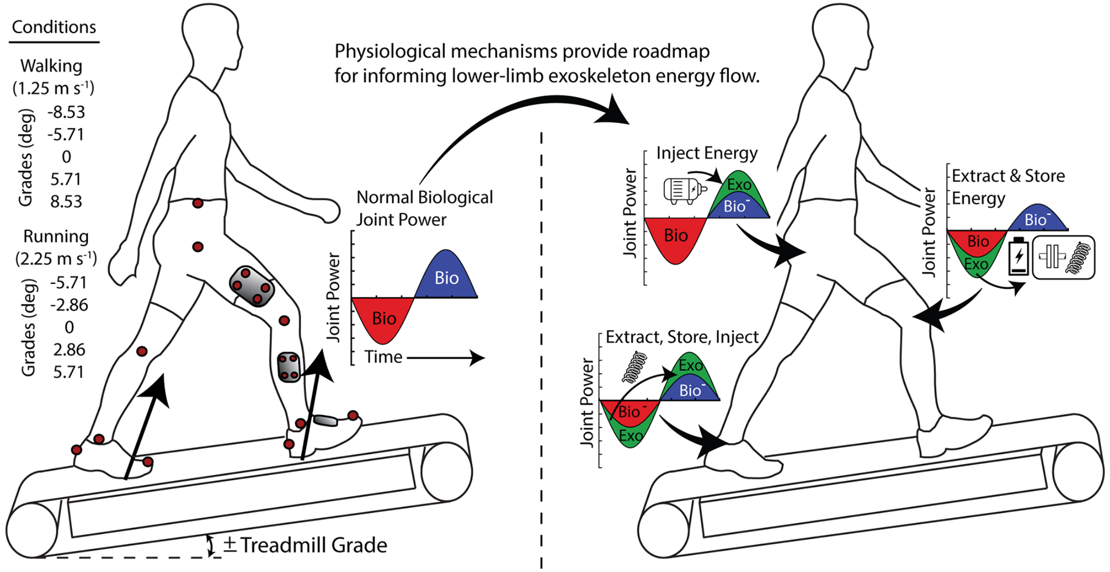


Leveraging Human Biomechanics Data to Guide Optimal Design of Lower-Limb Wearable Robots

IEEE EMBS
IEEE Engineering in Medicine & Biology Society

IEEE EMBC Symposium

July 15th, 2024
Orlando, FL

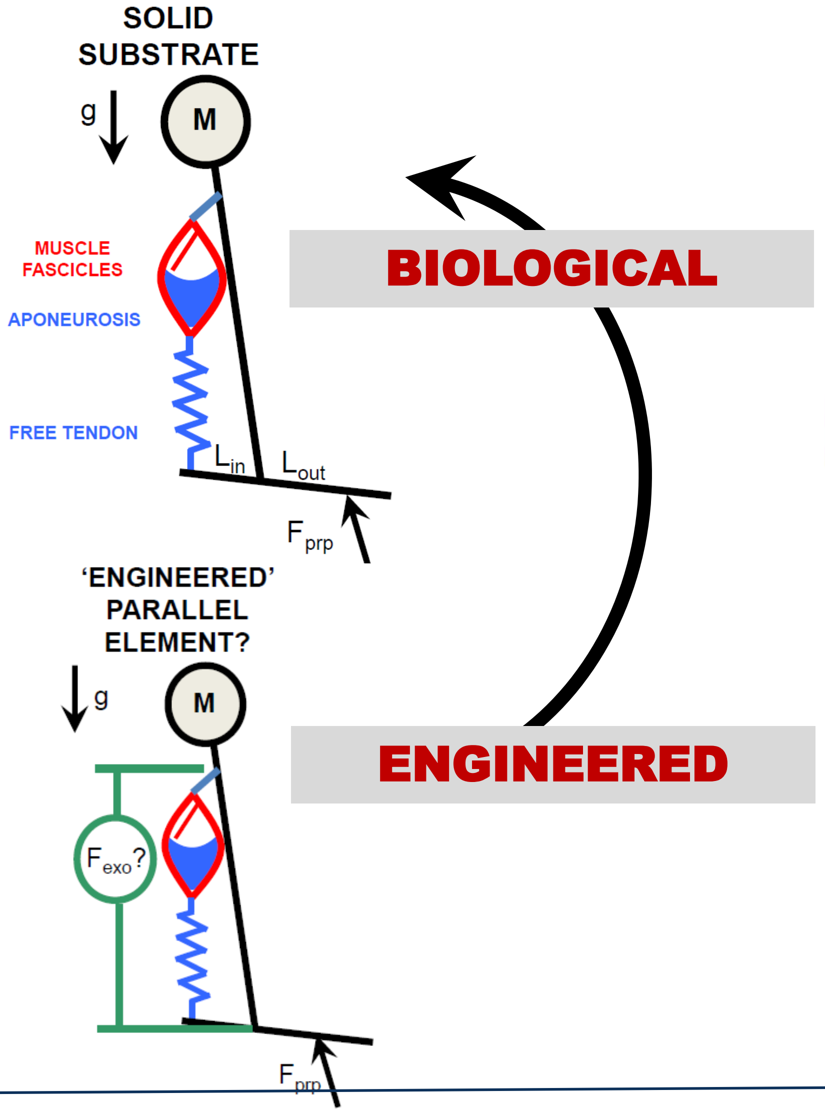
PoWeR Lab
Physiology of Wearable Robotics

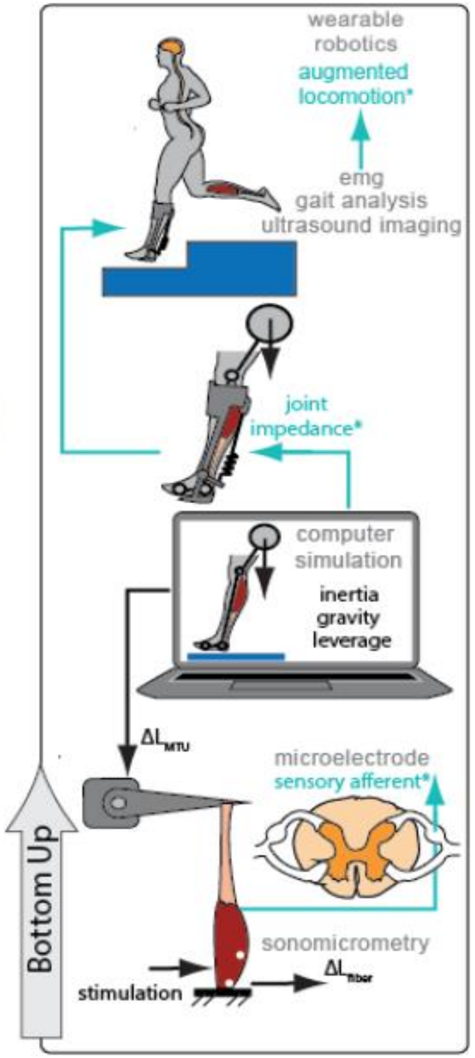
Gregory S. Sawicki, PhD

Professor
School of Mechanical Engineering
School of Biological Sciences

Georgia Tech The George W. Woodruff School of Mechanical Engineering
Georgia Tech Institute for Robotics and Intelligent Machines
ihmc FLORIDA INSTITUTE FOR HUMAN & MACHINE COGNITION

Physiology of Wearable Robotics (PoWeR)





Use human locomotion energy flow as a 'road-map' to guide exo design.

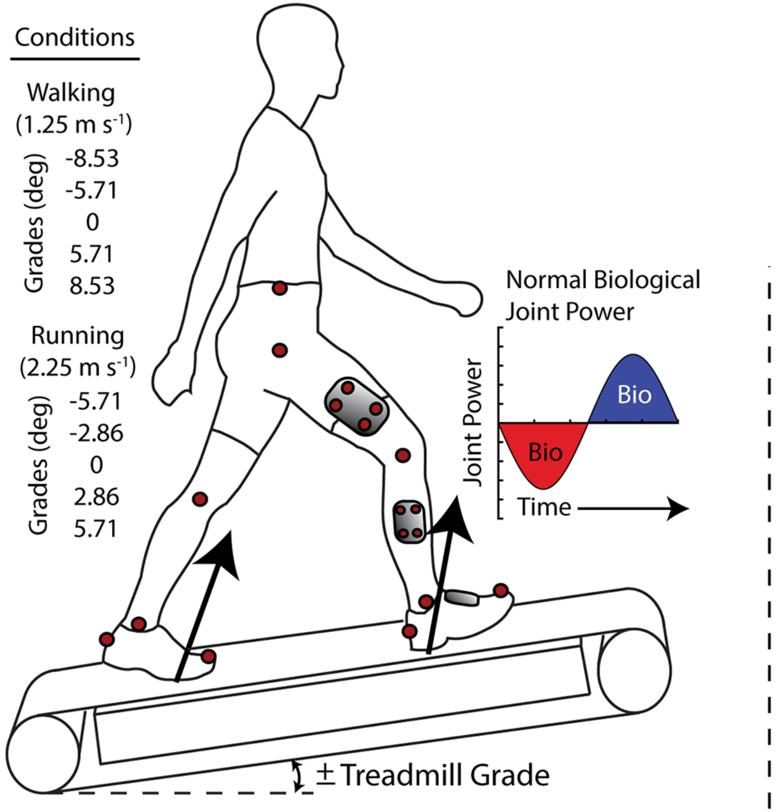
*Nuckols, Farris, Takahashi, Mizrachi, Riemer, Sawicki *JNER* (2020).

RICH NUCKOLS Ph.D.

RAZIEL RIEMER, Ph.D.

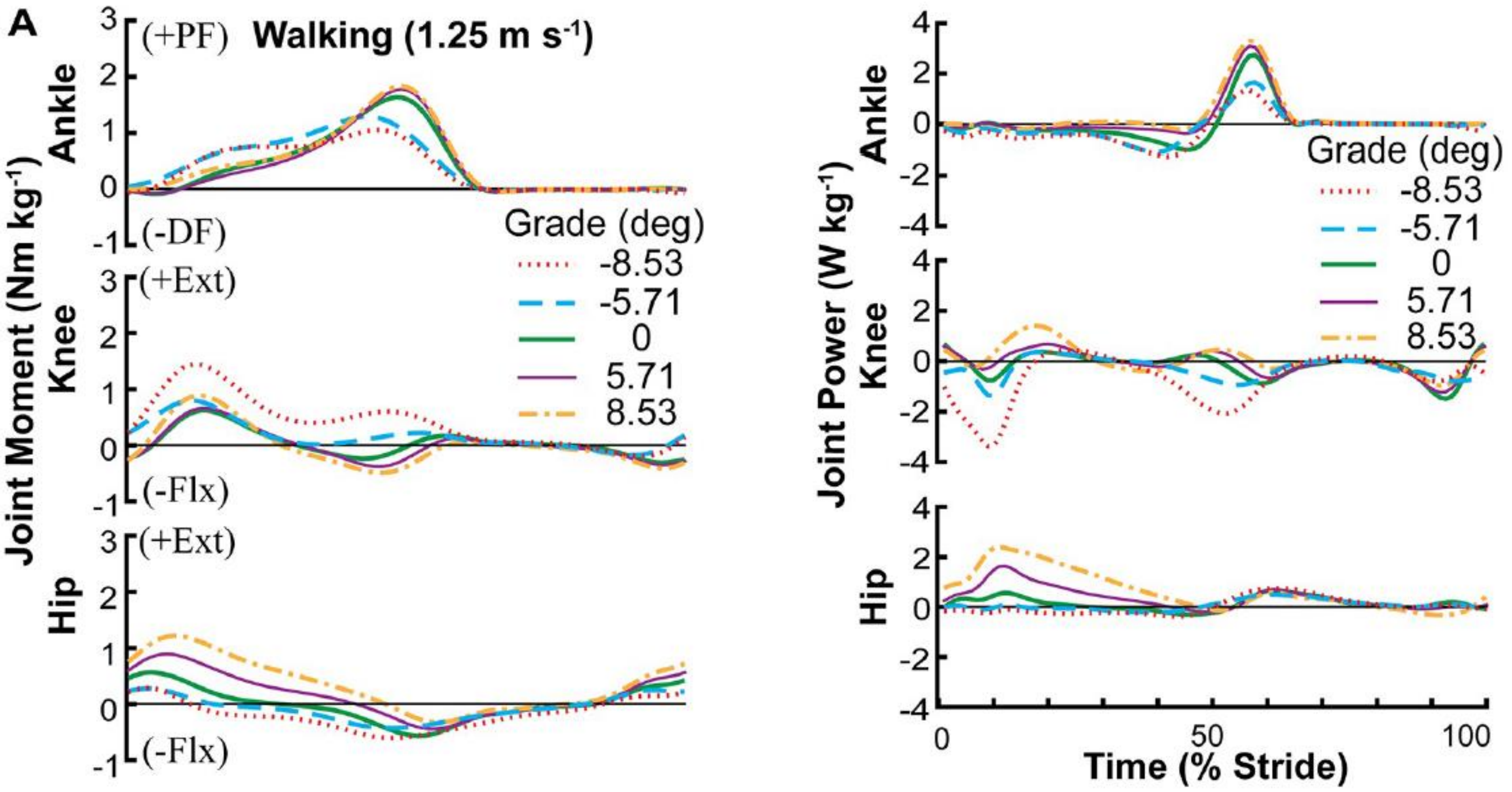
KOTA TAKAHASHI, Ph.D.

DOM FARRIS Ph.D.



Lower-limb moments and powers from laboratory based inverse dynamics.

*Nuckols, Farris, Takahashi, Mizrachi, Riemer, Sawicki *JNER* (2020).



Use human locomotion energy flow as a ‘road-map’ to guide exo design.

EPIC Exoskeleton & Prosthetic Intelligent Controls GEORGIA TECH

PoWeR Lab Physiology of Wearable Robotics

*Nuckols, Farris, Takahashi, Mizrachi, Riemer, Sawicki *JNER* (2020).

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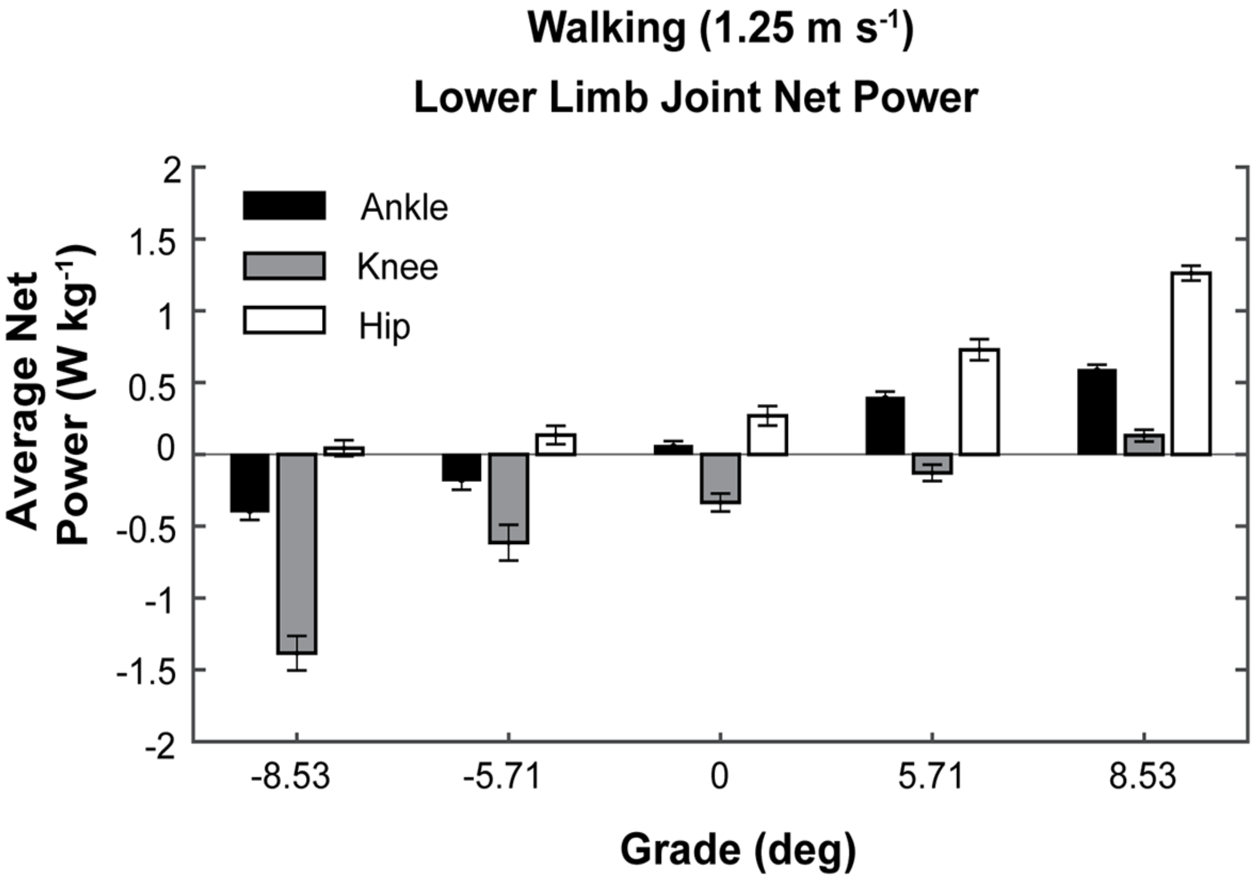
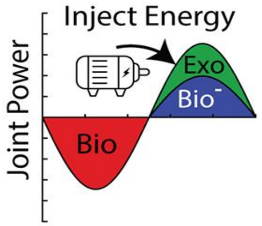
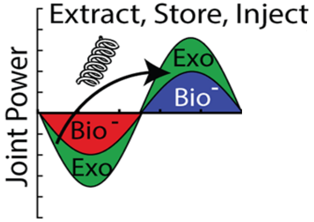
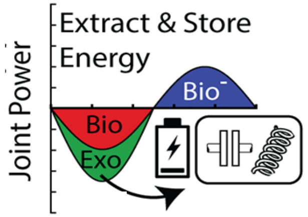




MOTOR



SPRING



DAMPER

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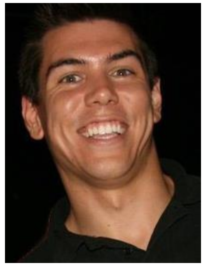
Build elastic ankle exoskeletons using parallel springs.

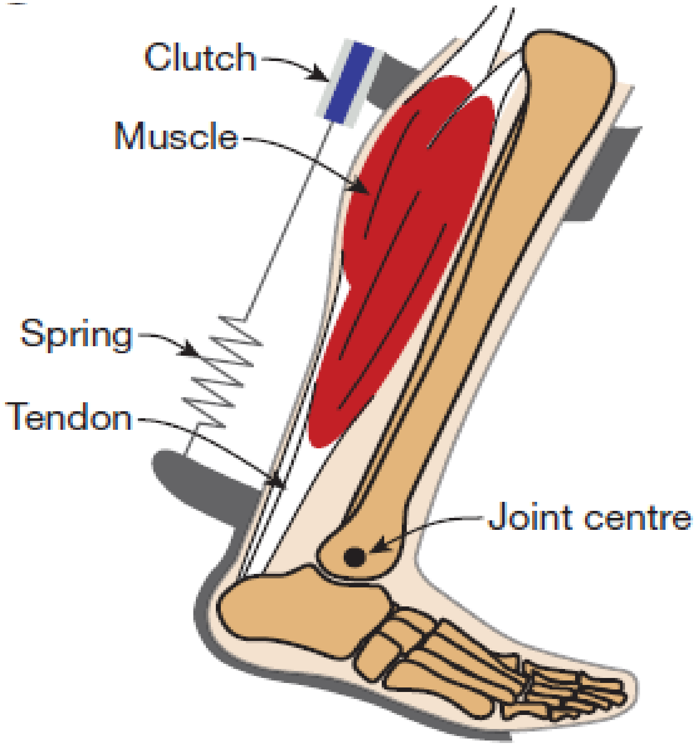


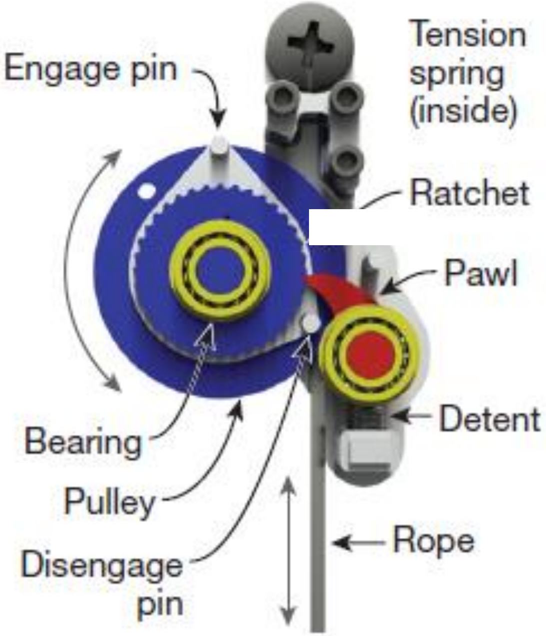
BRUCE WIGGIN, Ph.D.

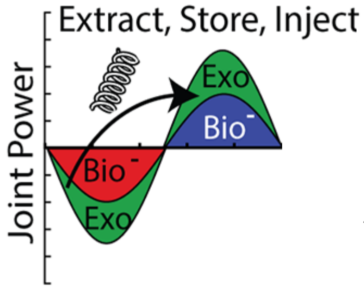
STEVE COLLINS, Ph.D.

***Lightweight: ~400g**

***Unpowered: No batteries, motors**





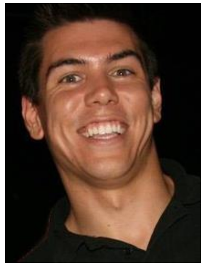


SPRING ANALOGY

US Patent #9,492,302: "Apparatus and clutch for using controlled energy storage and releases of mechanical energy to aid locomotion"

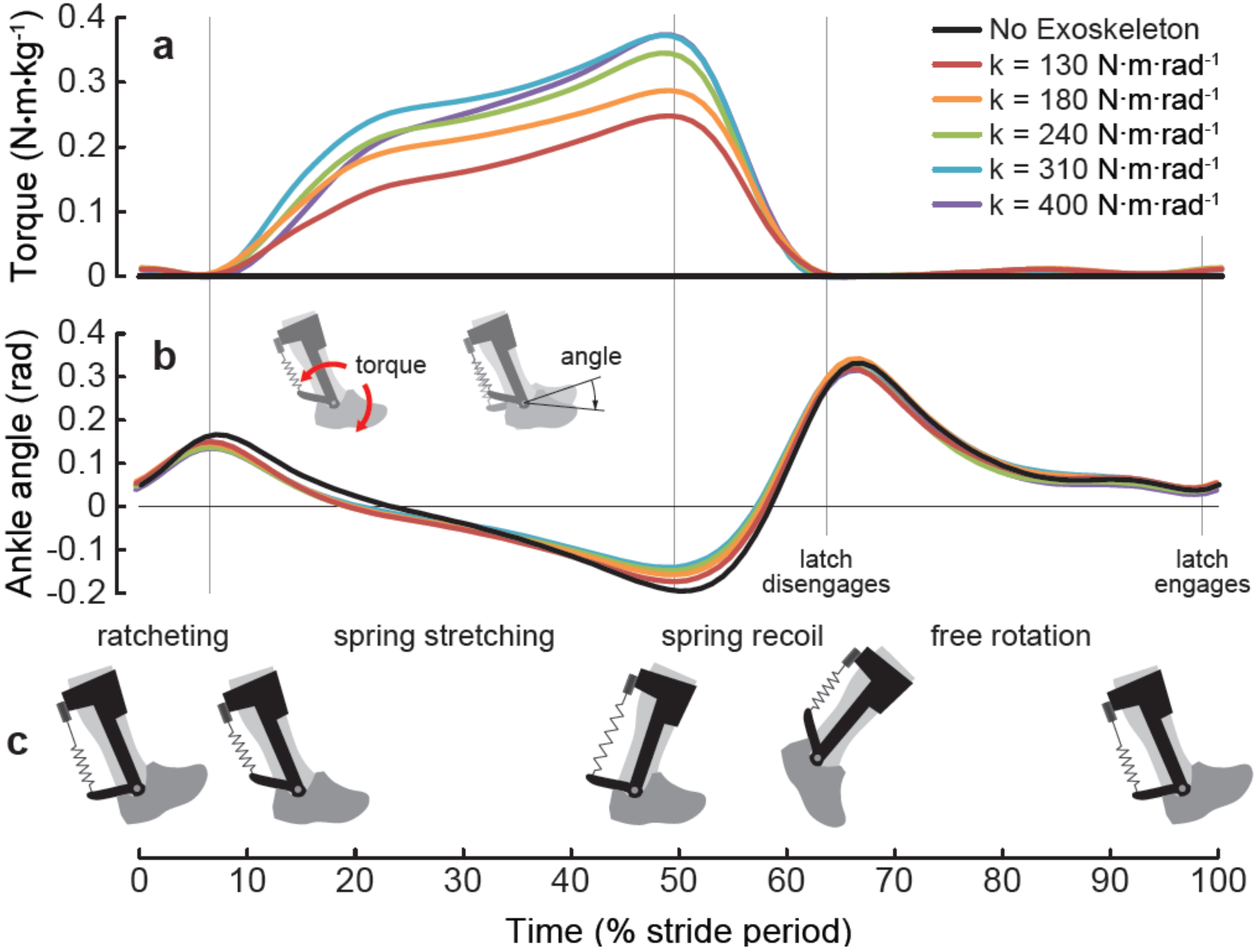
***Collins SH, Wiggin MB, Sawicki GS** *Nature* (2015).

Elastic ankle exoskeletons generate exo torques with 'natural' moment pattern.



BRUCE WIGGIN, Ph.D.

STEVE COLLINS, Ph.D.



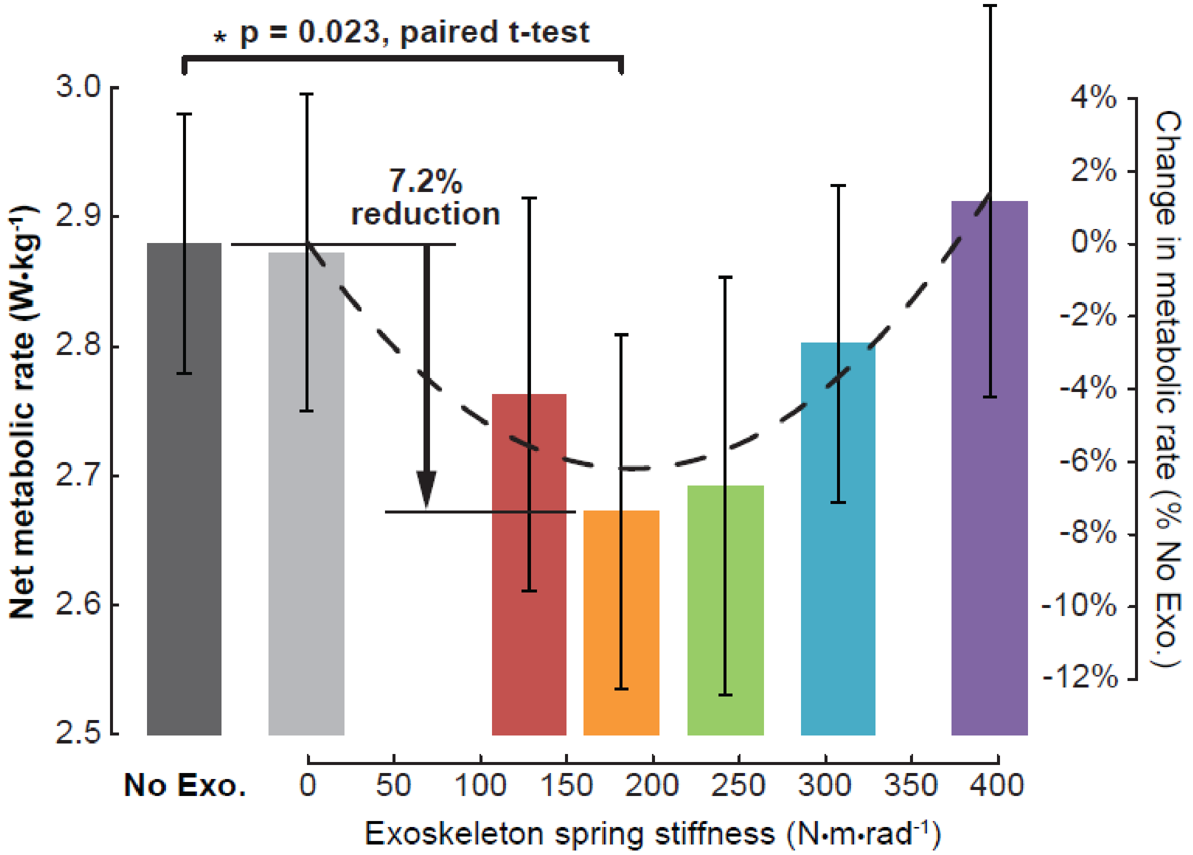
Exoskeleton delivers ~0.12 N-m/kg avg. torque at intermediate k_{exo}

Reduces biological ankle joint moment by ~25%

*Collins SH, Wiggin MB, Sawicki GS *Nature* (2015).

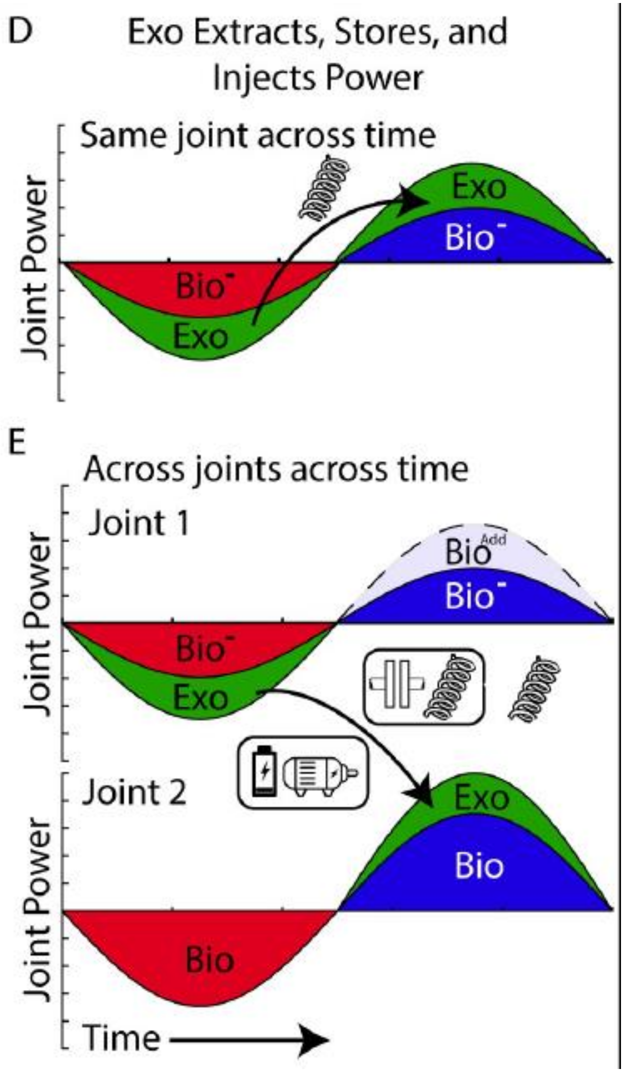
Recycling exoskeleton elastic energy offloads muscles and reduces metabolic cost.

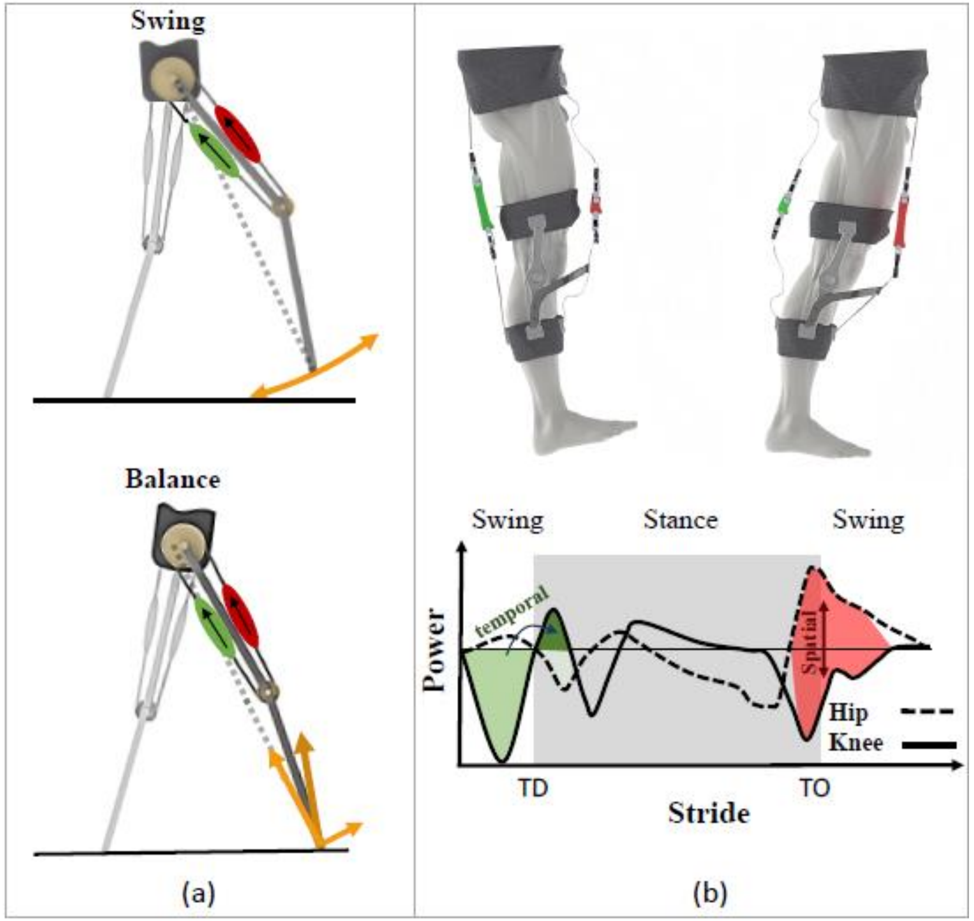
*Collins SH, Wiggin MB, Sawicki GS *Nature* (2015).

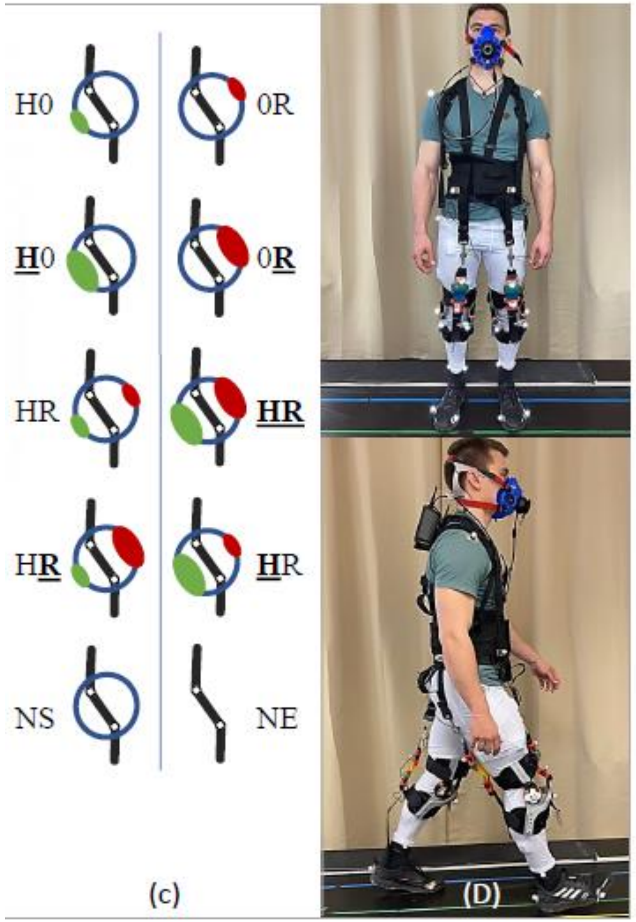


***Exoskeleton reduces metabolic cost 7% below normal walking at intermediate stiffness, k_{exo} = 180 N-m/rad**

More elaborate energy transfers revealed in mechanical power 'road-map'.





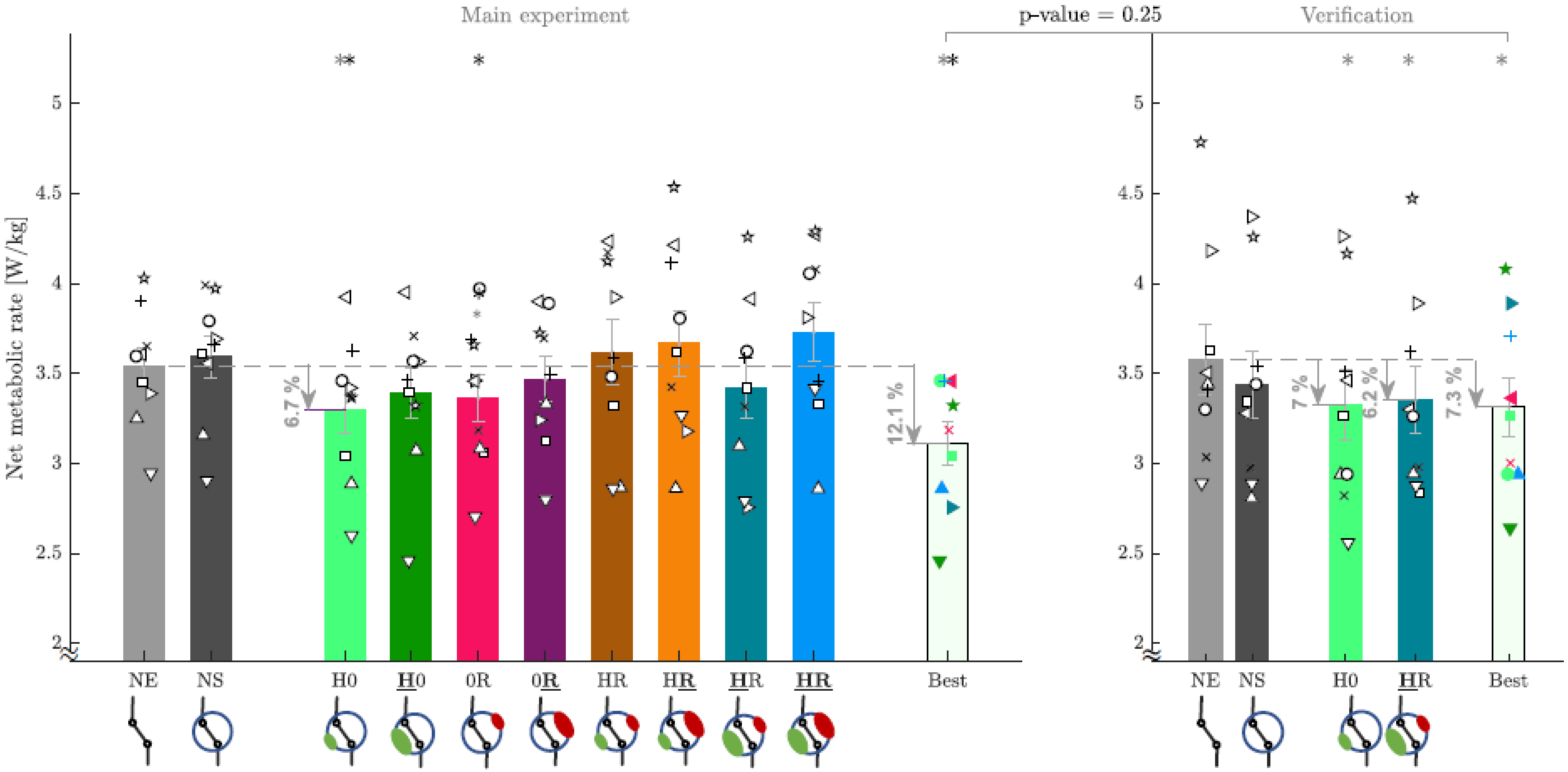


*Sharbafi …. Sawicki GS, Seyfarth *in prep*

Elastic, bi-articular hip-knee morphology can reduce metabolic cost of walking.

ANDRE SEYFARTH, Ph.D.

MAZIAR SHARBAFI, Ph.D.



*Sharbafi …. Sawicki GS, Seyfarth *in prep*

Go farther! Collect and leverage, large diverse movement biomechanics datasets.

Journal of Biomechanics 119 (2021) 110320

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journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

ELSEVIER

A comprehensive, open-source dataset of lower limb biomechanics in multiple conditions of stairs, ramps, and level-ground ambulation and transitions

Jonathan Camargo [a,b,*], Aditya Ramanathan [a], Will Flanagan [a], Aaron Young [a,b]

[a] George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA
[b] Institute of Robotics and Intelligent Machines, Georgia Institute of Technology, Atlanta, GA, USA

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Georgia Tech Institute for Robotics and Intelligent Machines

Collect, large diverse biomechanics datasets --->leverage for data driven hardware +control design

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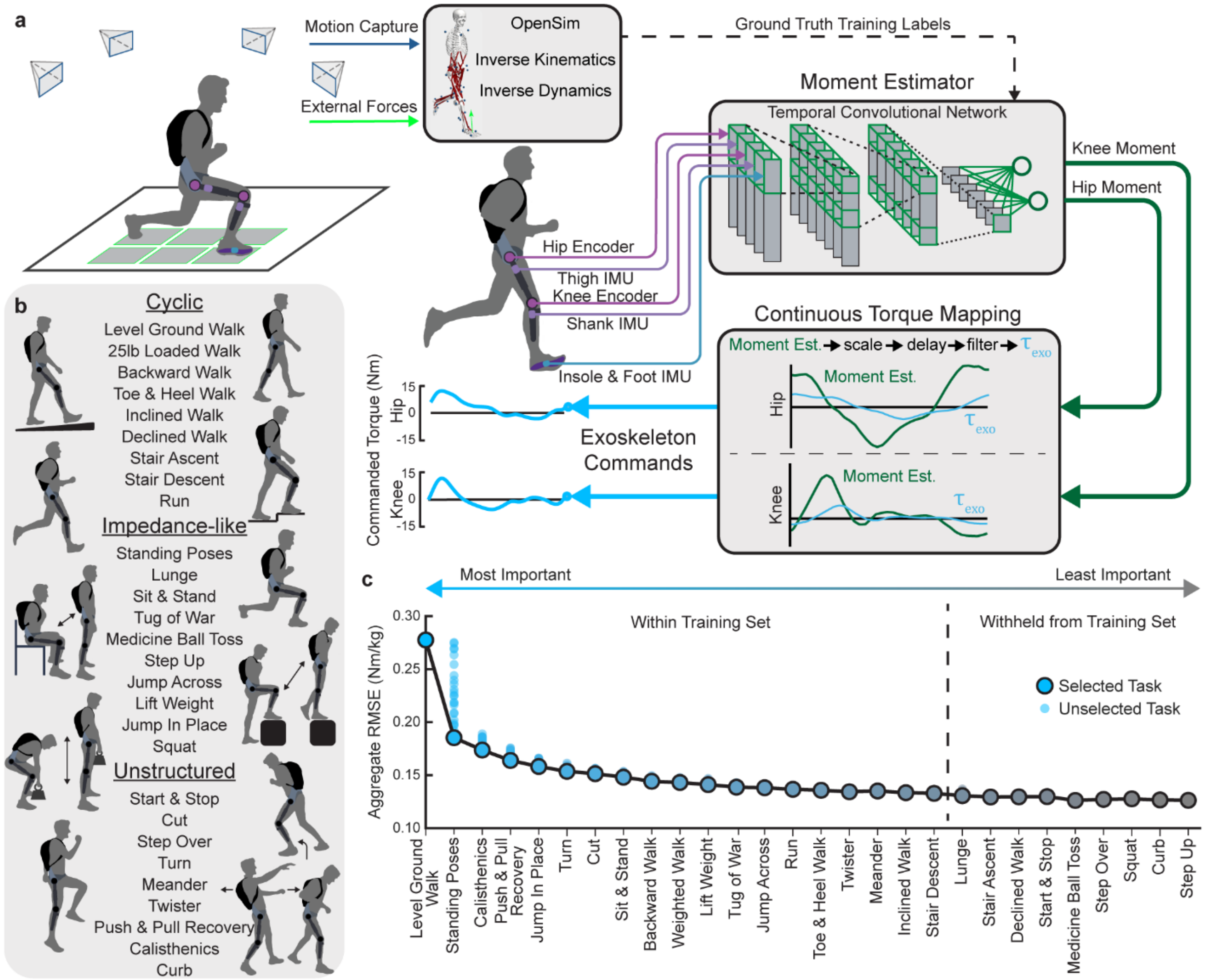
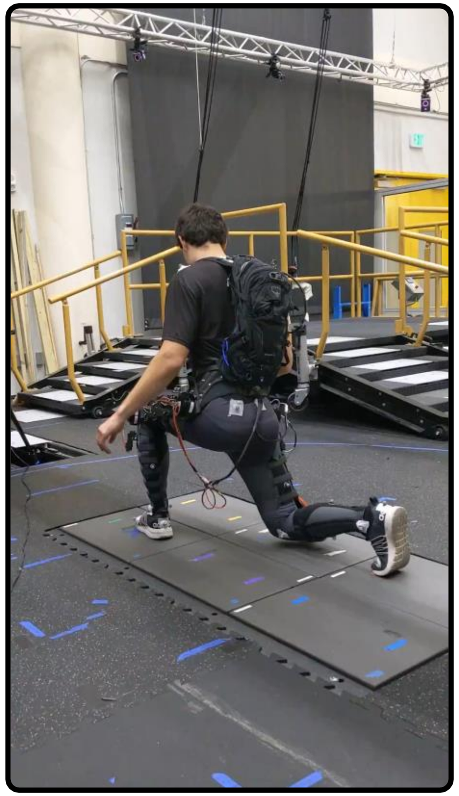
PoWeR Lab Physiology of Wearable Robotics





15 subjects performed **28** cyclic & non-cyclic tasks under **60** total conditions

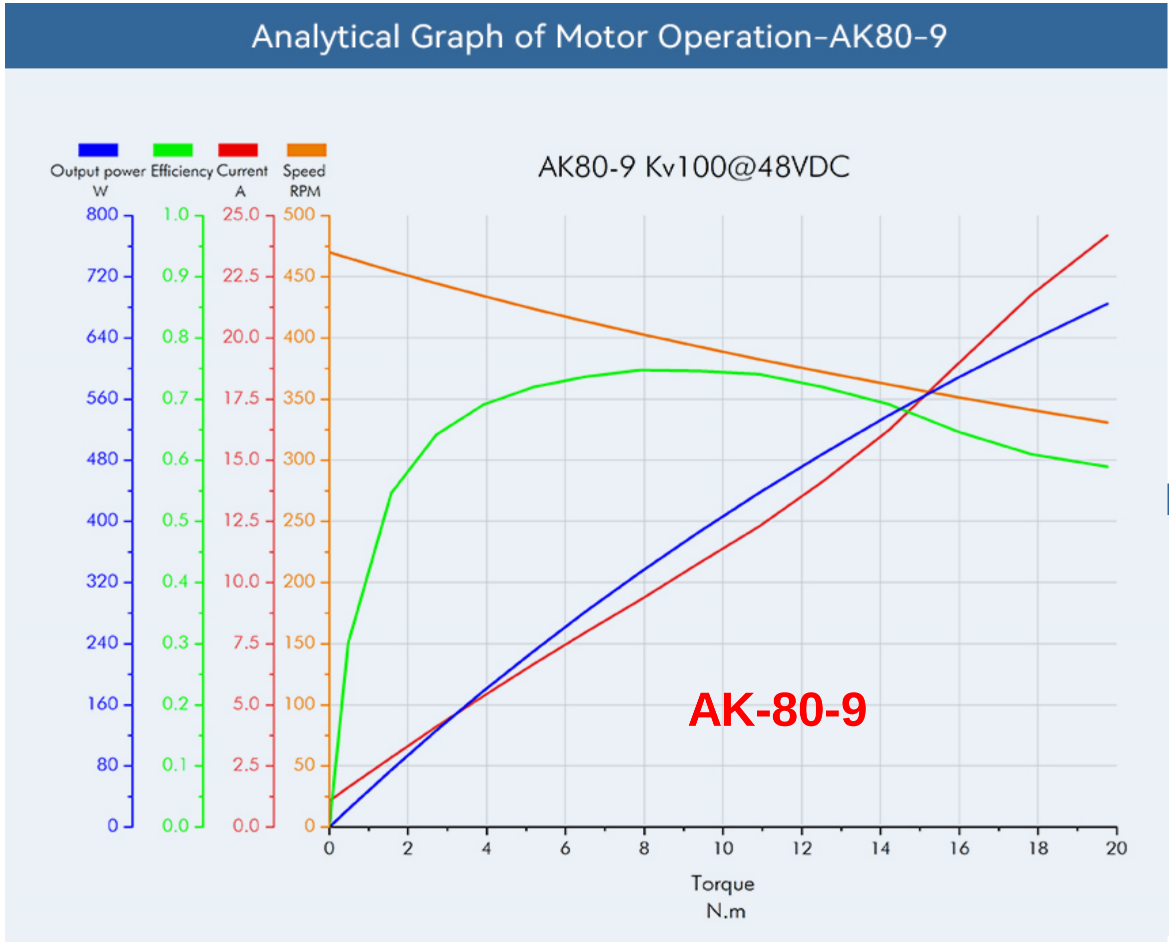
What to do with all the data?
--->Match motor specs to user demands.

T-MOTOR THE SAFER PROPULSION SYSTEM | UAV Power | Robot Dynamics | Model Power | Customized | News | About T-MOTOR | TMOTOR Store | HOBBY Store

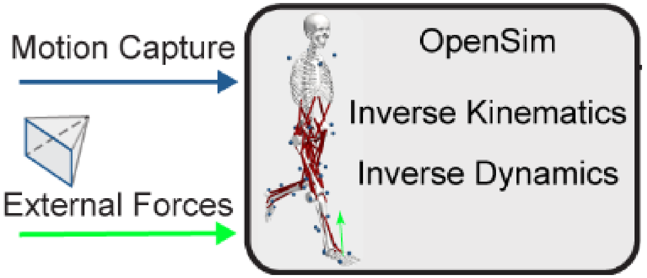
MOTOR SPECS-->

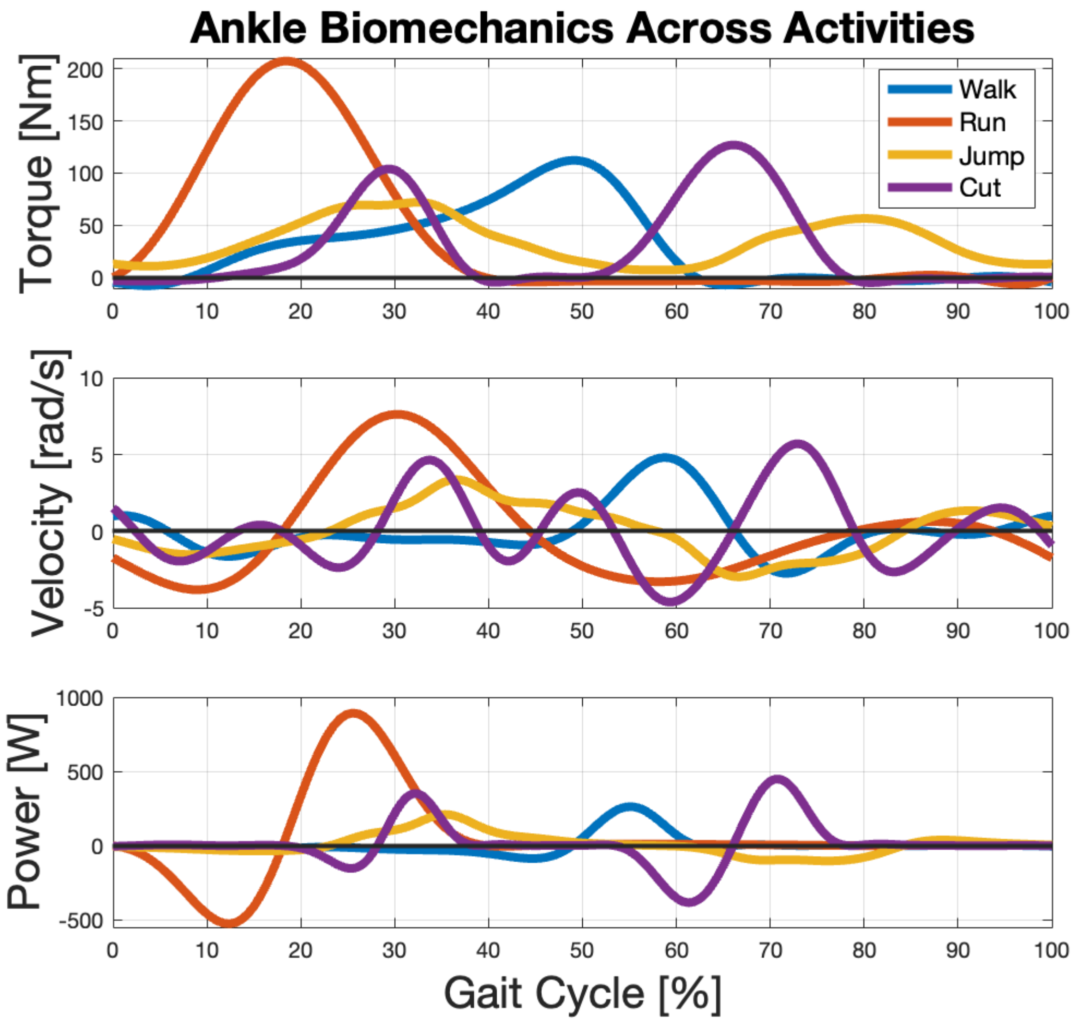
1. Peak and Continuous Torque
2. Torque (N-m) vs. Speed (rpm)
3. vs. Motor Efficiency
4. vs. Output Power (W)
5. vs. Heat (W) *from 3. and 4.

--->BIOLOGICAL DEMANDS



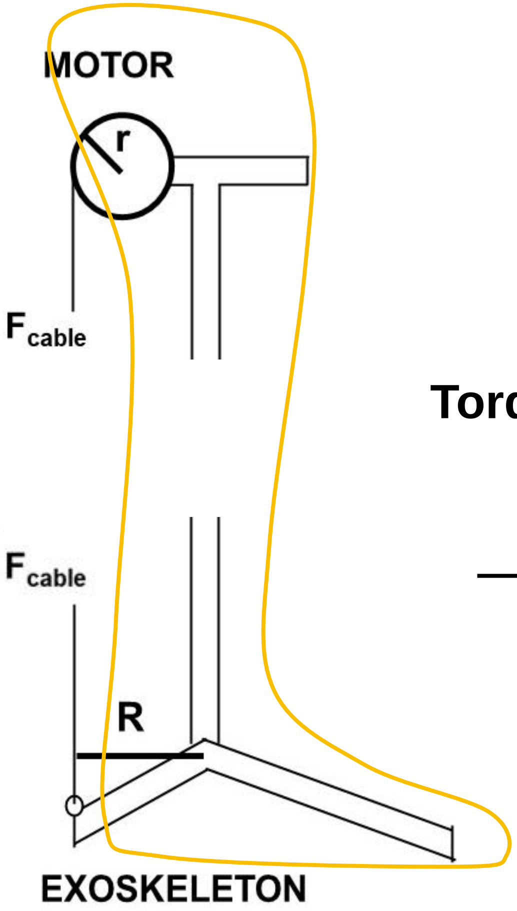
Matching game. Step 1. --> Plot biological joint moment versus angular velocity for a given task set.





Matching game. Step 2. Define gear ratio. Then compute to match T_{motor} to M_{bio}.

$\text{Torque}_{MOT} = r\,F_{cable}$



$\text{Torque}_{EXO} = R\,F_{cable}$

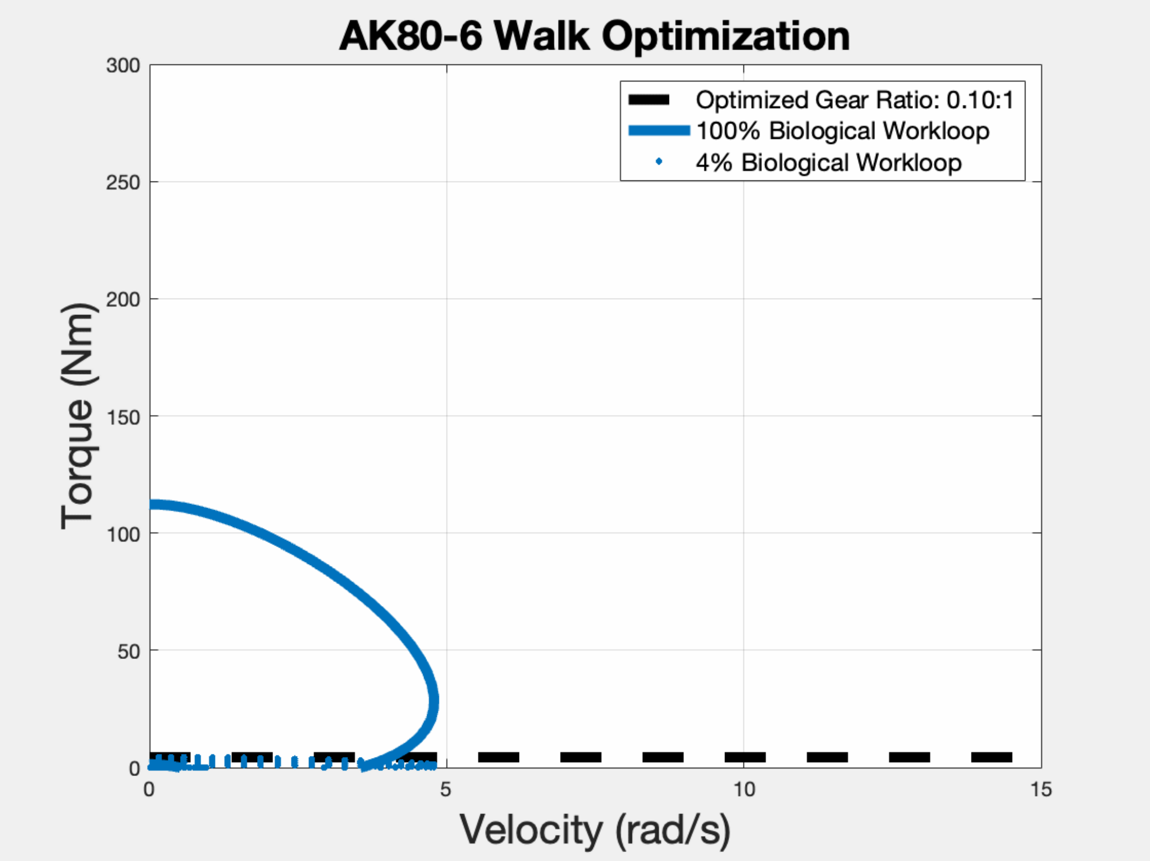
$\text{Torque}_{EXO} = (R/r)\,\text{Torque}_{MOT}$

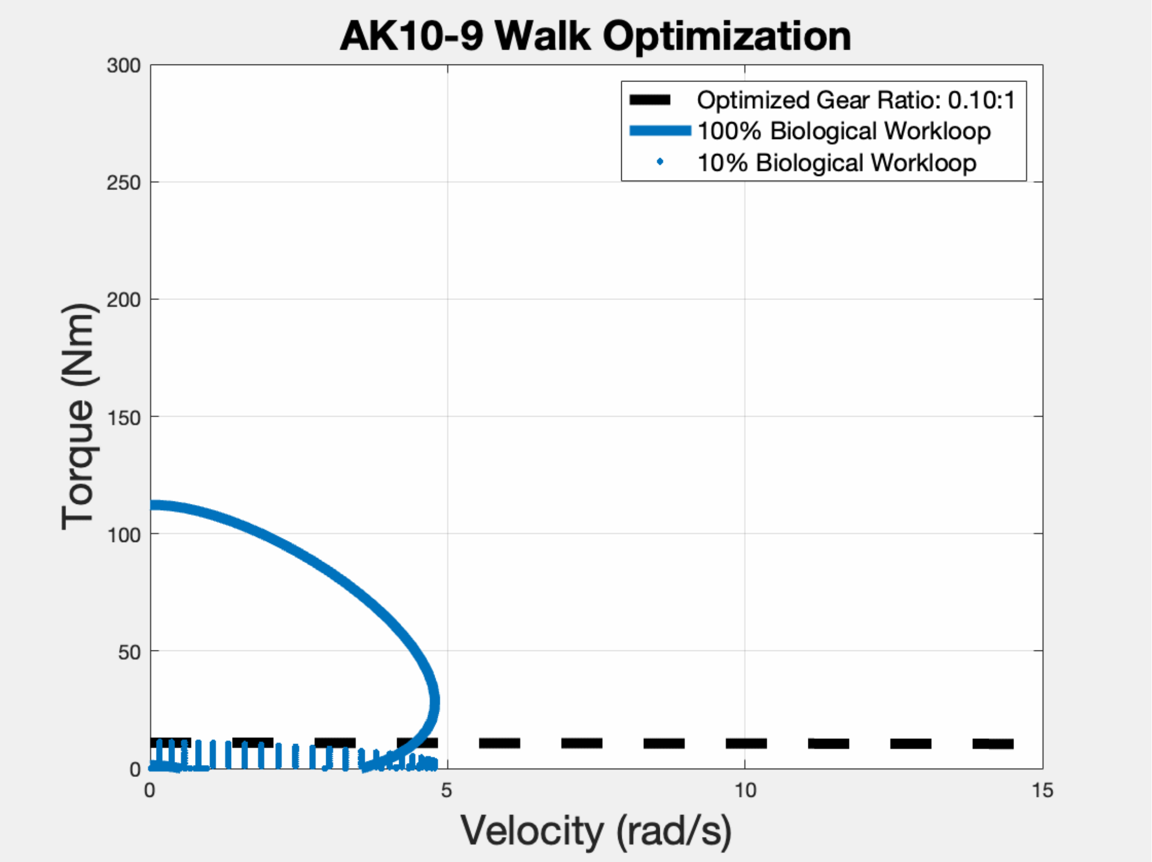
$$\frac{\text{Torque}_{EXO}}{\text{Torque}_{MOT}} = \frac{R}{r}$$

*From human data % $\text{Moment}_{BIO} = \text{Torque}_{EXO}$

$$GR = R/r = \frac{\%\,\text{Moment}_{BIO}}{\text{Torque}_{MOT}}$$

Matching game. Step 3. --> Compute 'optimal' gear ratio vs. task for all motors in the set.



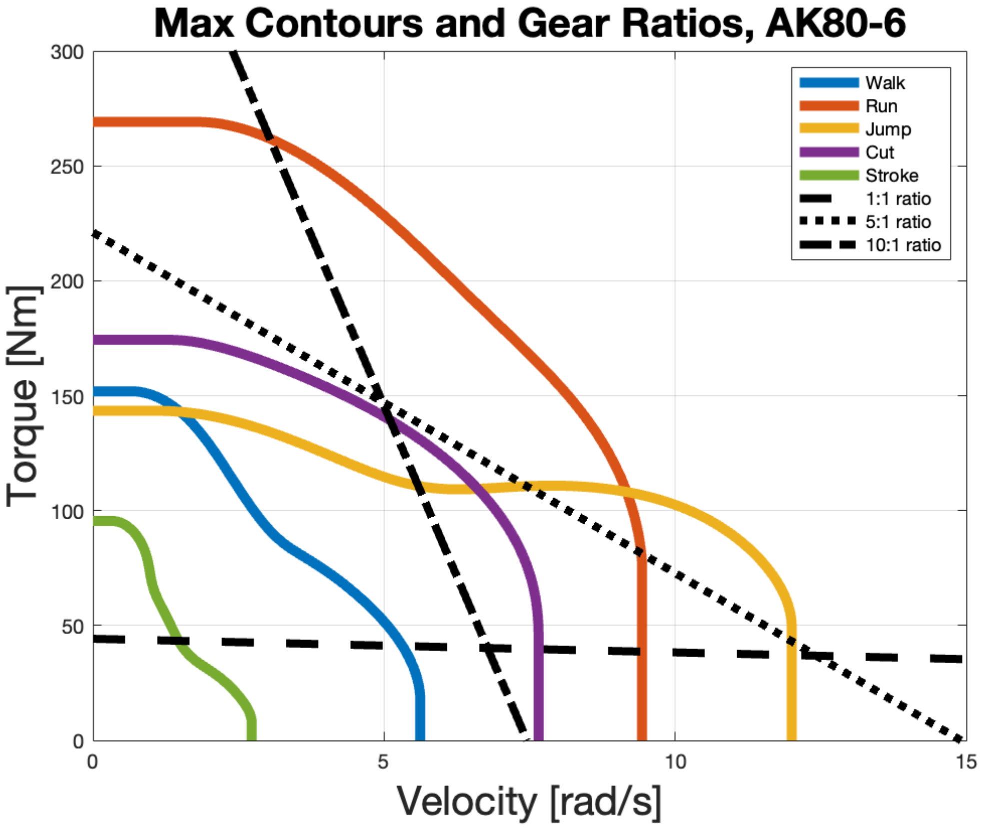


SMALLEST MOTOR -->
GETS 100% WALK Mbio AT GR= ~2.5

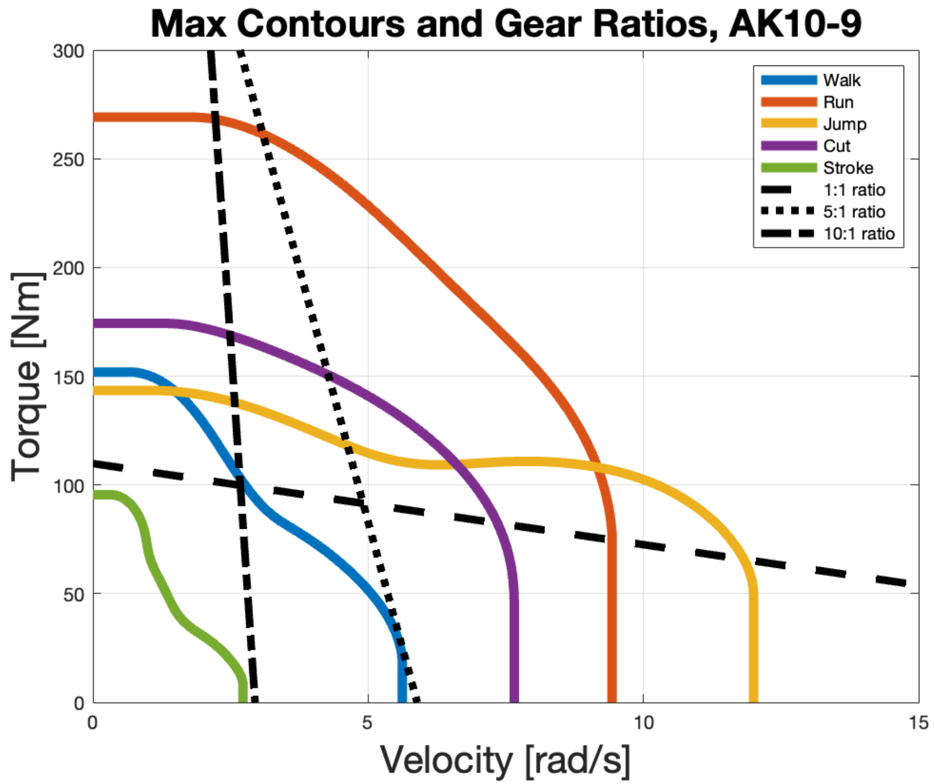
LARGEST MOTOR -->
GETS 100% WALK Mbio AT GR= ~1.15

Matching game. Step 4. --> Analyze gear ratio vs. task for motors in the set. Torque or speed can limit.

SMALLEST MOTOR



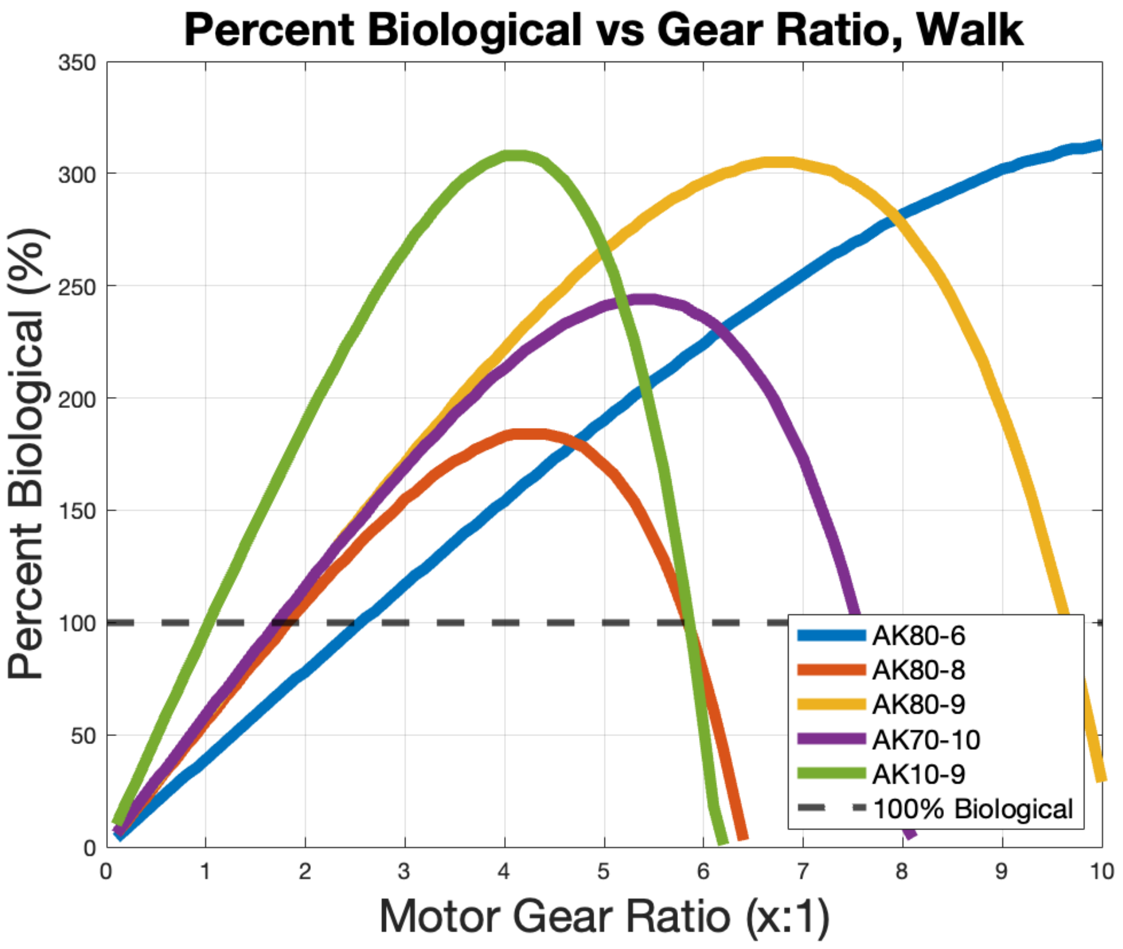
LARGEST MOTOR

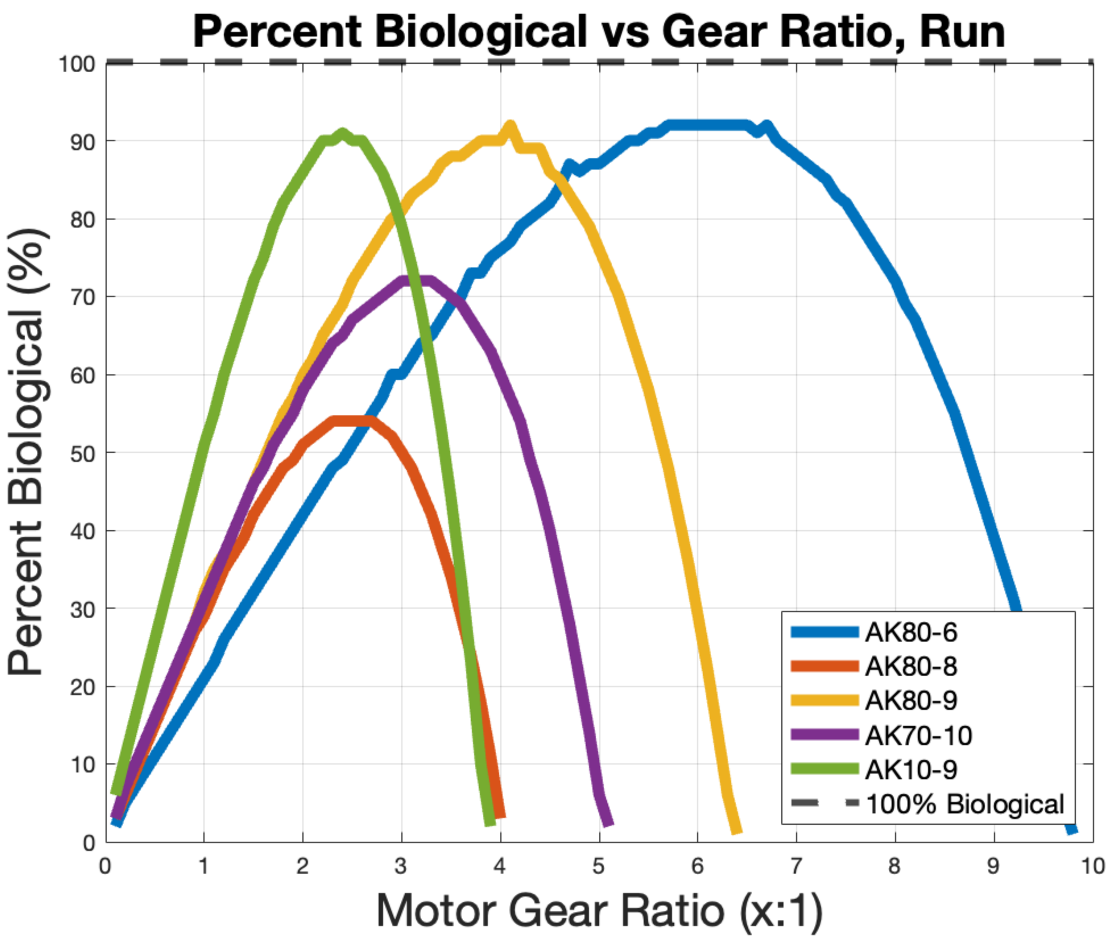


1:1 NO TASKS COVERED
5:1 CUT, WALK, STROKE COVERED

1:1 STROKE COVERED
5:1 WALK, STROKE COVERED

Matching game. Step 5. --> Make decisions. Minimize mass. Gear geometry. Avoid overheating.

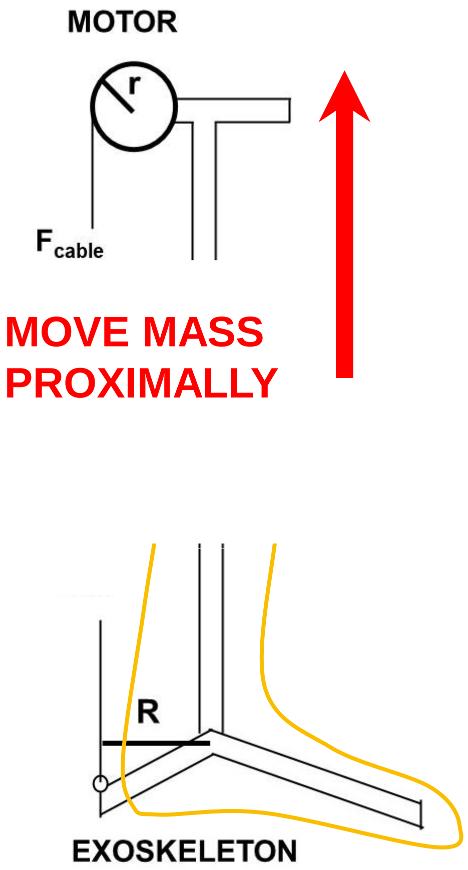




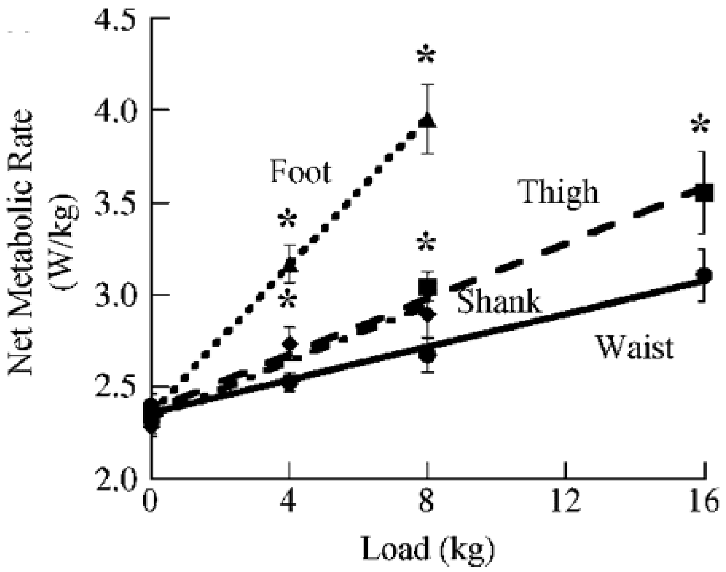
*MANY OPTIONS FOR 100% Mbio in WALKING. GR1-3

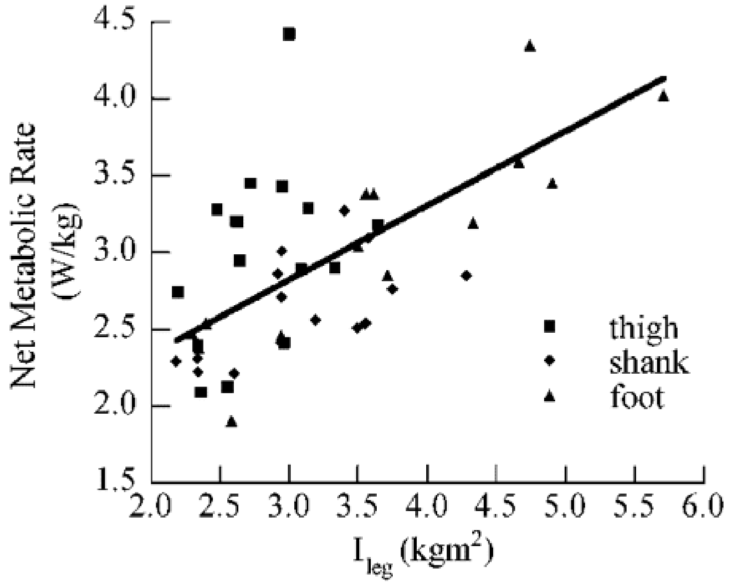
*NO SOLUTIONS FOR 100% Mbio in RUNNING.

Trade-offs. Tip #1: Proximal mass distribution.



*Browning R, ….. Kram R *MedSciSport* (2007).

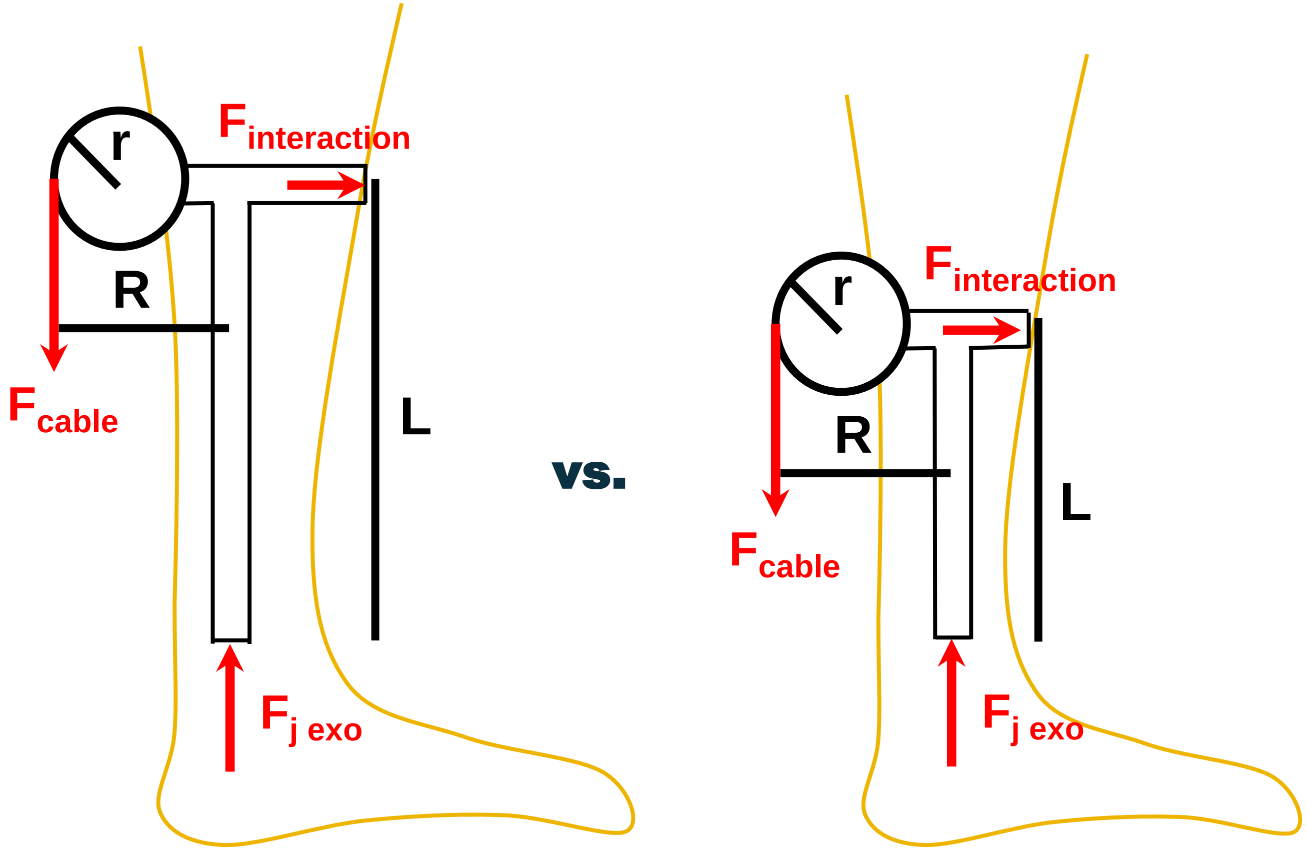




--> Can carry bigger motors without big increase in user effort.

Trade-offs. Tip #2: Large exoskeleton moment arms!

$$F_{interaction} = F_{cable} \frac{R}{L}$$

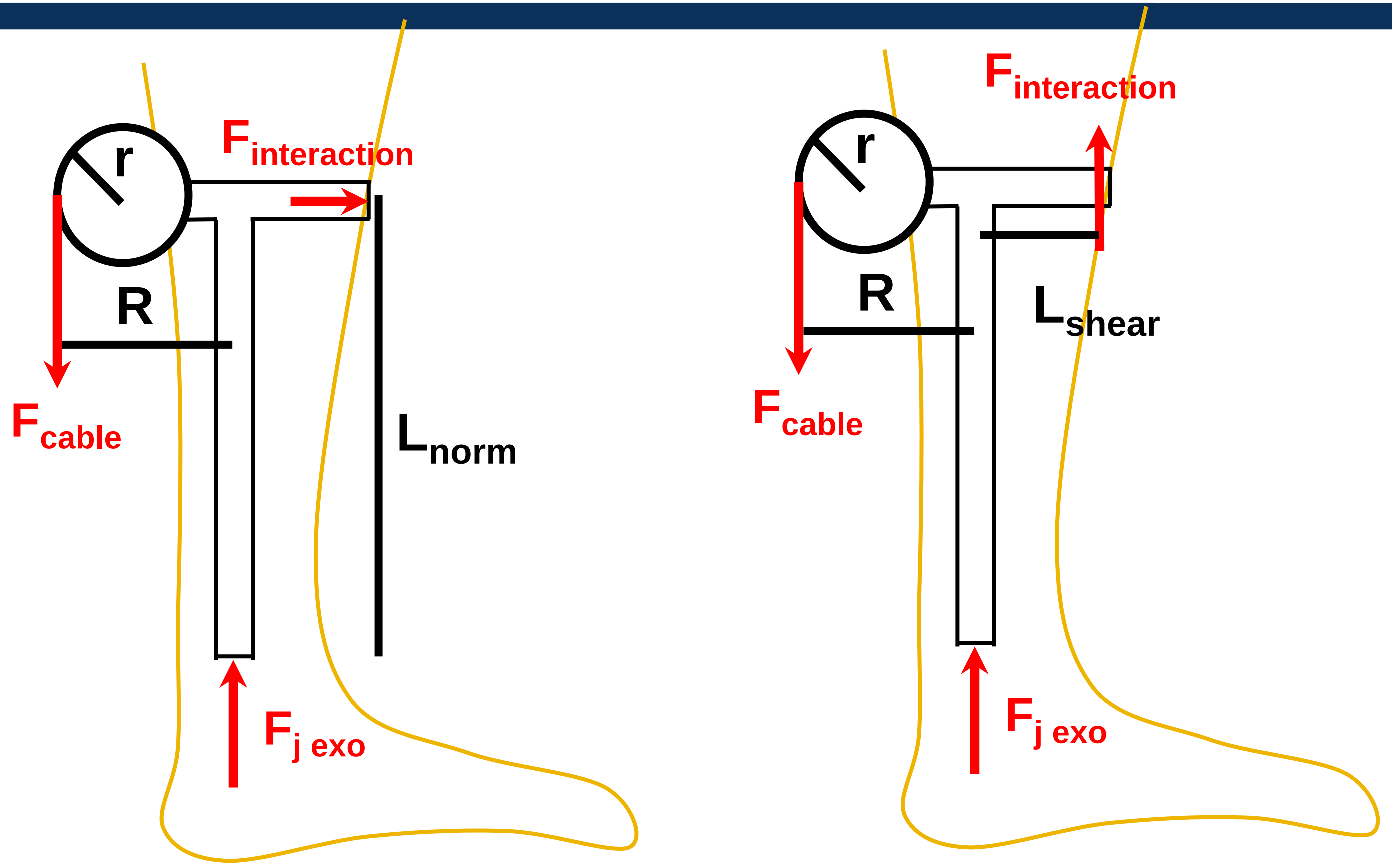


→ **Keeps $F_{interaction}$ low. Comfortable.**
→ **Reduces soft tissue losses.**

Trade-offs. Tip #3: Exoskeleton interactions directed as normal rather than shear forces on user's body!

$$F_{interaction} = F_{cable}\frac{R}{L}$$

norm vs. shear



--> Keeps $F_{interaction}$ frictionless. No slipping.
--> Better leverage.
--> Exoskeleton vs. Exosuit. Internal loading?

Key Takeaways.

1. HUMAN BIOMECHANICS PROVIDE KEY GUIDANCE FOR BOTH CONCEPTUAL AND FORMAL EXOSKELETON DESIGN.
2. TRANSMISSION DESIGN BRIDGES GAP BETWEEN MOTORS AND MUSCLES AND ENABLES STRATEGIC SELECTION OF EXO MASS DISTRIBUTION
3. EXOSKELETON INTERFACE DESIGN [e.g. FRAME GEOMETRY] IS A MISSED OPPORTUNITY FOR IMPPROVED PERFORMANCE
4. COMFORT, COMFORT, COMFORT! ---> PHYSICAL, THERMAL AND AESTHETIC (see Zelik LinkedIN +Twitter)
5. HUMAN-IN-LOOP OPTIMIZATION FOR HARDWARE DESIGN?