

Biomechatronics, Assistive Devices, Gait Engineering, & Rehabilitation

Development and Application of Semi-Active Prosthetic Foot-Ankle Systems



THE UNIVERSITY
of
WISCONSIN
MADISON

Kieran Nichols

Ph.D. Defense

Mechanical Engineering

Advisor: Peter Adamczyk



College of Engineering
UNIVERSITY OF WISCONSIN-MADISON

Committee: Darryl Thelen, Katherine Fu, Xiaobin Xiong, Aaron Dingle, Kristen Pickett

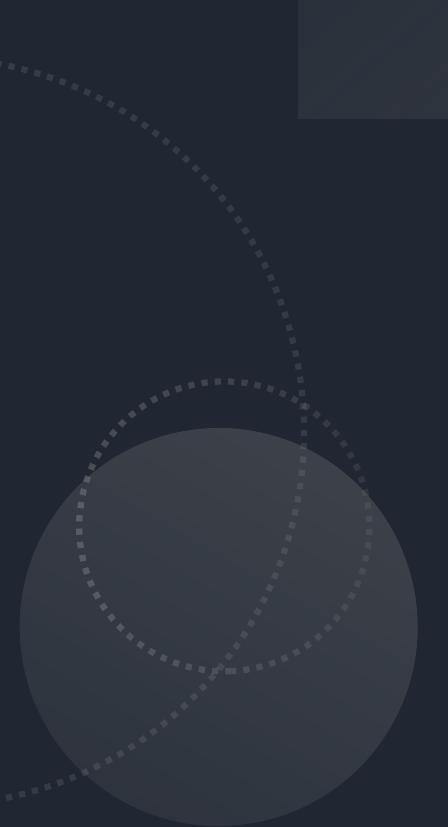
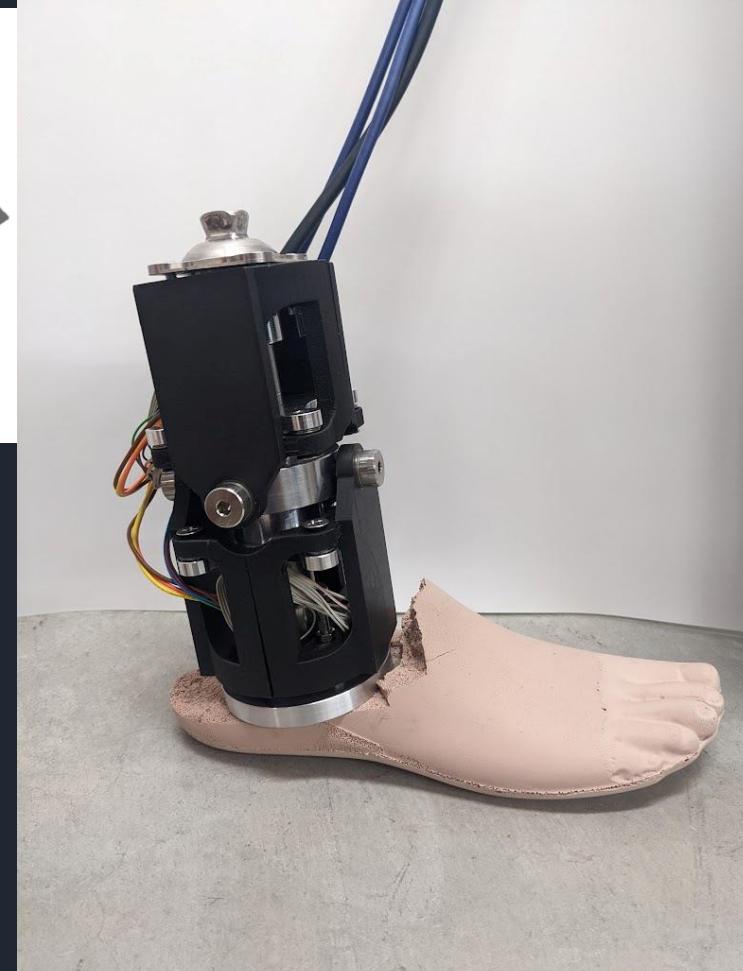
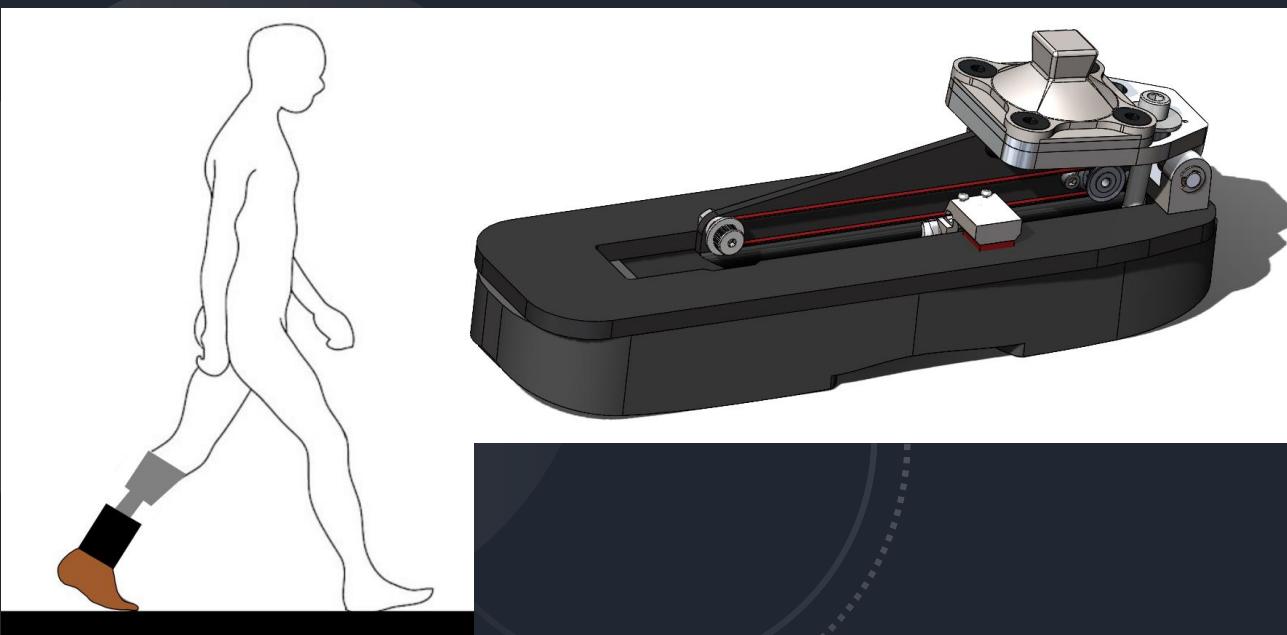
Presentation Overview

Background

Biomechanical
Evaluation of the
Variable Stiffness Foot
(VSF)

Motor control for the Two
Axis aDaptable Ankle
(TADA)

Pilot Biomechanical
Evaluation of the TADA



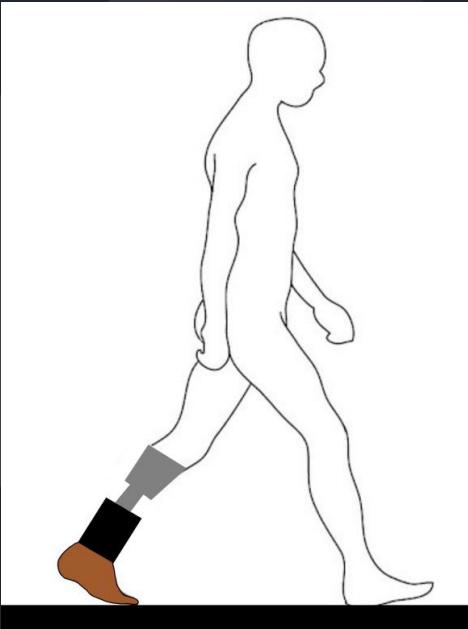
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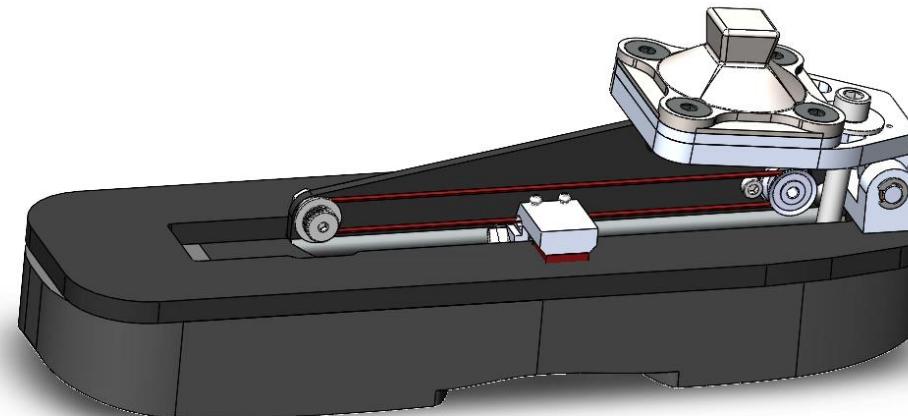
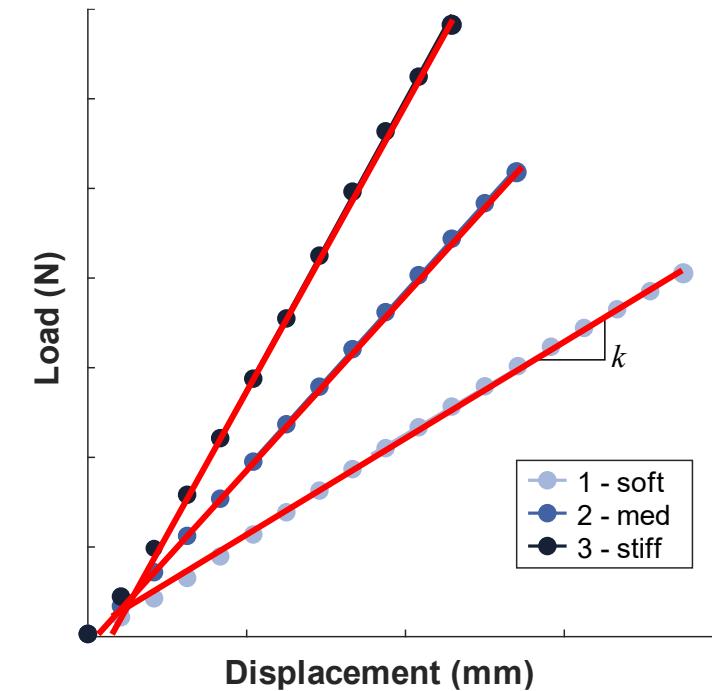
Pilot Biomechanical
Evaluation of the TADA



Background

Variable Stiffness Foot (VSF)¹

- change the forefoot stiffness while foot is in air
- semi-active device
- it can detect foot movement using inertial sensors



Background

- The Two Axis aDaptable Ankle (TADA) is a semi-active ankle prosthesis²
 - independently modulate two axes of ankle angles ($\pm 10^\circ$, sagittal and frontal)
 - prevent rotations of the attached foot when the motor shaft is not moving
 - changes ankle angle while foot is in air (swing phase)



Background

Dissertation objective:

Develop and Evaluate
Stiffness and Ankle angle control
for the Variable Stiffness Foot (VSF) and Two-Axis
aDaptable Ankle (TADA)

Background

- 280,000 people with transtibial amputation (TTA) in the U.S³
- Difficult to recreate the human ankle-foot
- There is a need to improve prosthetic design and control

Below-Knee Amputation



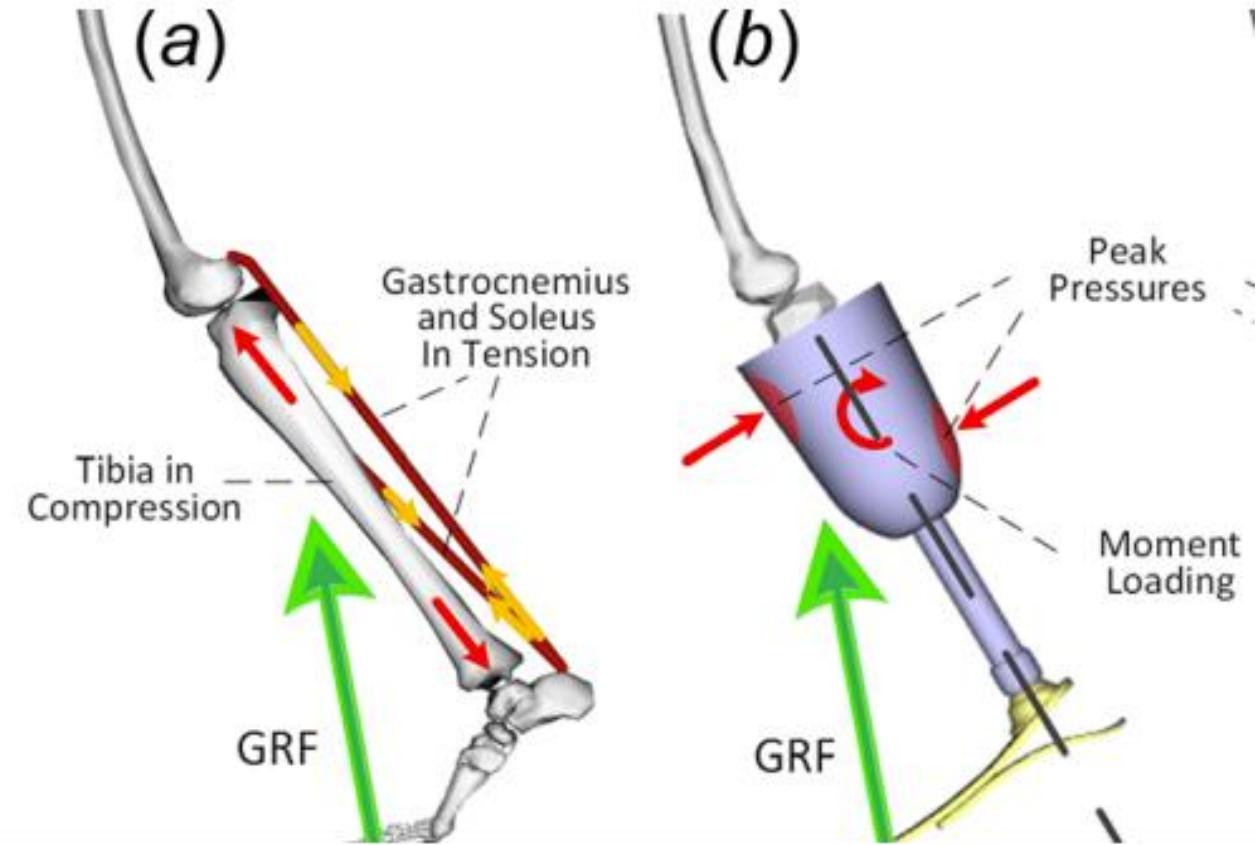
[Diagram: Guide | Physical Therapy Guide to Below-Knee Amputation \(Transtibial Amputation\) | Choose PT](#)

(3): Ziegler-Graham, Kathryn, Ellen J. MacKenzie, Patti L. Ephraim, Thomas G. Travison, and Ron Brookmeyer. "Estimating the Prevalence of Limb Loss in the United States: 2005 to 2050." *Archives of Physical Medicine and Rehabilitation* 89, no. 3 (March 2008): 422–29.
<https://doi.org/10.1016/j.apmr.2007.11.005>.

Background

Common issues of prosthetic walking⁴

- knee hyperextension
- hip circumduction
- Toe scuffing
- knee osteoarthritis
- High peak pressures at socket interaction⁵



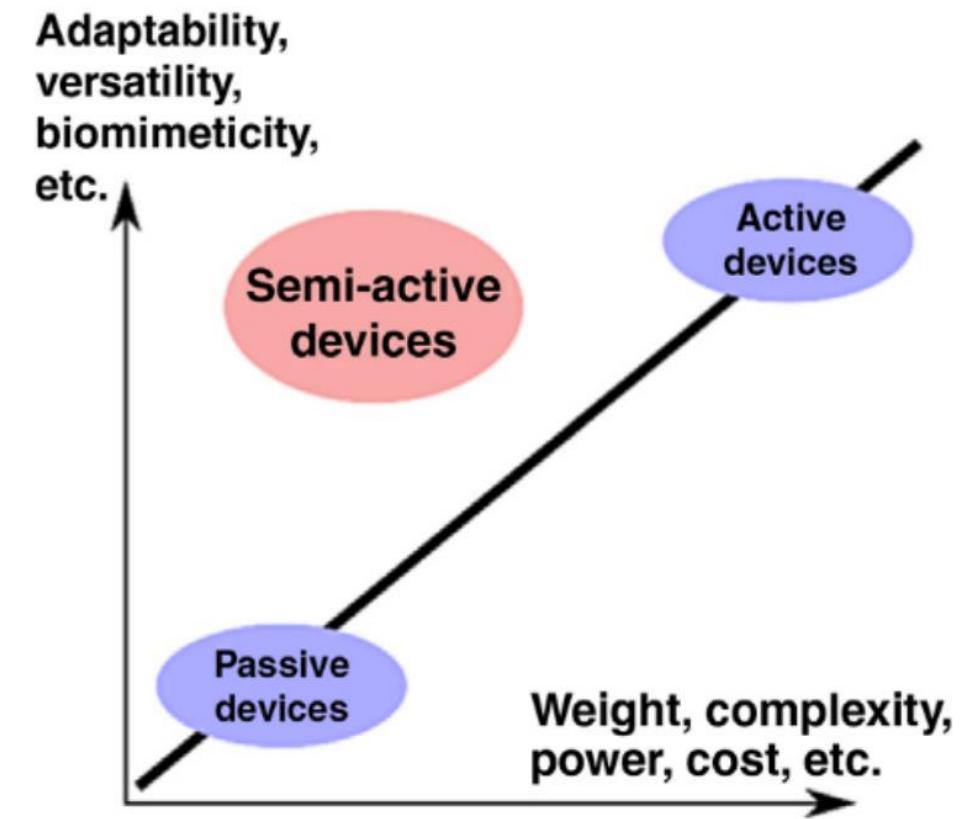
(4): Esquenazi, Alberto, and Stanley K. Yoo. "Lower limb amputations: epidemiology and assessment." PMR Knowledge Now 3 (2016).

(5): Kennedy LaPrè, Andrew, Brian R. Umberger, and Frank C. Sup IV. "A robotic ankle-foot prosthesis with active alignment." Journal of Medical Devices 10.2 (2016): 025001.

Background

Two common ways to describe prosthetic ankle-foot function²:

- Ankle angular stiffness
- Ankle angle control
- Passive ankle-foot prosthesis replaces some of the biological structures
- Semi-active prostheses attempt to recover more of the biological ankle mechanics



(2) and Diagram: Adamczyk, P. G. Chapter 9 - Semi-active prostheses for low-power gait adaptation. in Powered Prostheses (eds. Dallal, H., Demircan, E. & Rastgaar, M.) 201–259 (Academic Press, 2020). doi:10.1016/B978-0-12-817450-0.00009-2.

Research Questions

1. What are the biomechanical effects of changing forefoot stiffness on knee and ankle mechanics?
2. How to implement a real-time motor control for the new Two Axis aDaptable Ankle?
3. What is the Influence of Prosthetic ankle-angle and walking speed on Pylon moments of the Two Axis aDaptable Ankle?

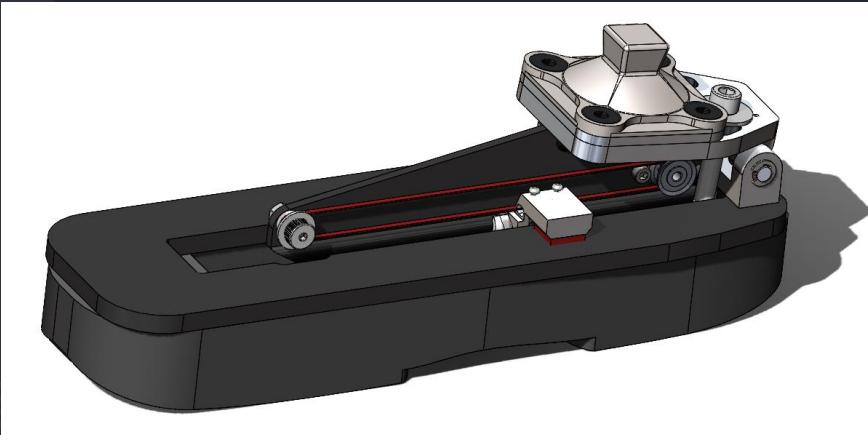
Presentation Overview

Background

BIOMECHANICAL
EVALUATION OF THE
VSF

Motor control for TADA

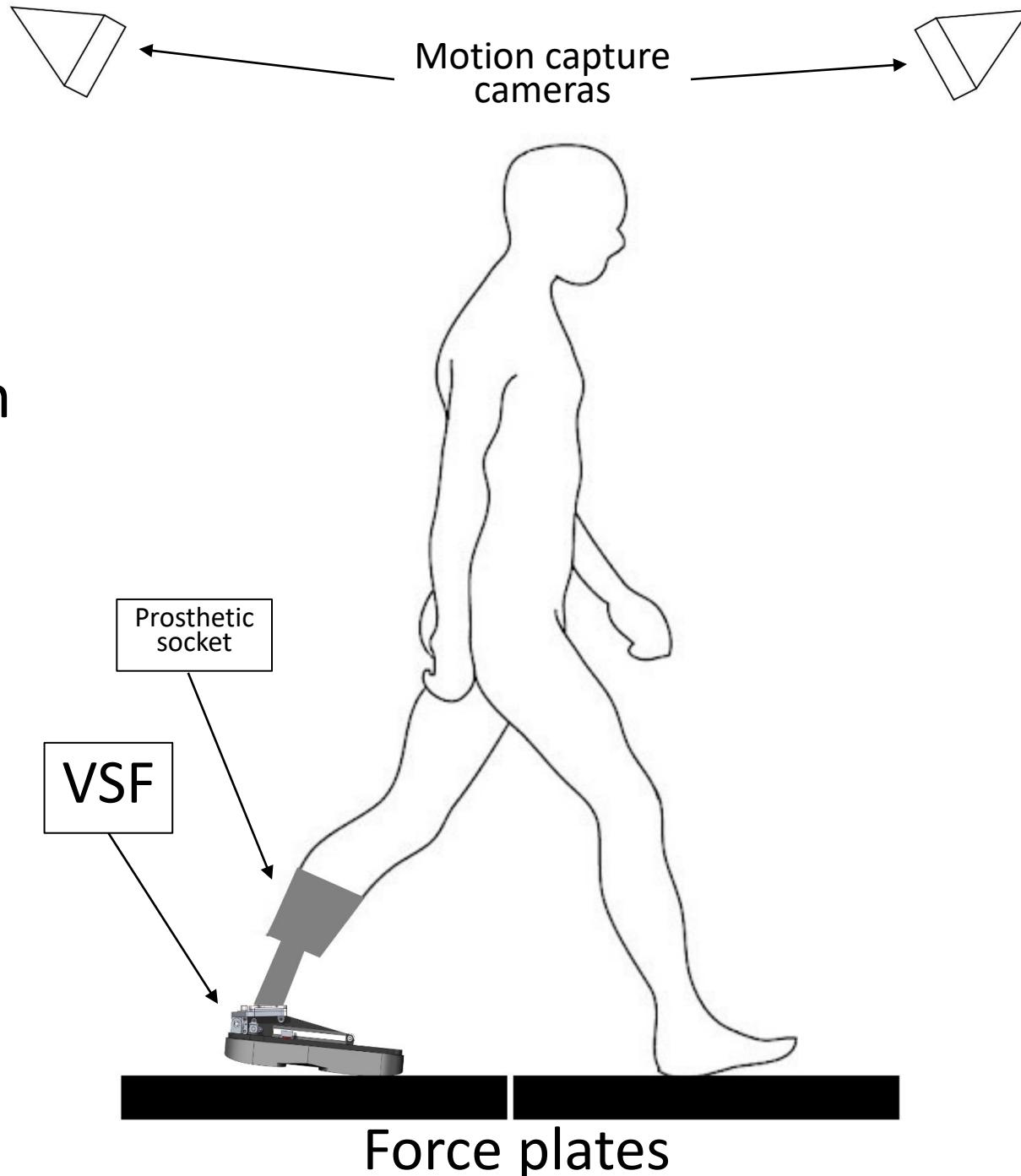
Pilot Biomechanical
Evaluation of TADA



VSF

- To evaluate the effect of various stiffness of VSF on joint mechanics in level-ground walking⁶
- Number of participants: 7
- Walking speed: 1.1 m/s
- Stiffness configurations: Compliant, Medium, Stiff
- Three successful trials per stiffness

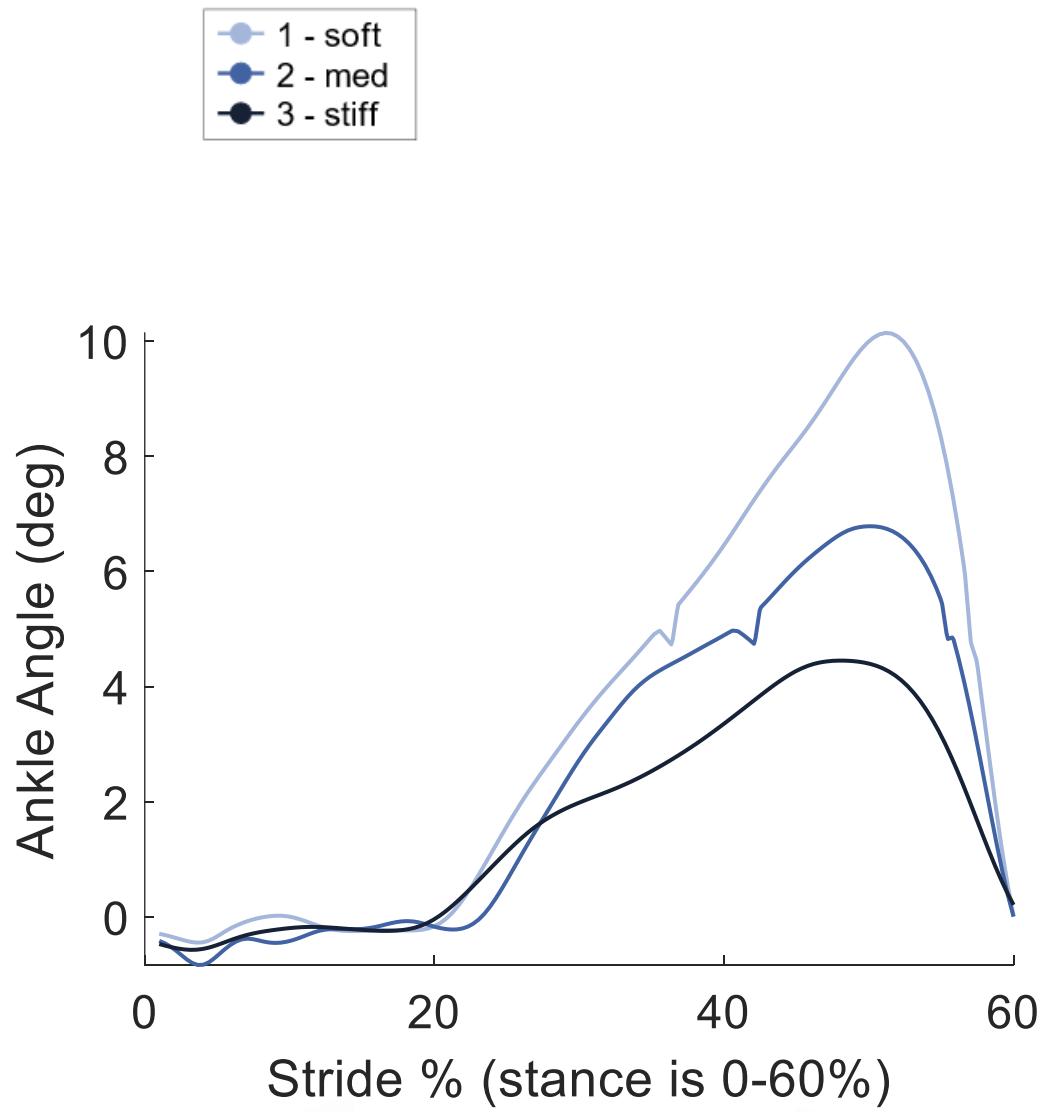
(6) Nichols, Kieran M., and Peter G. Adamczyk. "Sensitivity of Lower-Limb Joint Mechanics to Prosthetic Forefoot Stiffness with a Variable Stiffness Foot in Level-Ground Walking." *Journal of Biomechanics* (2023): 111436.



VSF

With less stiff VSF

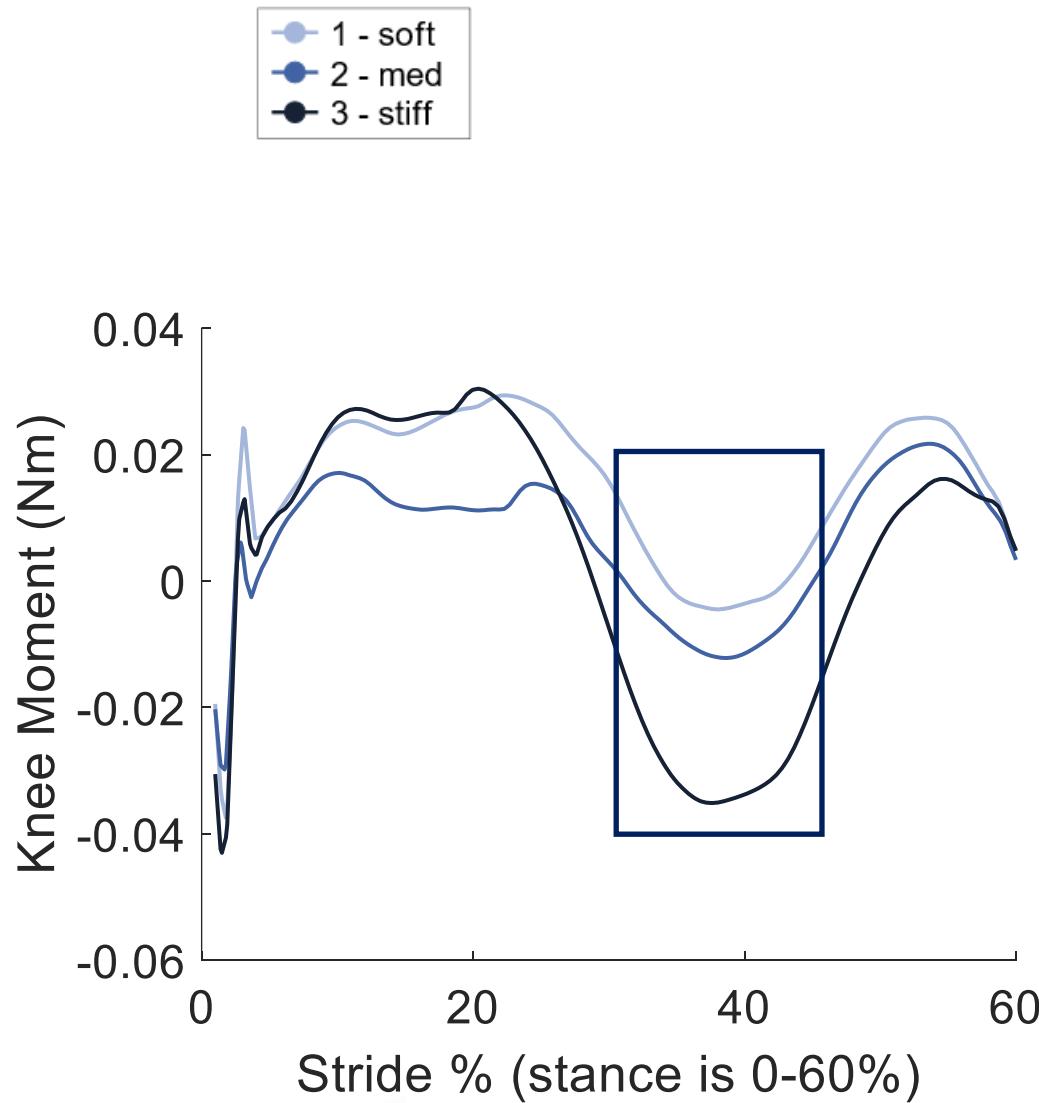
- higher stance ankle angle peaks



VSF

With less stiff VSF

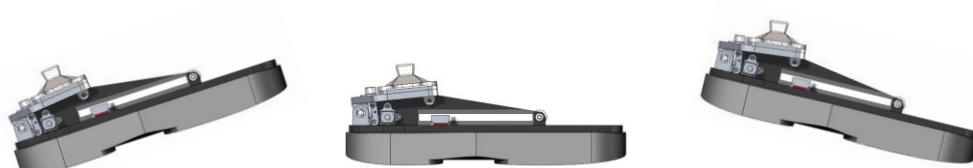
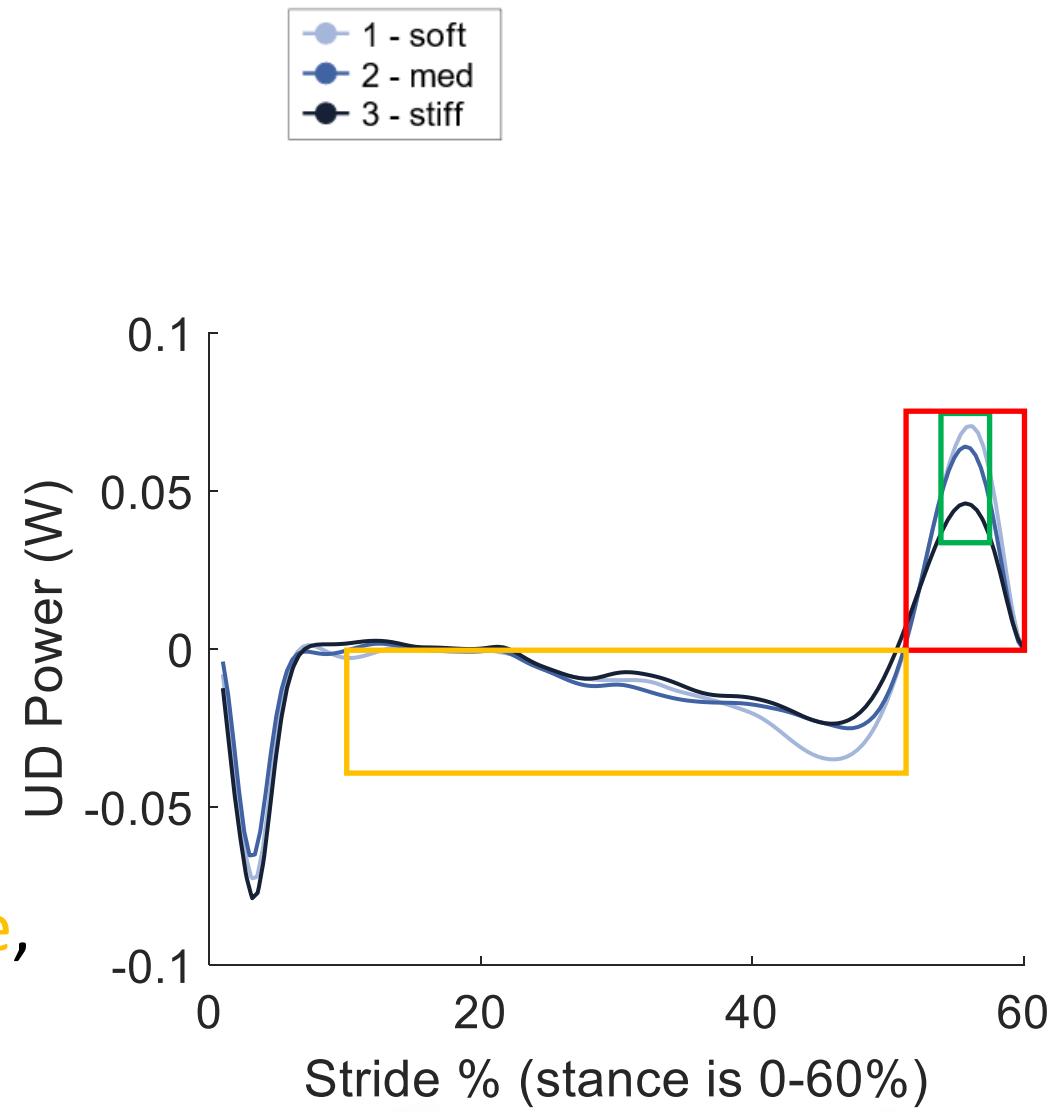
- higher stance-ankle angle peaks
- lower knee flexor peak moments
- vertical ground reaction force and its off-loading rate didn't change



VSF

With less stiff VSF

- higher stance-ankle angle peaks
- lower knee flexor peak moments
- the vertical ground reaction force and its off-loading rate didn't change
- Prosthesis (UD) **energy storage**, **energy return**, and **power** increased



VSF

Benefits of a less stiff VSF

- increased ankle range of motion
- increased prosthesis energy storage and return
- lower joint moment, which could lower joint overuse
- could benefit walking on ramps on stairs

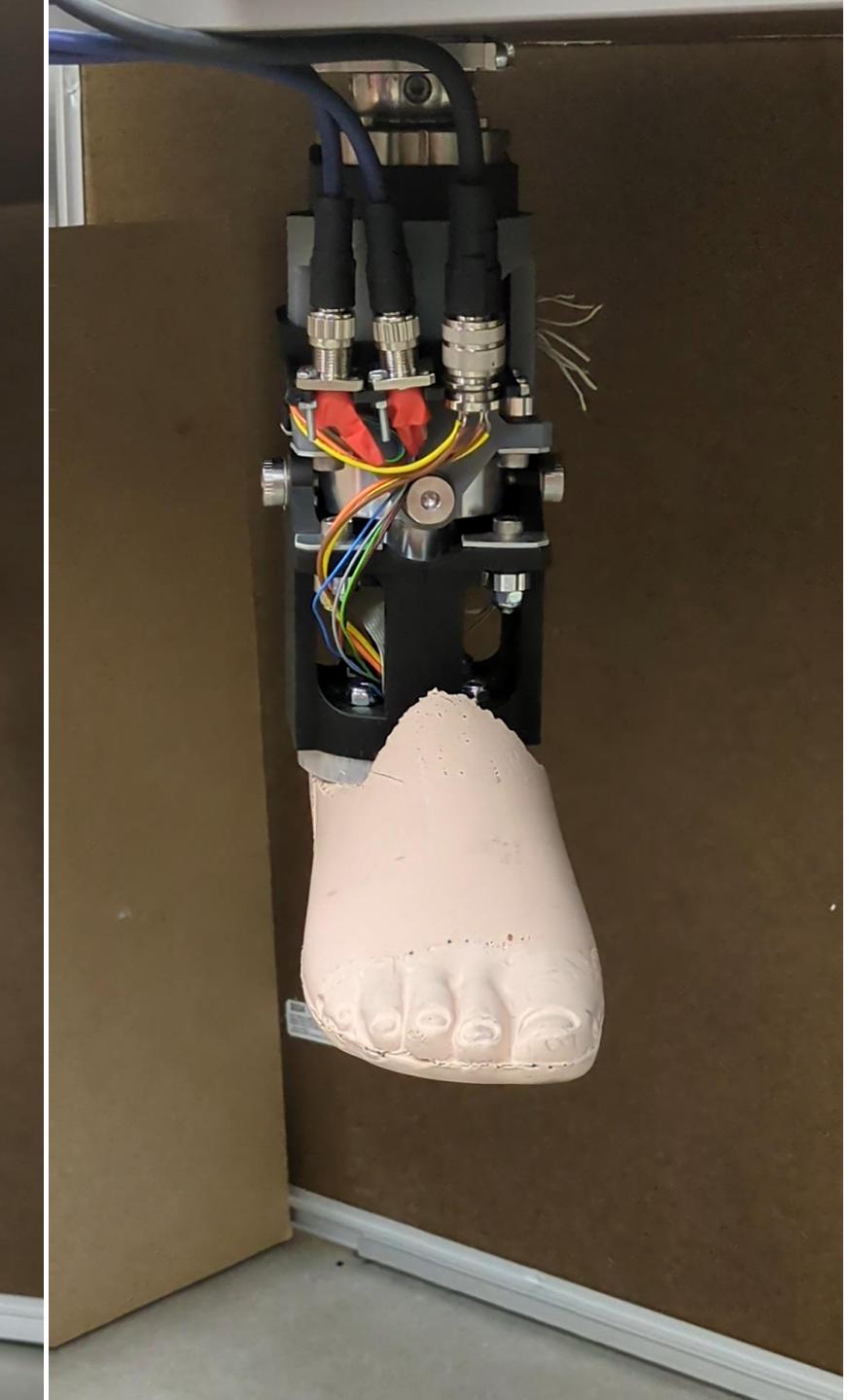
Presentation Overview



TADA

Purpose

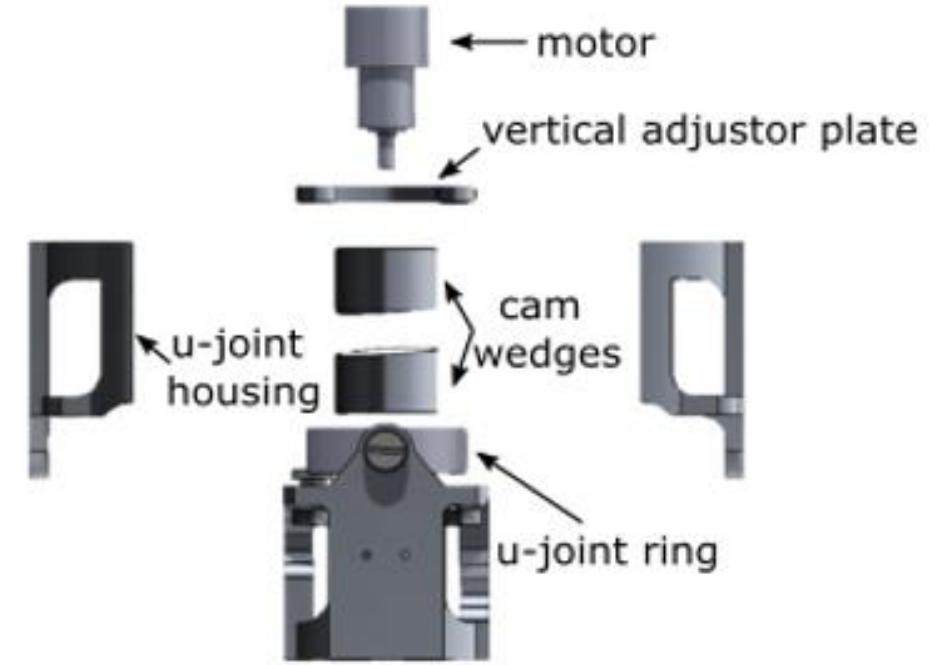
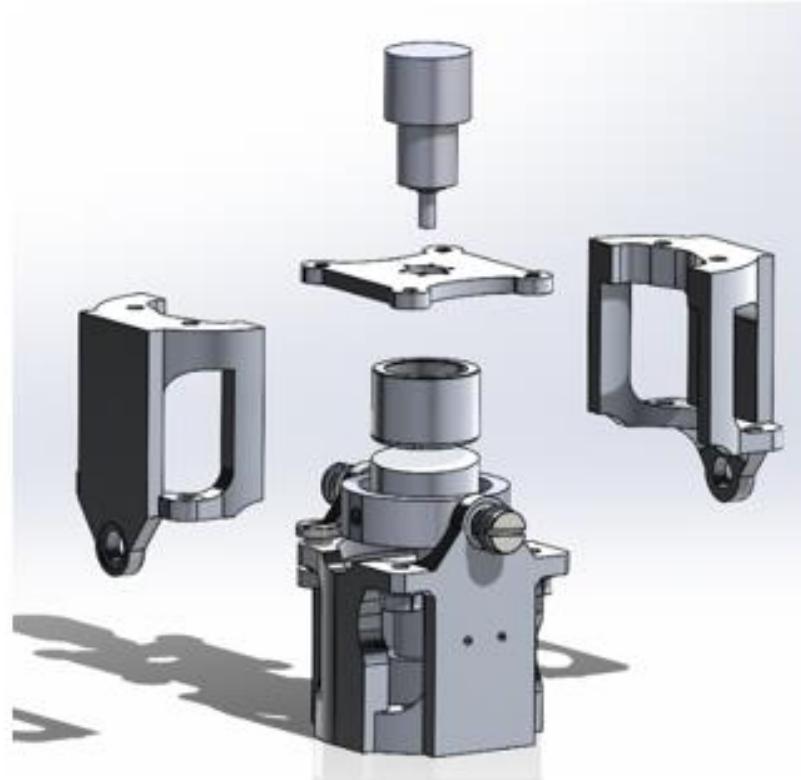
- Change ankle angle while the foot is in the air
- Detect foot motion and pylon load
- Sagittal (side view)
- Frontal (front view)



TADA

Hardware

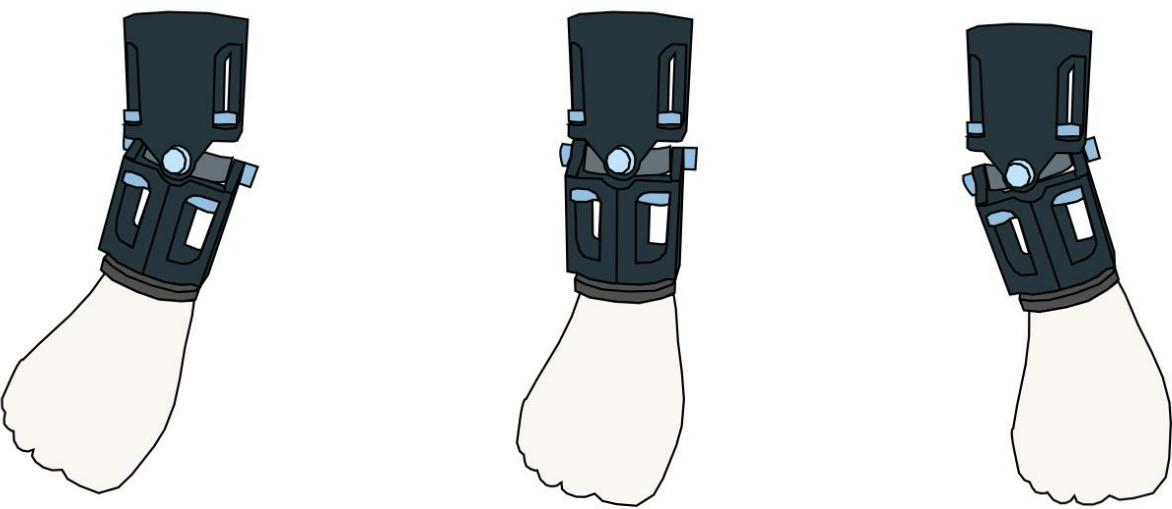
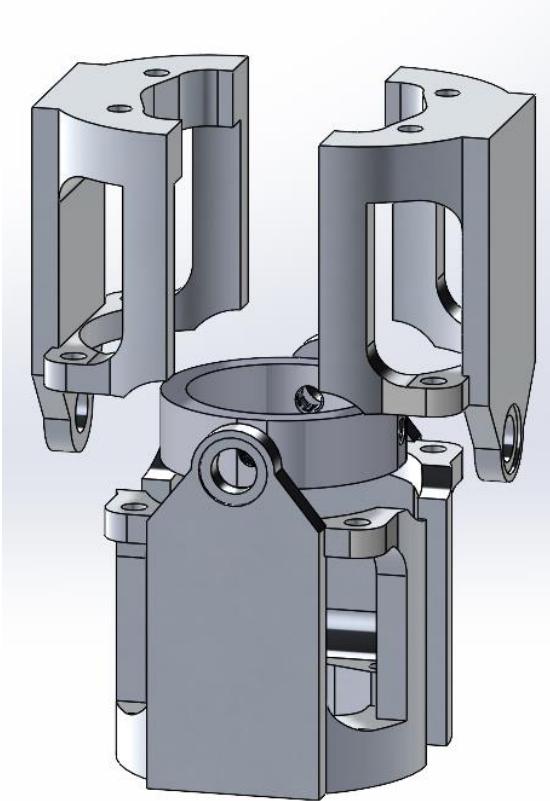
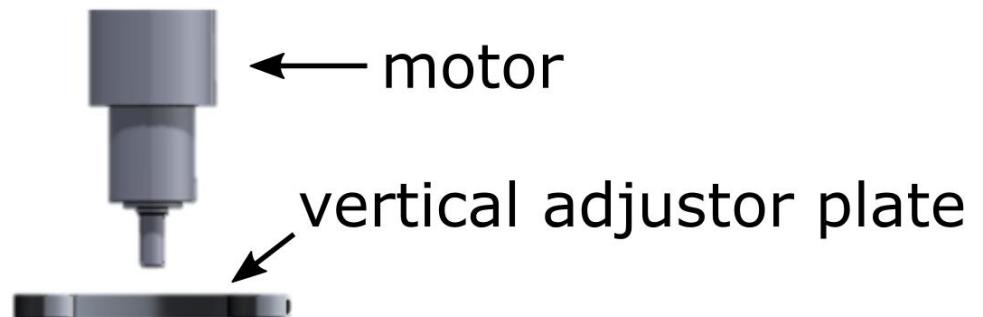
- Raspberry pi
- Motors
- Motor drivers
- Batteries



Software

- Real-time motor controller
- CANopen over EtherCAT communication
- Robotic Operating System software

TADA Mechanism



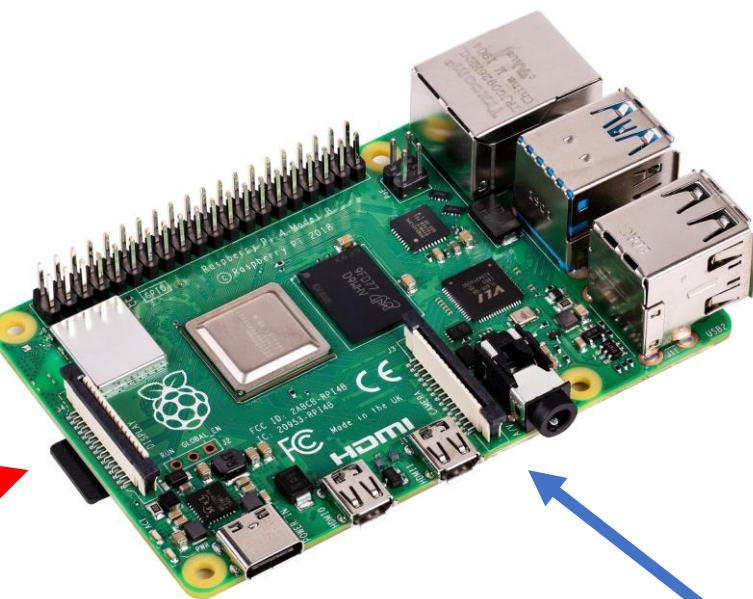
Motor Control

Software for TADA

Mobile hotspot



Windows laptop for
the User Interface
and Data saving



- Raspberry Pi 4
- Main controller
- Robotic Operating System (ROS)

Faulhaber
Brushless Direct
Current Motors



TADA: Control Validation

The TADA was randomly moved through 33 ankle configurations

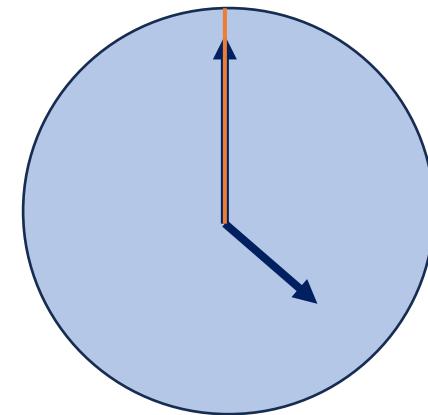
- **tested the reliability of the CANopen over EtherCAT communication**
 - mean value, mean error, and standard deviation of the sampling period
 - mean and standard deviation of CPU loads
- **tested the precision of motor control for ankle angles**
 - final absolute plantarflexion error
 - movement times

Reliability Test

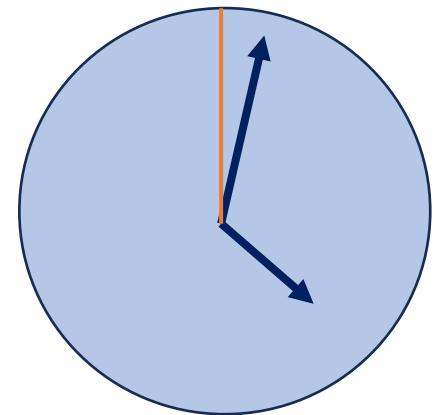
How to synchronize the clocks of the computer (Linux) and motor controller systems?⁷

- Synchronization necessary for real-time (CANopen over EtherCAT) communication
- Minimize mean error and variability of the sampling period
- Eliminate disconnection and reduce the need for error correction

Synchronization of Sampling Periods



Linux computer
Clock

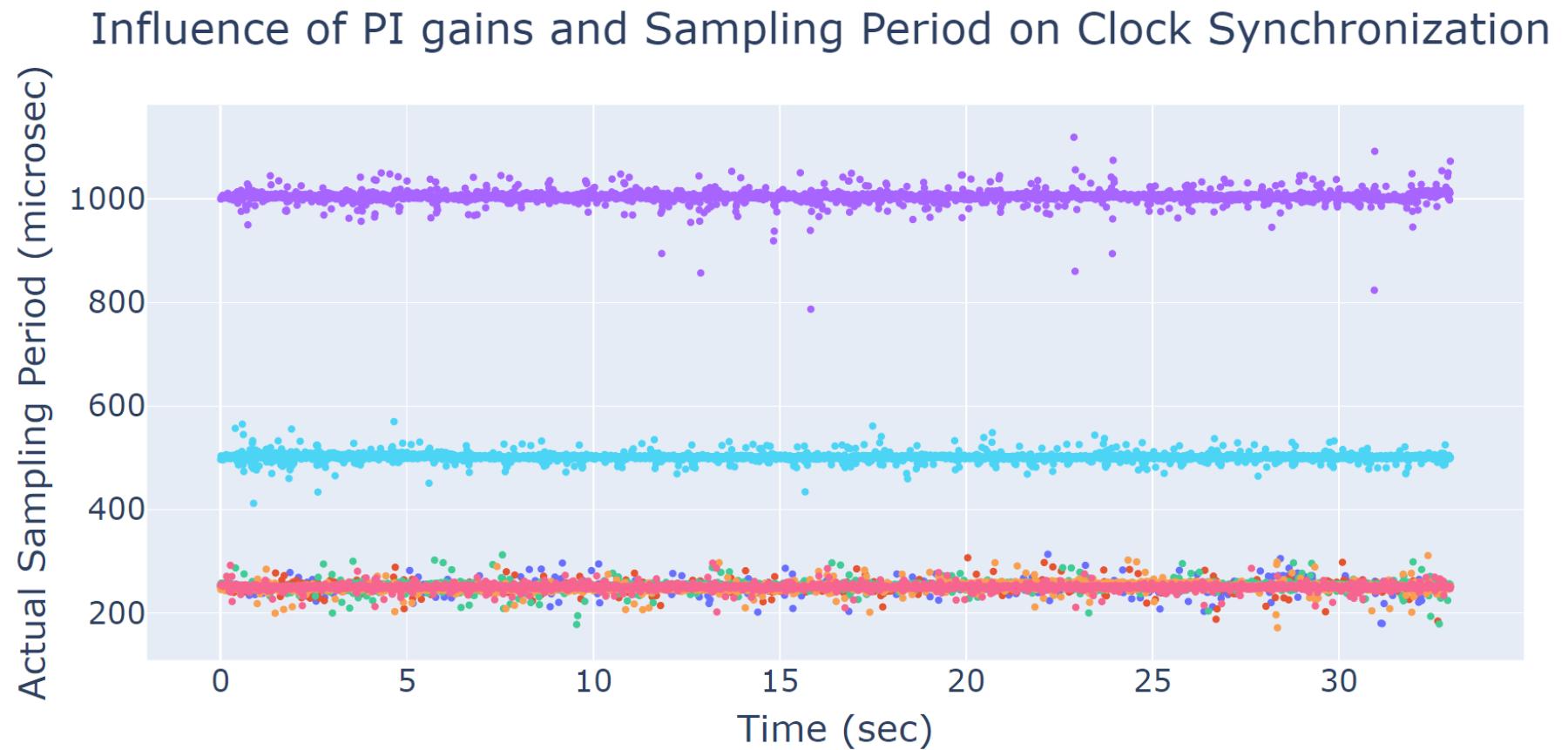


Motor controller
Clock

Reliability Test

For multiple settings, clock synchronization using a Proportional Integrative (PI) control had

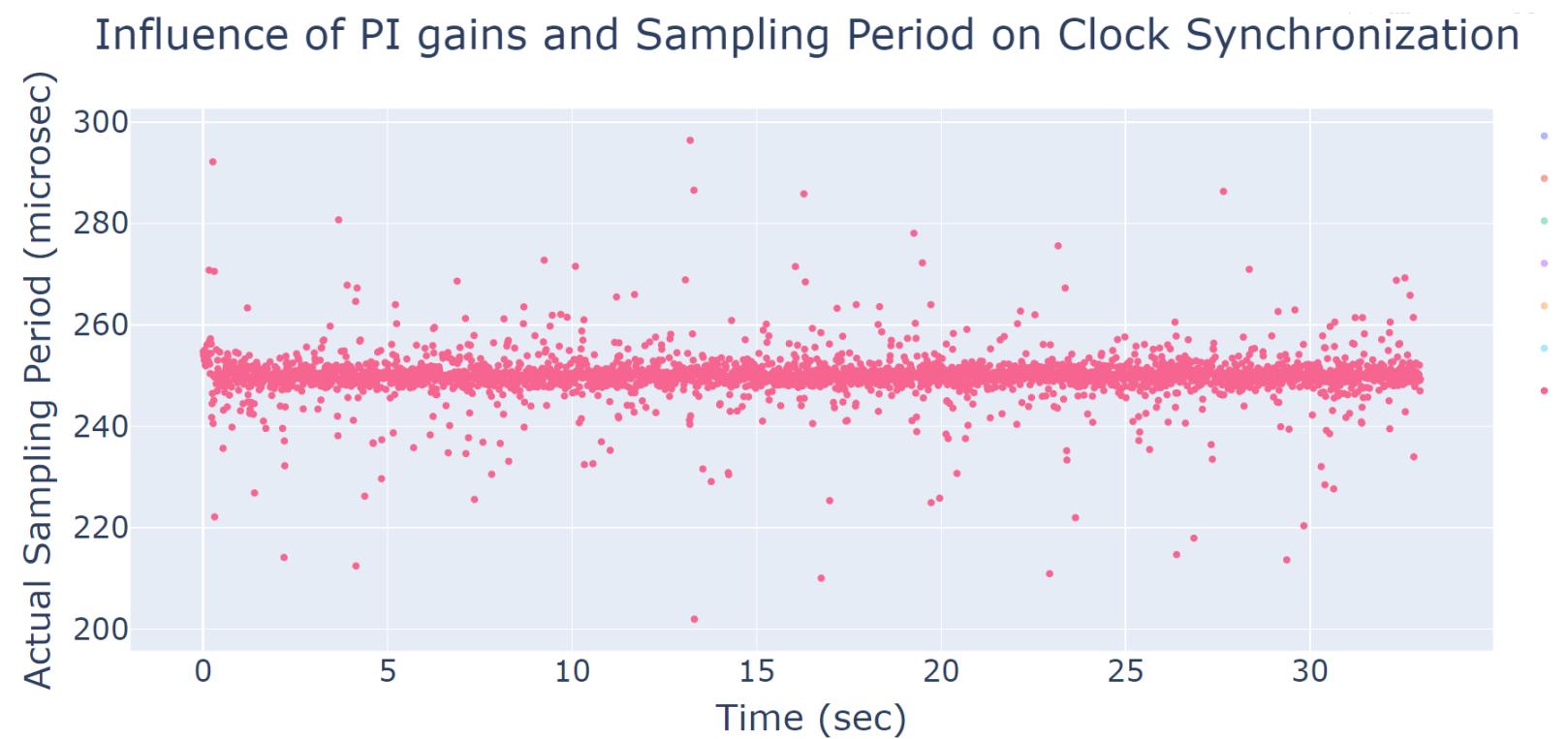
- Low mean error
- Low variability
- Reliable communication (no permanent drop-out)



Reliability Test

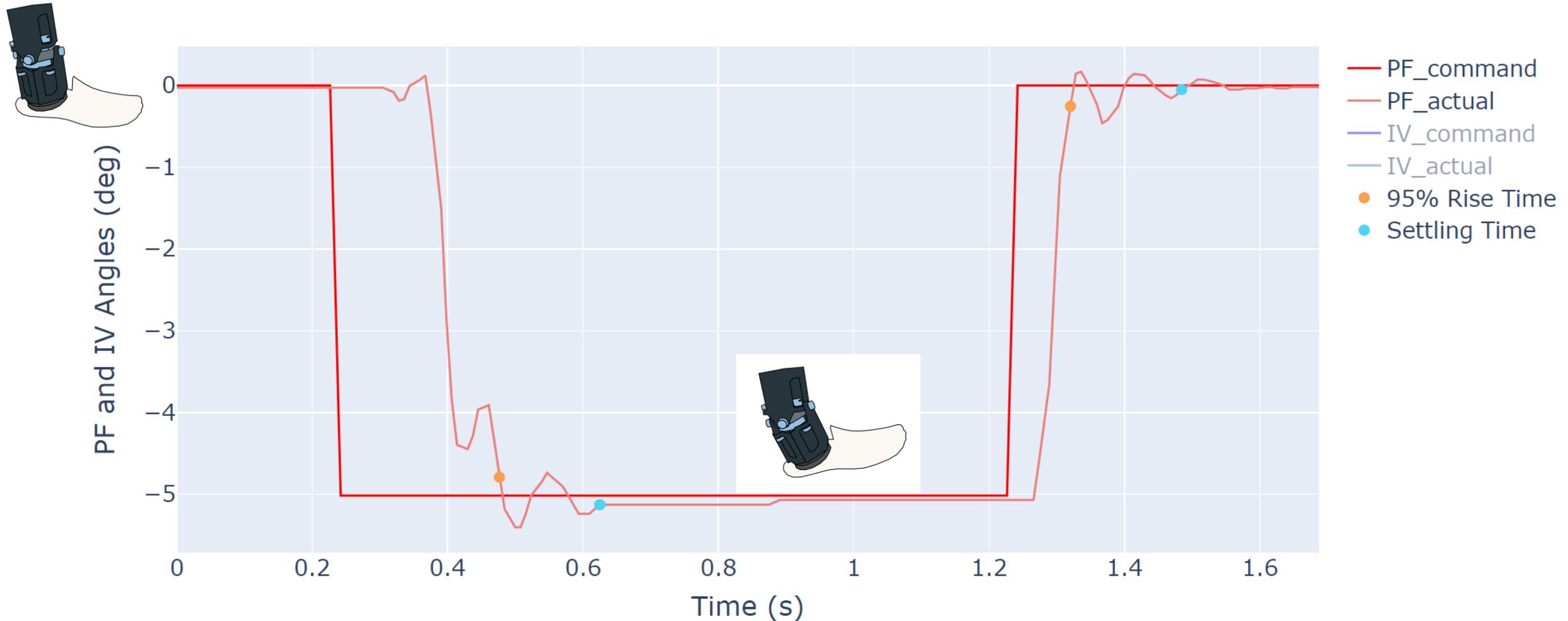
For the optimal setting,
clock synchronization had

- Consistent mean of 250 us
- Low mean error (0.02 us)
- Low variability (4.51 us)
- Modest CPU loads (21.3%)



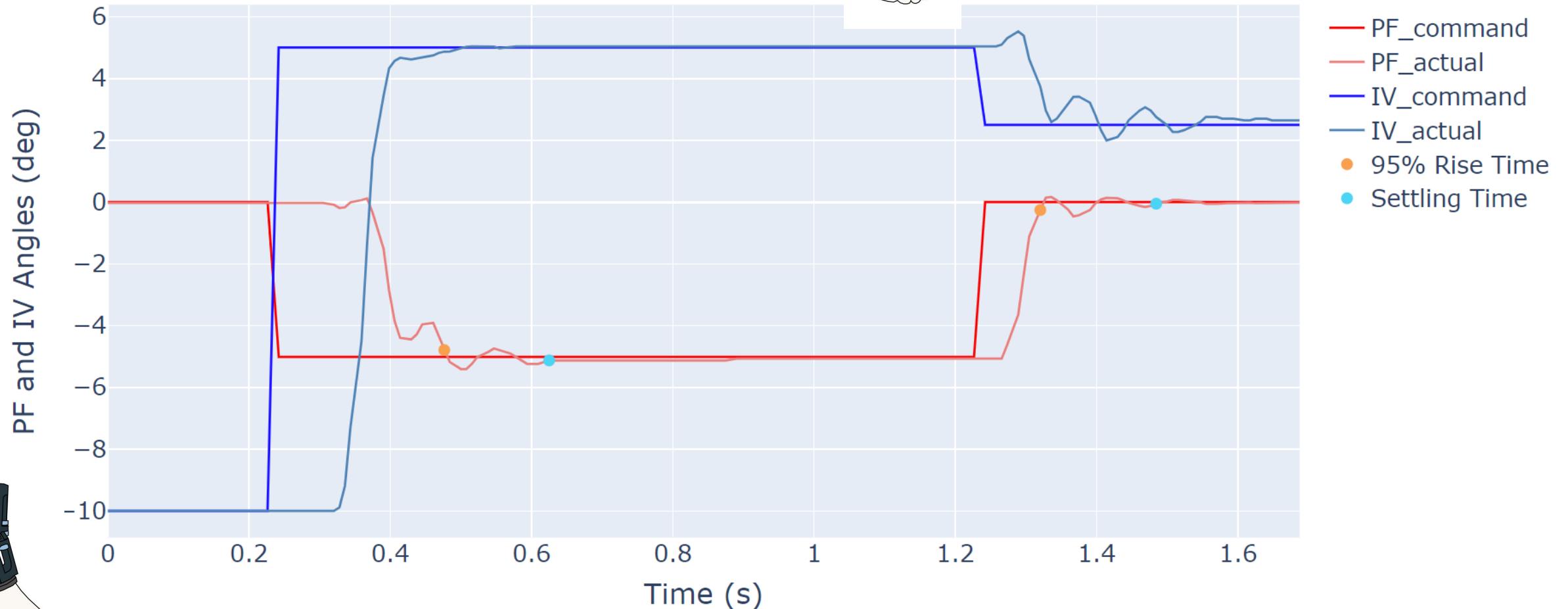
Precision Test

Ankle Angle commands and actual positions

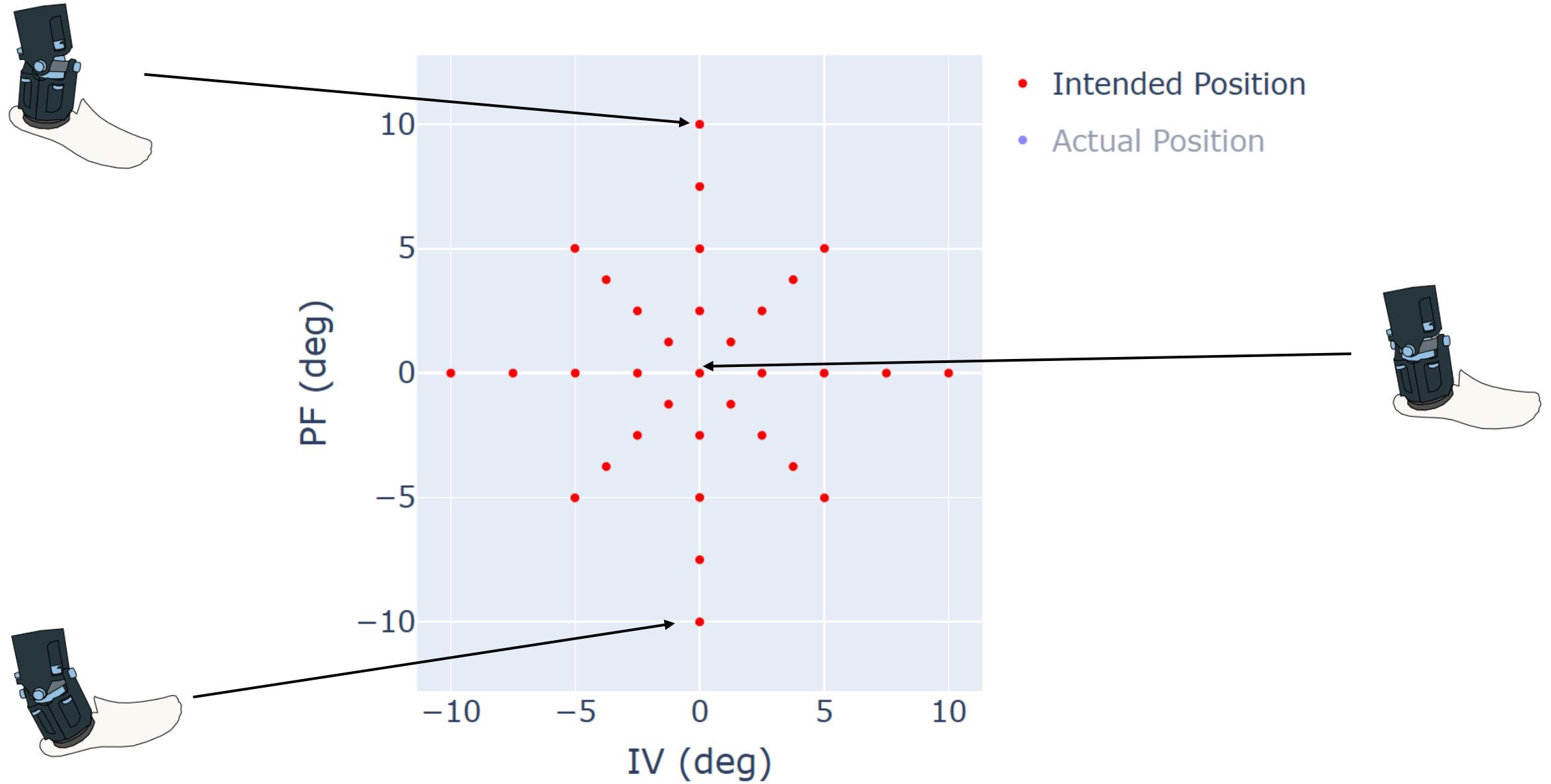


Precision Test

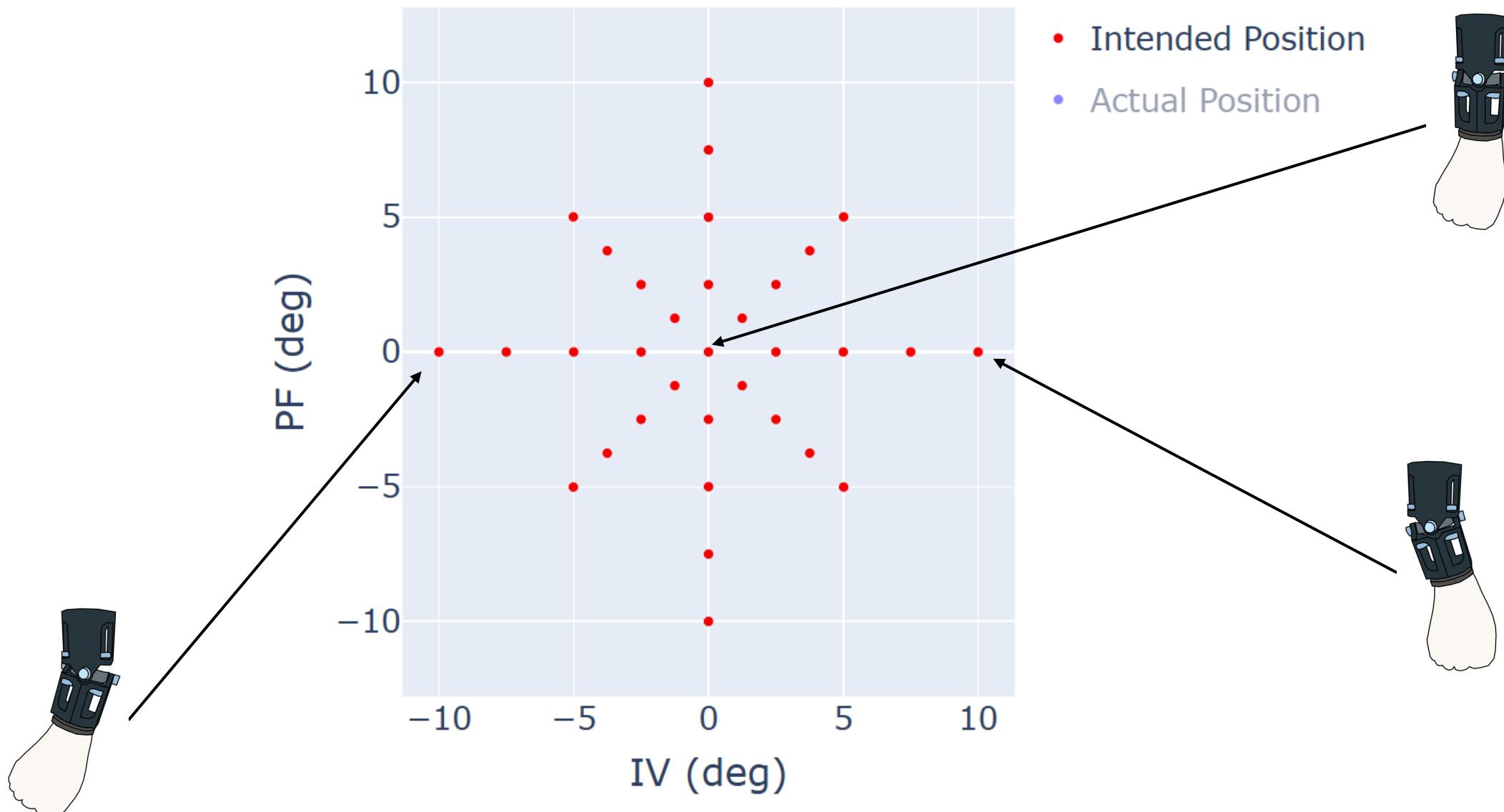
Ankle Angle commands and actual positions



Pose Precision and Repeatability



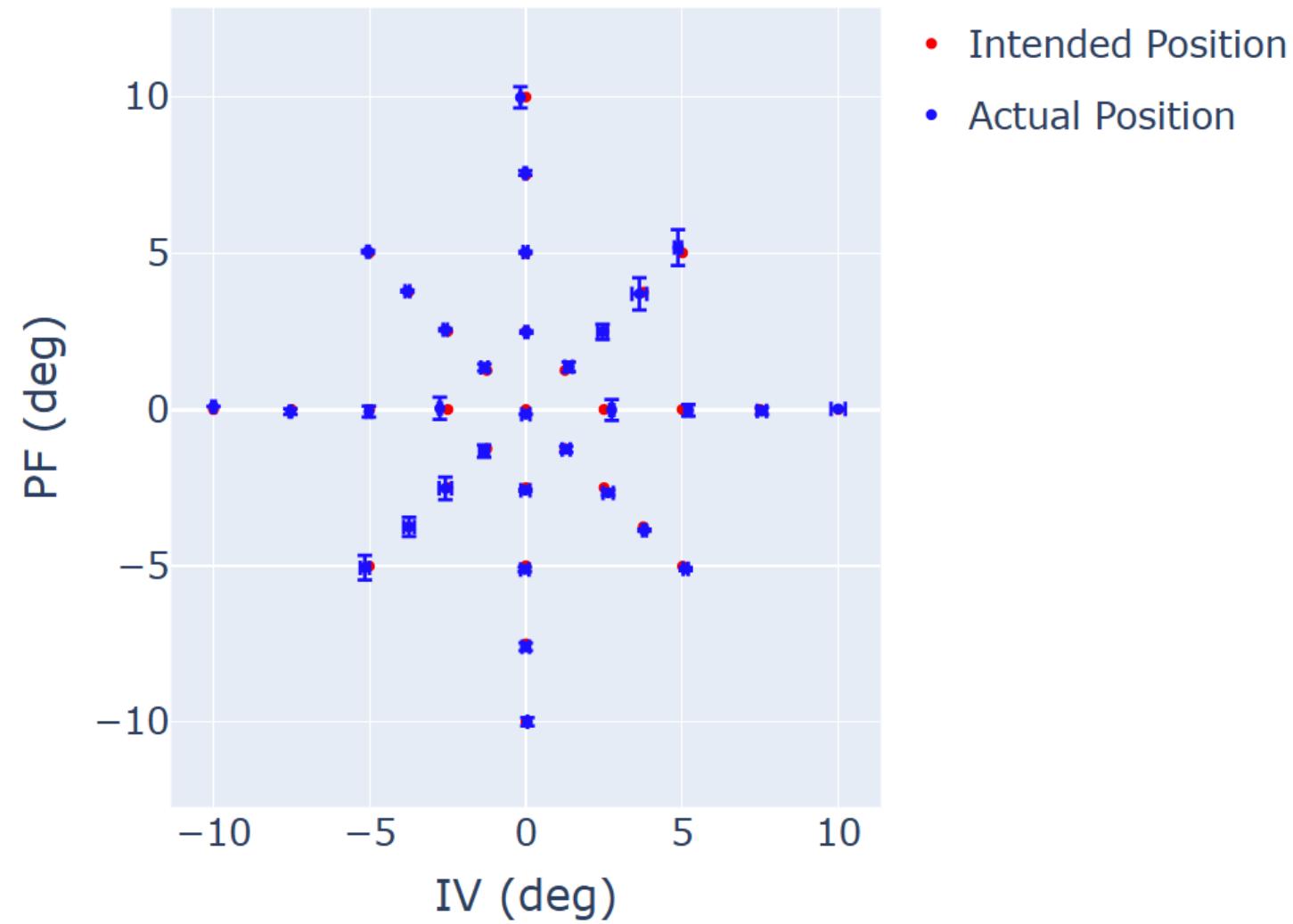
Pose Precision and Repeatability



Results

Metrics	Movement Time (seconds)		Movement Error (degrees)	
	95% Rise Time	Settling Time	PF	IV
Mean	0.13	0.20	0.05	0.07
SD	0.04	0.08	0.01	0.04

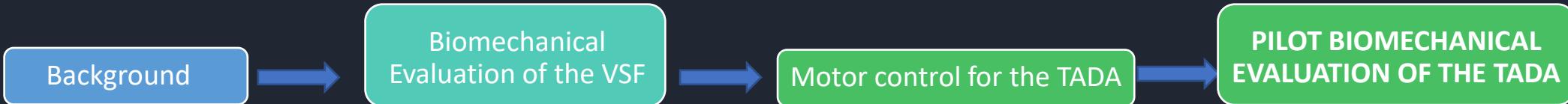
Pose Precision and Repeatability



Conclusion

- TADA was set up with real-time motor control with reliable communication
- Motor movements
 - in less than 0.4 seconds (one leg swing)
 - average of 0.2 seconds
- Customizable system that can support wearable instrumentation to aid and evaluate prosthetic walking

Presentation Overview



TADA Instrumentation

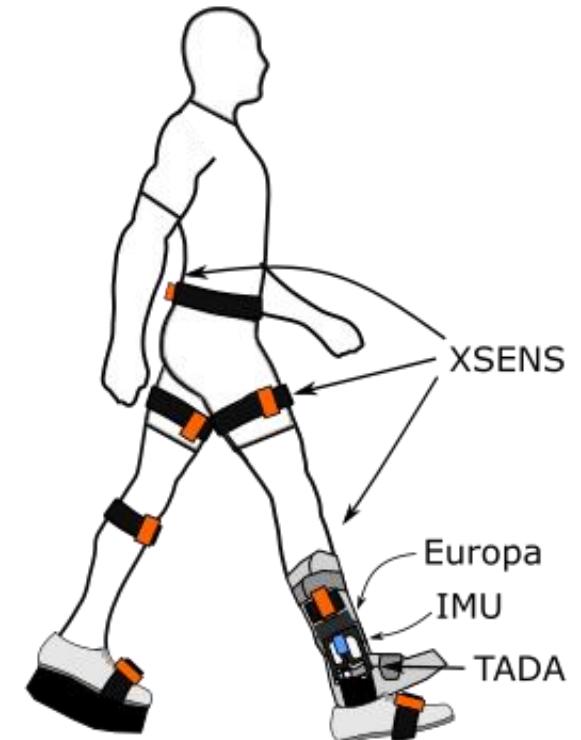
Lower-leg-specific

- Load cell for pylon moments and forces
- Motor angles
- Inertial measurement unit (IMU) for leg movement



Front view

Frontal



Side view

Sagittal

Body-specific

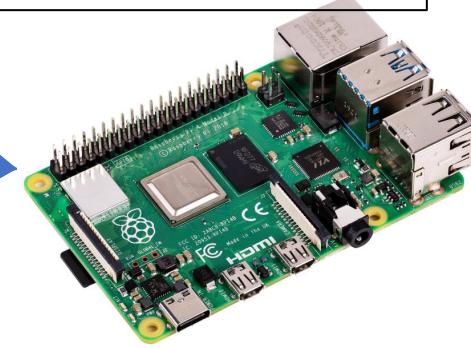
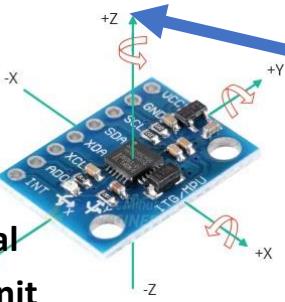
- Xsens IMU suit
- Waist pack

Raspberry Pi

Fully Wearable Instrumentation System

MPU6050 Inertial
Measurement Unit
(IMU)

- Leg swing detection



Europa+ load cell

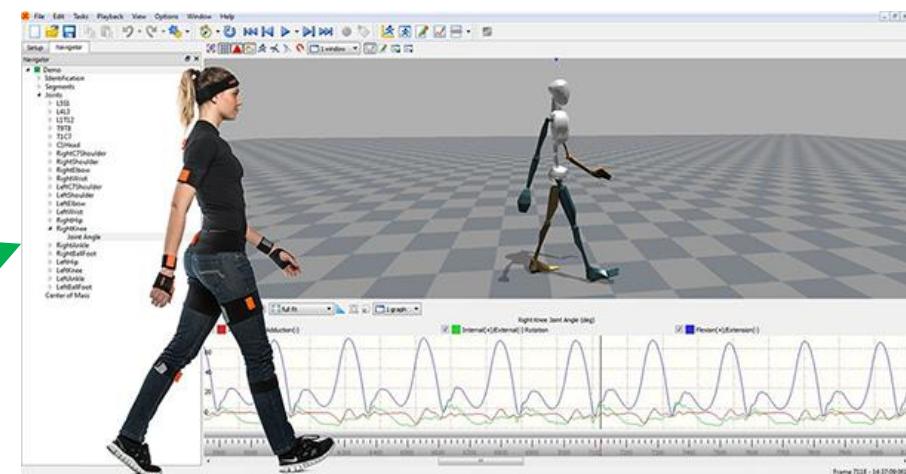
- Axial force
- Sagittal and frontal moments



Xsens lower-body Motion

Capture suit

- Joint angles
- Segment motion
- center of mass motion



Mobile hotspot

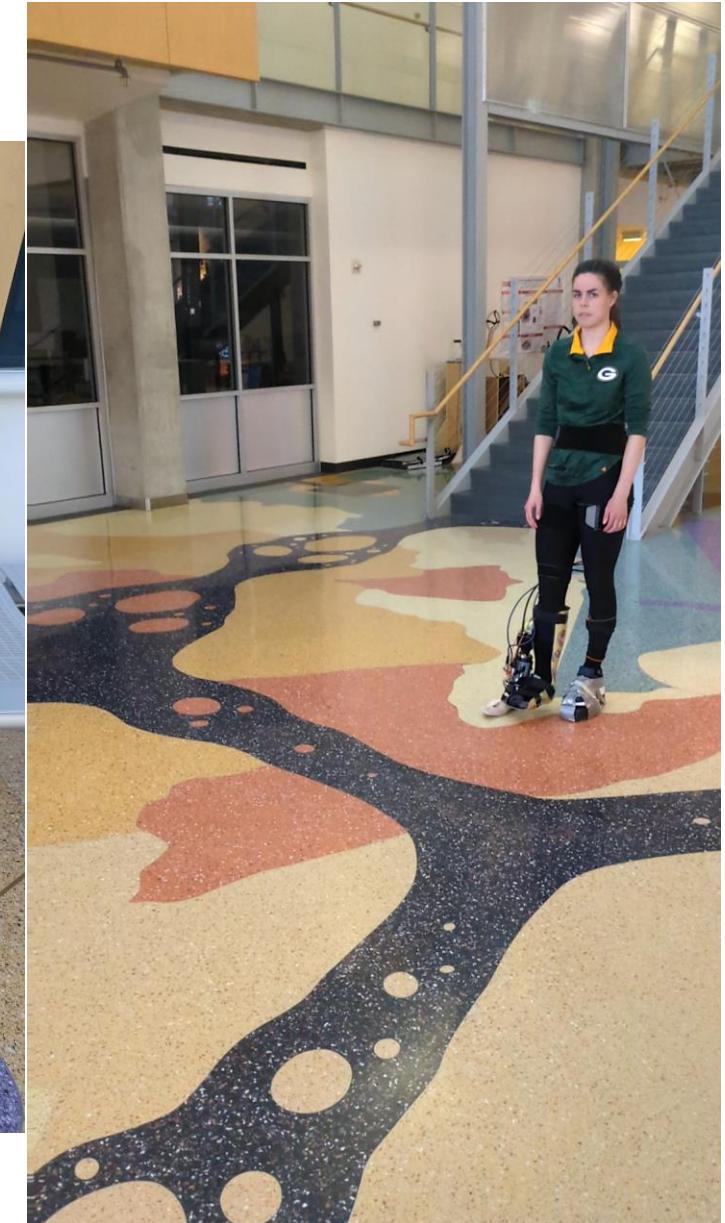


Windows laptop



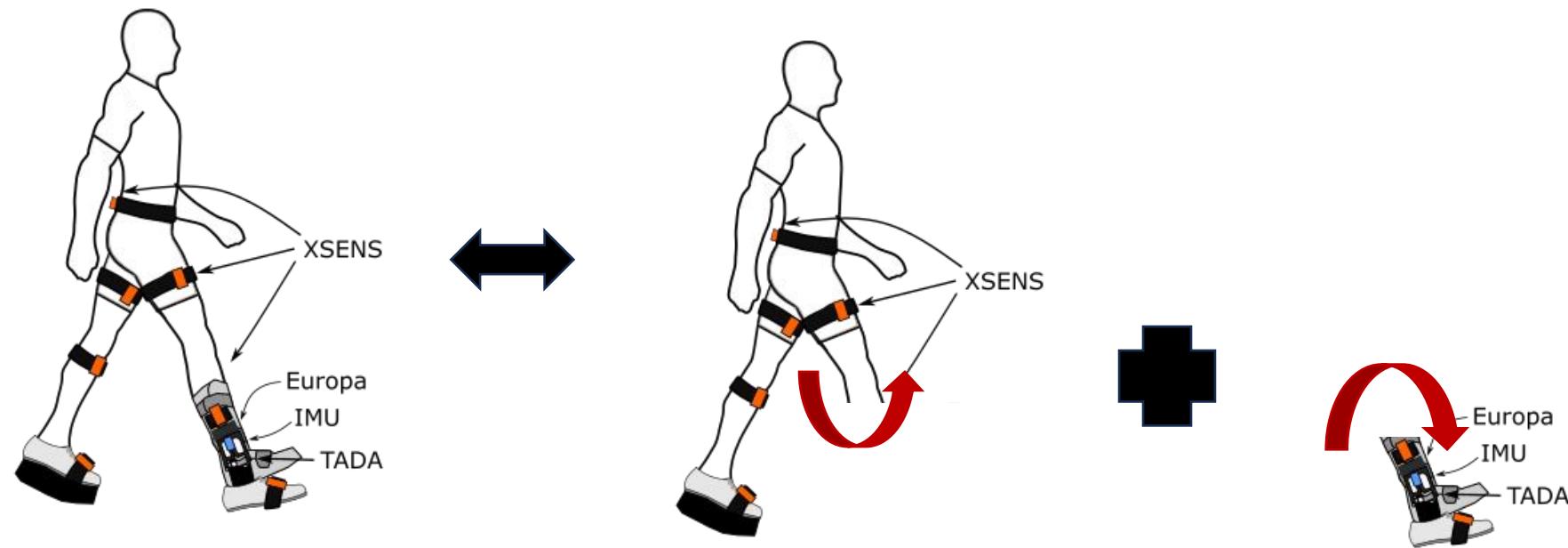
Goals of Pilot Test

1. To demonstrate synchronous collection of all wearable sensors
2. To pilot test the influence of ankle angle and walking speed on pylon moment for the TADA
 - One participant
 - Walked at slow, medium, and fast self-selected walking speeds
 - TADA alternated between
 - 8 steps of chosen angles
 - 5 steps of neutral



TADA

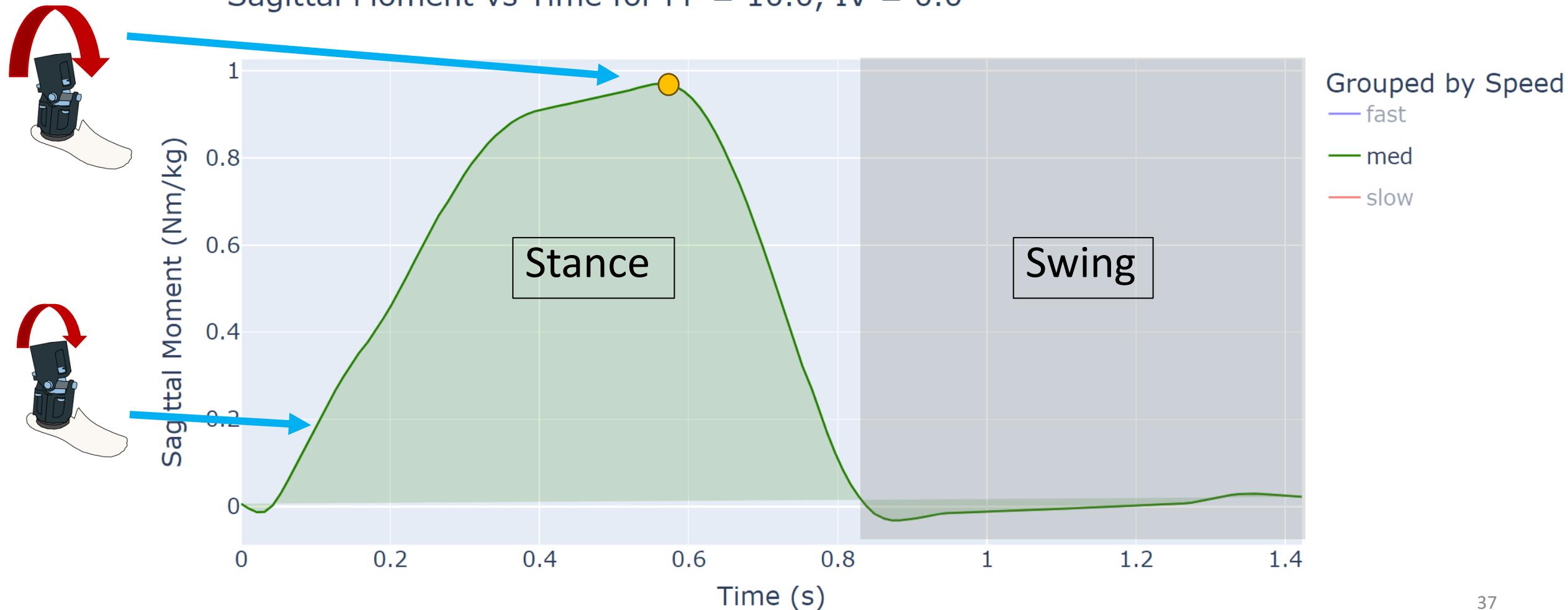
- Pylon Load cell
 - Sagittal Plantarflexor Moments
 - Frontal Evertor Moments
- Moments = Rotational Action of upper shank on prosthetic device
- For this presentation, we will focus on Plantarflexor Moments



TADA



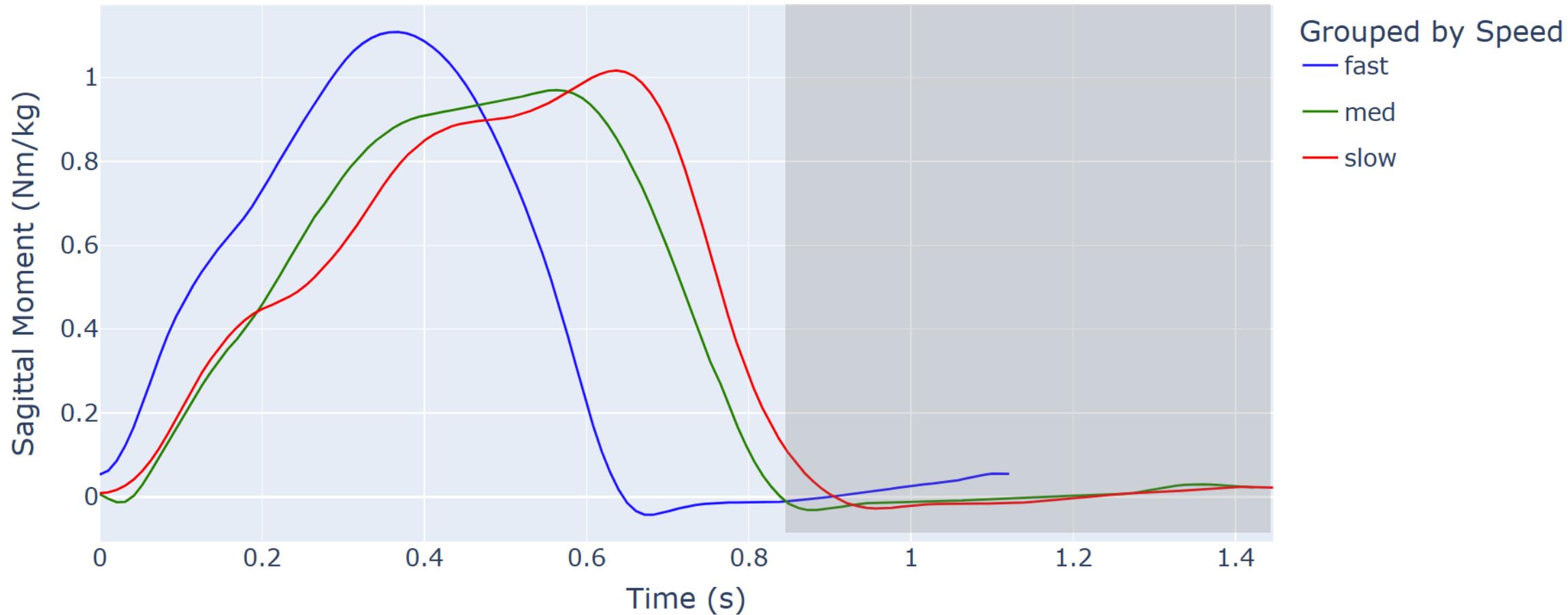
Sagittal Moment vs Time for PF = 10.0, IV = 0.0



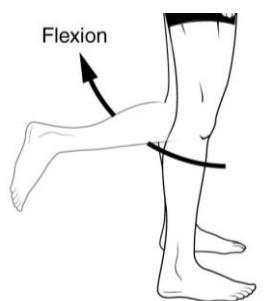
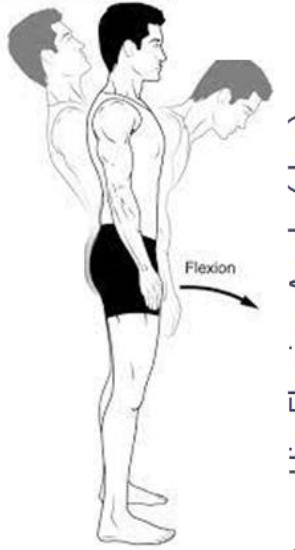
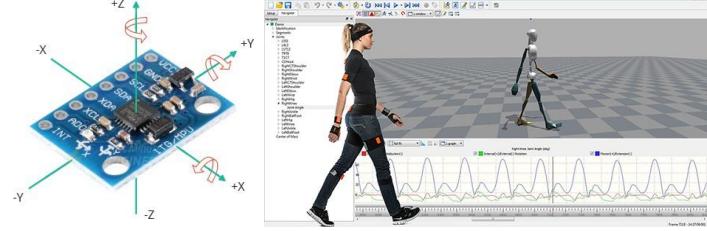


TADA

Sagittal Moment vs Time for PF = 10.0, IV = 0.0



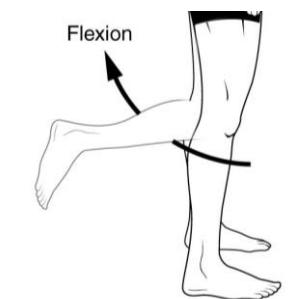
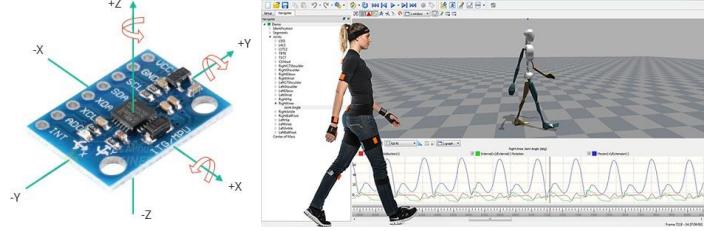
TADA



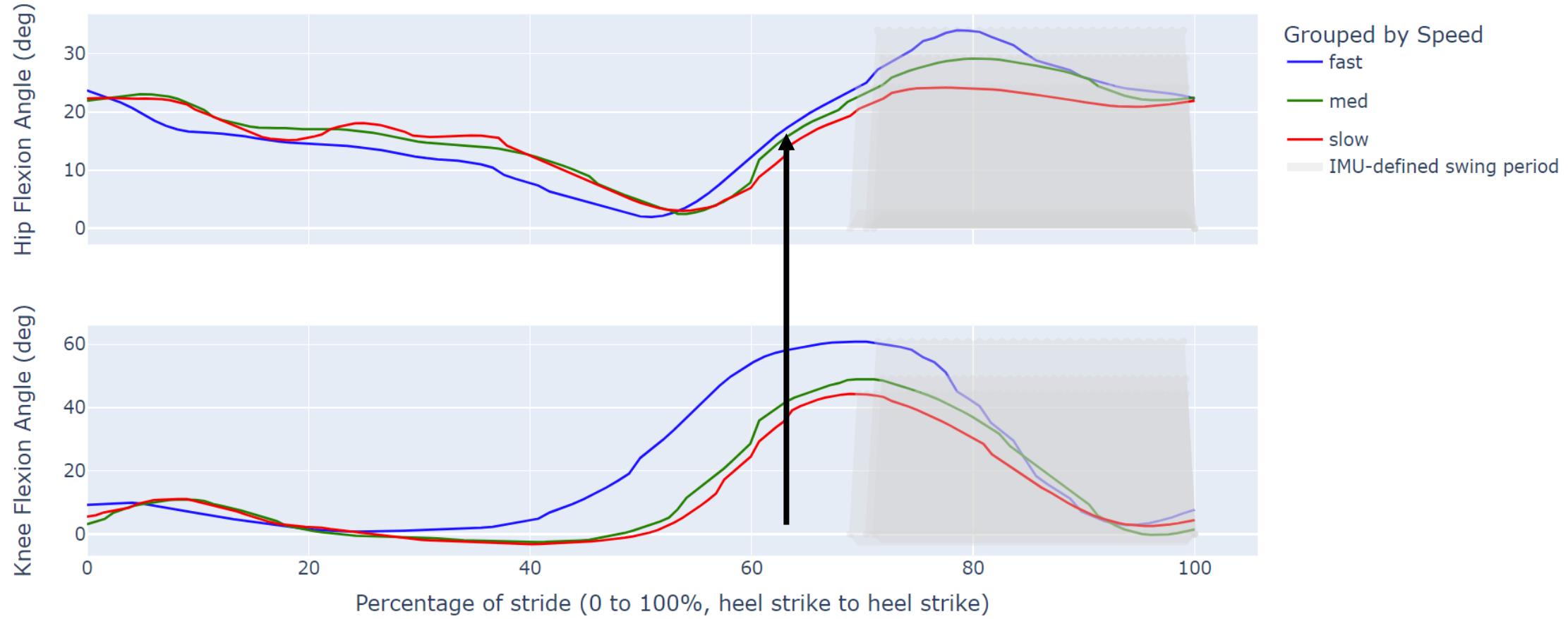
Hip and Knee sagittal angles for one stride of PF= 10.0, IV = 0.0



TADA



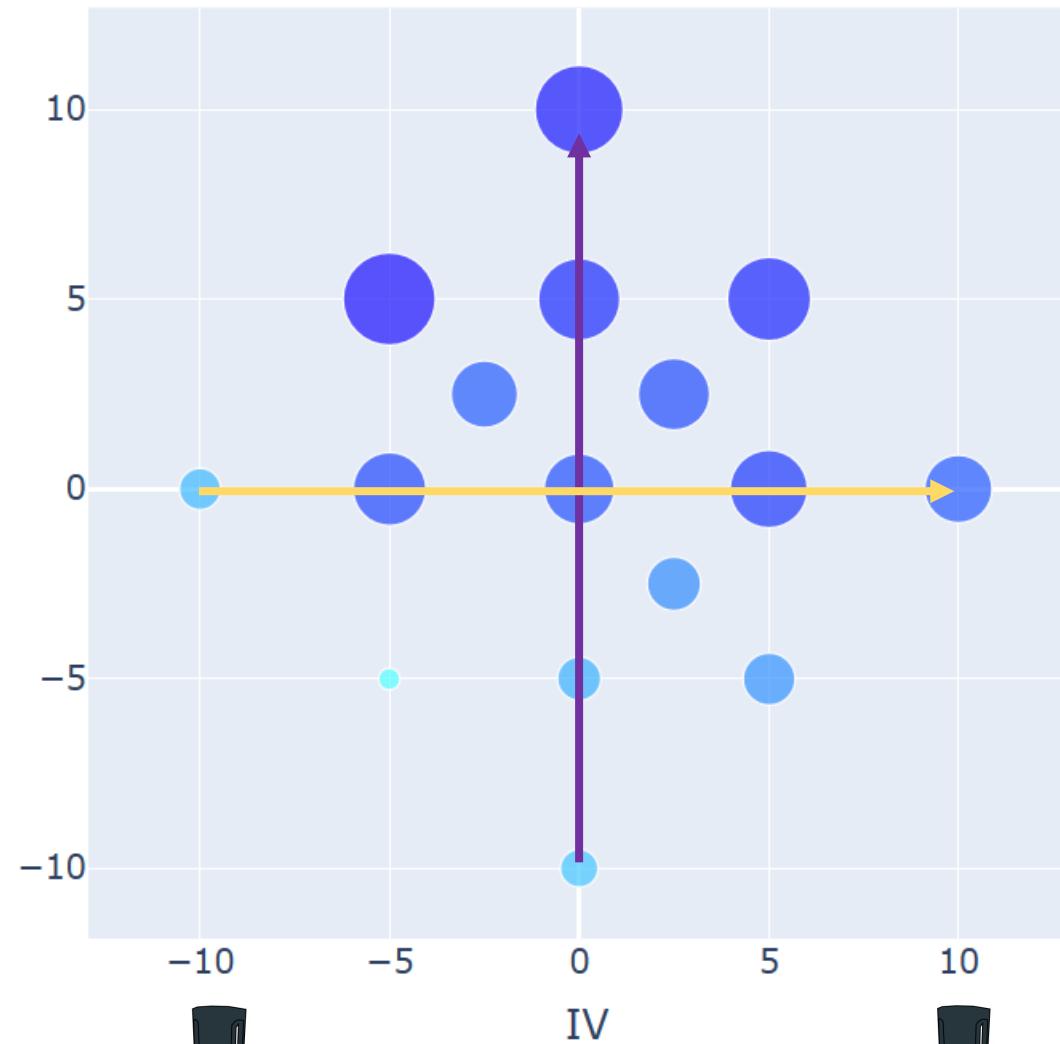
Hip and Knee sagittal angles for one stride of PF= 10.0, IV = 0.0



PF vs IV with Sagittal Moment Peak Moments



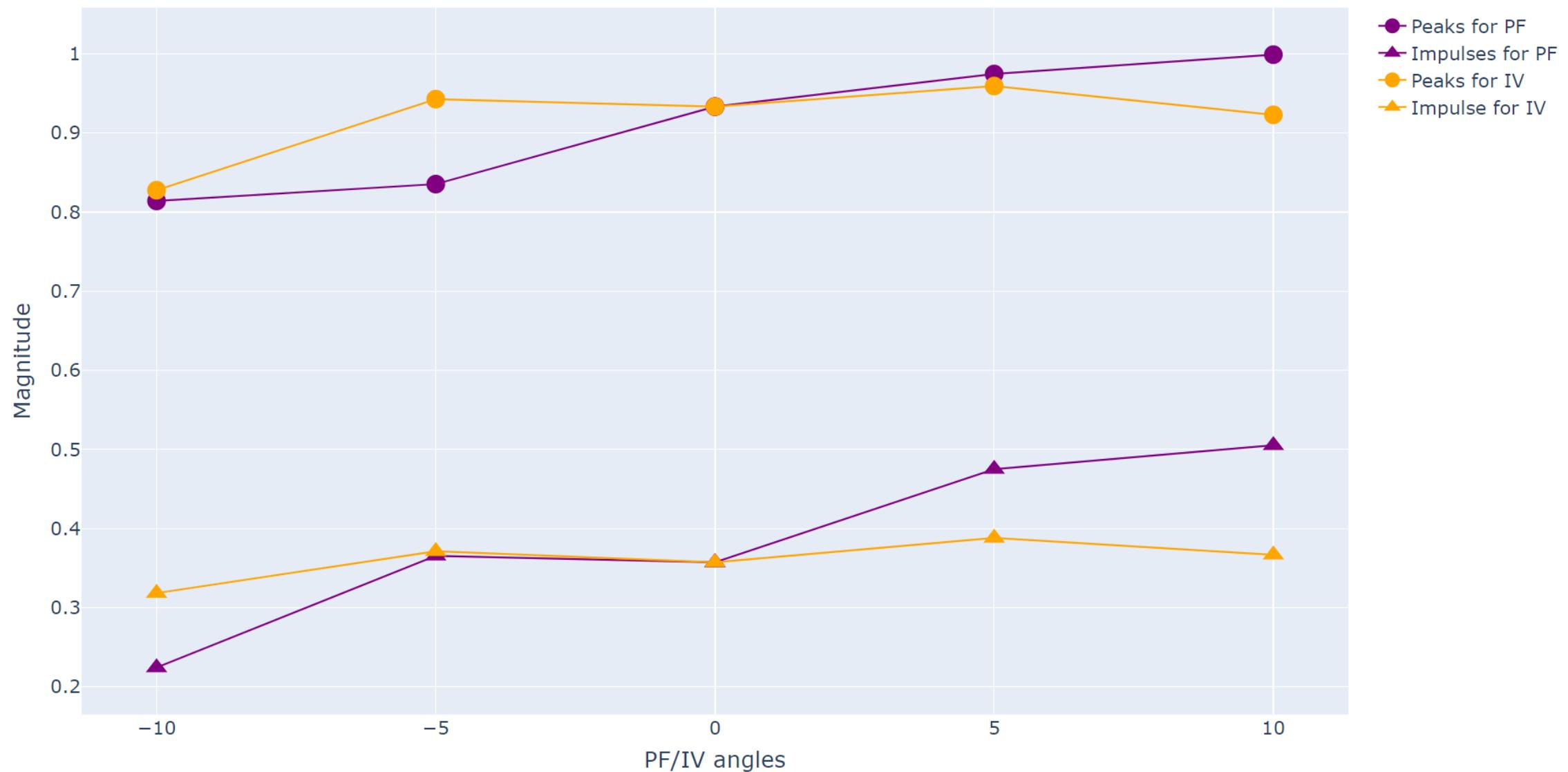
PF



Sagittal Impulses
show similar trends

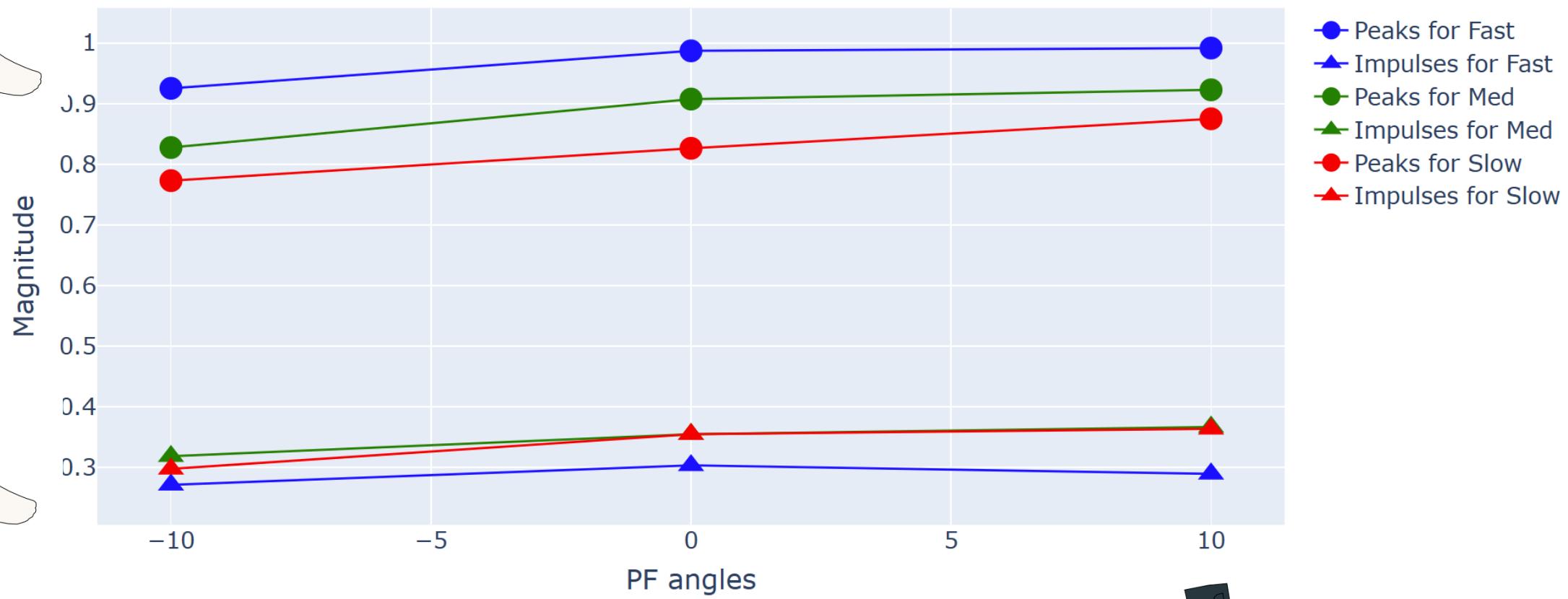


Peaks and Impulses for Sagittal Moments for various Ankle Angles



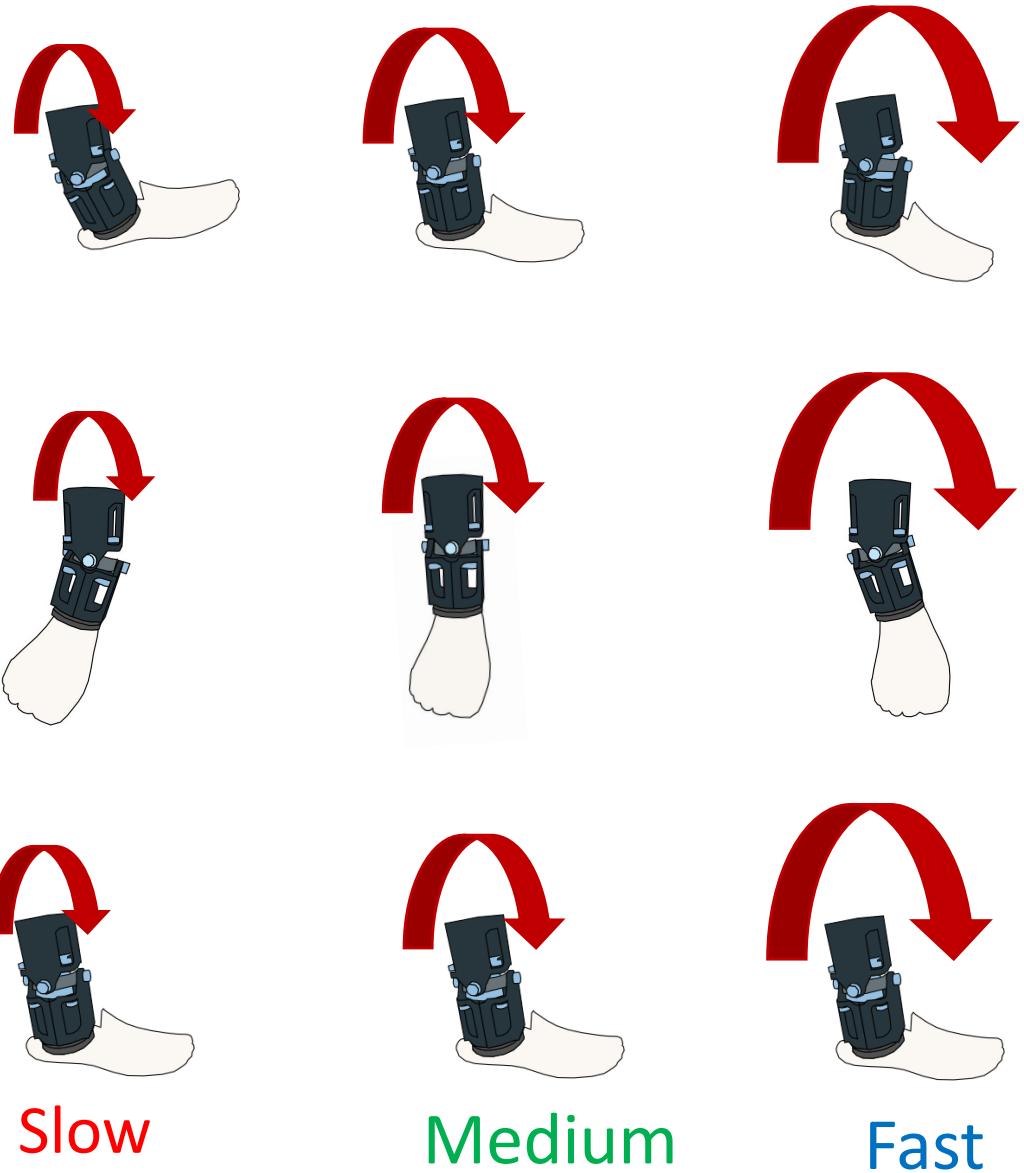


Effect of Walking Speed on Peaks and Impulses of Sagittal Moments for only changes in PF



Results

- peak Plantarflexor moment and impulses increased with increased plantarflexion angles
- peak Evertor moment and impulses increased with increased Inversion angles
- peak Plantarflexor pylon moments increased with increased walking speed



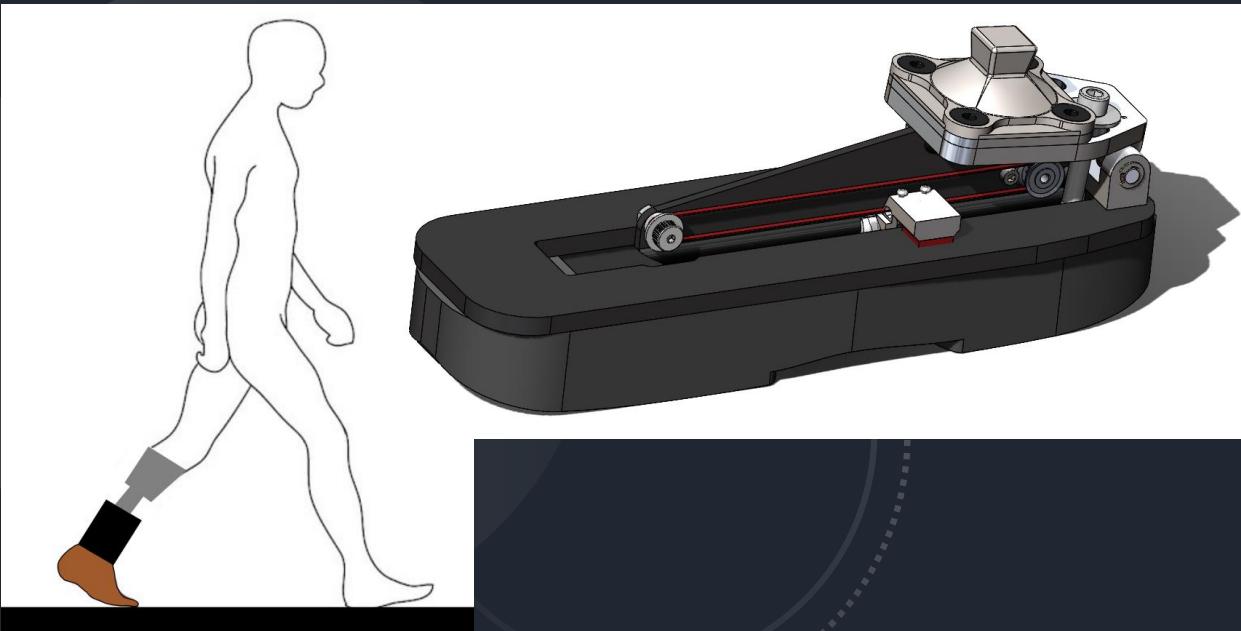
General Discussion

Background

Biomechanical
Evaluation of
VSF

Motor control for TADA

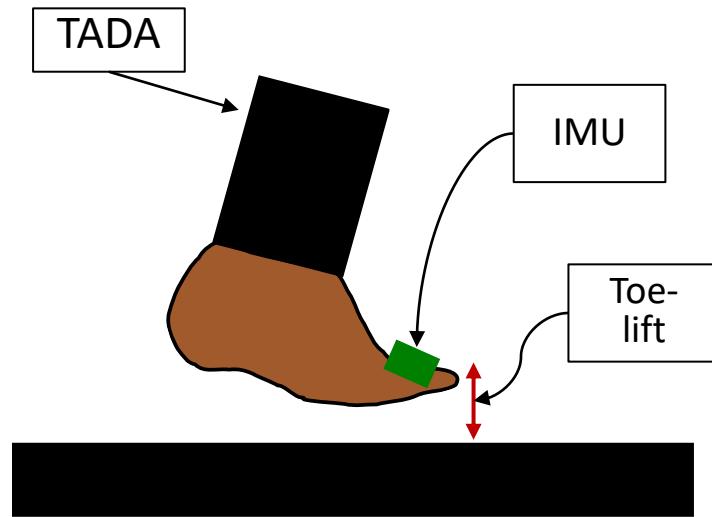
Biomechanical Evaluation
of TADA



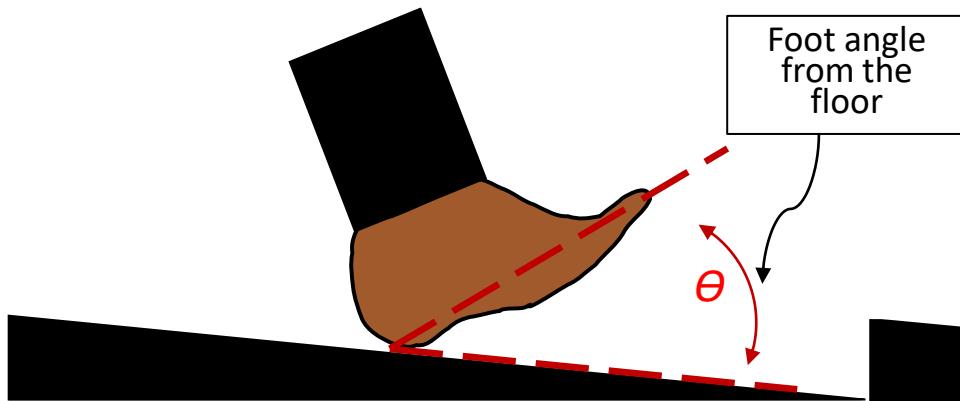
Key takeaways

- The VSF could help reduce joint overuse and return more intact ankle functionality
- The TADA can control 2D ankle angle in a reliable and precise way
- Lower pylon moments could help lower socket discomfort
- The TADA is ready for out-of-the-lab experiments

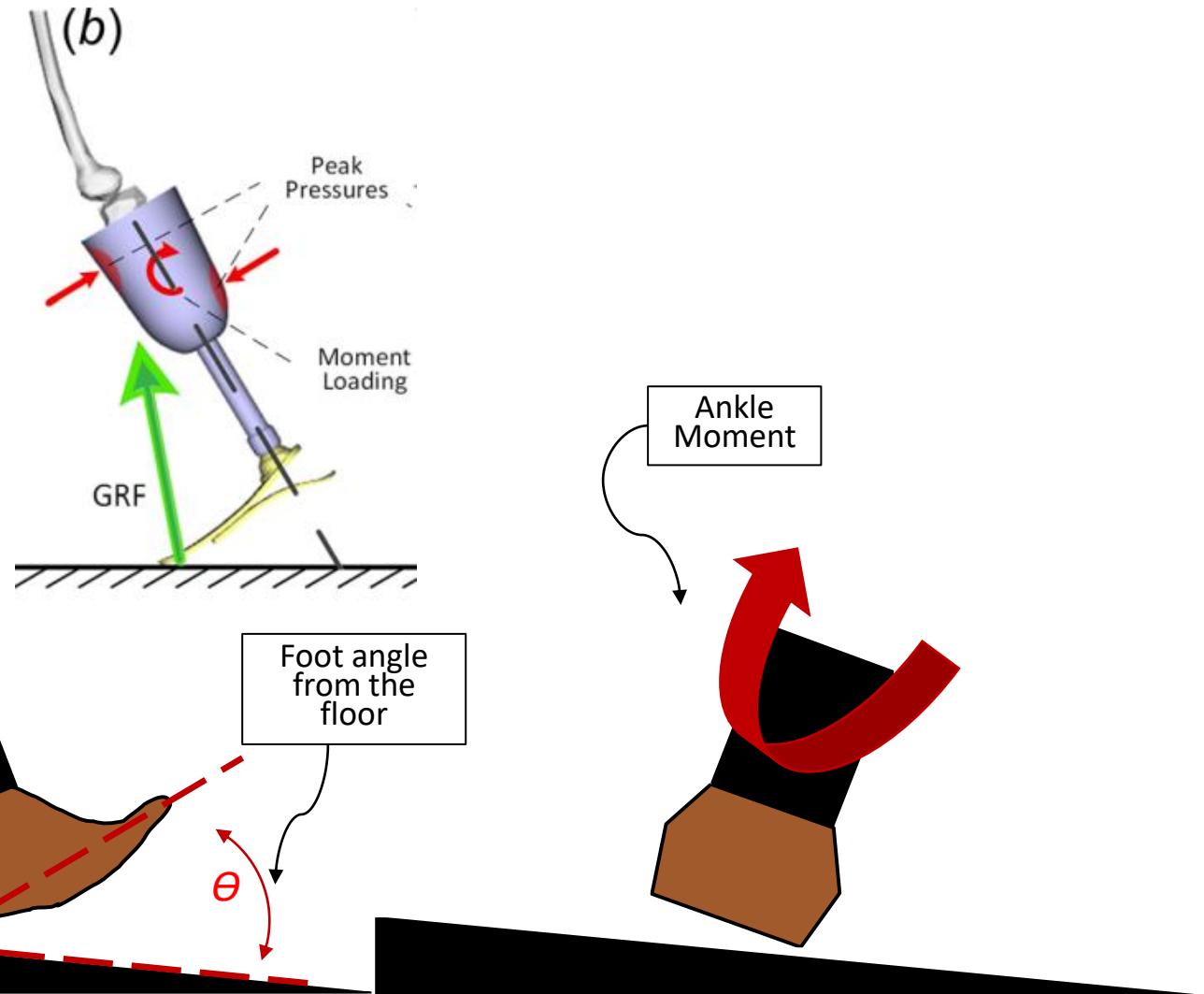
Future Work: TADA Control Algorithms



Toe-lift control



Slope-Matching Control



Moment-
Targeting Control⁶

Acknowledgements

- Marie, Keanu, and Mummy
- Family and close friends
- Peter and my committee
- My loved ones in Trinidad and Tobago
- BADGER Lab and colleagues
- Department of Mechanical Engineering

References

1. Glanzer, E. M. & Adamczyk, P. G. Design and Validation of a Semi-Active Variable Stiffness Foot Prosthesis. *IEEE Trans. Neural Syst. Rehabil. Eng.* 26, 2351–2359 (2018).
2. Adamczyk, Peter Gabriel. "Semi-active prostheses for low-power gait adaptation." *Powered Prostheses*. Academic Press, 2020. 201-259.
3. Ziegler-Graham, Kathryn, Ellen J. MacKenzie, Patti L. Ephraim, Thomas G. Travison, and Ron Brookmeyer. "Estimating the Prevalence of Limb Loss in the United States: 2005 to 2050." *Archives of Physical Medicine and Rehabilitation* 89, no. 3 (March 2008): 422–29. <https://doi.org/10.1016/j.apmr.2007.11.005>.
4. Esquenazi, Alberto, and Stanley K. Yoo. "Lower limb amputations: epidemiology and assessment." *PMR Knowledge Now* 3 (2016).
5. Kennedy LaPrè, Andrew, Brian R. Umberger, and Frank C. Sup IV. "A robotic ankle–foot prosthesis with active alignment." *Journal of Medical Devices* 10.2 (2016): 025001.
6. Nichols, Kieran M., and Peter G. Adamczyk. "Sensitivity of Lower-Limb Joint Mechanics to Prosthetic Forefoot Stiffness with a Variable Stiffness Foot in Level-Ground Walking." *Journal of Biomechanics* (2023): 111436.
7. Voss, W., 2008. A Comprehensible Guide to Controller Area Network. Copperhill Media

Post defense festivities

- 1410 Engineering Dr. Rm. 150 from 4 pm
- Catered food and drinks
- Bring food and drink to contribute, if you can
- Games, chats, relaxation
- Come by for a little or a lot

List of accomplishments

Patent

- K.G. Gruben, W.L. Boehm, and **K.M. Nichols**. "Apparatus for Assessing Human Balance Capability." U.S. Patent,

Published manuscripts

- **K.M. Nichols**. "The Characterization of Foot Force Vector Control in Human Standing." Master's Thesis. University of Wisconsin--Madison (2016).
- W.L. Boehm, **K.M. Nichols**, and K.G. Gruben. "Frequency-dependent contributions of sagittal-plane foot force to upright human standing." *Journal of Biomechanics* (2019).
- M.A. McGeehan, P.G. Adamczyk, **K.M. Nichols**, and M.E. Hahn.
 - "A Reduced-Order Computational Model of a Semi-Active Variable-Stiffness Foot Prosthesis." *Journal of Biomechanical Engineering* (2021).
 - "A computational gait model with a below-knee amputation and a semi-active variable-stiffness foot prosthesis." *Journal of Biomechanical Engineering* (2021).
 - "A simulation-based analysis of the effects of variable prosthesis stiffness on interface dynamics between the prosthetic socket and residual limb." *Journal of Rehabilitation and Assistive Technologies*. (2022).
- **K.M. Nichols** and P.G. Adamczyk. "Sensitivity of Lower-Limb Joint Mechanics to Prosthetic Forefoot Stiffness with a Variable Stiffness Foot in Level-Ground Walking." *Journal of Biomechanics* (2023).

List of accomplishments

Submitted Manuscripts

- J. Bartloff, W.L. Boehm, **K.M. Nichols**, and K.G. Gruben. "Frequency-dependent behavior of paretic and non-paretic leg force during standing post stroke." *Journal of Biomechanics*.
- S. Harper, R. Roembke, Y. Wang, **K.M. Nichols**, D.Thelen, and P.G. Adamczyk. "Wearable sensing for understanding and influencing human movement in ecological contexts." *Current Opinion in Biomedical Engineering*.

In Progress Manuscripts

- M.J. Greene, I.F.E. Simones, P.R. Lewis, **K.M. Nichols**, and P.G. Adamczyk. "Non-backdrivable Wedge-Cam Mechanism for a Semi-Active Two-Axis Prosthetic Ankle." *Elsevier Mechatronics*.
- **K.M. Nichols**, R. Roembke, S. Akhetova, P.G. Adamczyk. "Influence of Prosthetic Ankle Angle and Walking Speed on Pylon Moments in the Two Axis aDaptable Ankle." *IEEE/AMSE Transactions on Mechatronics*
- **K.M. Nichols**, R. Roembke, P.G. Adamczyk. "Real-time control of the New Two Axis aDaptable Ankle using a Raspberry Pi, ROS, and CANopen motor communication." *MDPI Actuators*.

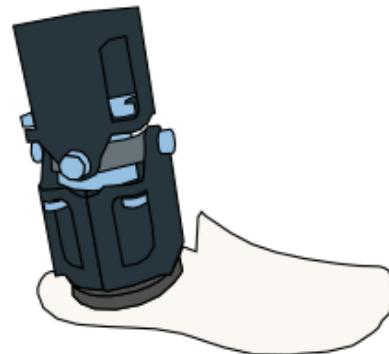
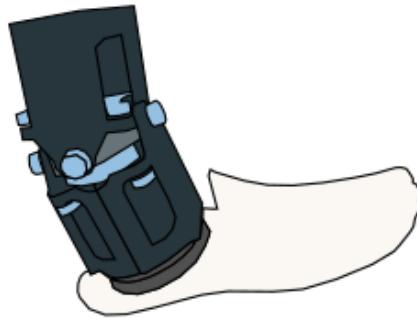
Extra material



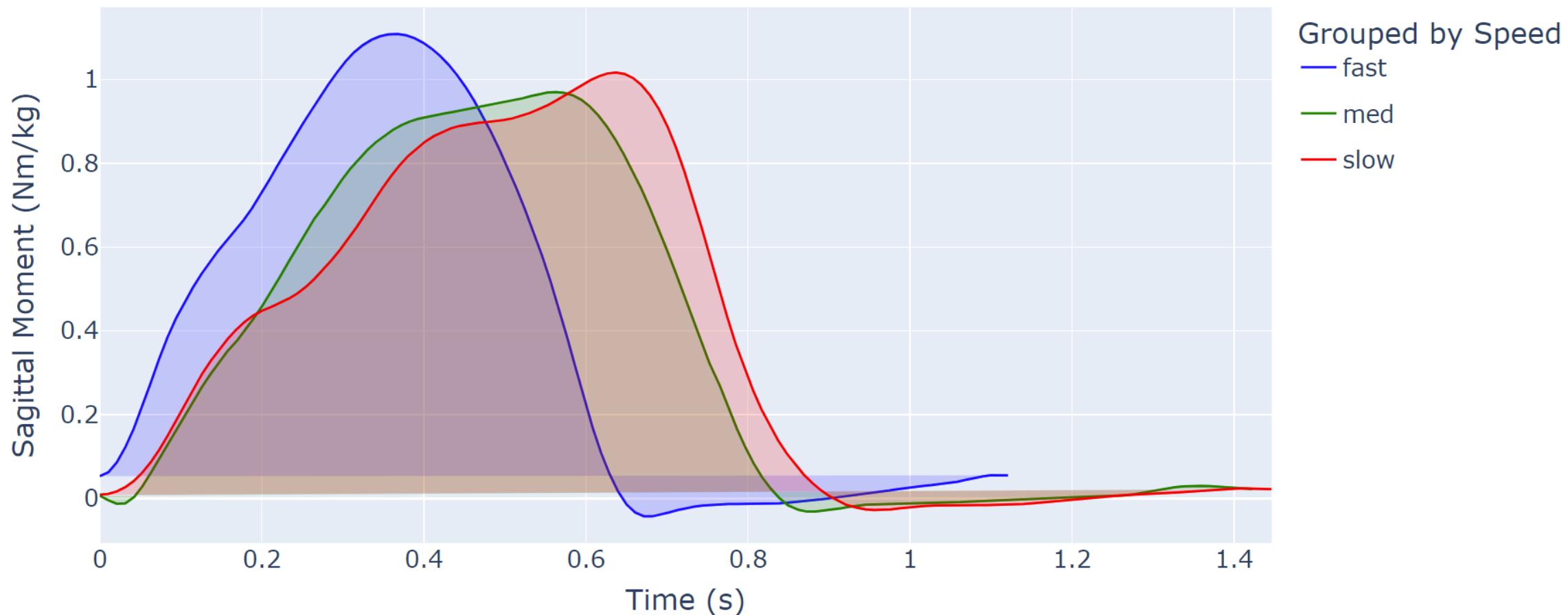
Limitations

1. TADA with unimpaired person vs. person with a transtibial amputation
2. Need to collect more data with unimpaired and impaired participants

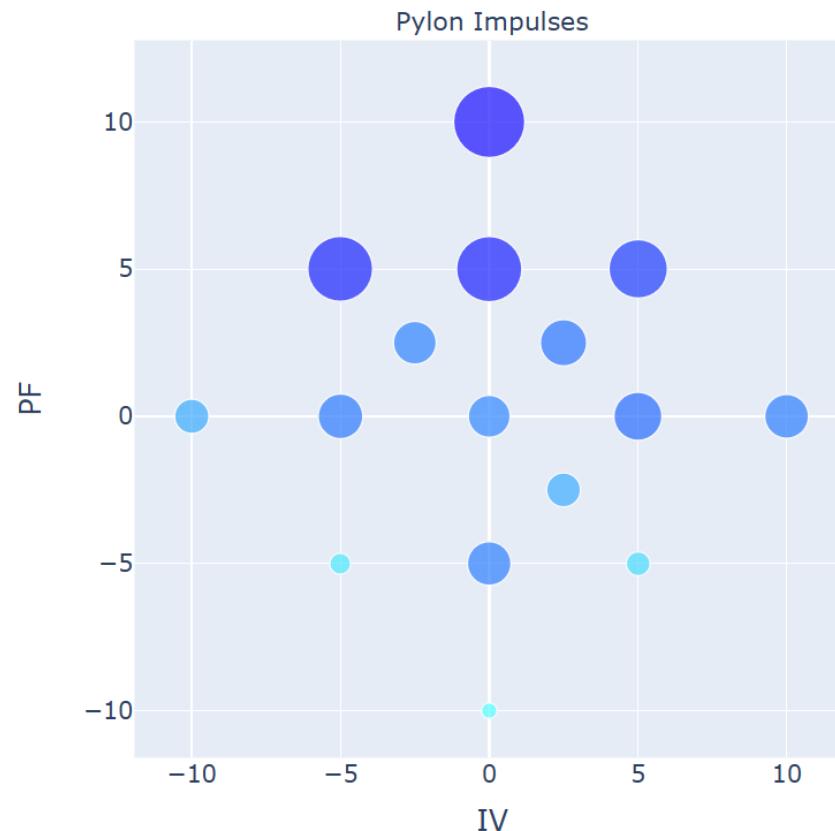
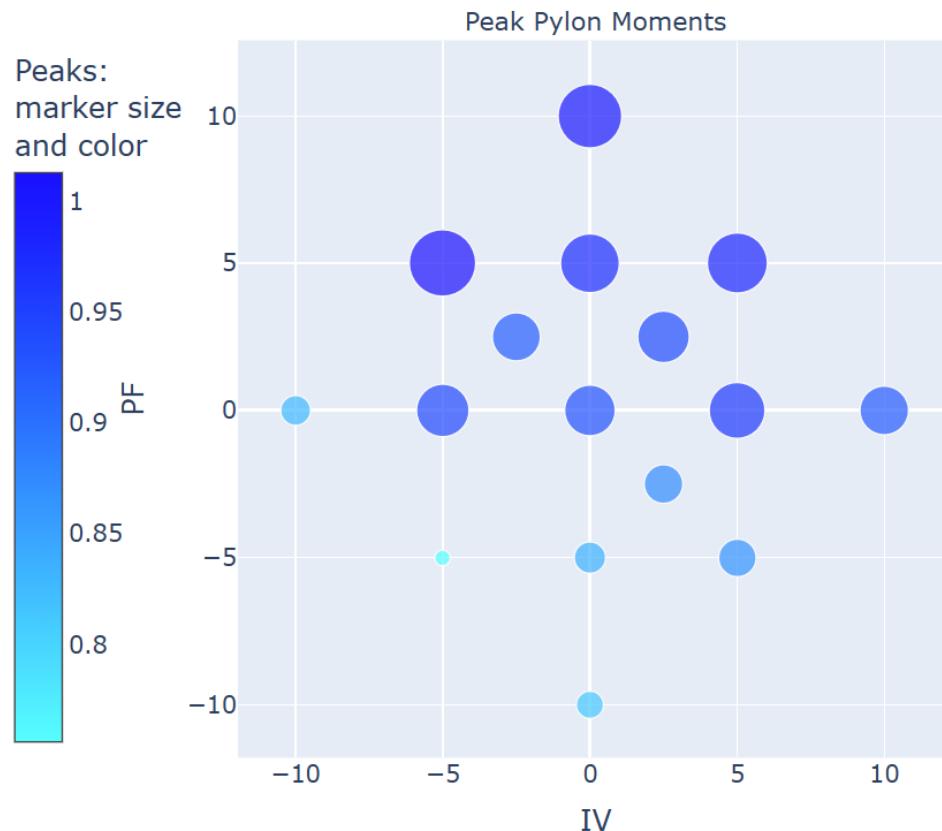




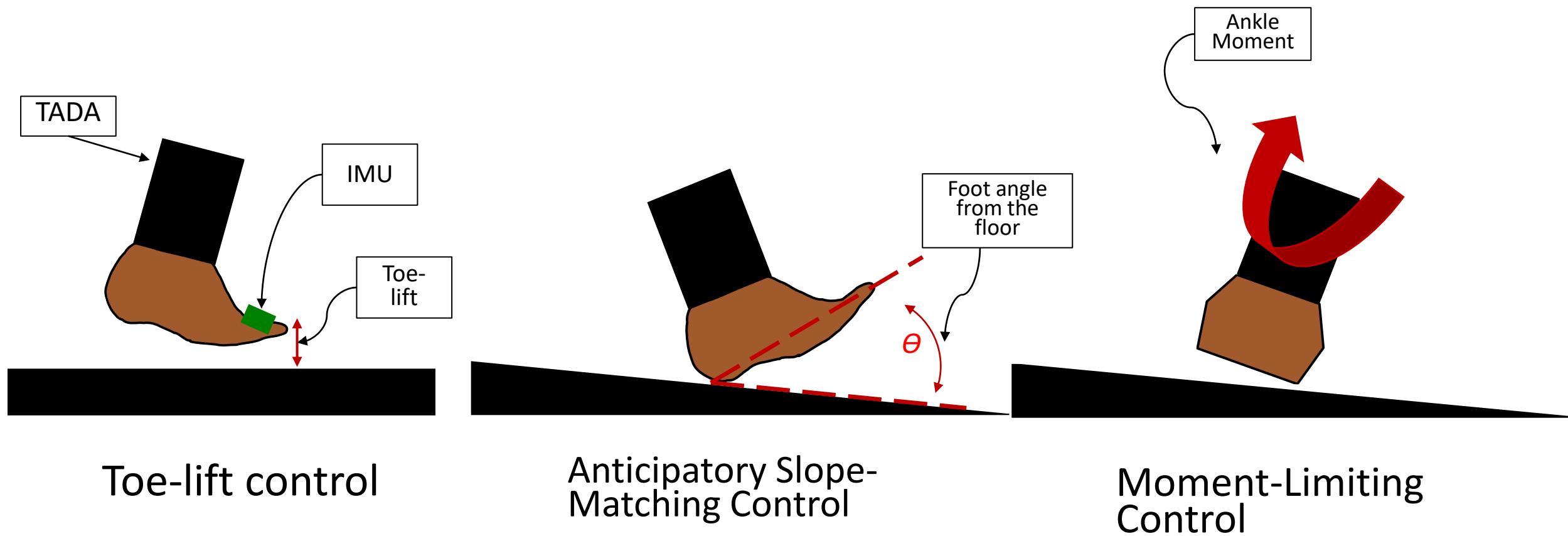
Sagittal Moment vs Time for PF = 10.0, IV = 0.0



PF vs IV with Sagittal Moment Moments



Current and Future Work: Main Control Laws

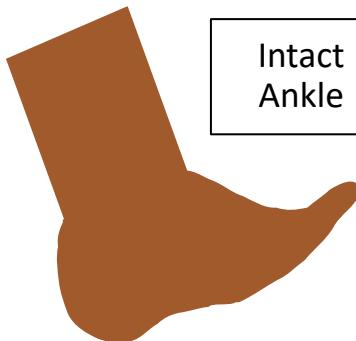


Toe-lift control

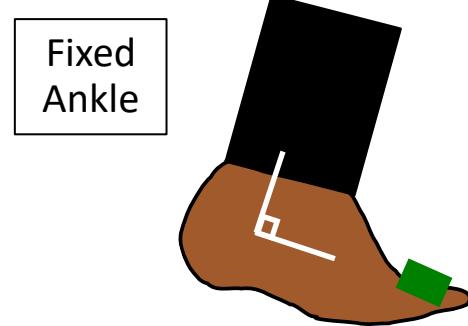
Anticipatory Slope-Matching Control

Moment-Limiting Control

Current and Future Work: Comparisons



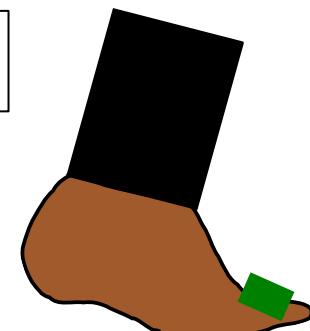
VS.



VS.

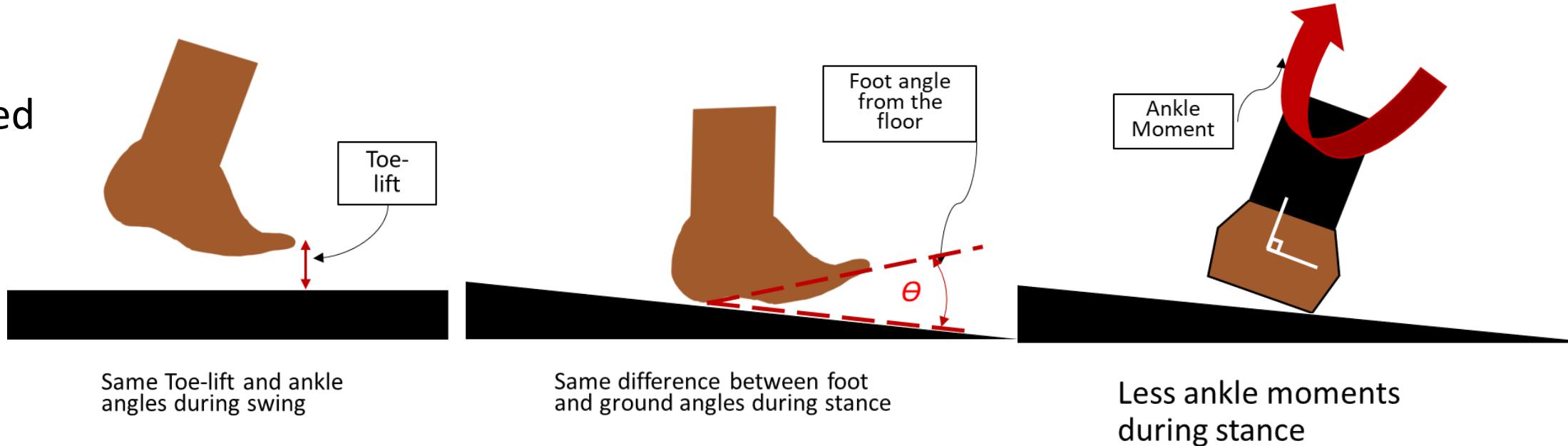


Adaptable
Ankle

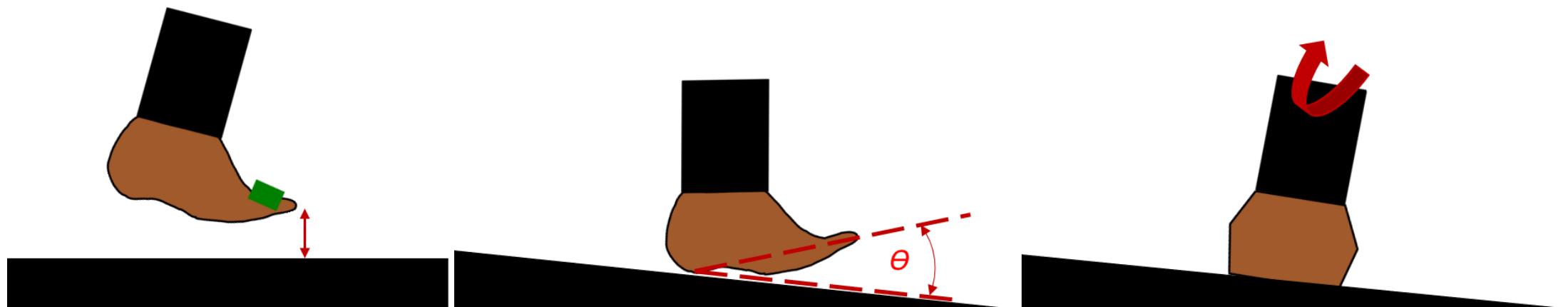


Current and Future Work: Aim 1

Intact or Fixed
Ankle

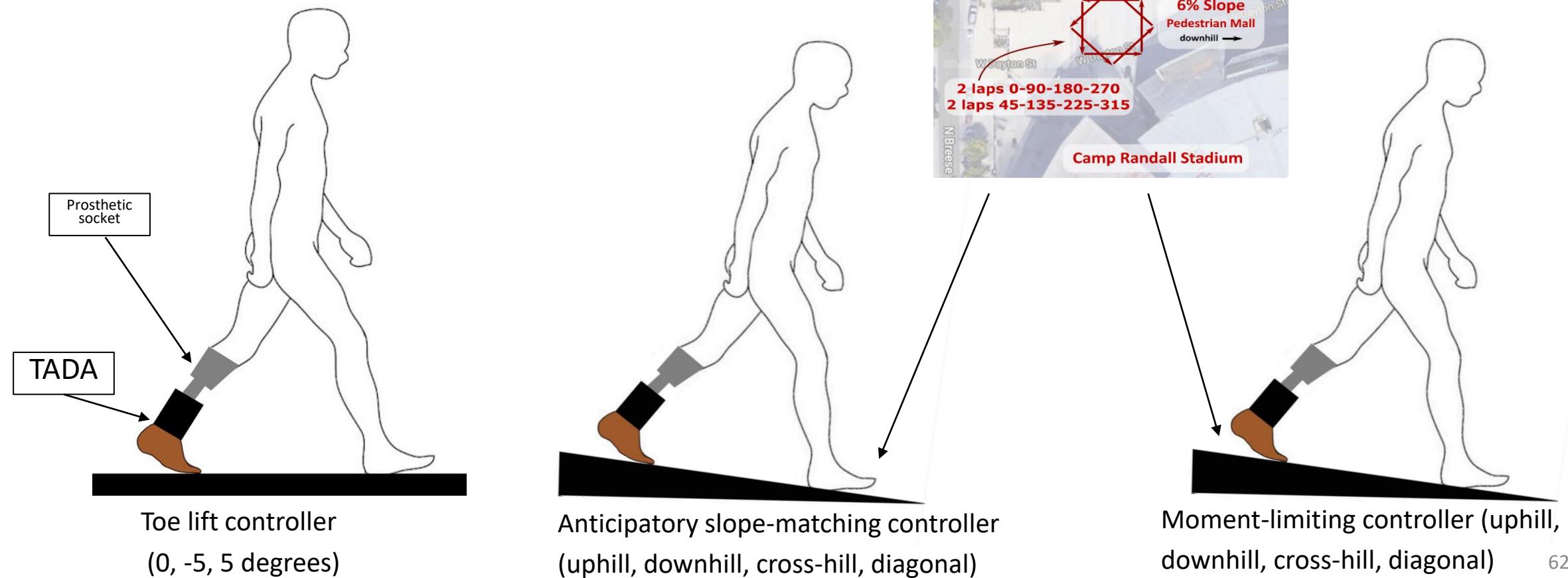


Adaptable
Ankle



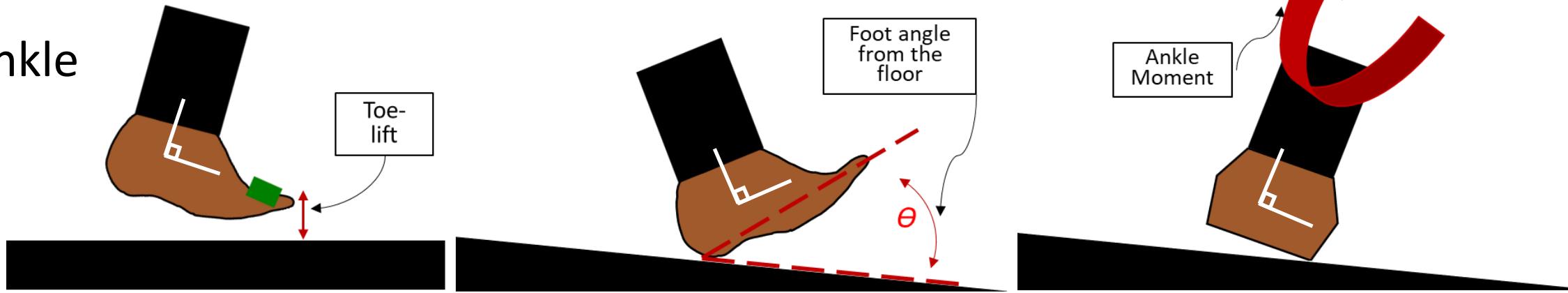
Current and Future Work: Aim 2

Evaluate the biomechanical effects of the TADA on *out-of-the-lab* walking on ten persons with transtibial amputations



Current and Future Work: Aim 2

Fixed ankle



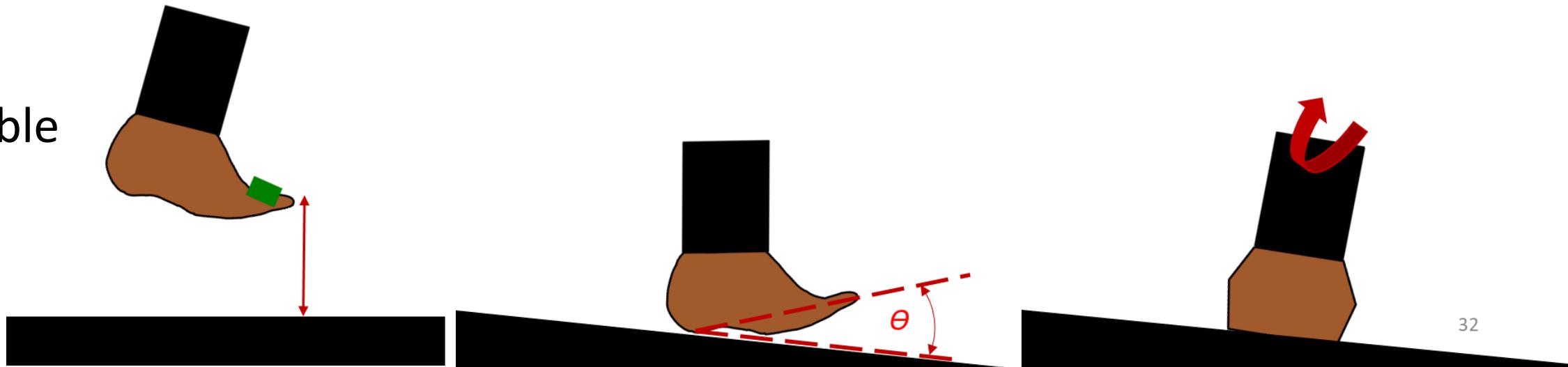
VS.

More Toe-lift at first
then less over time

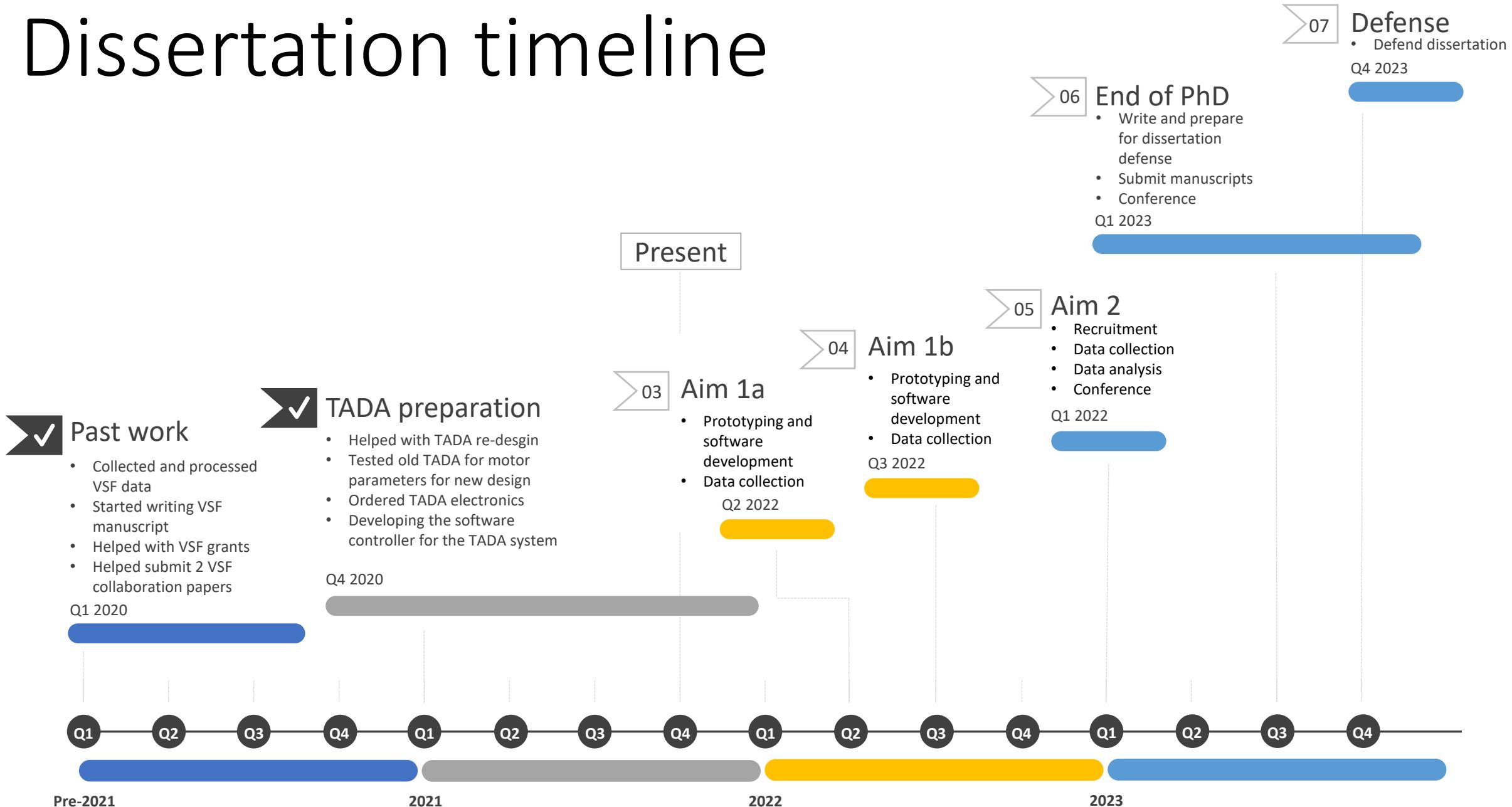
Less difference between
ankle and ground angles

Less ankle moments

Adaptable
Ankle



Dissertation timeline



Current and Future Work: Impact of Proposed Work

- Sensing locomotion modes and transitions
- Combine with other semi-active prostheses like the VSF2K
- Next step will the STADA (Sheep TADA):
 - osseointegrated
 - bidirectional neural interface

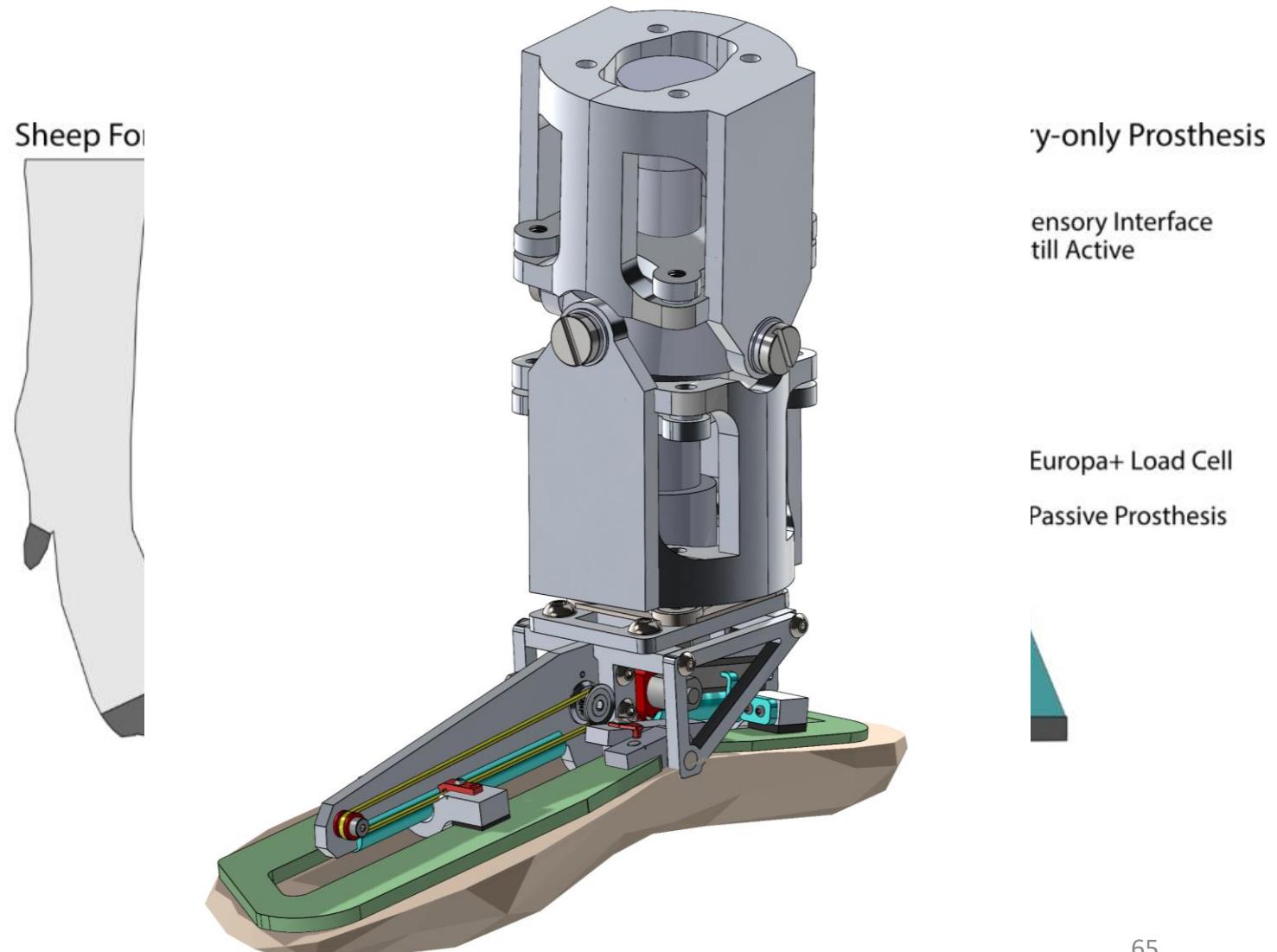
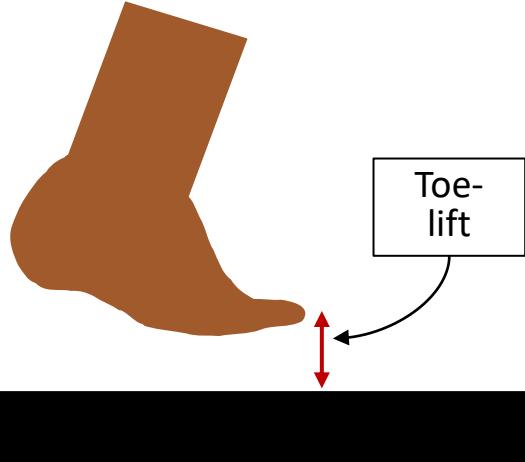
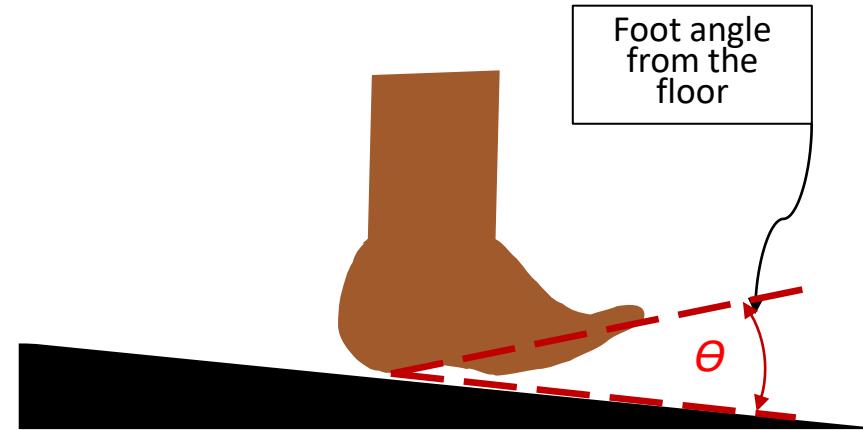


Figure of STADA: Congressionally Directed Medical Research Programs (CDMRP) Search Awards. https://cdmrp.army.mil/search.aspx?LOG_NO=DM190827.

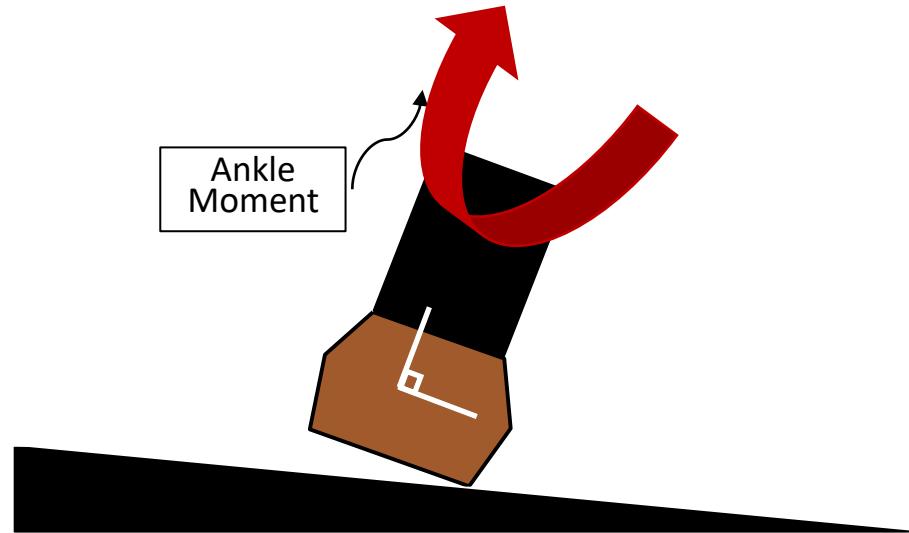
Current and Future Work: Specific Aim 1



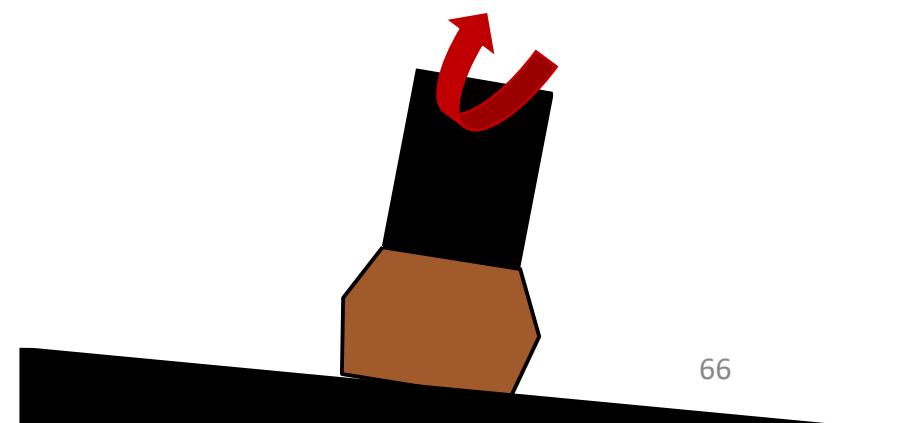
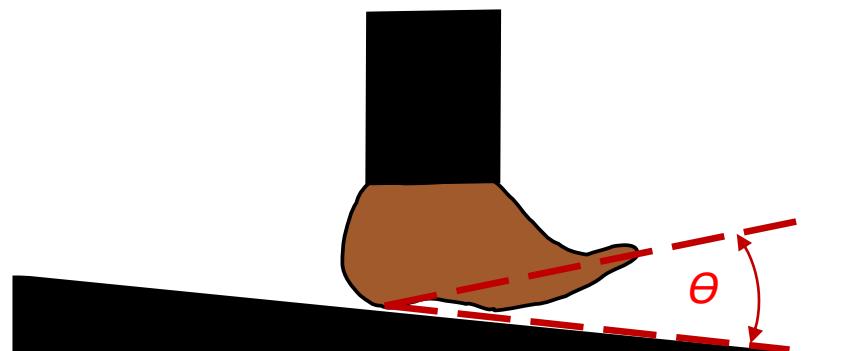
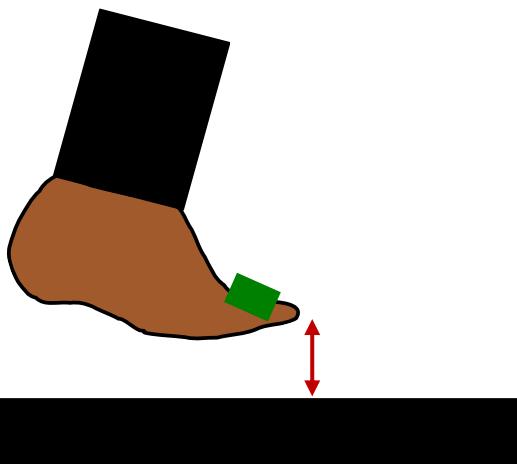
Same Toe-lift and ankle angles during swing



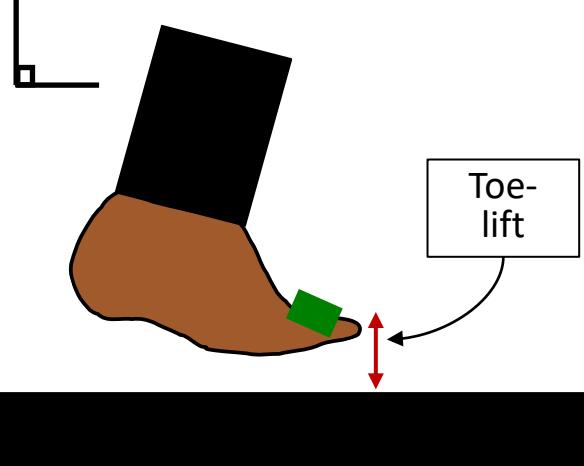
Same difference between foot and ground angles during stance



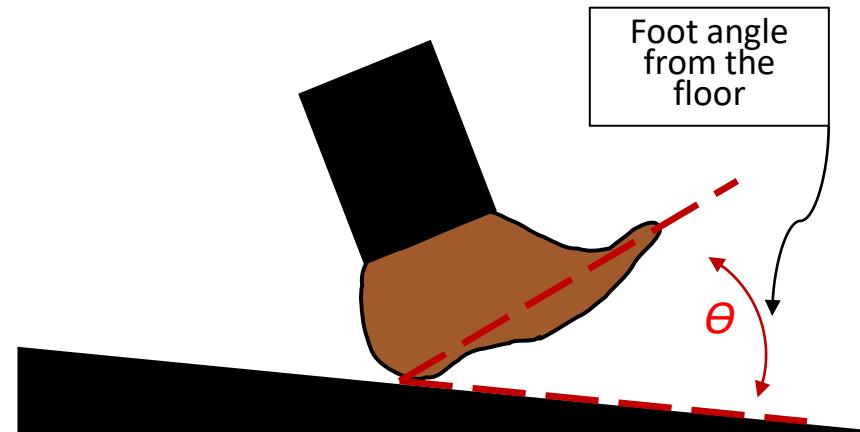
Less ankle moments during stance



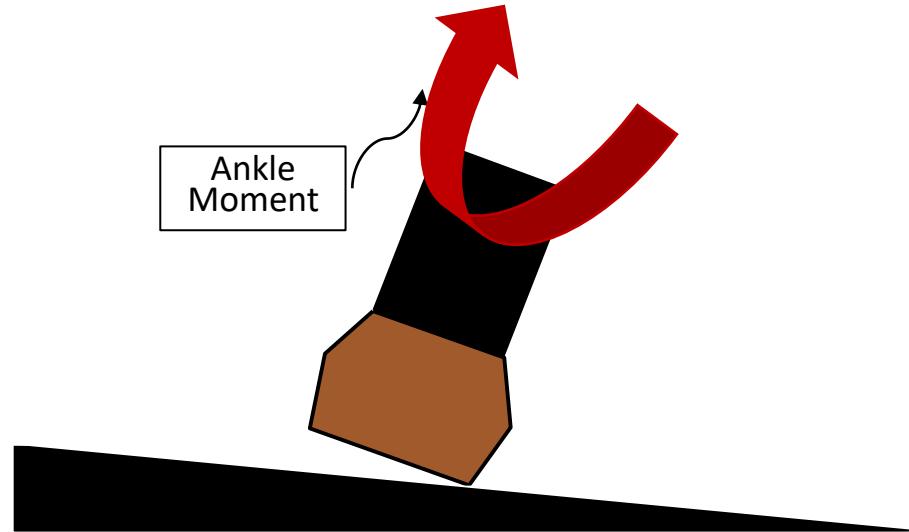
Current and Future Work: Specific Aim 2



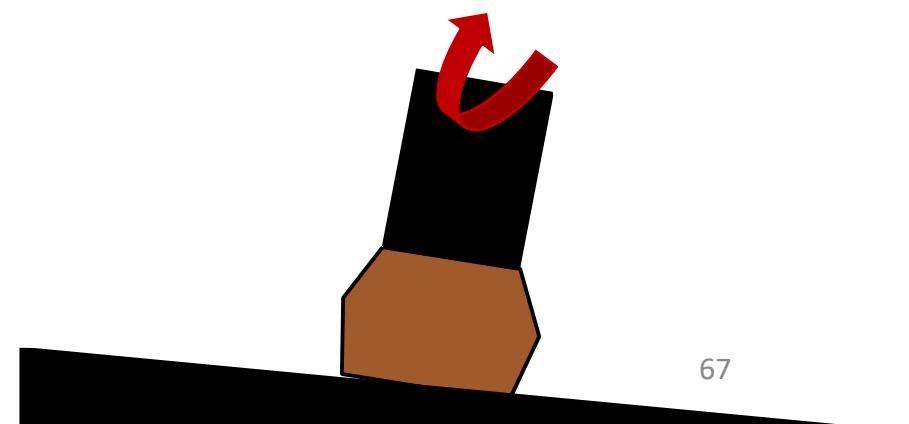
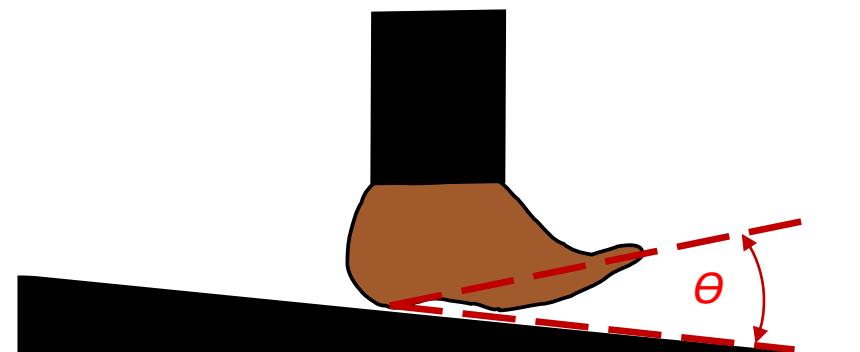
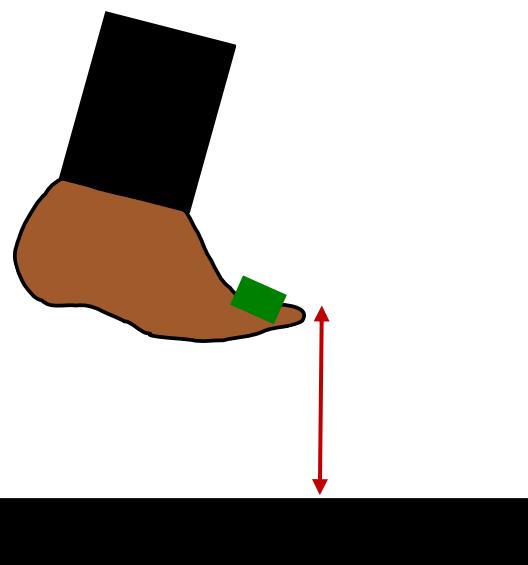
More Toe-lift at first
then less over time



Less difference between
ankle and ground angles

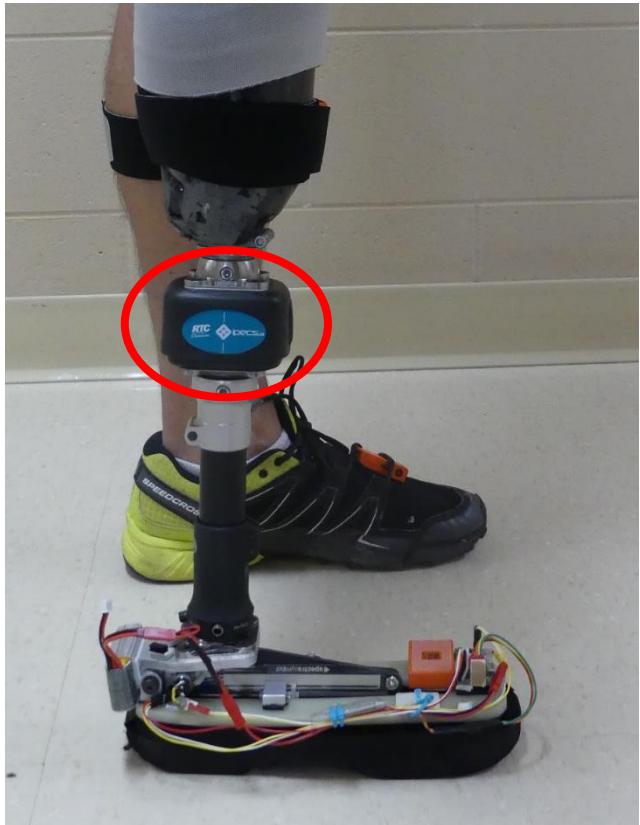


Less ankle moments

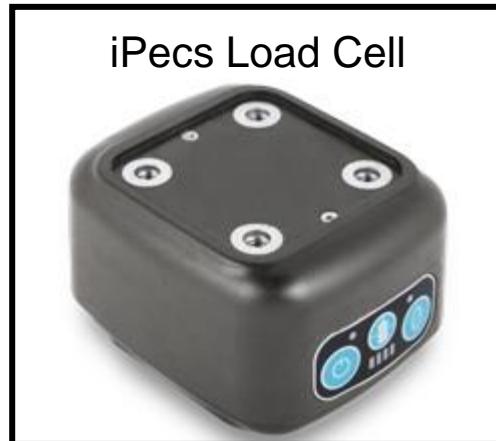


Sensors

Xsens IMU Suit



iPecs Load Cell



Microcontroller and IMU



Concerns

- May be too much development over a short period of time
- May not see enough adaptation for persons with amputations
- The prosthetic ankle + electronics may be too bulky and heavy
- The TADA feedback controller should be able to estimate ankle kinetics (forces), but it is not clear yet how to estimate knee kinetics to assess how persons with amputations will adapt to wearing the TADA