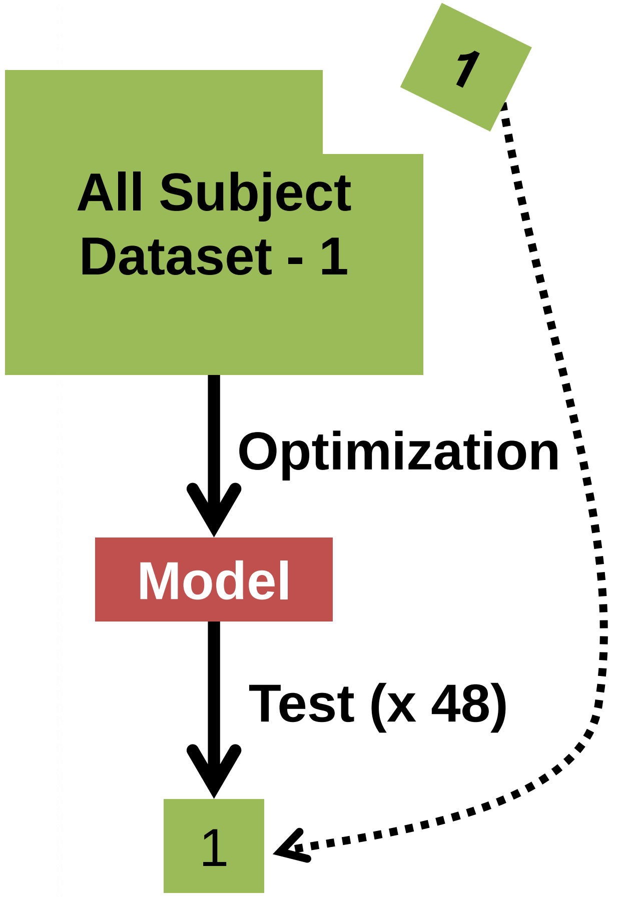
    → **Leave-one-out cross-validation over all subject data**

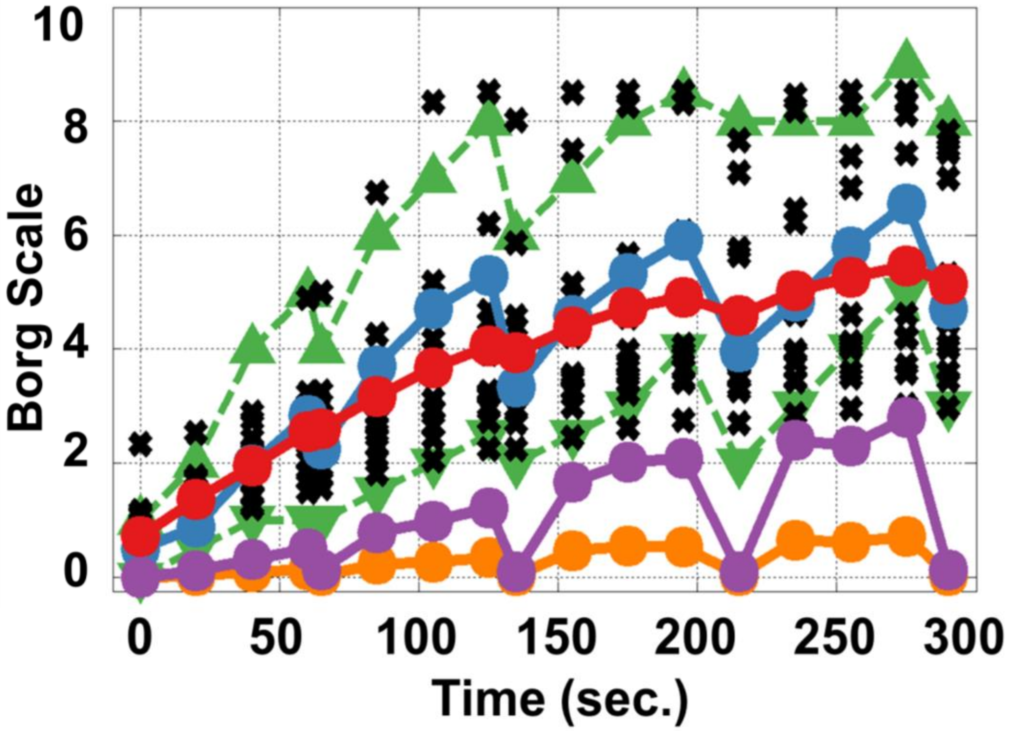
  - **Effect of interaction conditions** (interaction zones, rest period orders) to the model performance.

    → **ANOVA mixed interaction factors analysis**

Model Performance Analysis – Leave-One-Out

- Leave-one-out cross-validation over all subject data





Blue circles: averaged ground truth (Borg CR-10 Ratings),

Red circles: averaged TCM (ours) estimates,

Black crosses: TCM (ours) estimates,

Green-upward/downward triangles: upper/lower bound of ground truth,

Orange circles: averaged CE (Hincapié-Ramos et al. [2014]) estimates,

Purple circles: averaged CE estimates (averaged exertion > 15%)

Overall-RMSE = 1.46, (Range=[0.83,1.9])

Ours: overall-RMSE = 0.93, (Range=[0.67,1.19])

CE: overall-RMSE = 2.96, (Range=[2.12,3.60])

ANOVA Mixed Interaction Factors Test

	Group 1	Group 2
Interaction zones	G1-H: shoulder level	G2-H: shoulder level
	G1-L:waist level	G2-L:waist level
Rest order	[20s, 5s, 15s, 10s]	[5s, 10s, 20s, 15s]

- Within-subject factor = interaction zones
- Between-subject factor = rest period order

Robust to between group conditions (rest orders, $p = 0.071$)

Relatively more affected by interaction space conditions
(high and low interaction zone, $p < 0.001$)

Conclusion

- Simple and effective **max. shoulder strength measurement** (8.4 %Error)
- Our model estimates **cumulative subjective fatigue** considering both **rest and active periods**: RMSE = 1.46 (14.6%)
- **Real-time (50Hz) evaluation** of cumulative fatigue
- Our model does **not limit the range of exertion** (i.e., 15% exertion)

- Ergonomic evaluation of interaction techniques
- Proactive fatigue management
- Personalized training
- Smart-home/mobile therapy apps

Sujin Jang
PhD Candidate
(jang64@purdue.edu)
Purdue University, IN, USA

Satyajit Ambike
Assistant Professor
(sambike@purdue.edu)
Purdue University, IN, USA

Karthik Ramani
Donald W. Feddersen Professor
(ramani@purdue.edu)
Purdue University, IN, USA

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PURDUE ENGINEERING

Wolfgang Stuerzlinger
Professor
(w.s@sfu.ca)
Simon Fraser University, BC, Canada

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CODE RELEASE!

[TINYURL.COM/CUMULATIVE-ARM-FATIGUE](https://tinyurl.com/cumulative-arm-fatigue)

QUESTIONS?