UW BADGER Lab

Biomechatronics, Assistive Devices, Gait Engineering, & Rehabilitation

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

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Ph.D. Defense

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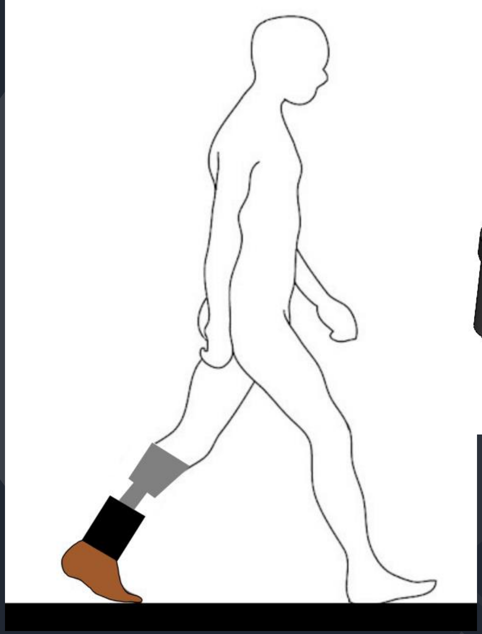
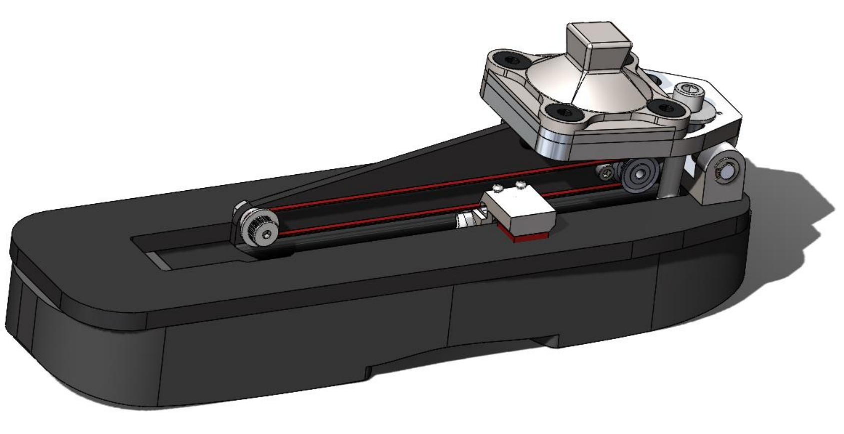
Presentation Overview

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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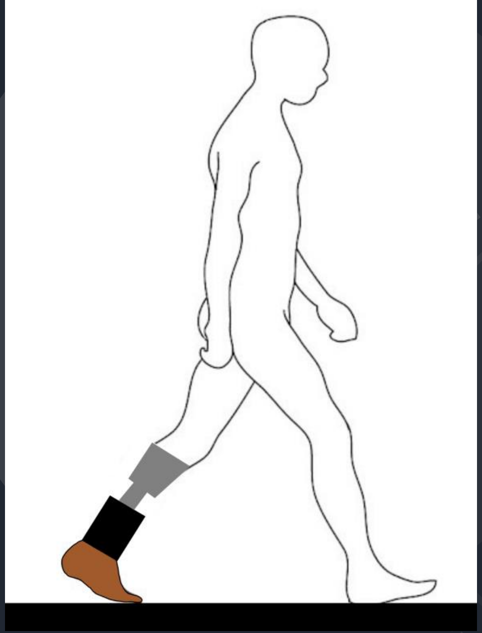
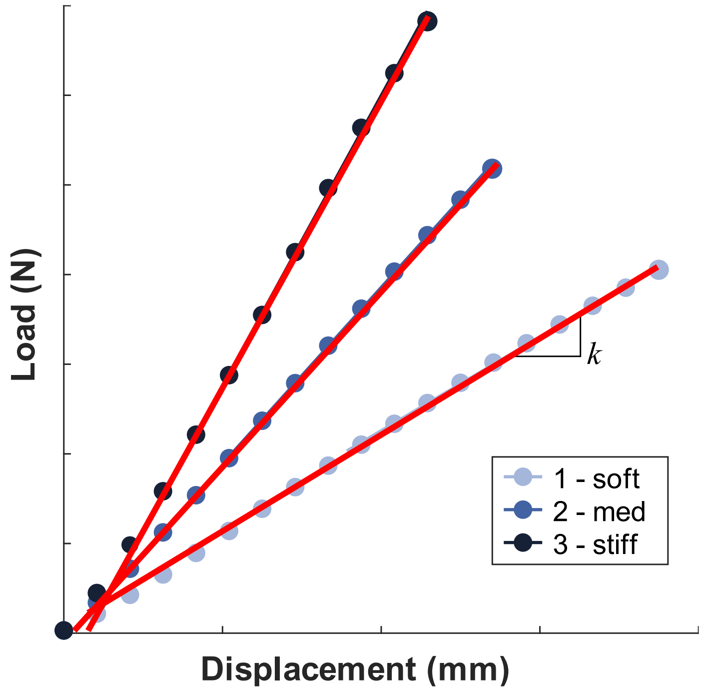
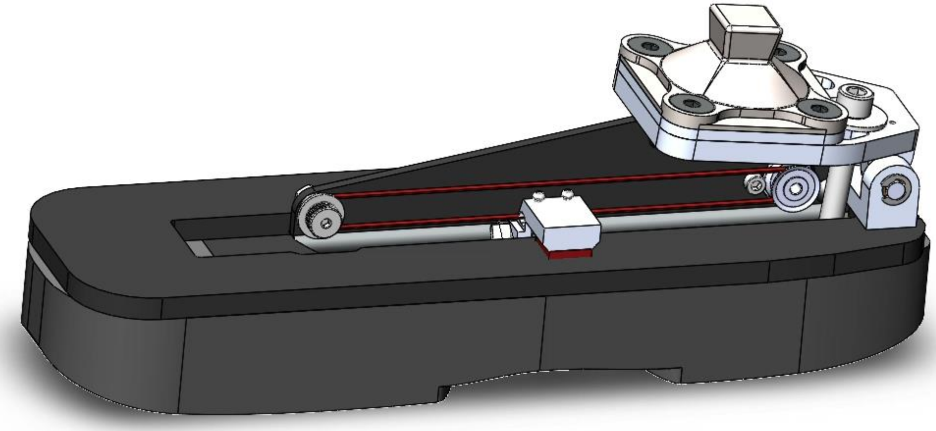


Background

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





Stiffness figure (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).

Background

- The Two Axis aDaptable Ankle (TADA) is a semi-active ankle prosthesis[2]
  - independently modulate two axes of ankle angles (±10°, 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)

(2): Adamczyk, Peter Gabriel. "Semi-active prostheses for low-power gait adaptation." Powered Prostheses. Academic Press, 2020. 201-259.

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.S[3]
- Difficult to recreate the human ankle-foot
- There is a need to improve prosthetic design and control

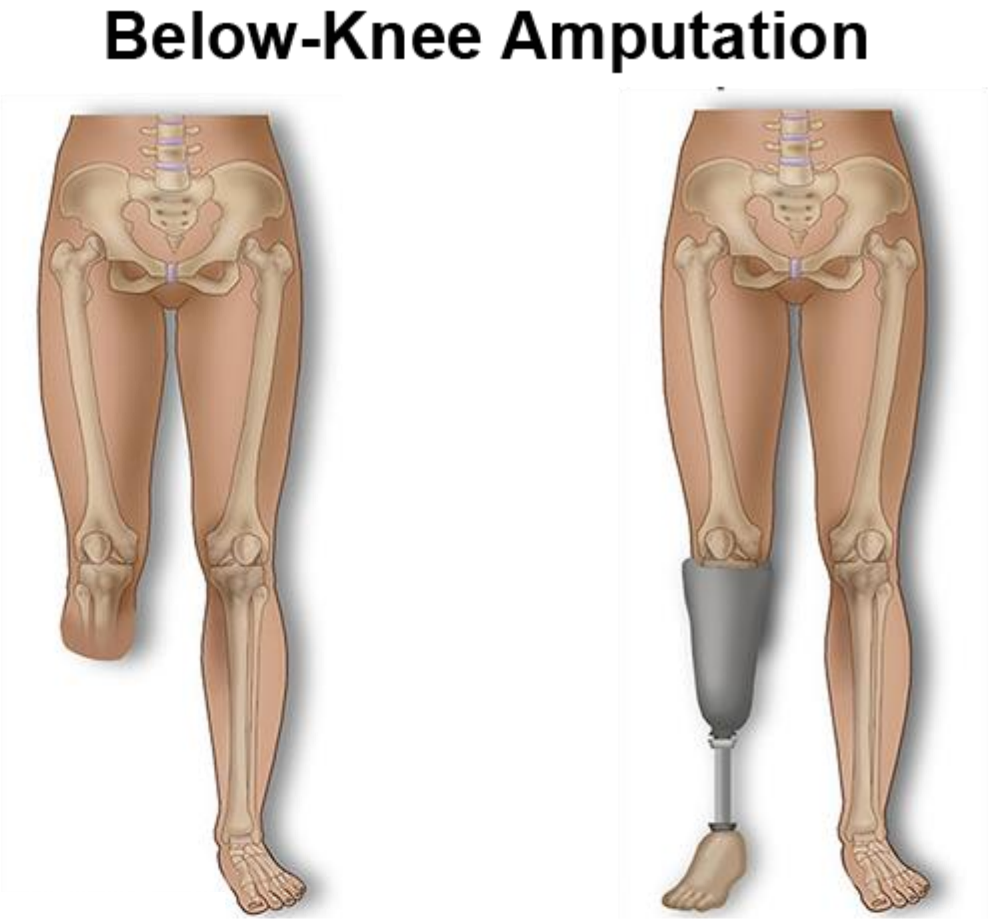


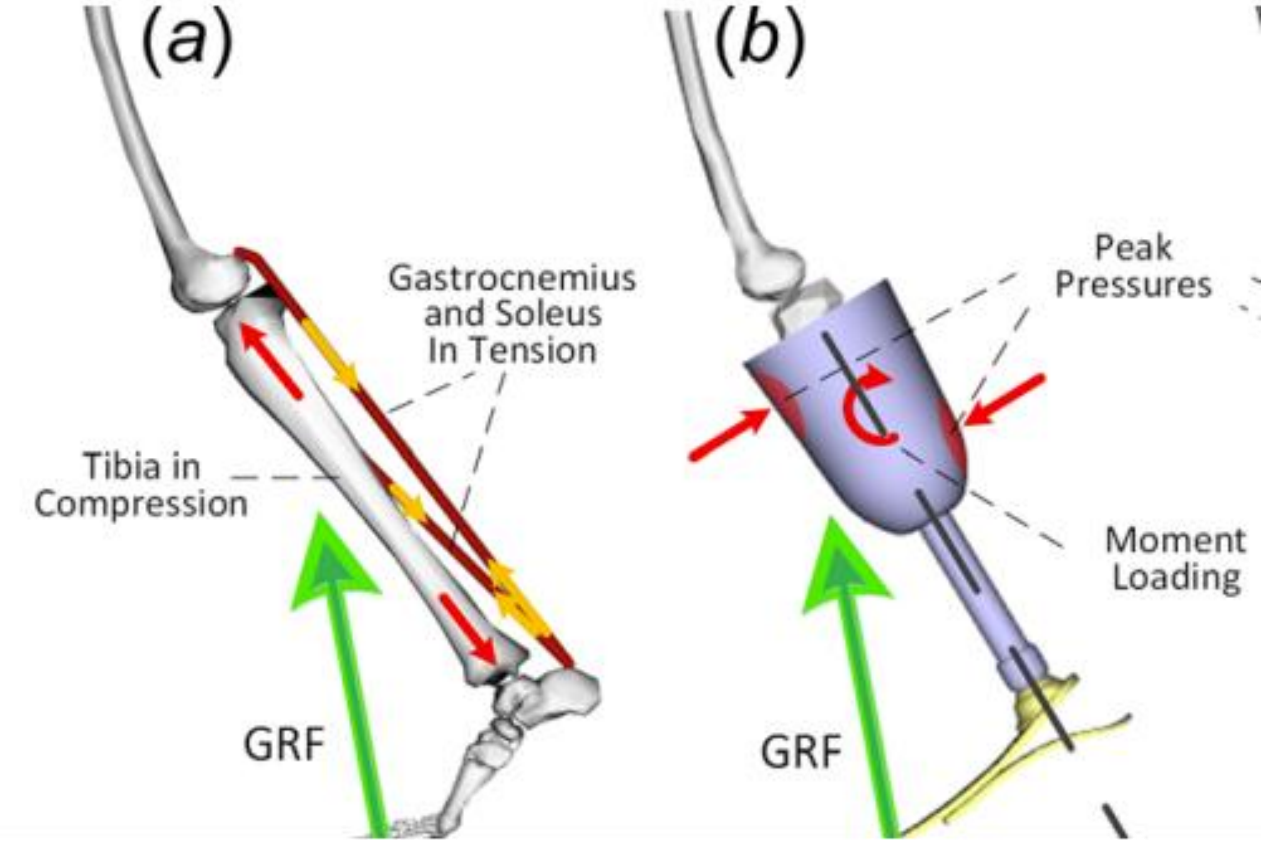
Diagram: Guide | Physical Therapy Guide to Below-Knee Amputation (Transtibial Amputation) | Choose PT

(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 walking[4]

- knee hyperextension
- hip circumduction
- Toe scuffing
- knee osteoarthritis
- High peak pressures at socket interaction[5]



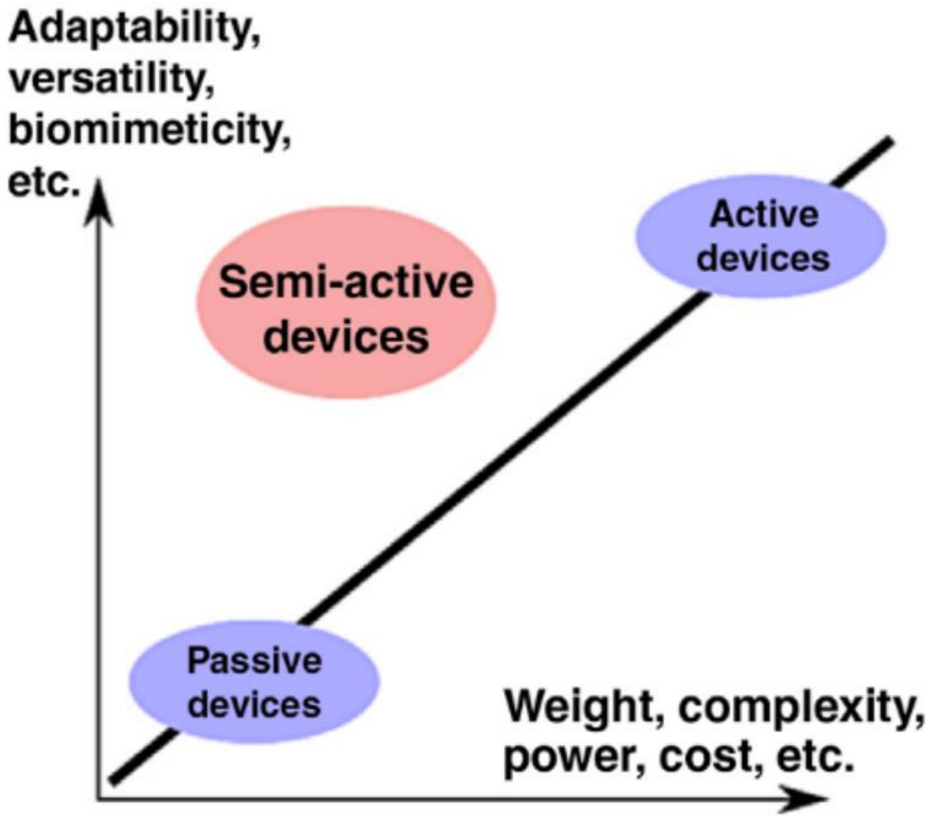
(4): Esquenazi, Alberto, and Stanley K. Yoo. “Lower limb amputations: epidemiology and assessment.” PMR Knowledge Now 3 (2016).
(5): Kennedy LaPrè, Andrew, Brian R. Umberger, and Frank C. Sup IV. "A robotic ankle–foot prosthesis with active alignment." Journal of Medical Devices 10.2 (2016): 025001.

Background

Two common ways to describe prosthetic ankle-foot function[2]:

- 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



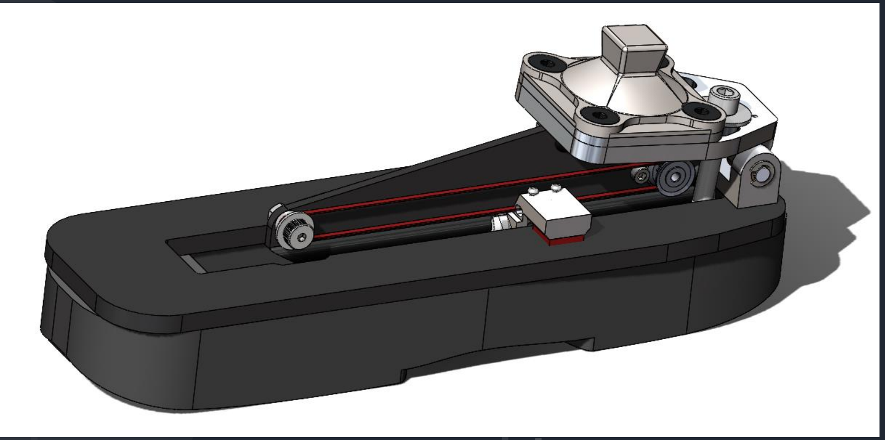
(2) and Diagram: Adamczyk, P. G. Chapter 9 - Semi-active prostheses for low-power gait adaptation. in Powered Prostheses (eds. Dallali, H., Demircan, E. & Rastgaar, M.) 201–259 (Academic Press, 2020). doi:10.1016/B978-0-12-817450- 0.00009-2.

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 <u>Prosthetic ankle-angle and walking speed</u> on Pylon moments of the Two Axis aDaptable Ankle?

Presentation Overview

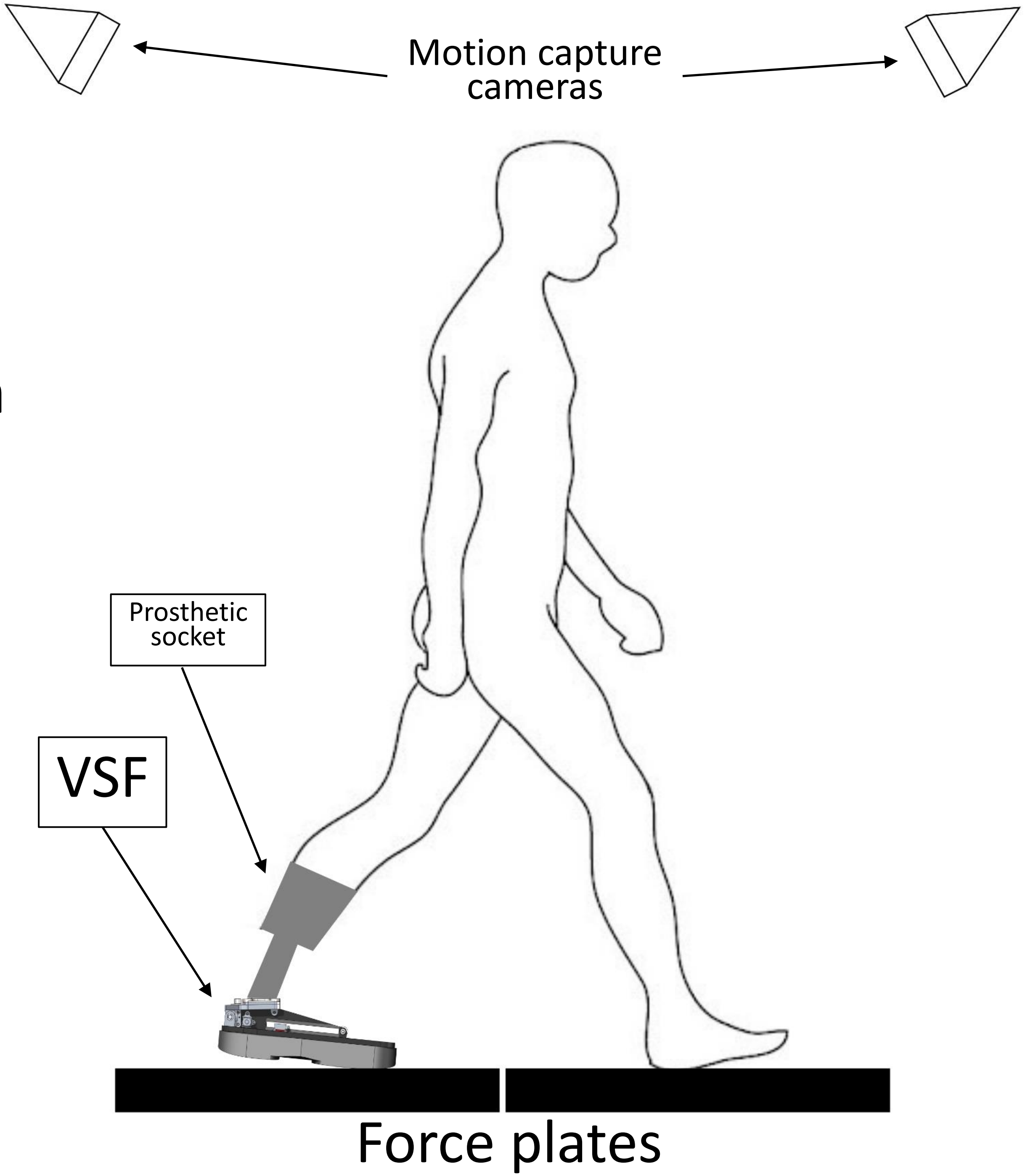
Background → BIOMECHANICAL EVALUATION OF THE VSF → Motor control for TADA → Pilot Biomechanical Evaluation of TADA



VSF

- To evaluate the effect of various stiffness of VSF on joint mechanics in level-ground walking[6]

- Number of participants: 7
- Walking speed: 1.1 m/s
- Stiffness configurations: Compliant, Medium, Stiff
- Three successful trials per stiffness

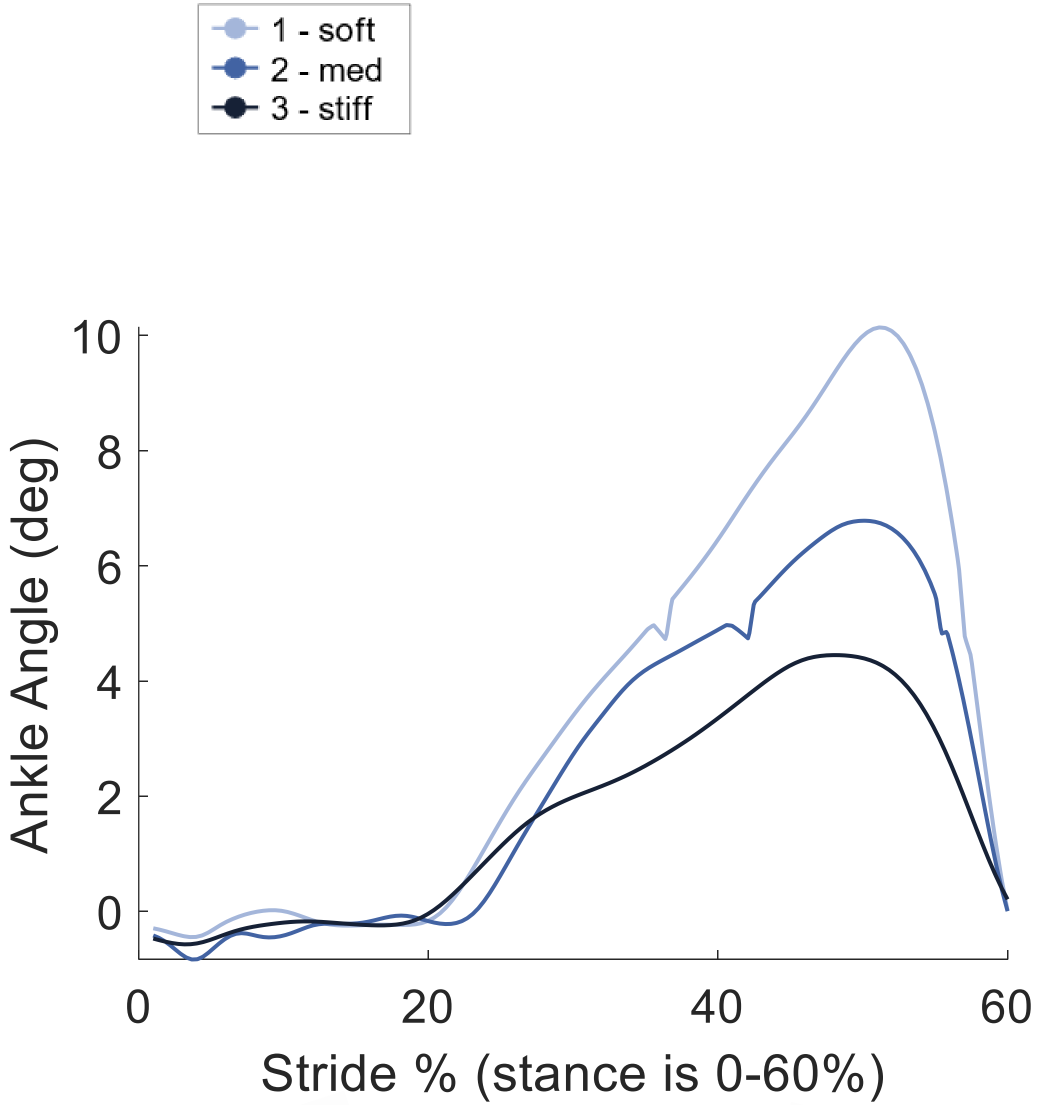


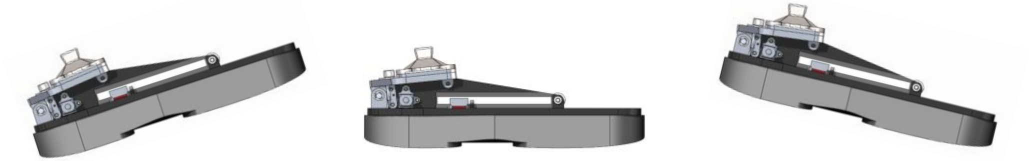
(6) Nichols, Kieran M., and Peter G. Adamczyk. "Sensitivity of Lower-Limb Joint Mechanics to Prosthetic Forefoot Stiffness with a Variable Stiffness Foot in Level-Ground Walking." Journal of Biomechanics (2023): 111436.

VSF

With less stiff VSF

- higher stance ankle angle peaks

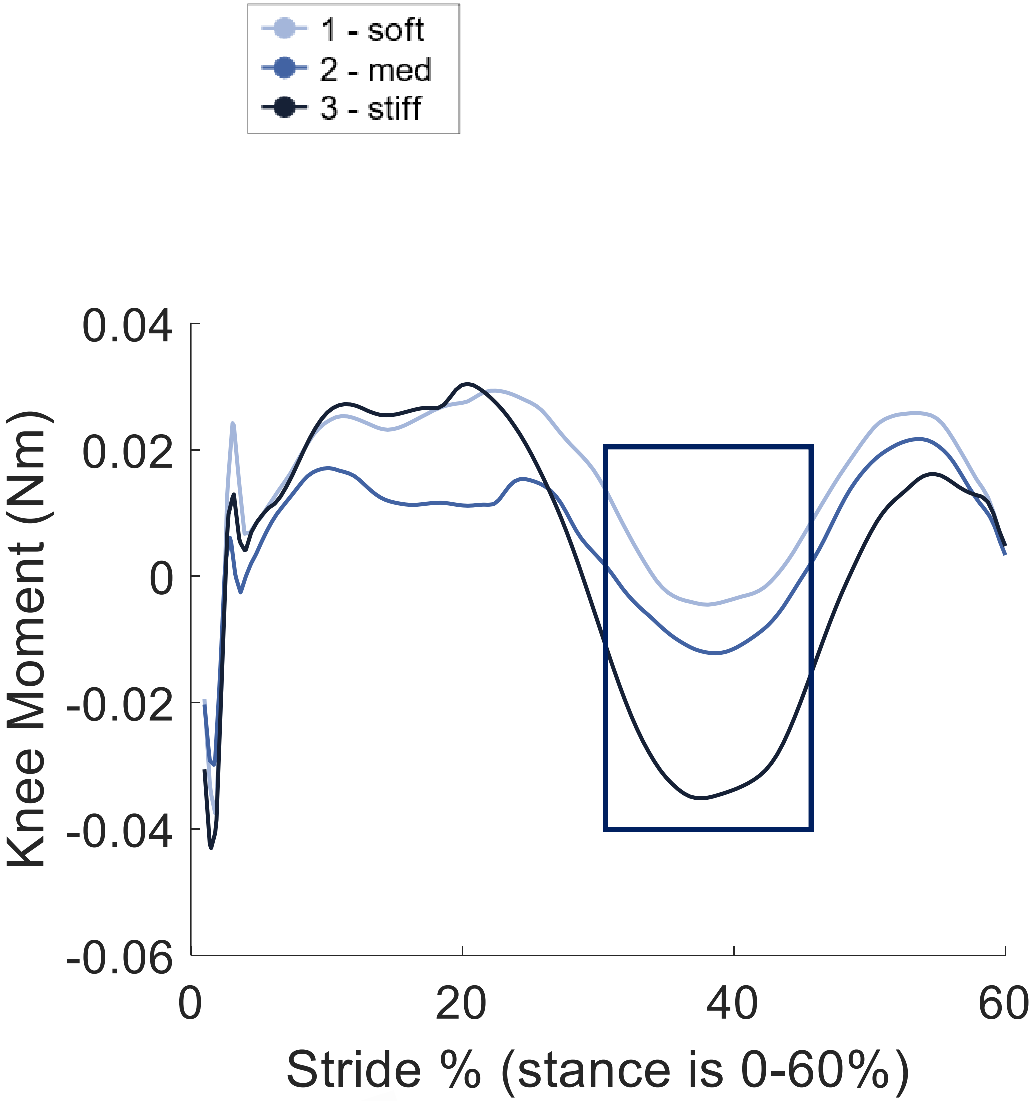


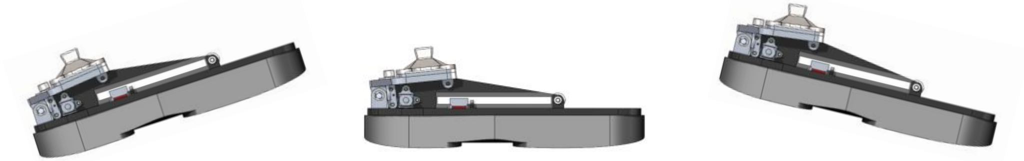


VSF

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

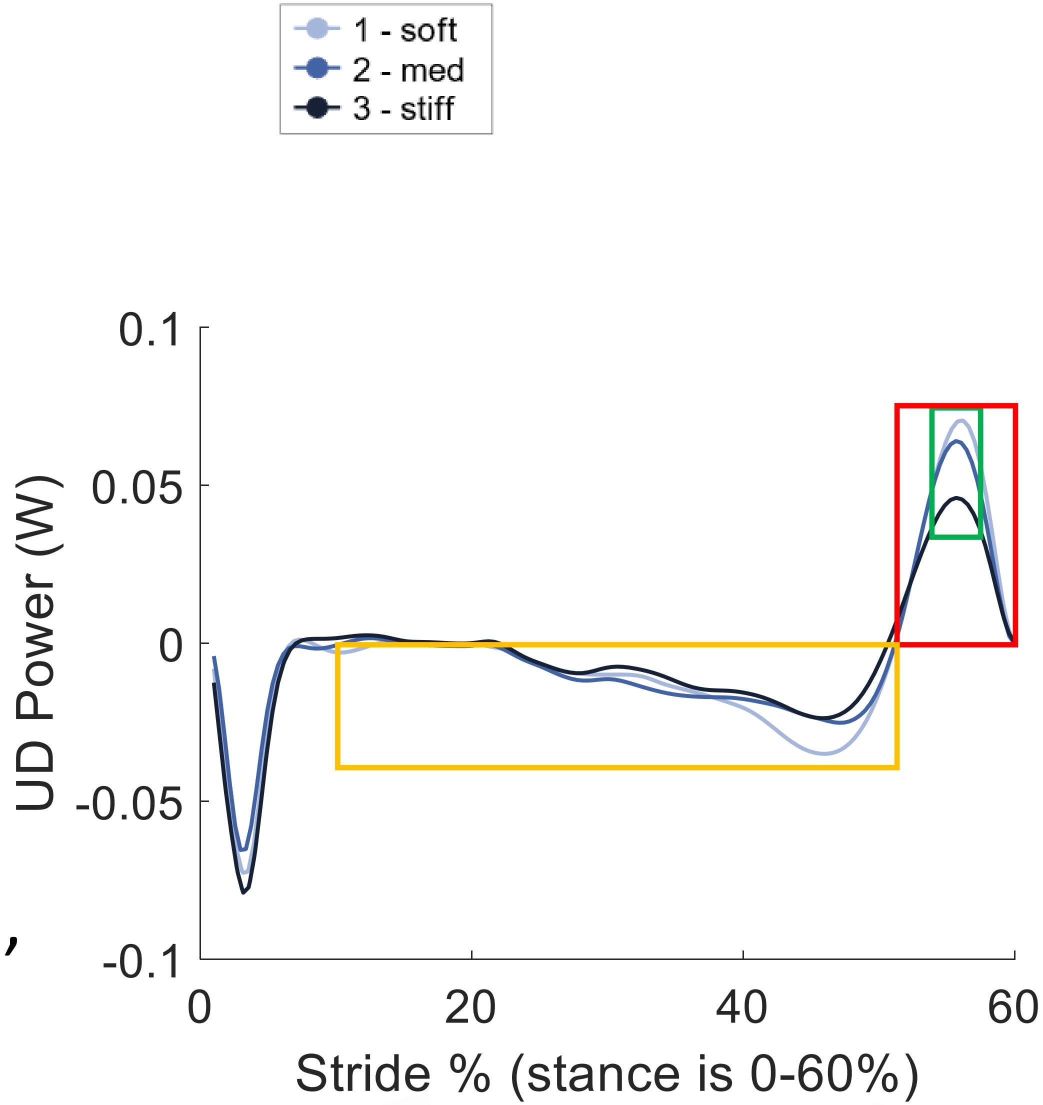


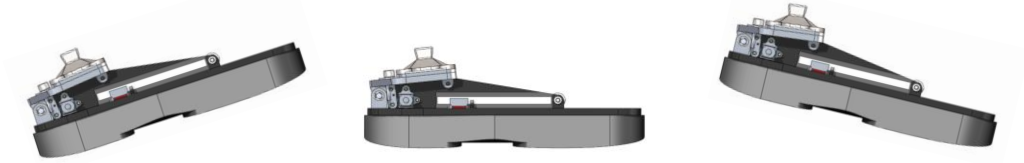


VSF

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





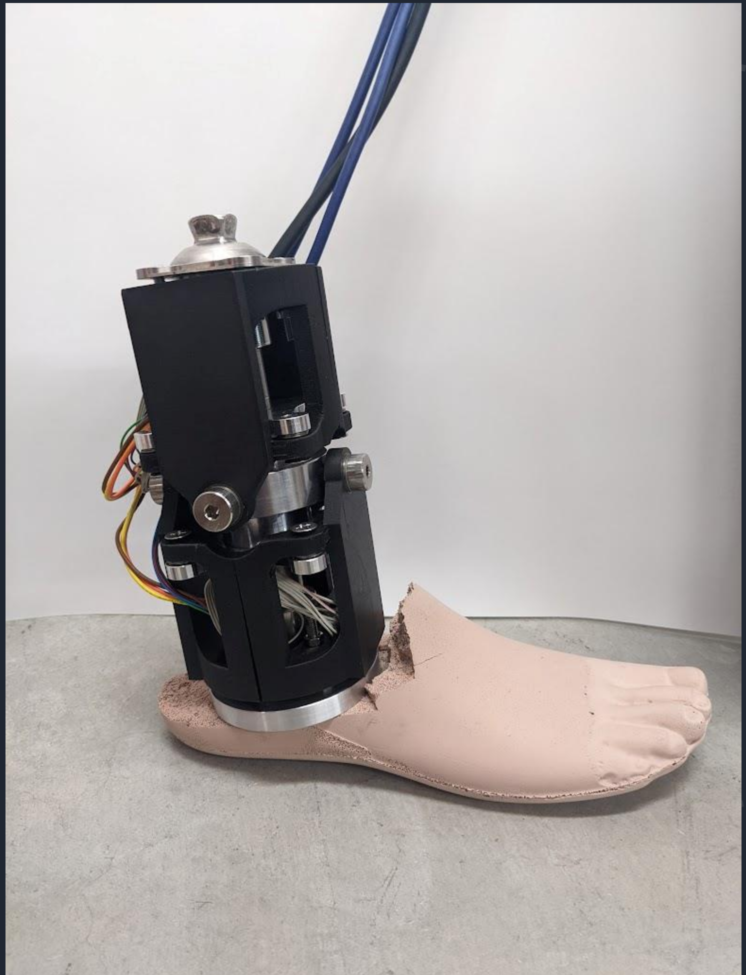
VSF

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

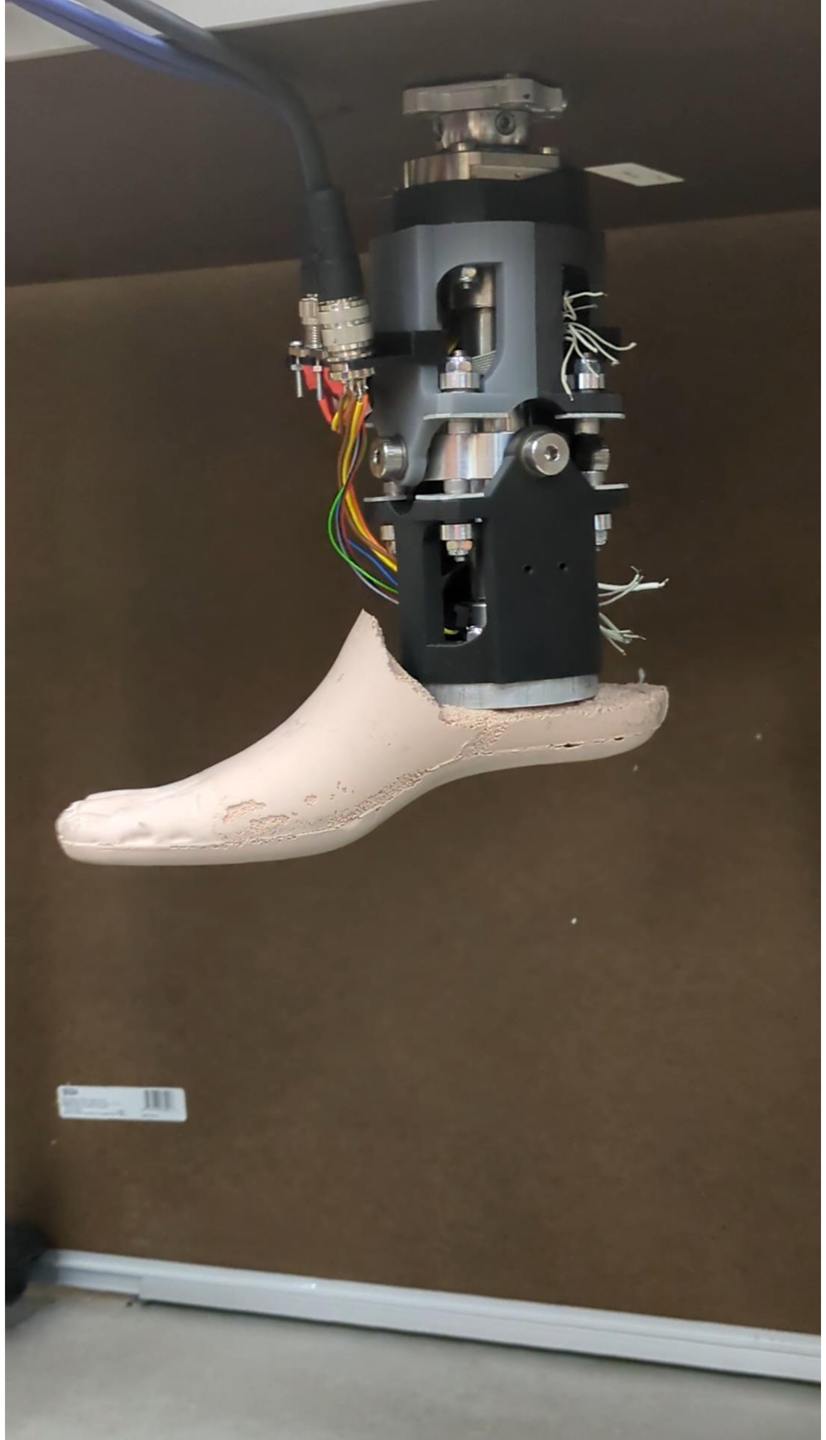
Background → Biomechanical Evaluation of the VSF → **MOTOR CONTROL FOR THE TADA** → Pilot Biomechanical Evaluation of the TADA

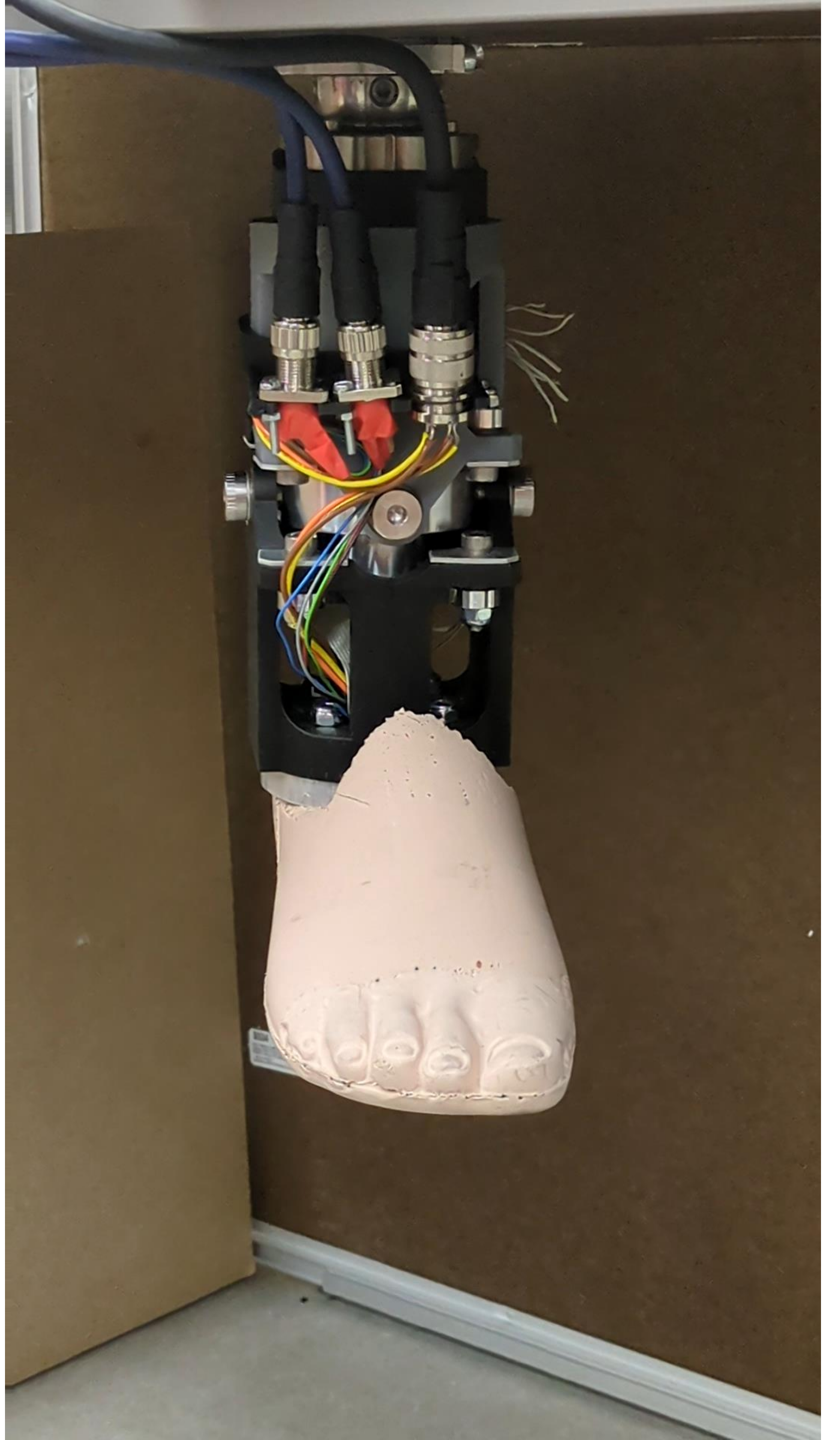


TADA

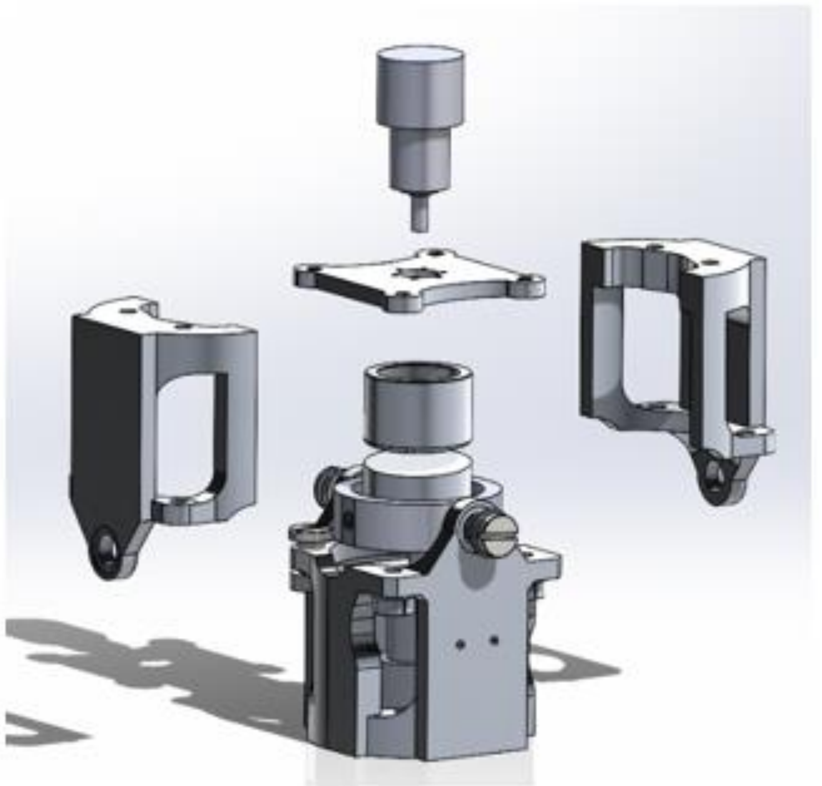
Purpose

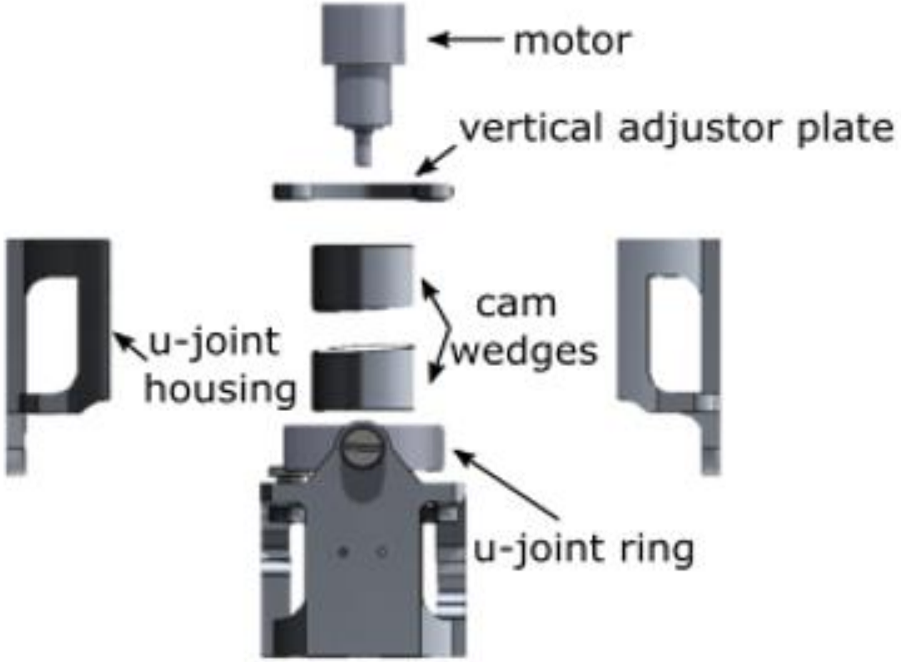
- Change ankle angle while the foot is in the air
- Detect foot motion and pylon load
- Sagittal (side view)
- Frontal (front view)





TADA





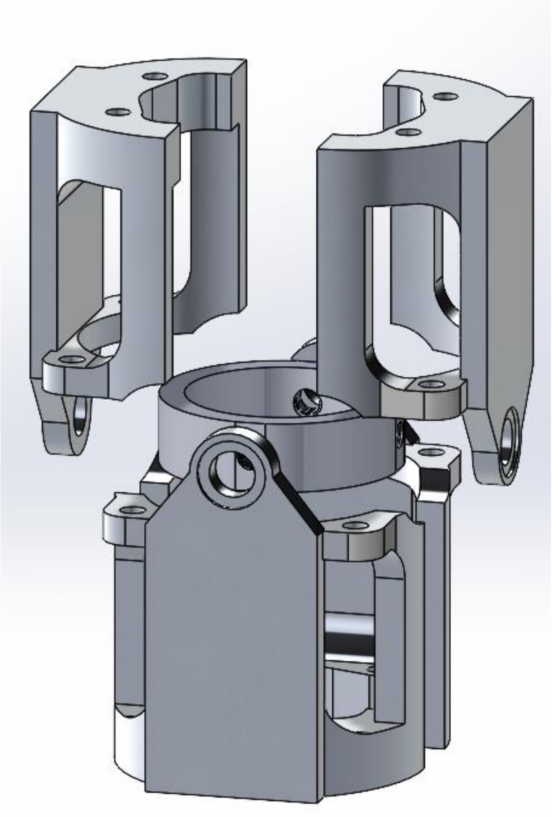
<u>Hardware</u>

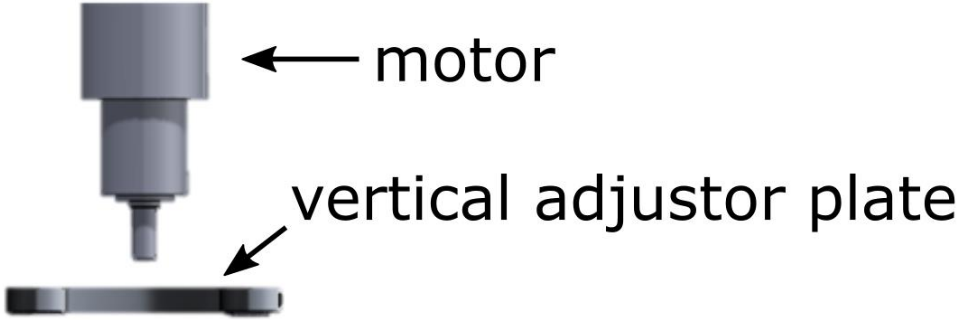
- Raspberry pi
- Motors
- Motor drivers
- Batteries

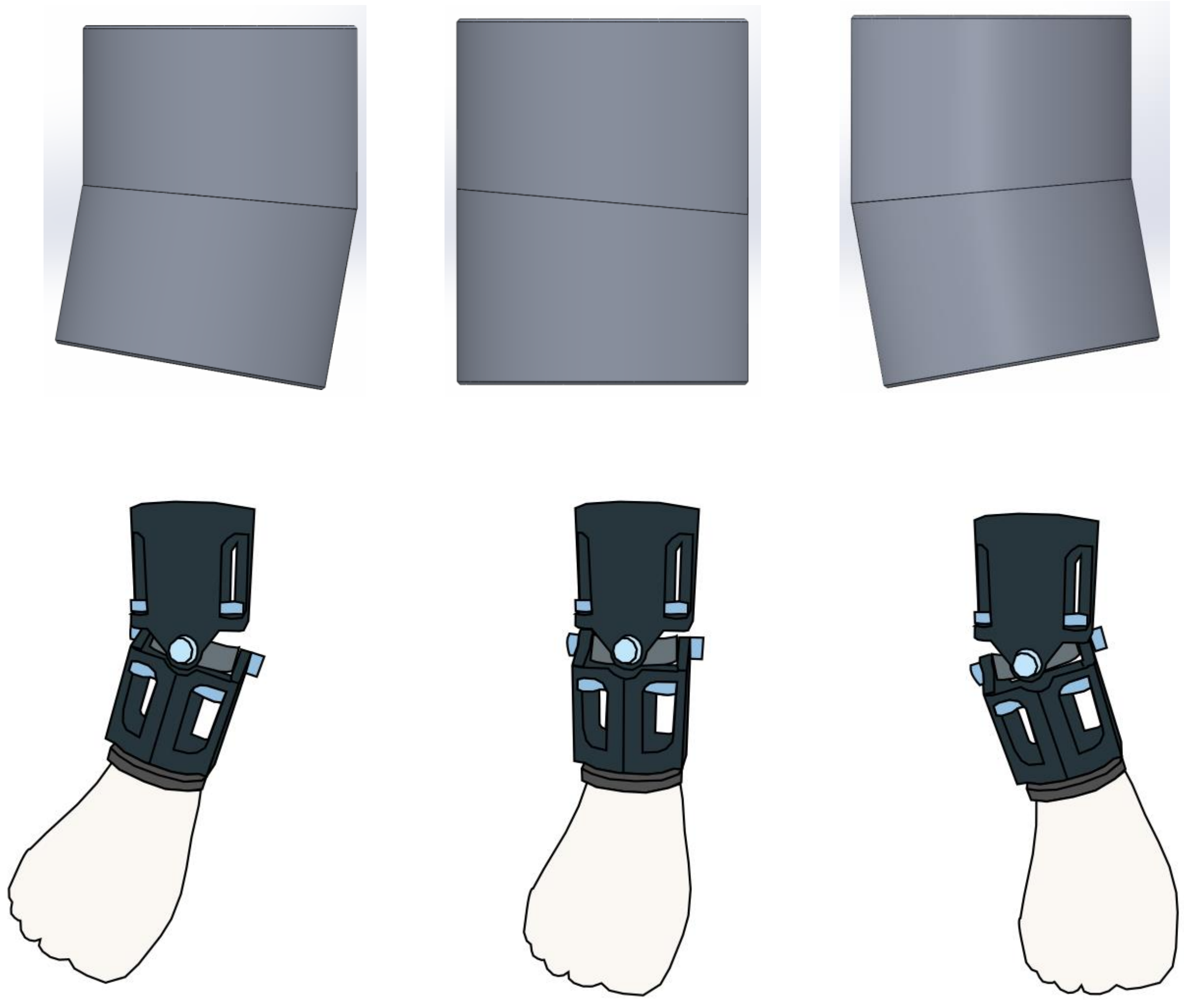
<u>Software</u>

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

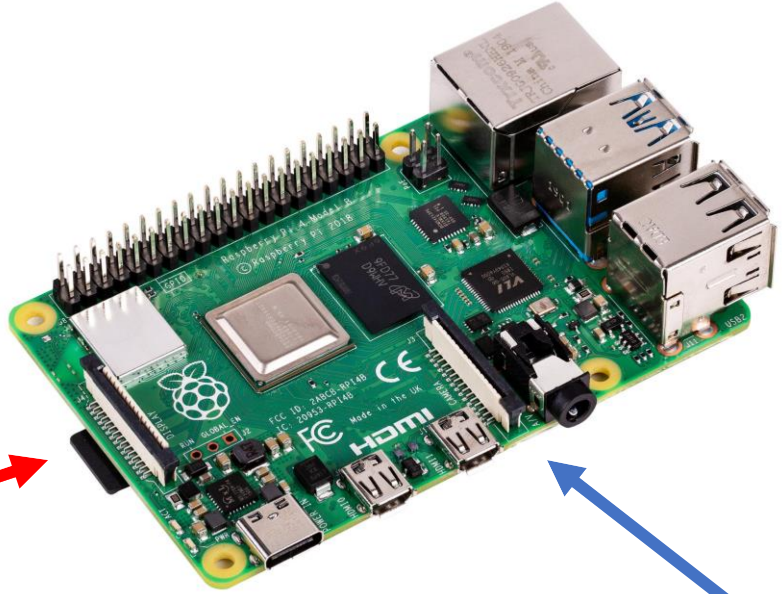
TADA Mechanism







Motor Control Software for TADA

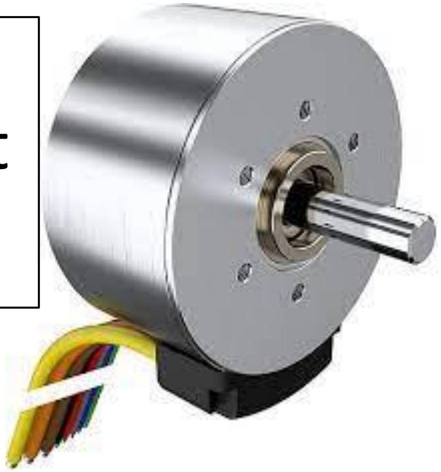


- Raspberry Pi 4
- Main controller
- Robotic Operating System (ROS)

Mobile hotspot

Windows laptop for the User Interface and Data saving

Faulhaber Brushless Direct Current Motors



TADA: Control Validation

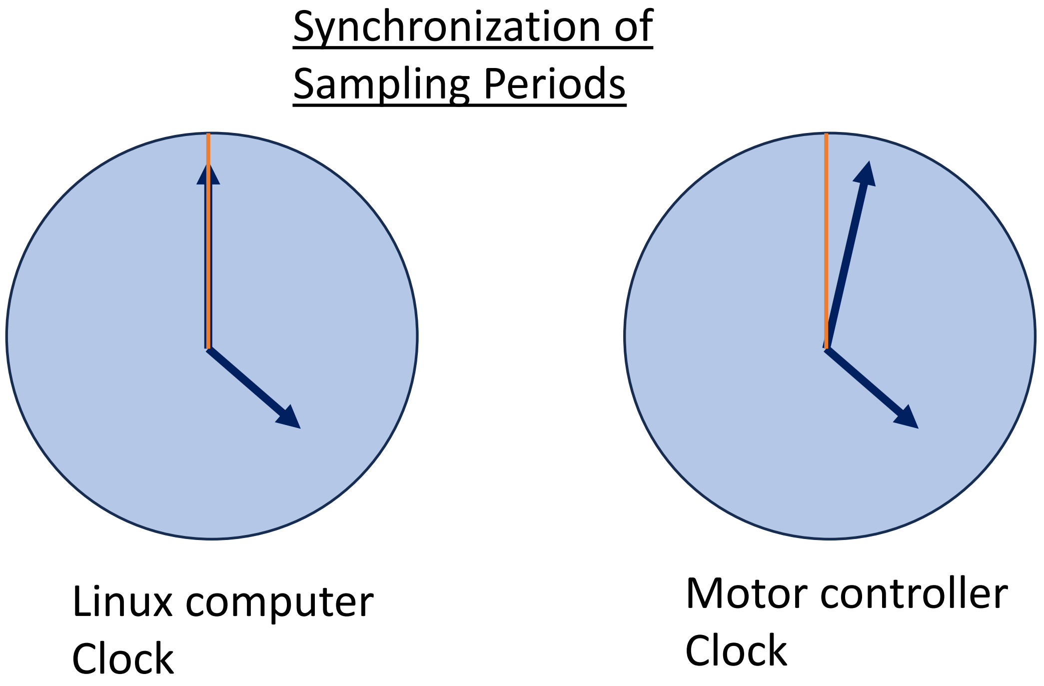
The TADA was randomly moved through 33 ankle configurations

- **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



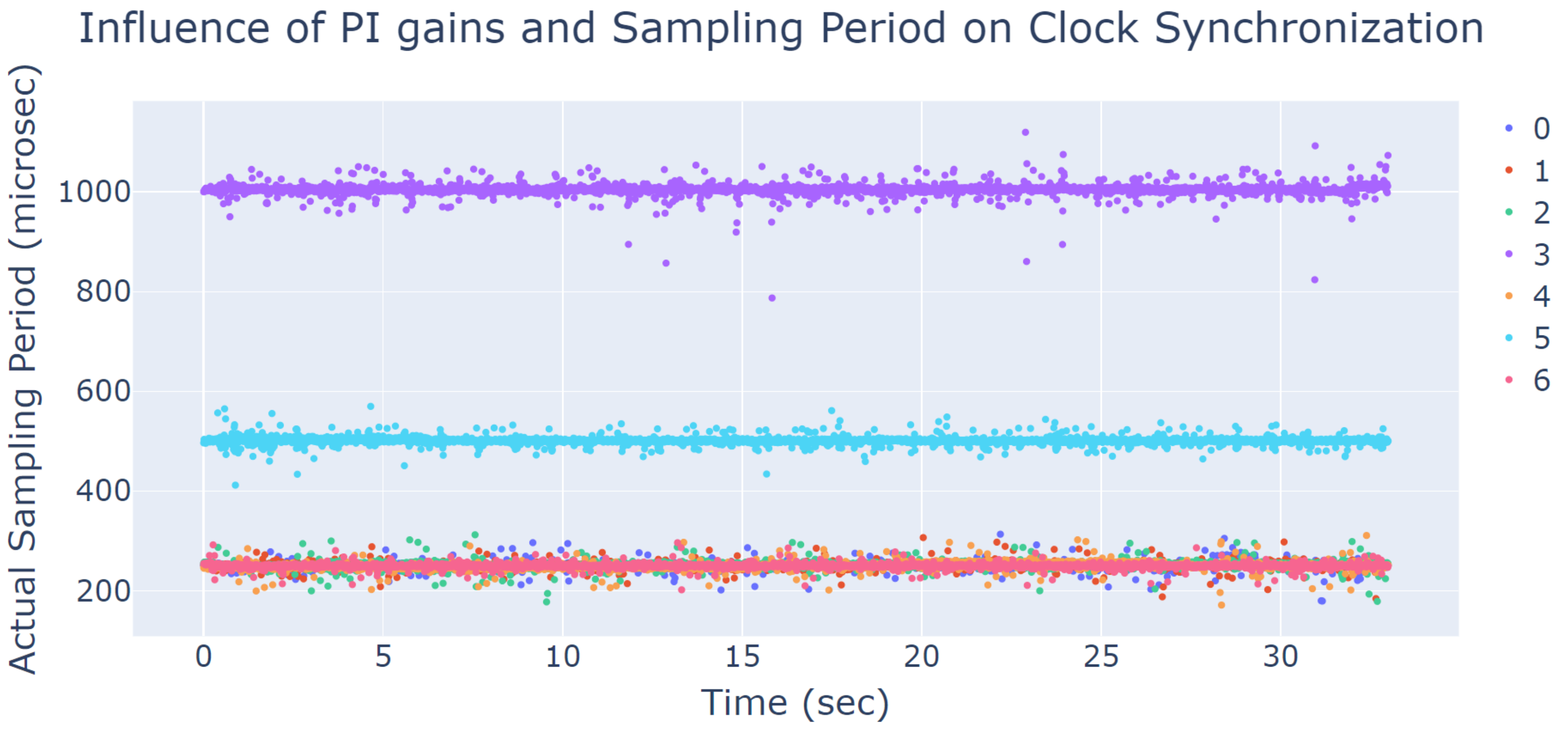
(7): Voss, W., 2008. A Comprehensible Guide to Controller Area Network. Copperhill Media

Reliability Test

For multiple settings,

clock synchronization using a Proportional Integrative (PI) control had

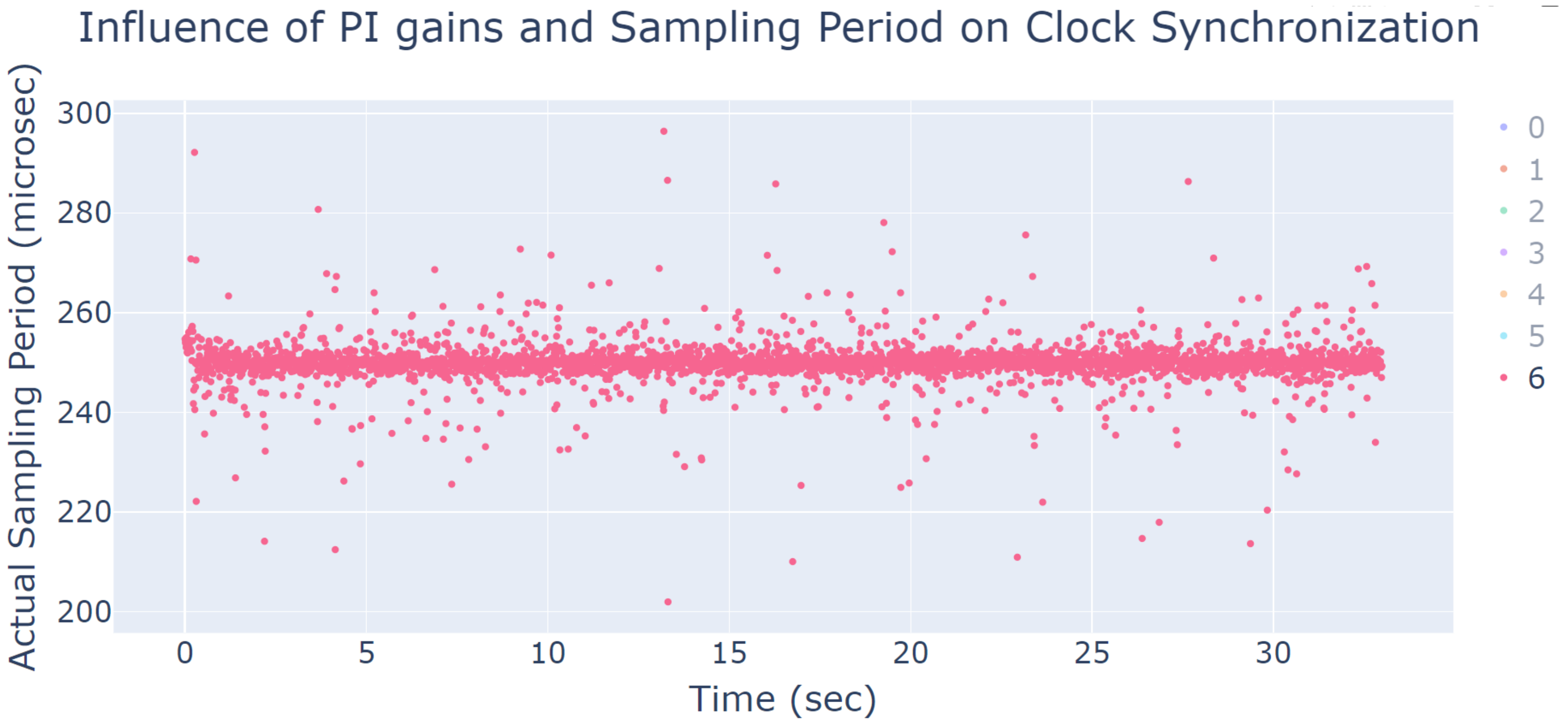
- Low mean error
- Low variability
- Reliable communication (no permanent drop-out)



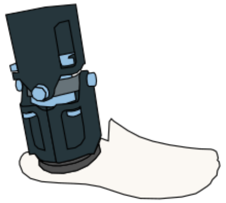
Reliability Test

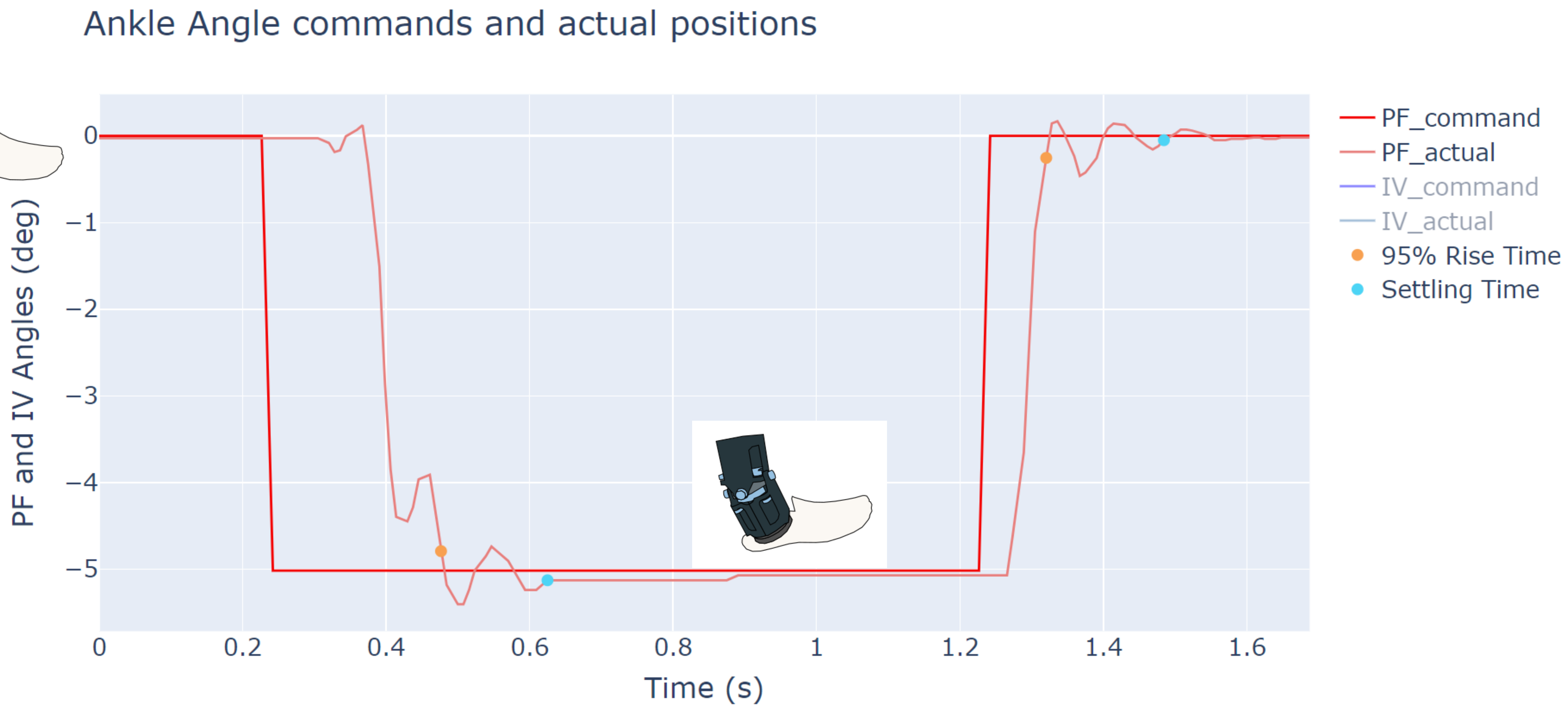
For the optimal setting,
clock synchronization had

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



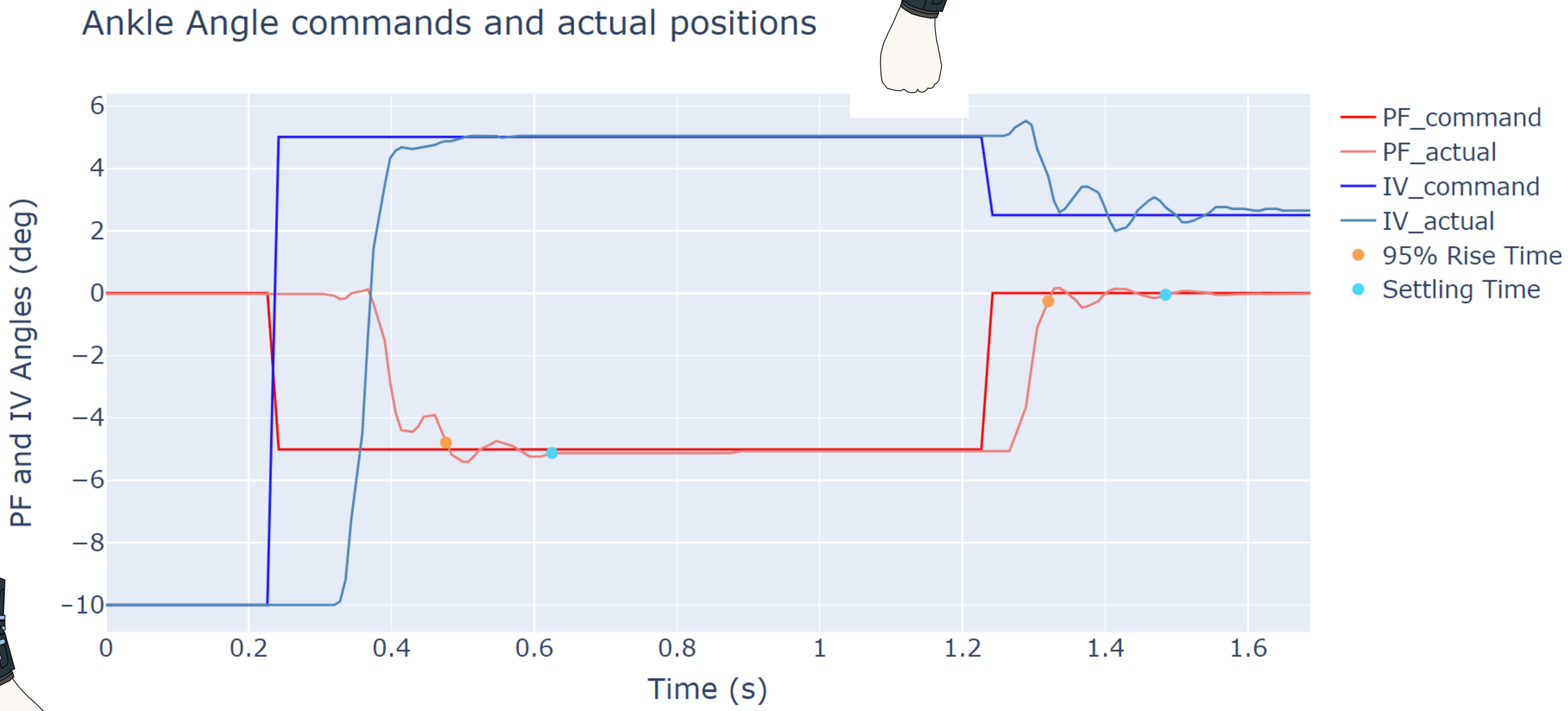
Precision Test



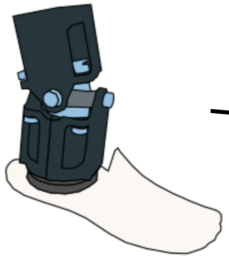


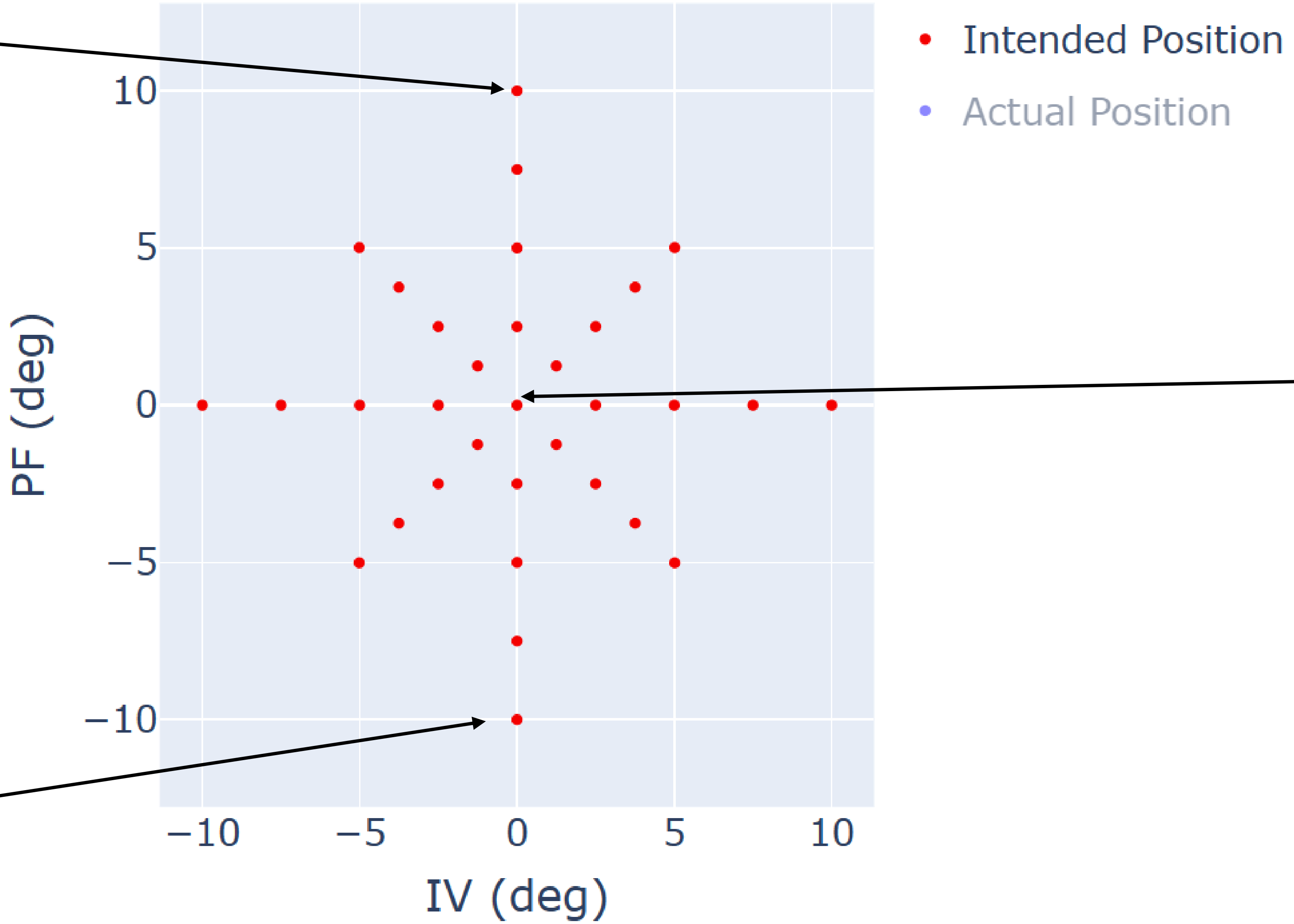
IV: inversion (foot inwards)

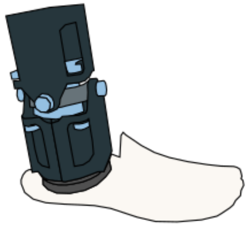
Precision Test

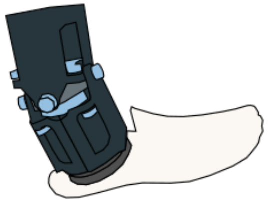


Pose Precision and Repeatability



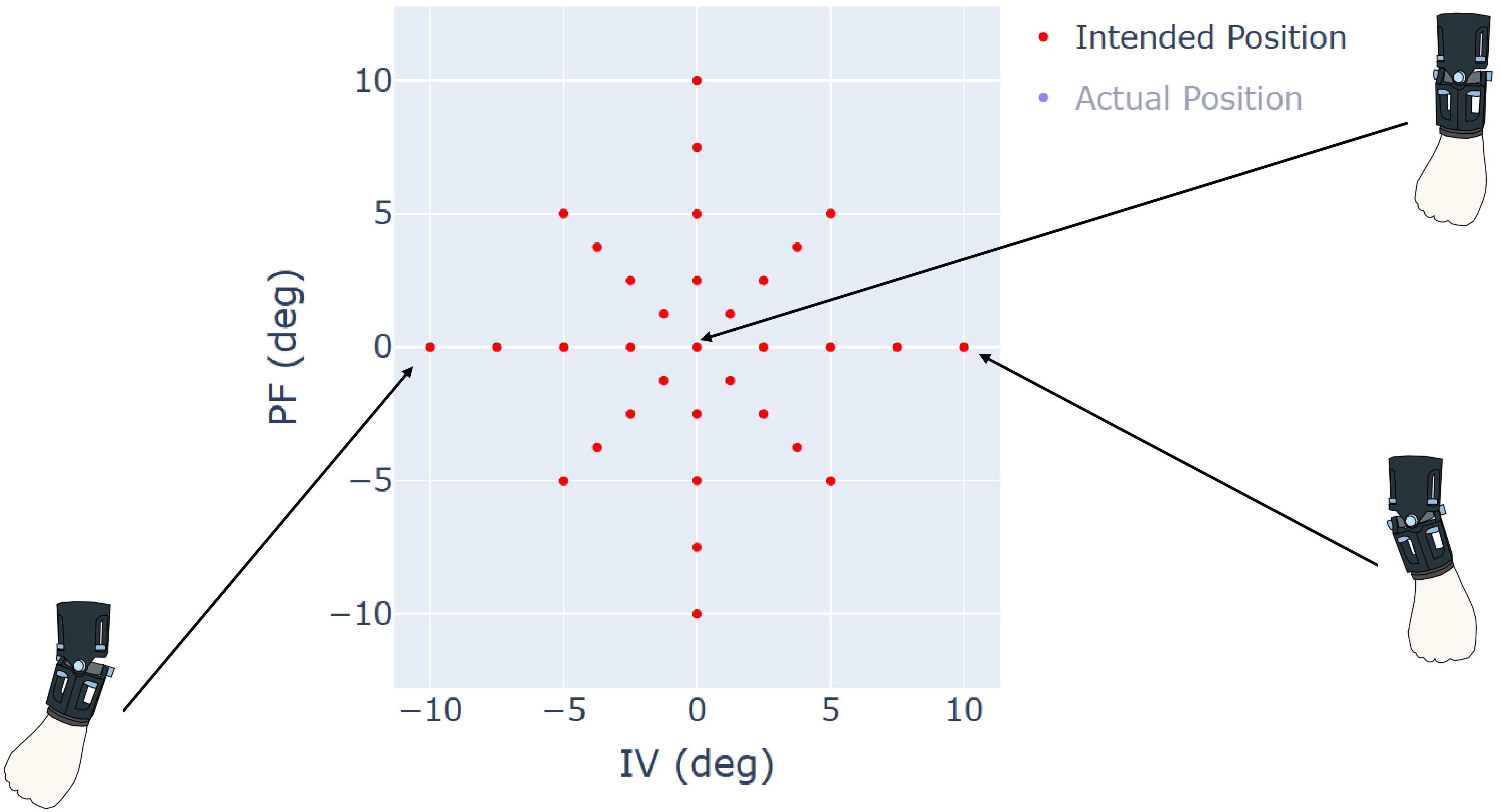






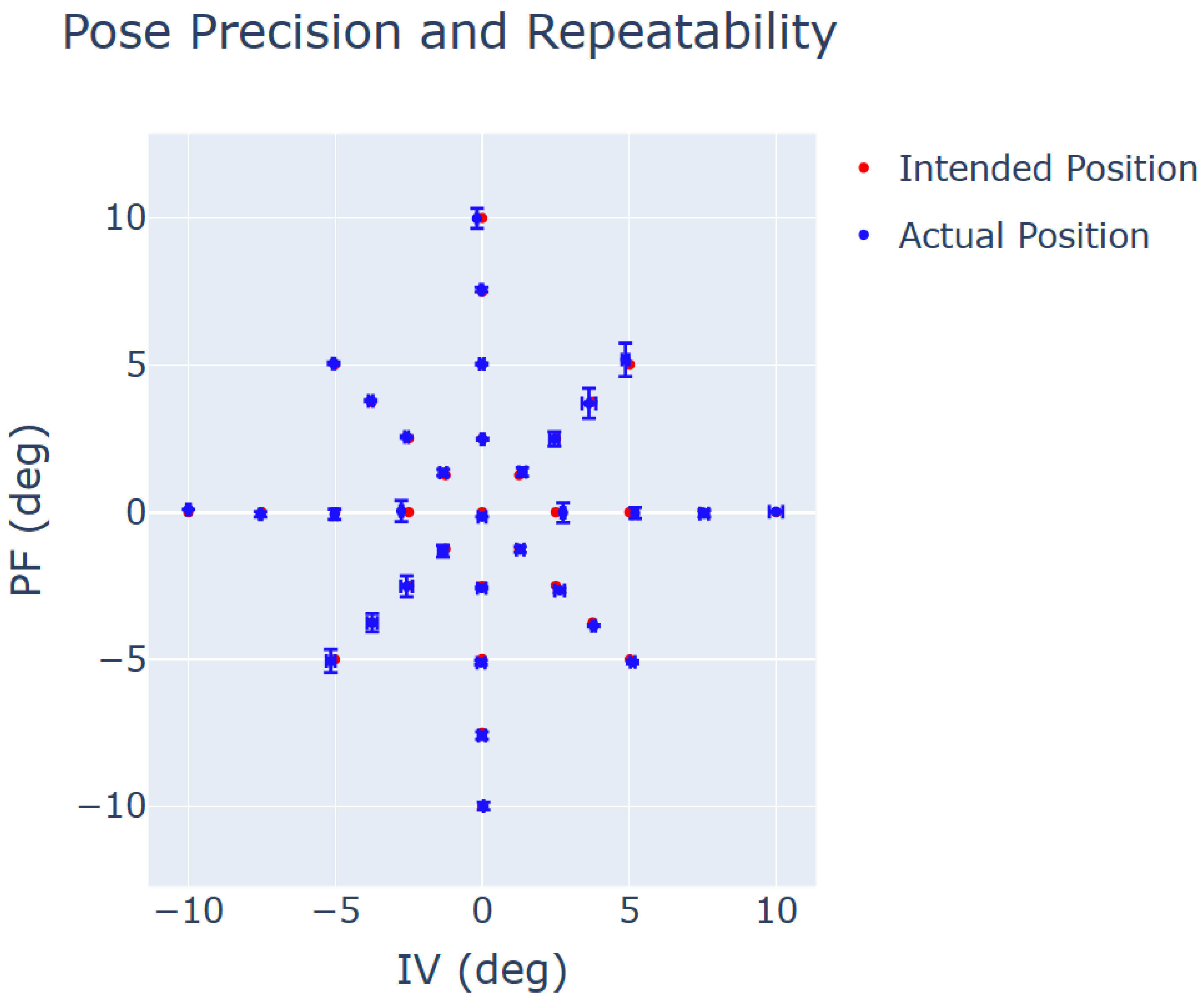
IV: inversion (foot inwards)

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

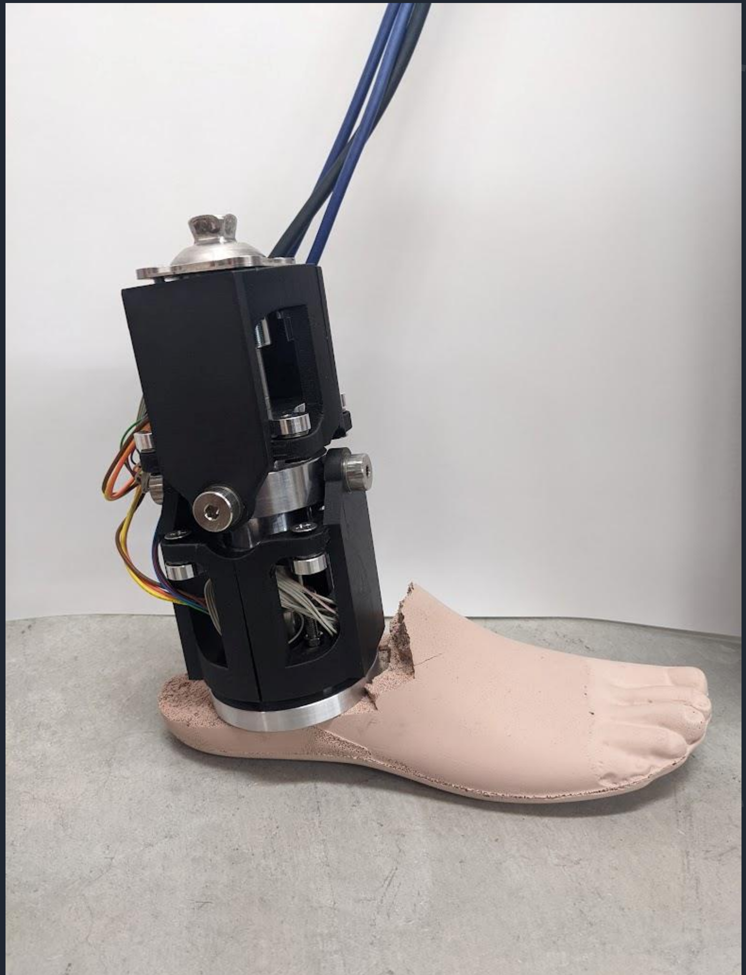


Conclusion

- 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

Background → Biomechanical Evaluation of the VSF → Motor control for the TADA → **PILOT BIOMECHANICAL EVALUATION OF THE TADA**



TADA Instrumentation

Lower-leg-specific

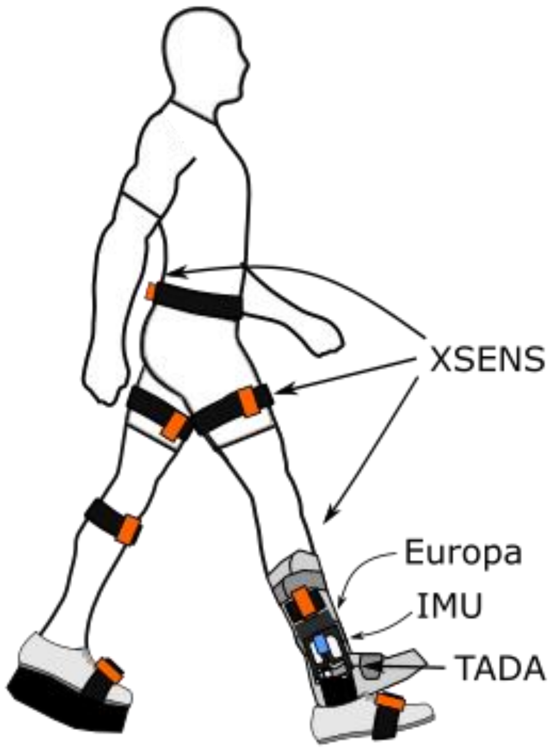
- Load cell for pylon moments and forces
- Motor angles
- Inertial measurement unit (IMU) for leg movement

Body-specific

- Xsens IMU suit
- Waist pack

Front view

Frontal

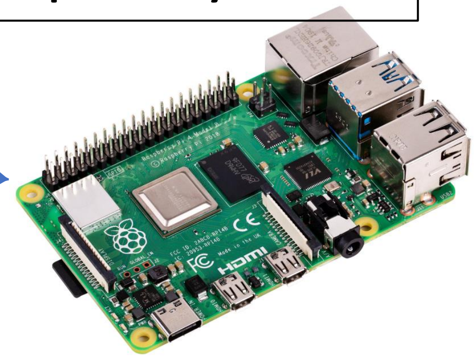


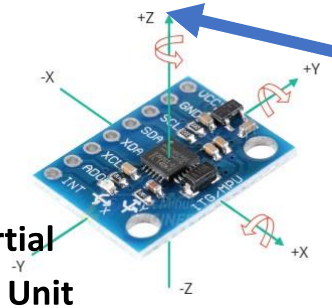
Side view

Sagittal

Fully Wearable Instrumentation System

Raspberry Pi





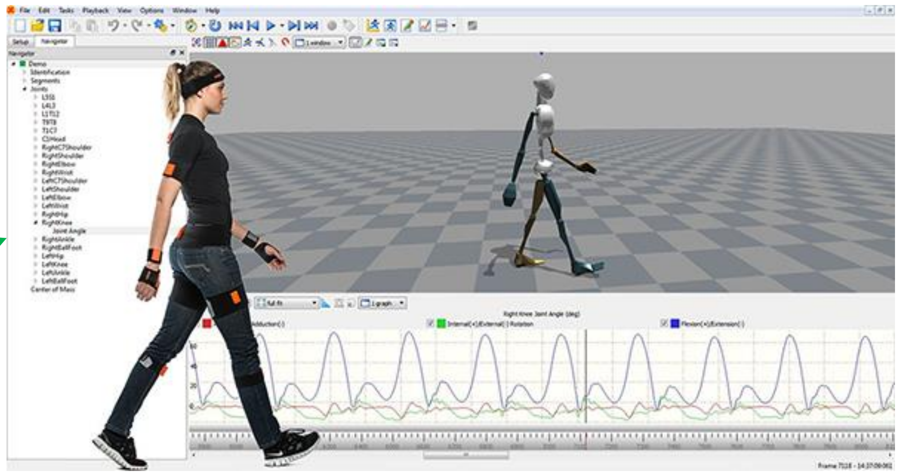
MPU6050 Inertial Measurement Unit (IMU)
- Leg swing detection

Europa+ load cell
- Axial force
- Sagittal and frontal moments

Mobile hotspot

Xsens lower-body Motion Capture suit
- Joint angles
- Segment motion
- center of mass motion

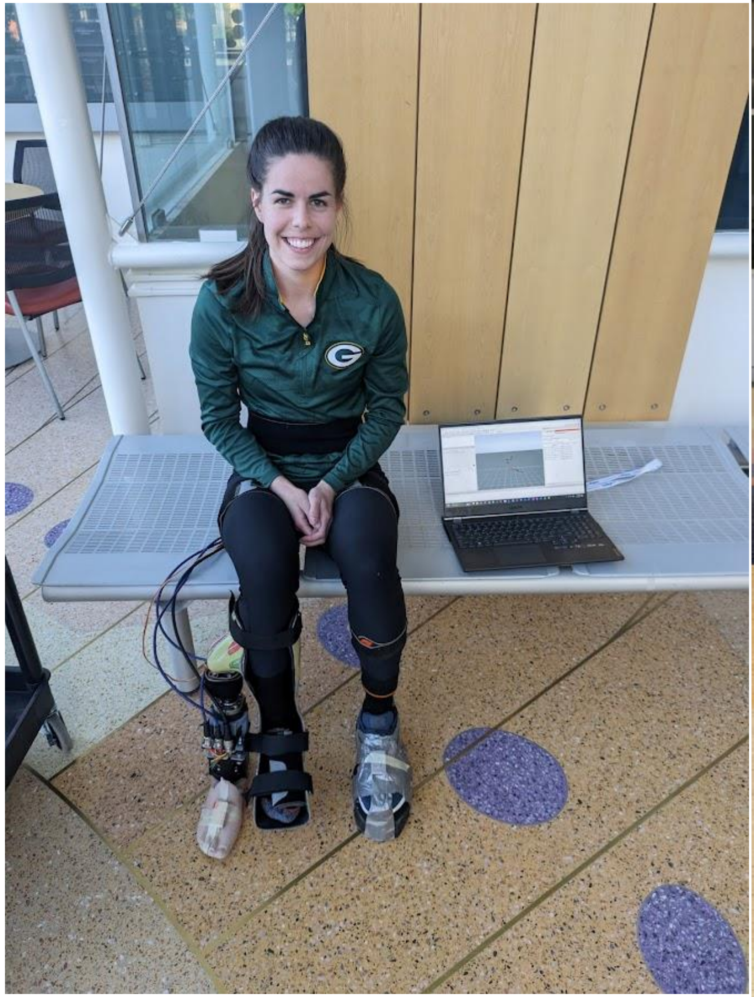
Windows laptop

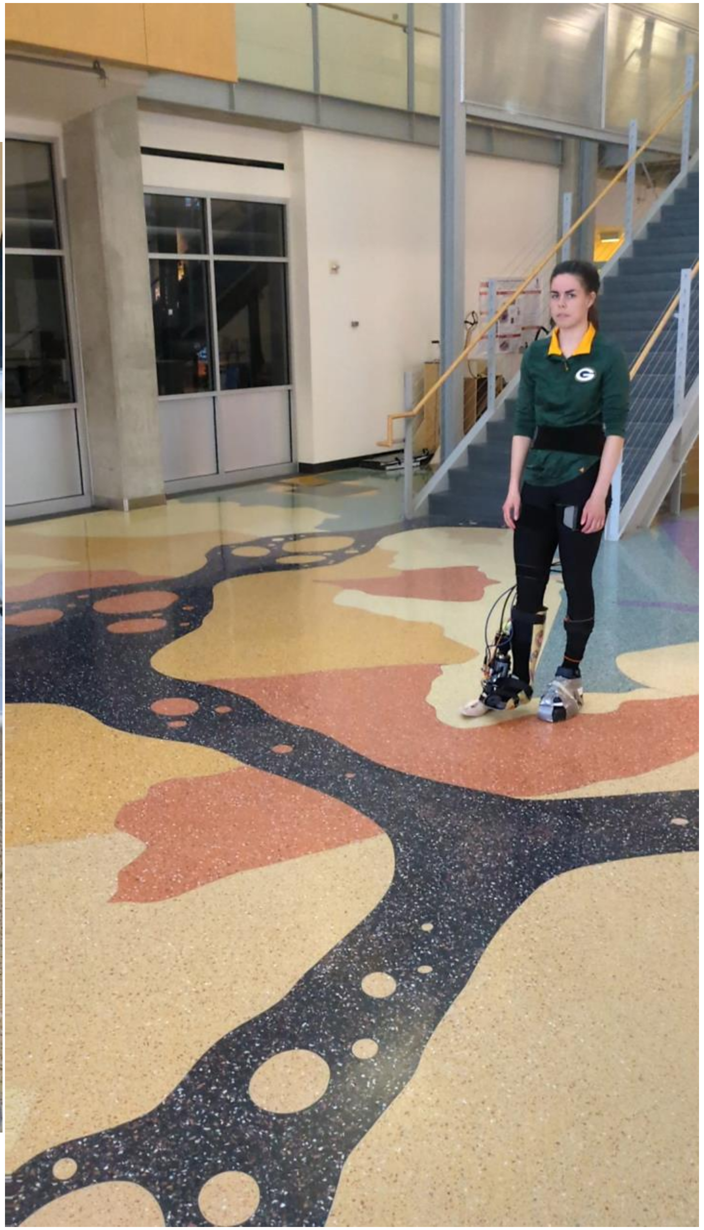


Goals of Pilot Test

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

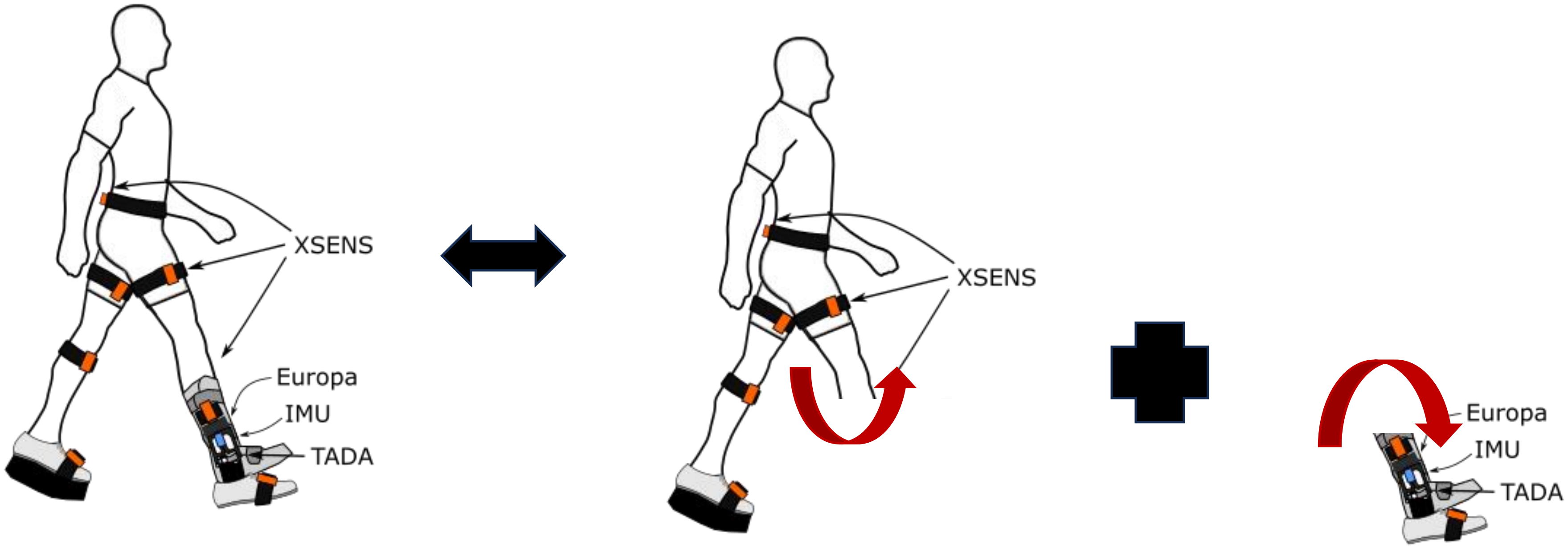
- One participant
- Walked at slow, medium, and fast self-selected walking speeds
- TADA alternated between
  - 8 steps of chosen angles
  - 5 steps of neutral



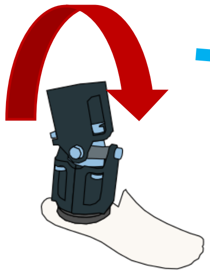


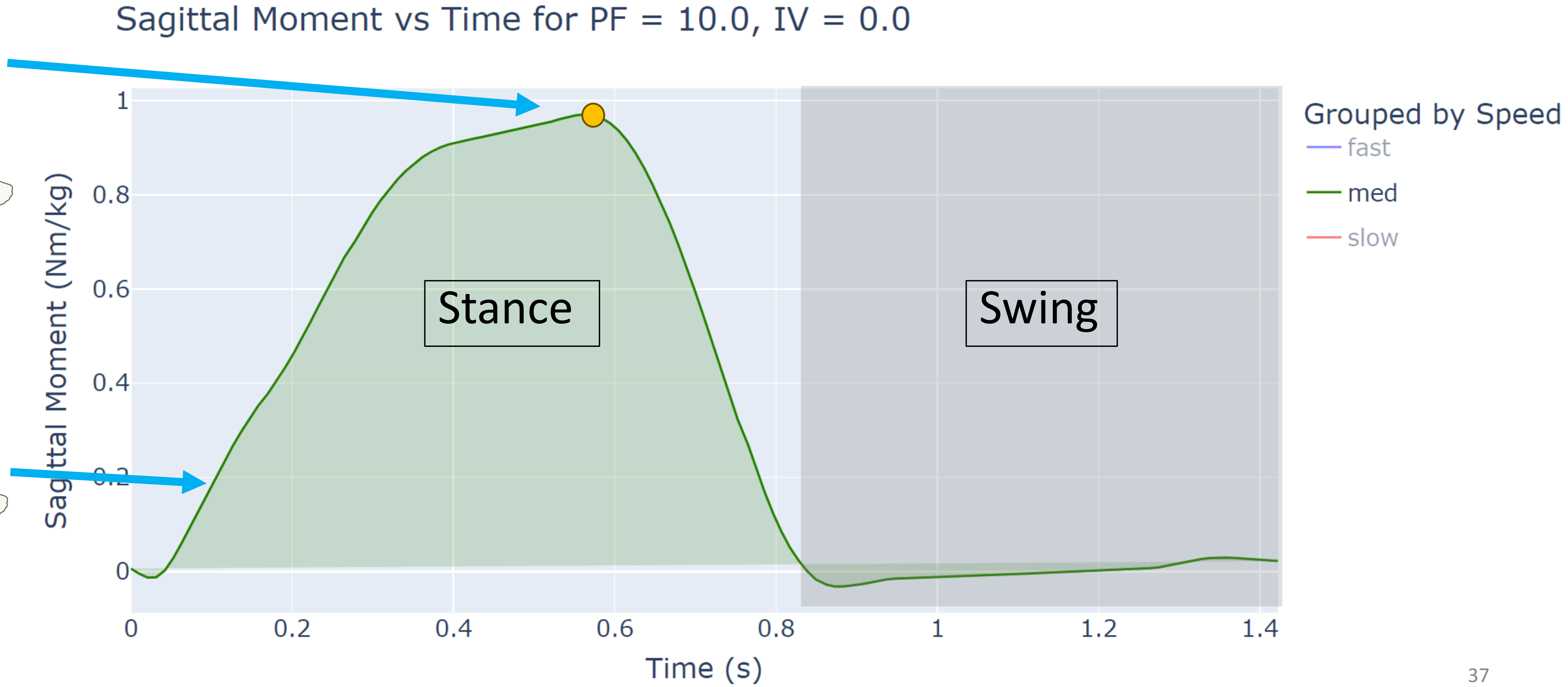
TADA

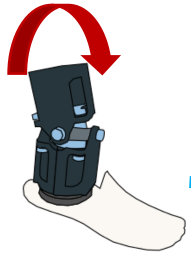
- Pylon Load cell
  - Sagittal Plantarflexor Moments
  - Frontal Evertor Moments
- Moments = Rotational Action of upper shank on prosthetic device
- For this presentation, we will focus on Plantarflexor Moments



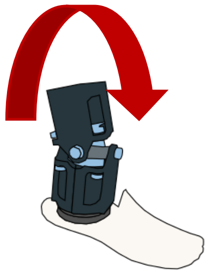
TADA

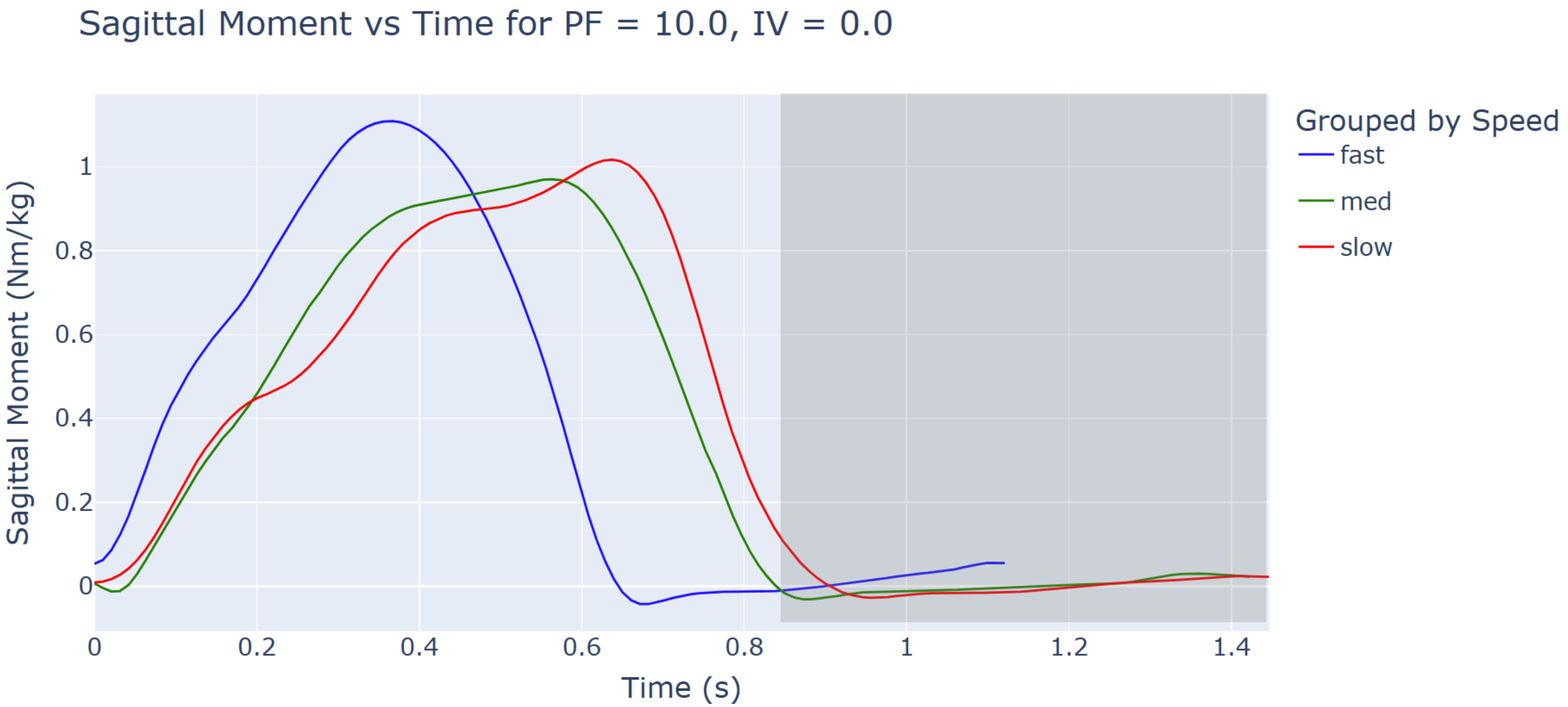



Sagittal Moment vs Time for PF = 10.0, IV = 0.0
Sagittal Moment (Nm/kg)
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Time (s)
Stance
Swing
Grouped by Speed
fast
med
slow

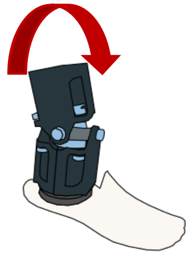


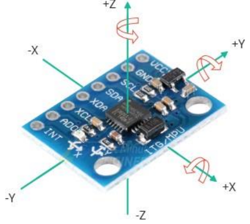
TADA

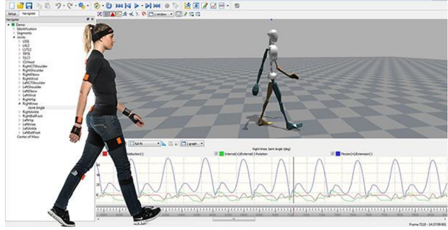




Sagittal Moment vs Time for PF = 10.0, IV = 0.0
Sagittal Moment (Nm/kg)
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Time (s)
Grouped by Speed
fast
med
slow

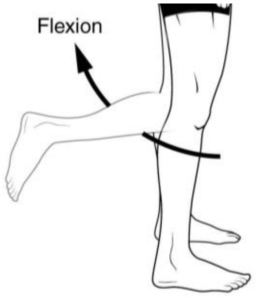


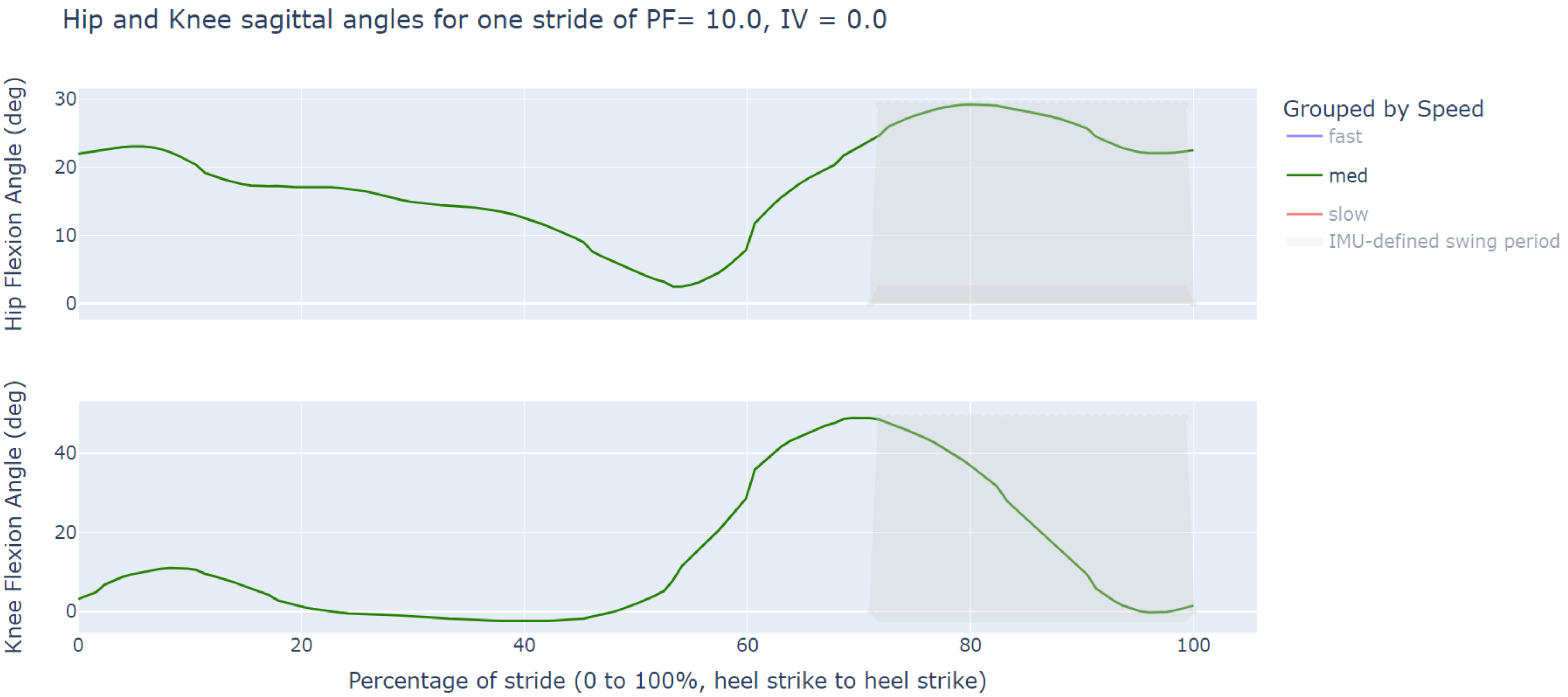




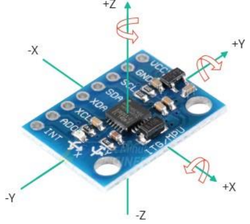
TADA


Flexion

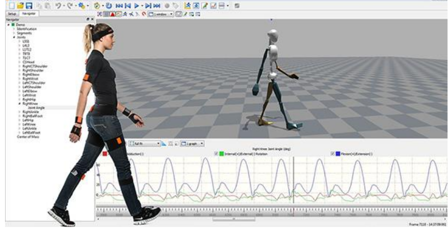

Flexion


Hip and Knee sagittal angles for one stride of PF= 10.0, IV = 0.0
Hip Flexion Angle (deg)
30
20
10
0
Knee Flexion Angle (deg)
40
20
0
0
20
40
60
80
100
Percentage of stride (0 to 100%, heel strike to heel strike)
Grouped by Speed
fast
med
slow
IMU-defined swing period

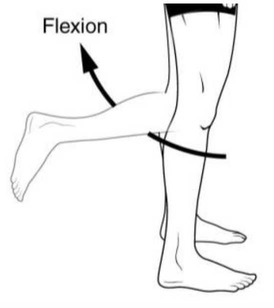
TADA



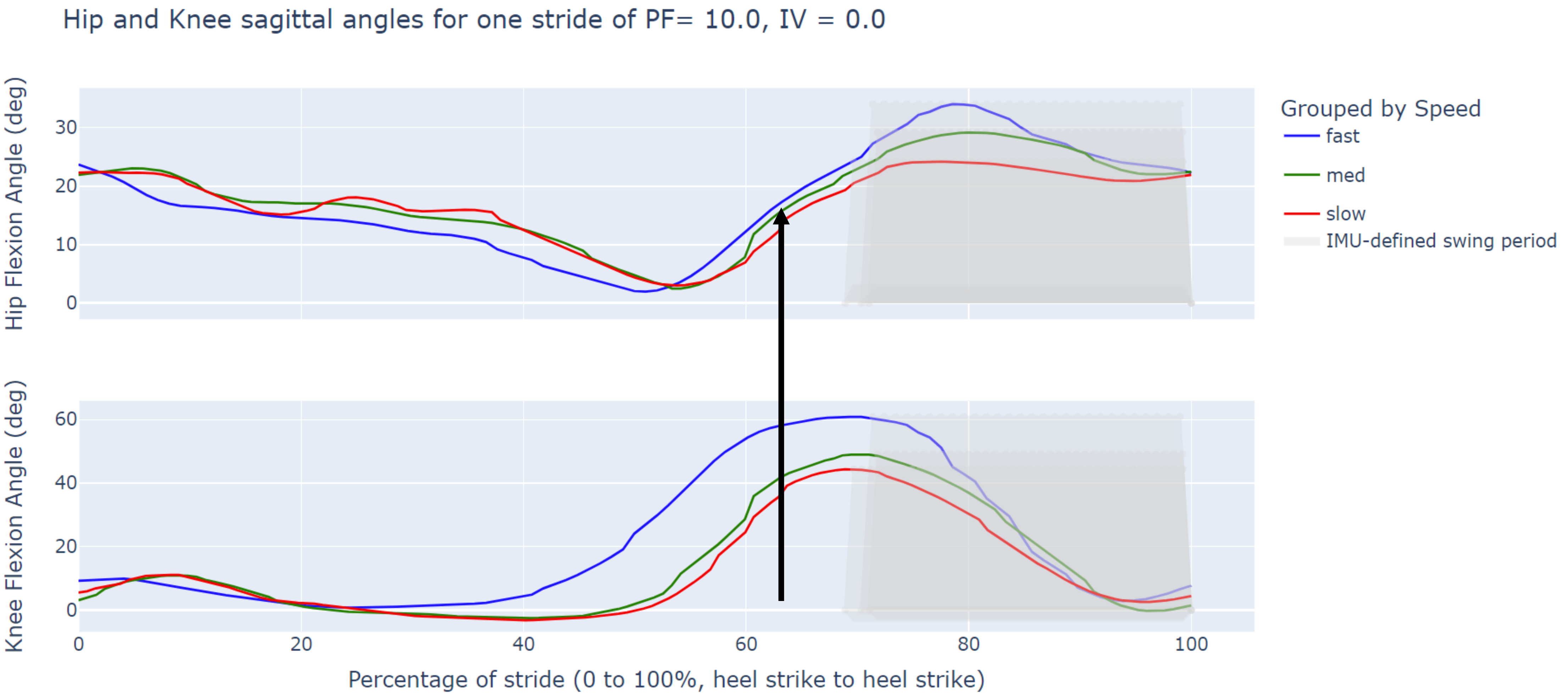
+Z
-X
+Y
-Y
+X
-Z



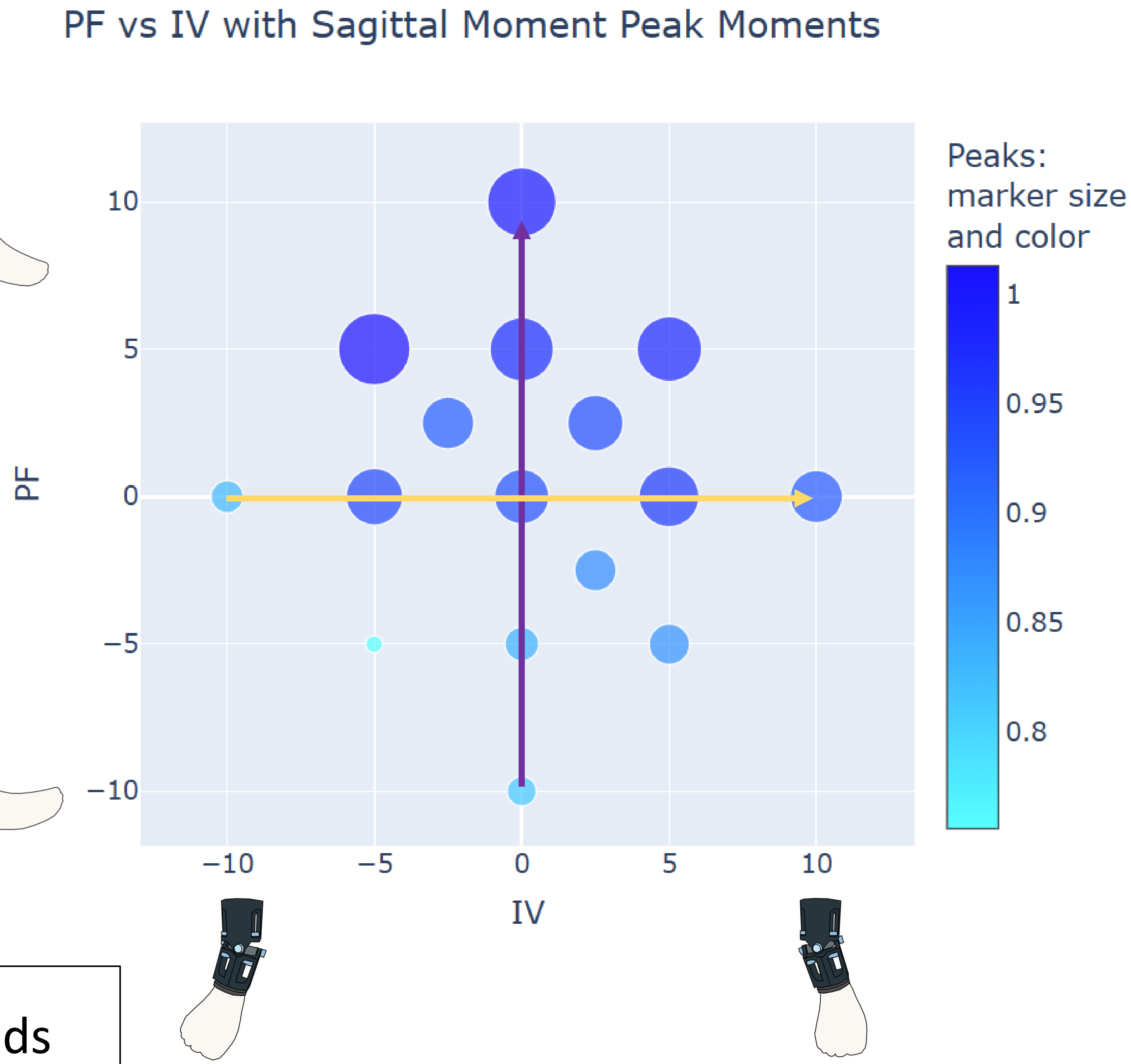
Flexion



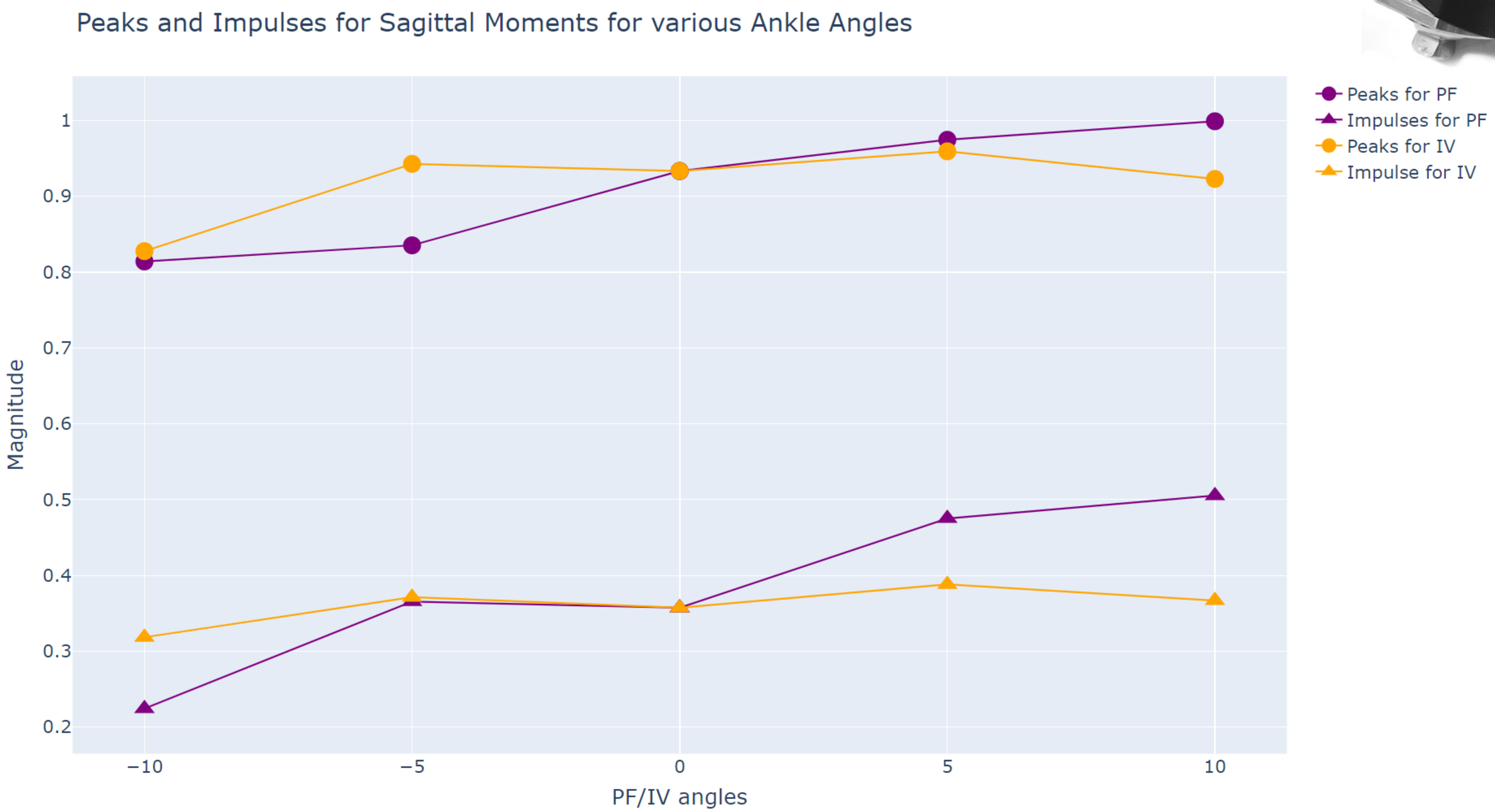
Flexion



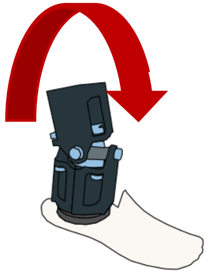
Hip and Knee sagittal angles for one stride of PF= 10.0, IV = 0.0
Hip Flexion Angle (deg)
0
10
20
30
Knee Flexion Angle (deg)
0
20
40
60
0
20
40
60
80
100
Percentage of stride (0 to 100%, heel strike to heel strike)
Grouped by Speed
fast
med
slow
IMU-defined swing period

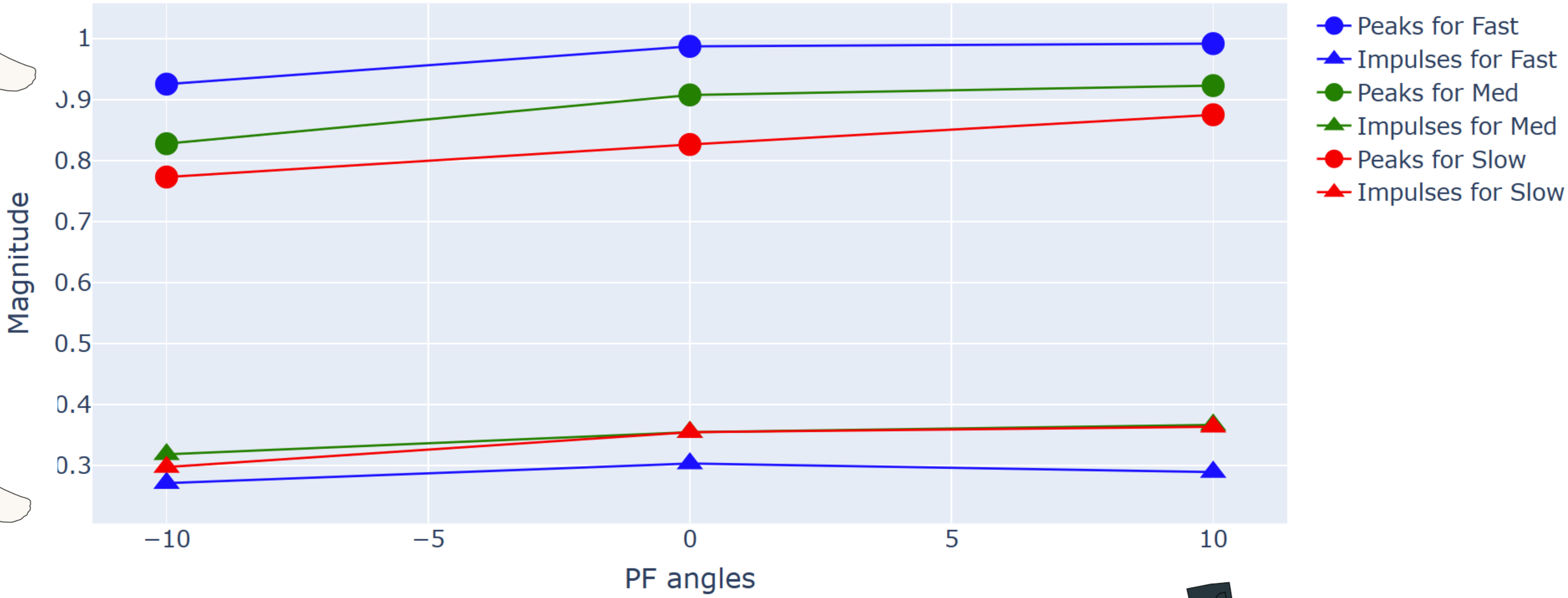


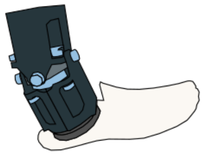
Sagittal Impulses show similar trends

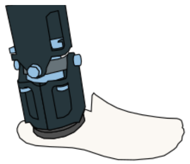

Peaks and Impulses for Sagittal Moments for various Ankle Angles
Magnitude
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
−10
−5
0
5
10
PF/IV angles
Peaks for PF
Impulses for PF
Peaks for IV
Impulse for IV

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







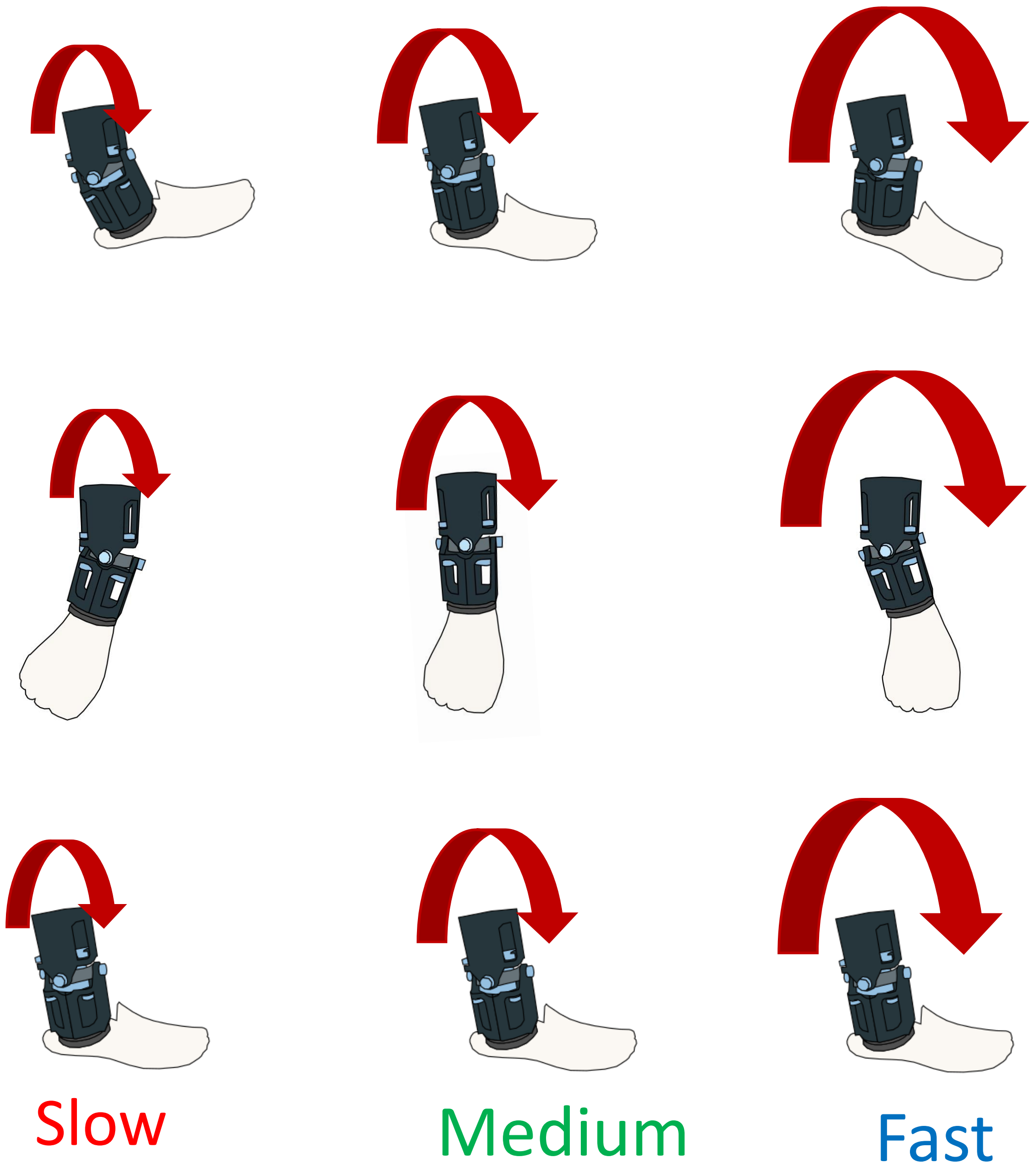


Results

- peak Plantarflexor moment and impulses increased with increased plantarflexion angles

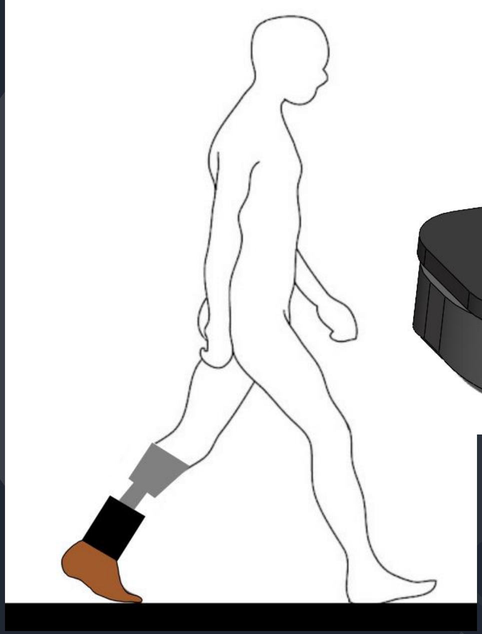
- peak Evertor moment and impulses increased with increased Inversion angles

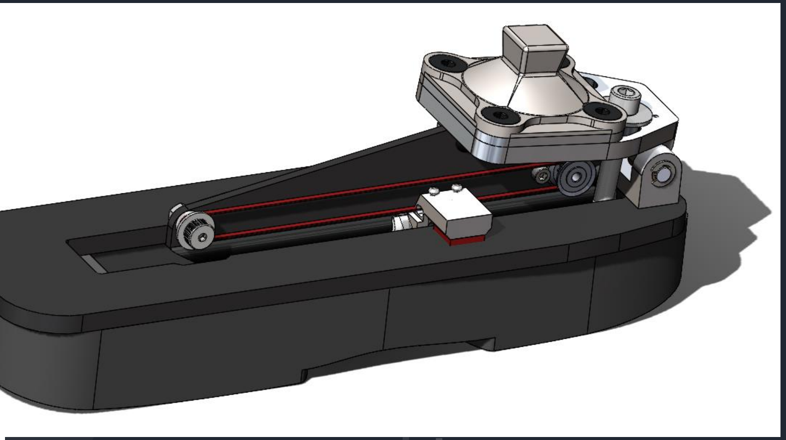
- peak Plantarflexor pylon moments increased with increased walking speed

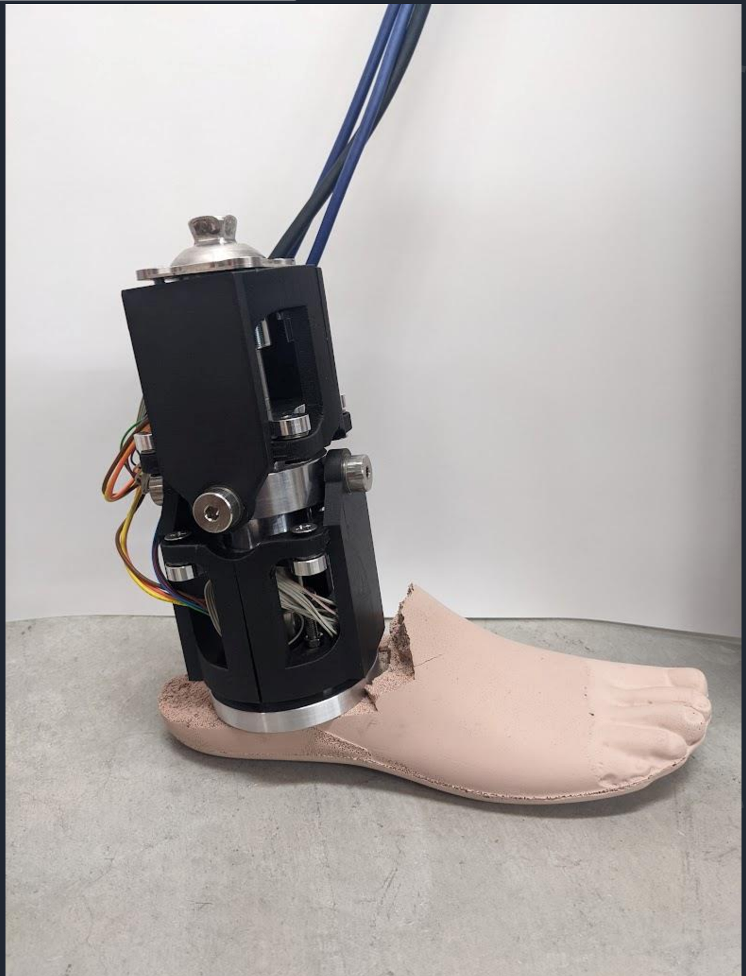


General Discussion

Background → Biomechanical Evaluation of VSF → Motor control for TADA → Biomechanical Evaluation of TADA



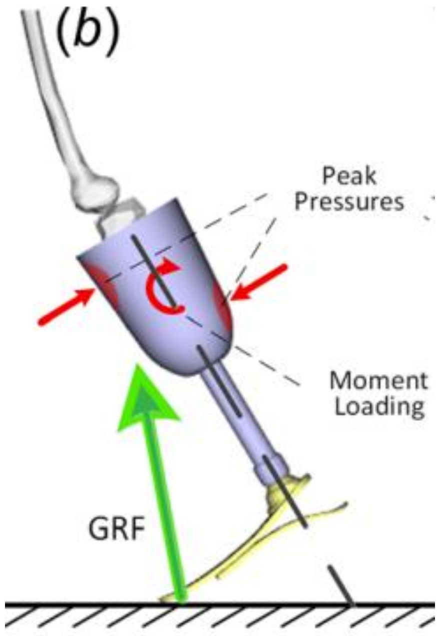


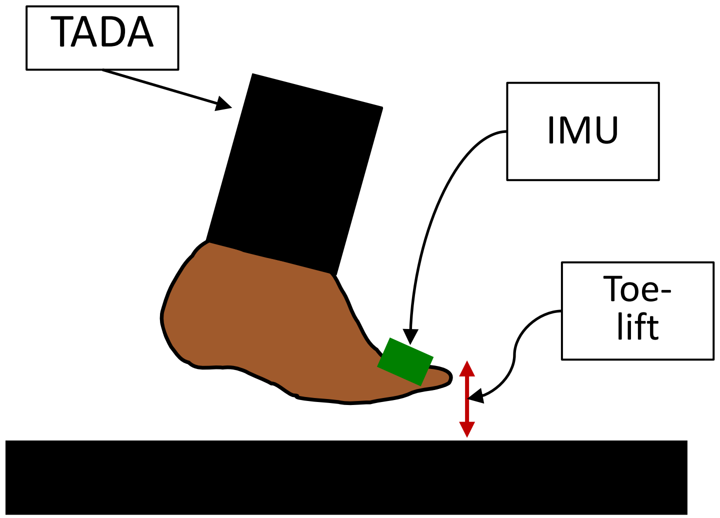


Key takeaways

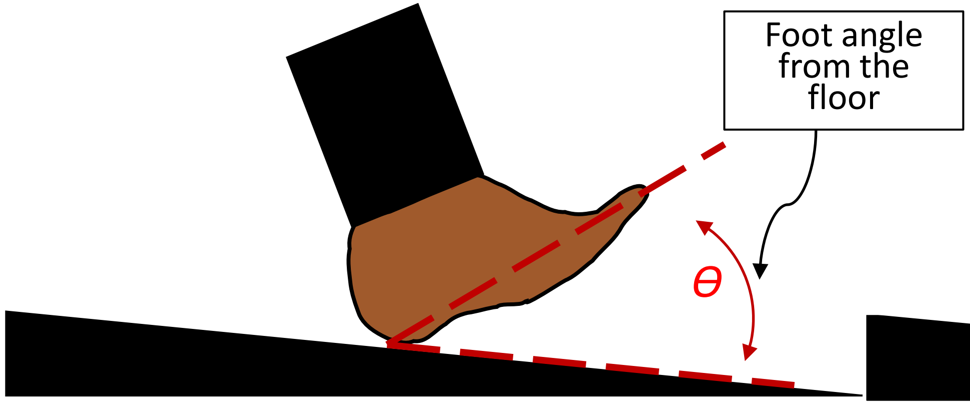
- The VSF could help reduce joint overuse and return more intact ankle functionality
- The TADA can control 2D ankle angle in a reliable and precise way
- Lower pylon moments could help lower socket discomfort
- The TADA is ready for out-of-the-lab experiments

Future Work: TADA Control Algorithms

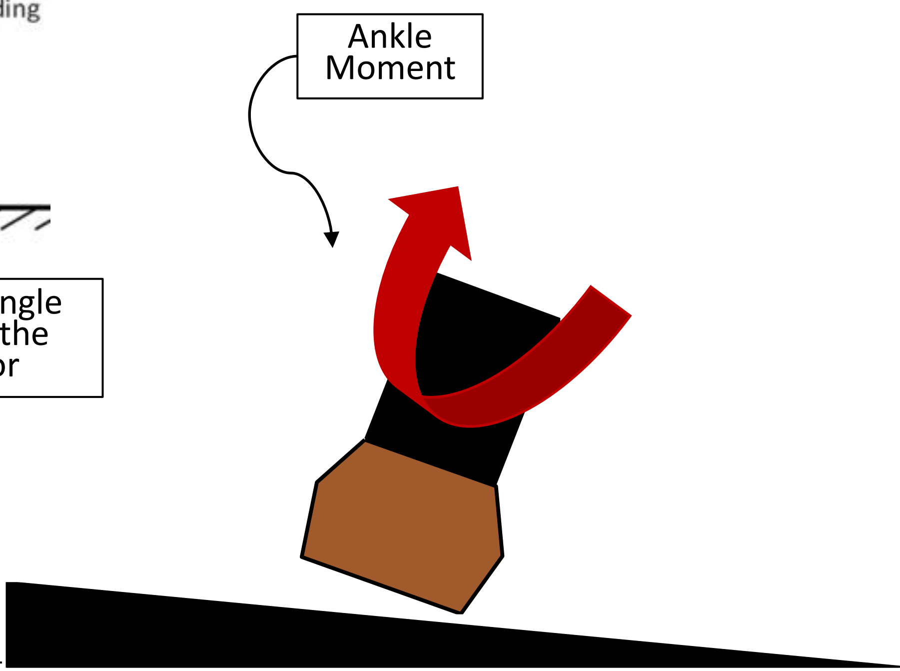




Toe-lift control



Slope-Matching Control



Moment-Targeting Control[6]

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

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2. Adamczyk, Peter Gabriel. "Semi-active prostheses for low-power gait adaptation." Powered Prostheses. Academic Press, 2020. 201-259.
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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

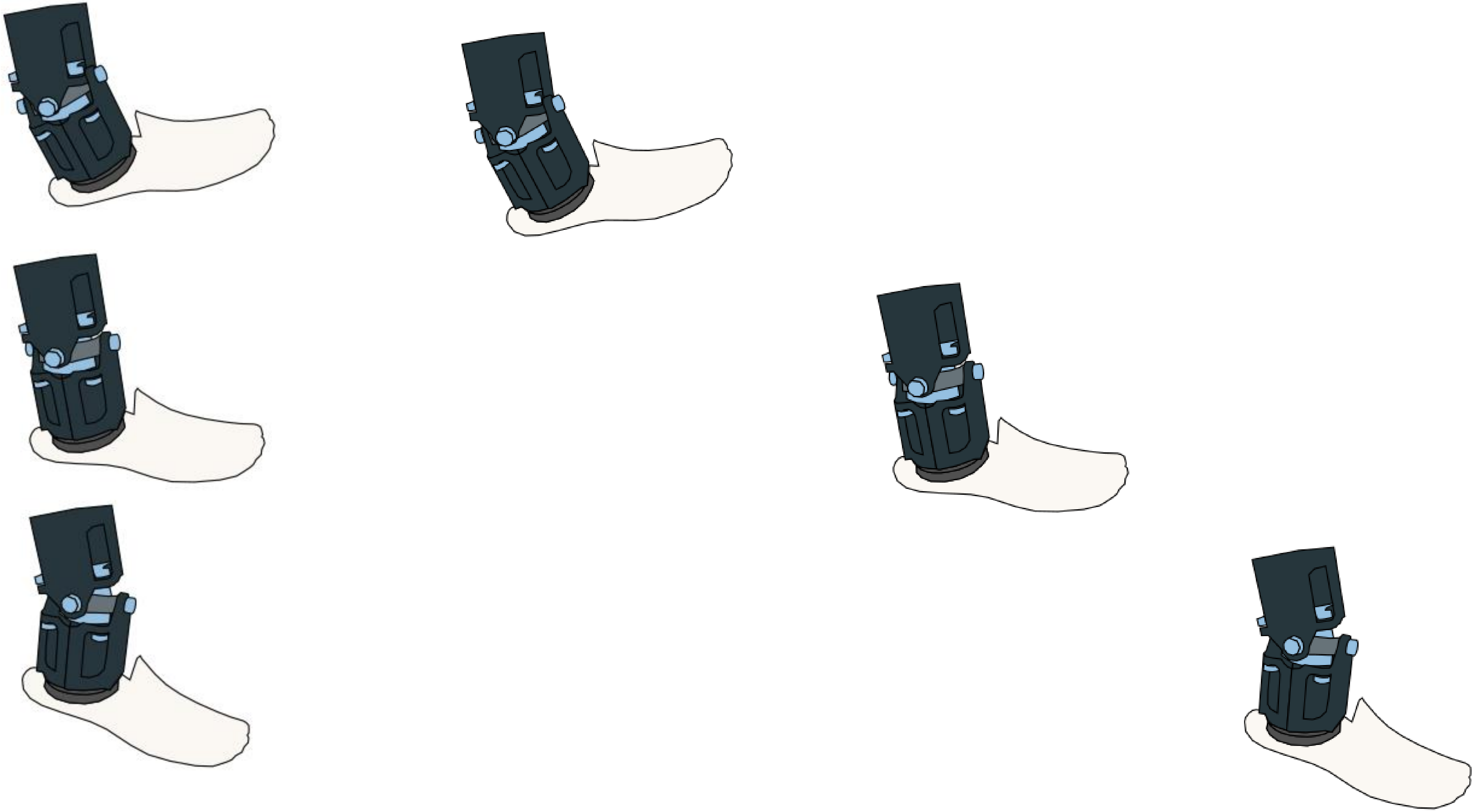
Limitations

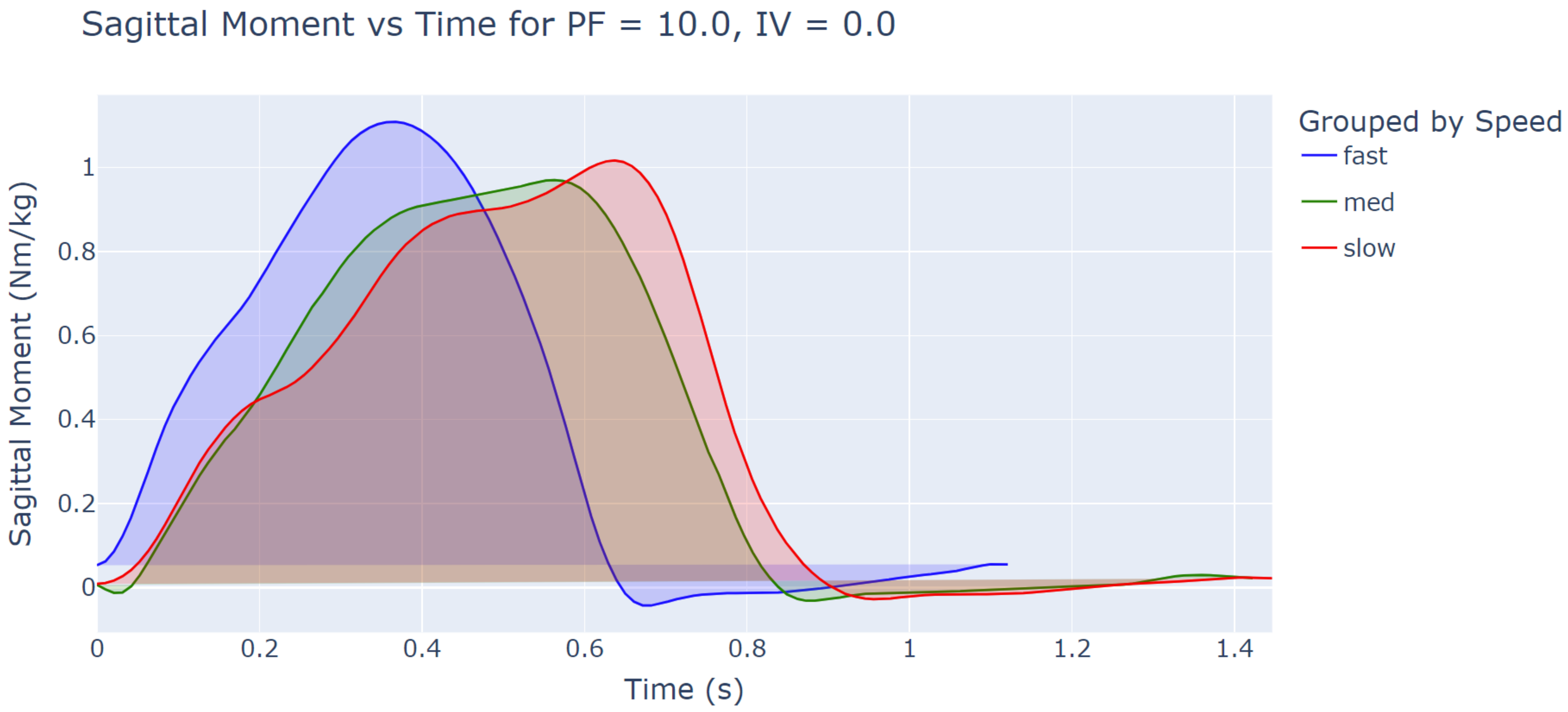
1. TADA with unimpaired person vs. person with a transtibial amputation

2. Need to collect more data with unimpaired and impaired participants

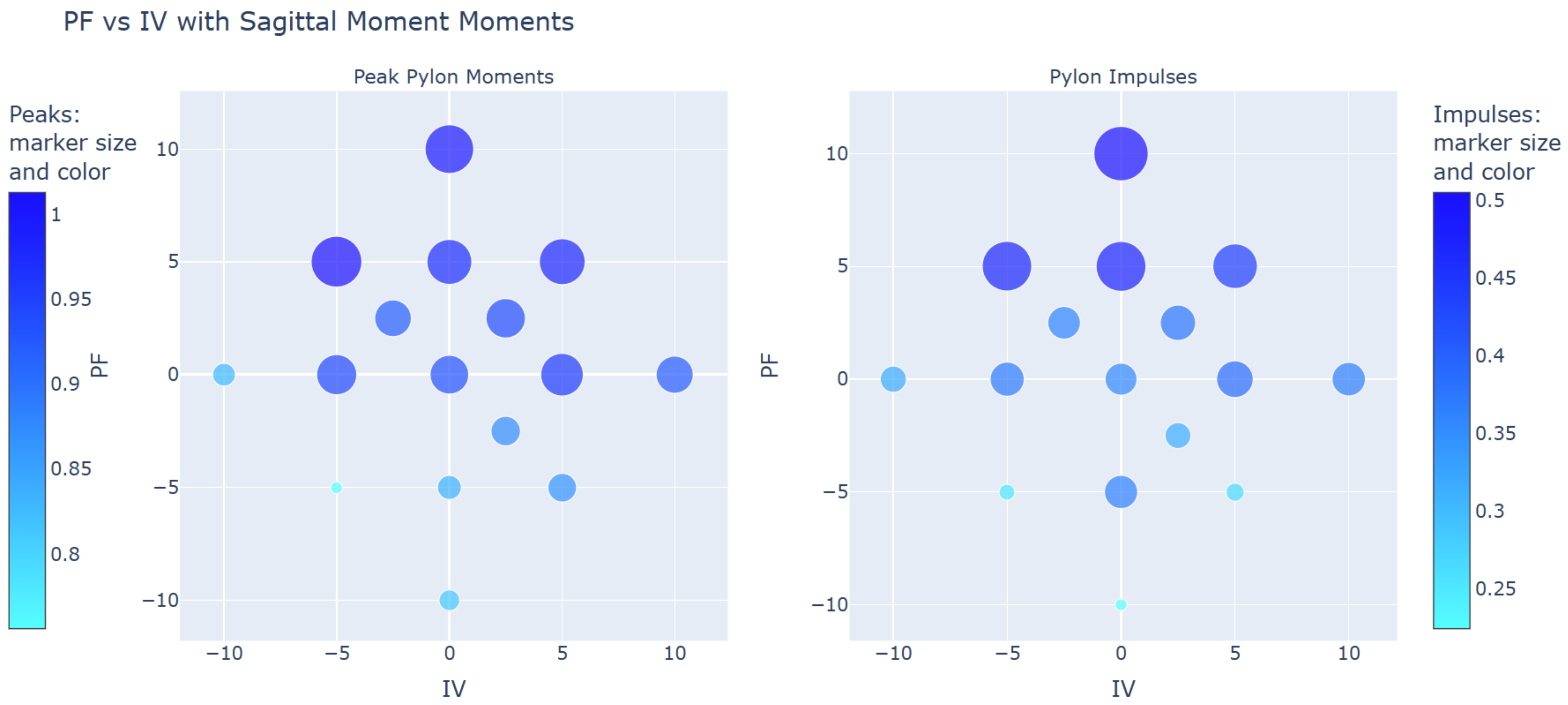




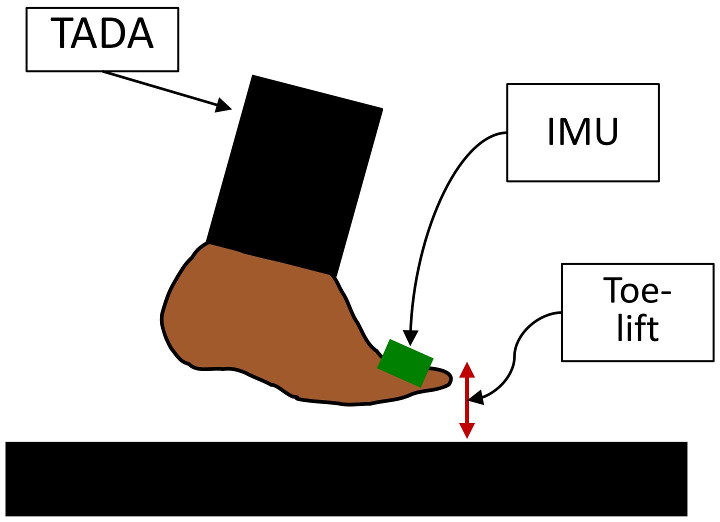





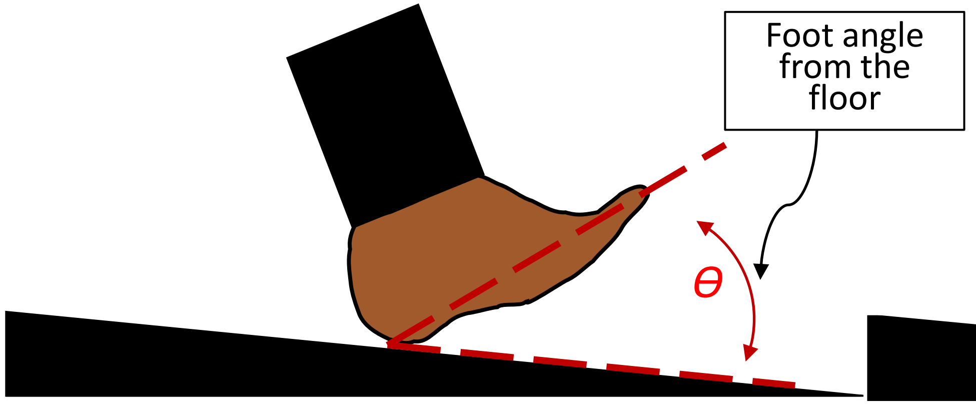
Sagittal Moment vs Time for PF = 10.0, IV = 0.0
Grouped by Speed
fast
med
slow
Sagittal Moment (Nm/kg)
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Time (s)


PF vs IV with Sagittal Moment Moments
Peak Pylon Moments
Pylon Impulses
Peaks:
marker size
and color
1
0.95
0.9
0.85
0.8
PF
10
5
0
−5
−10
−10
−5
0
5
10
IV
Impulses:
marker size
and color
0.5
0.45
0.4
0.35
0.3
0.25

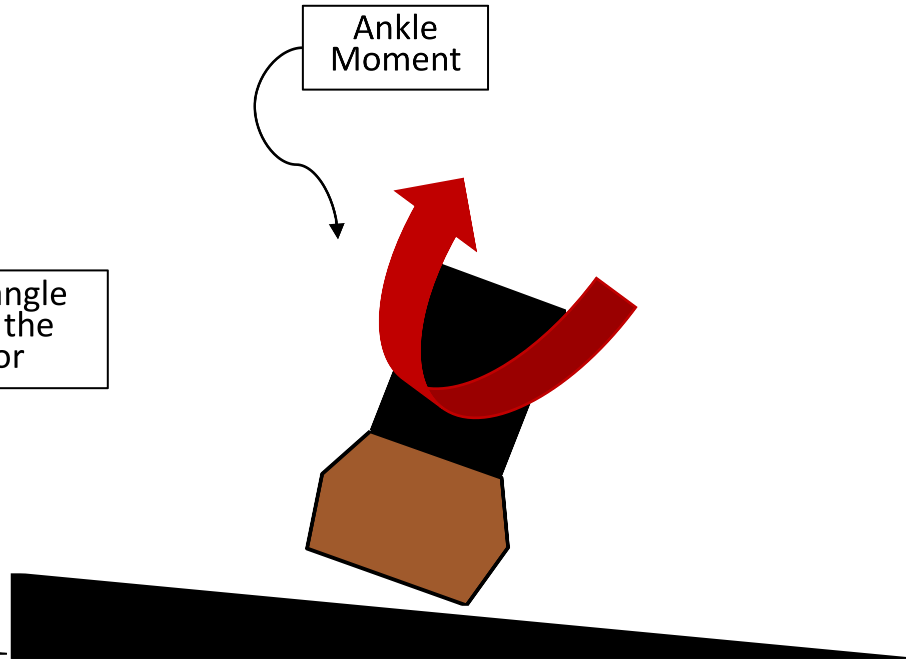
Current and Future Work: Main Control Laws



Toe-lift control

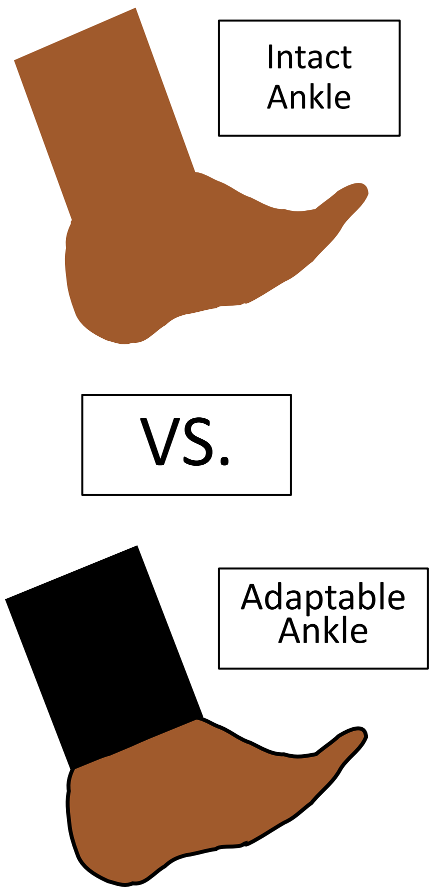


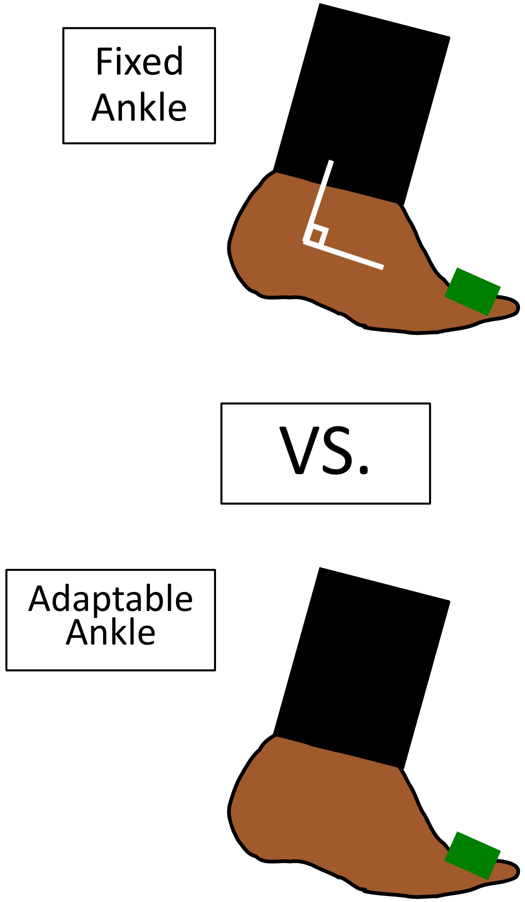
Anticipatory Slope-Matching Control



Moment-Limiting Control

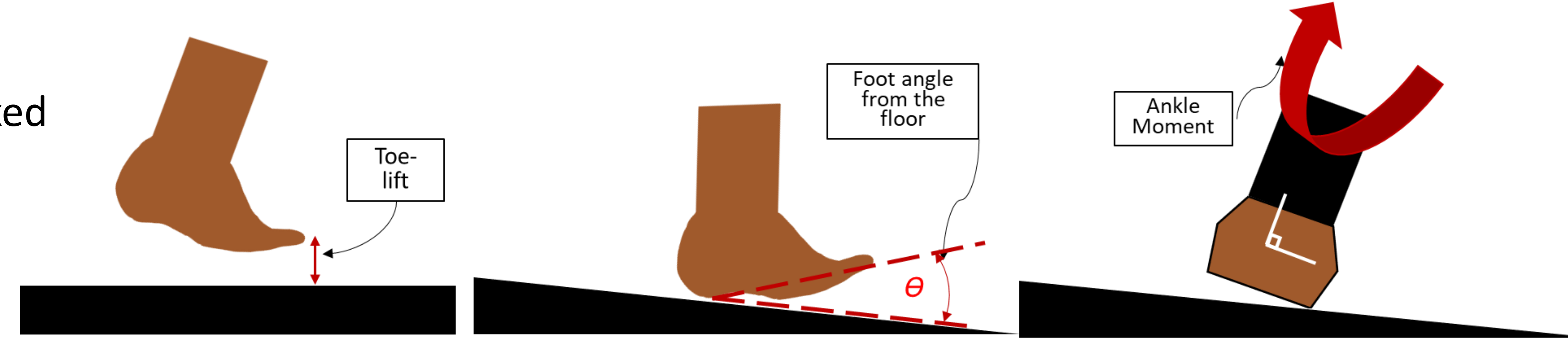
Current and Future Work: Comparisons





Current and Future Work: Aim 1

Intact or Fixed Ankle



VS.

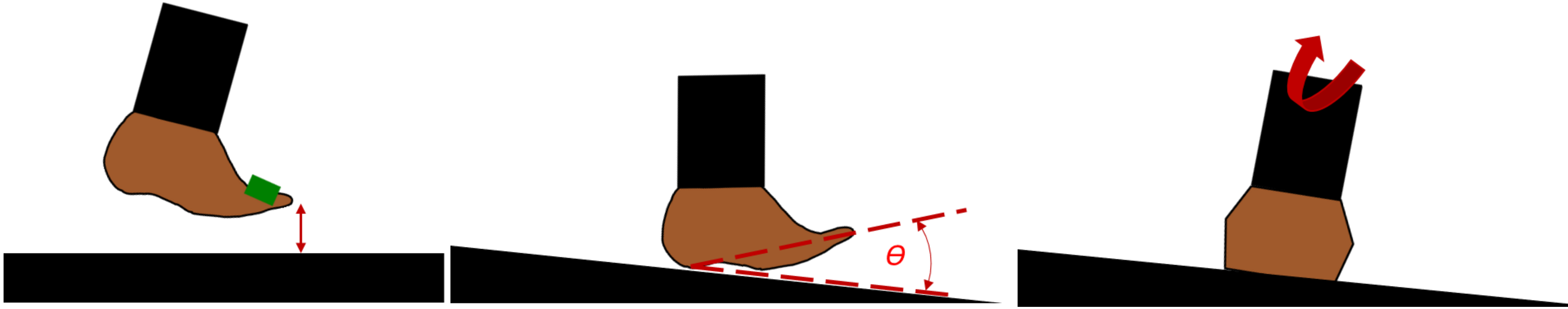
Same Toe-lift and ankle angles during swing

Same difference between foot and ground angles during stance

Less ankle moments during stance

Adaptable

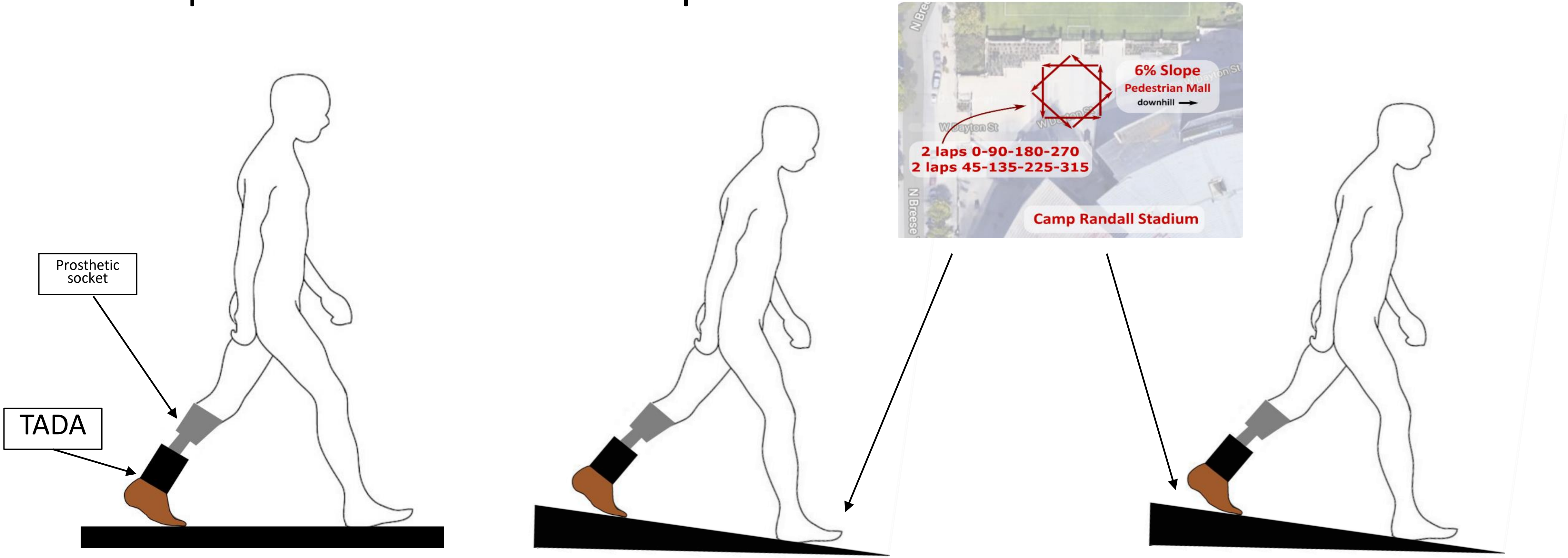
Ankle



Map from TADA grant: Congressionally Directed Medical Research Programs (CDMRP) Search Awards. https://cdmrp.army.mil/search.aspx?LOG_NO=DM190827.

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



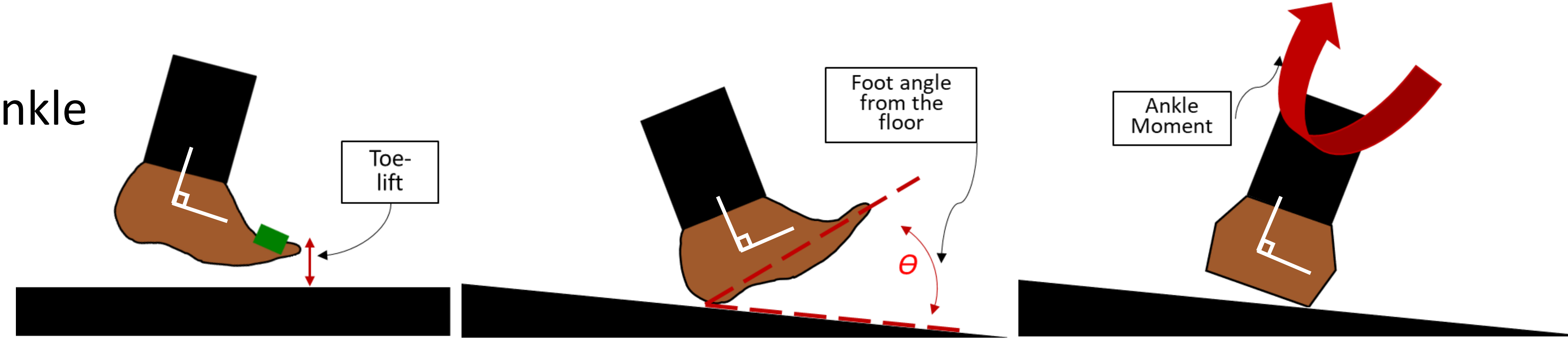
Toe lift controller (0, -5, 5 degrees)

Anticipatory slope-matching controller (uphill, downhill, cross-hill, diagonal)

Moment-limiting controller (uphill, downhill, cross-hill, diagonal)

Current and Future Work: Aim 2

Fixed ankle



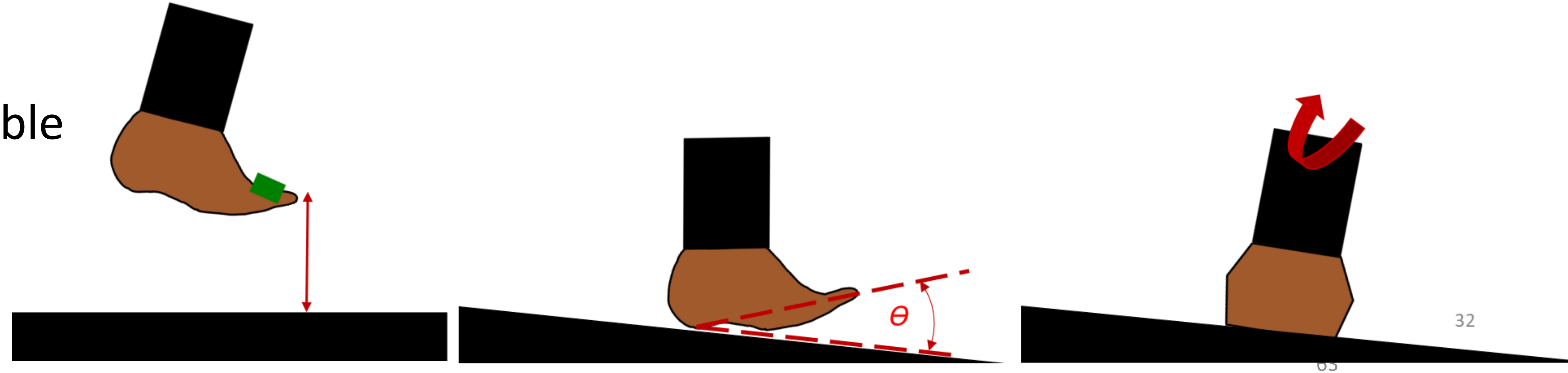
VS.

More Toe-lift at first then less over time

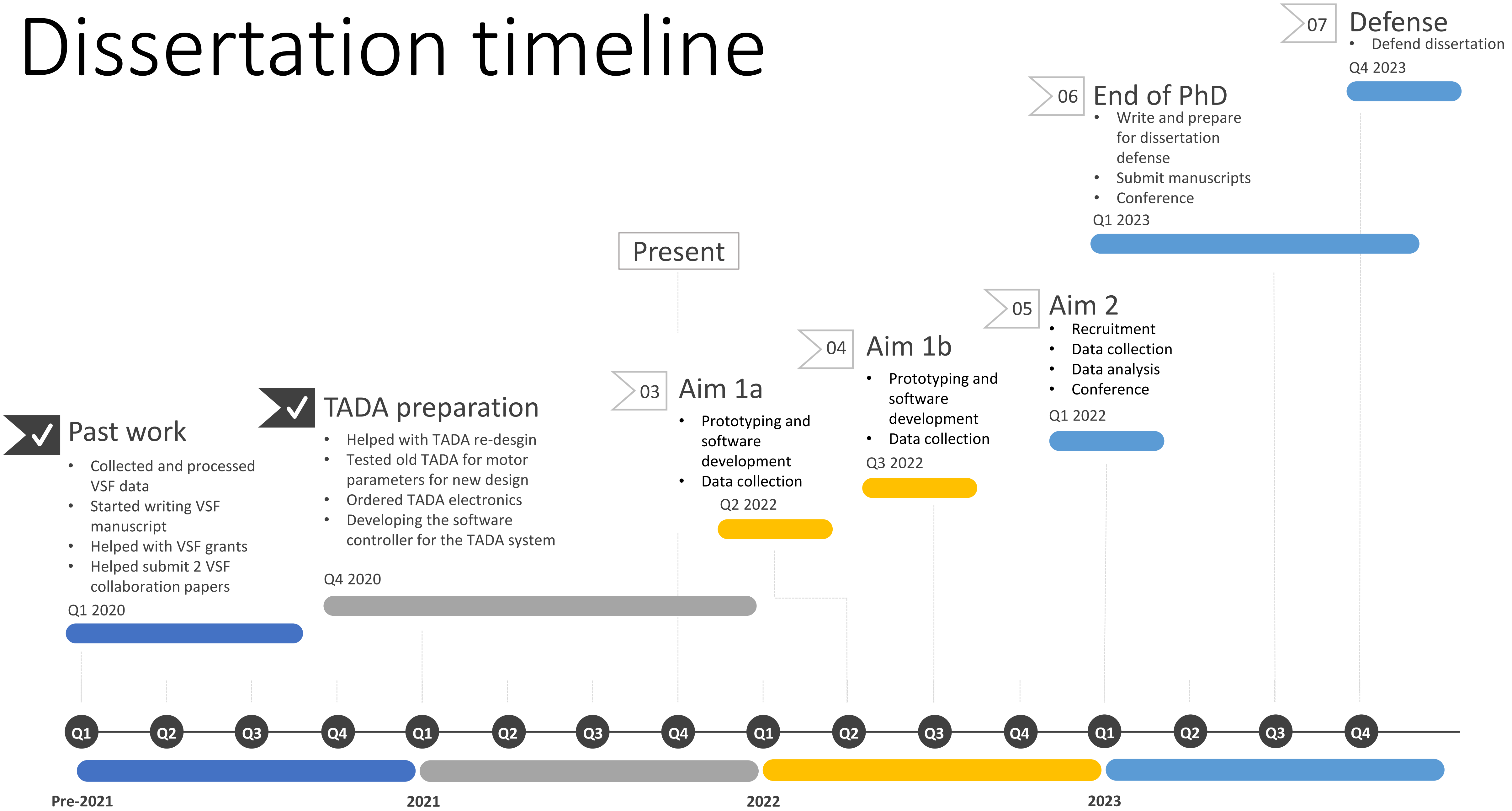
Less difference between ankle and ground angles

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

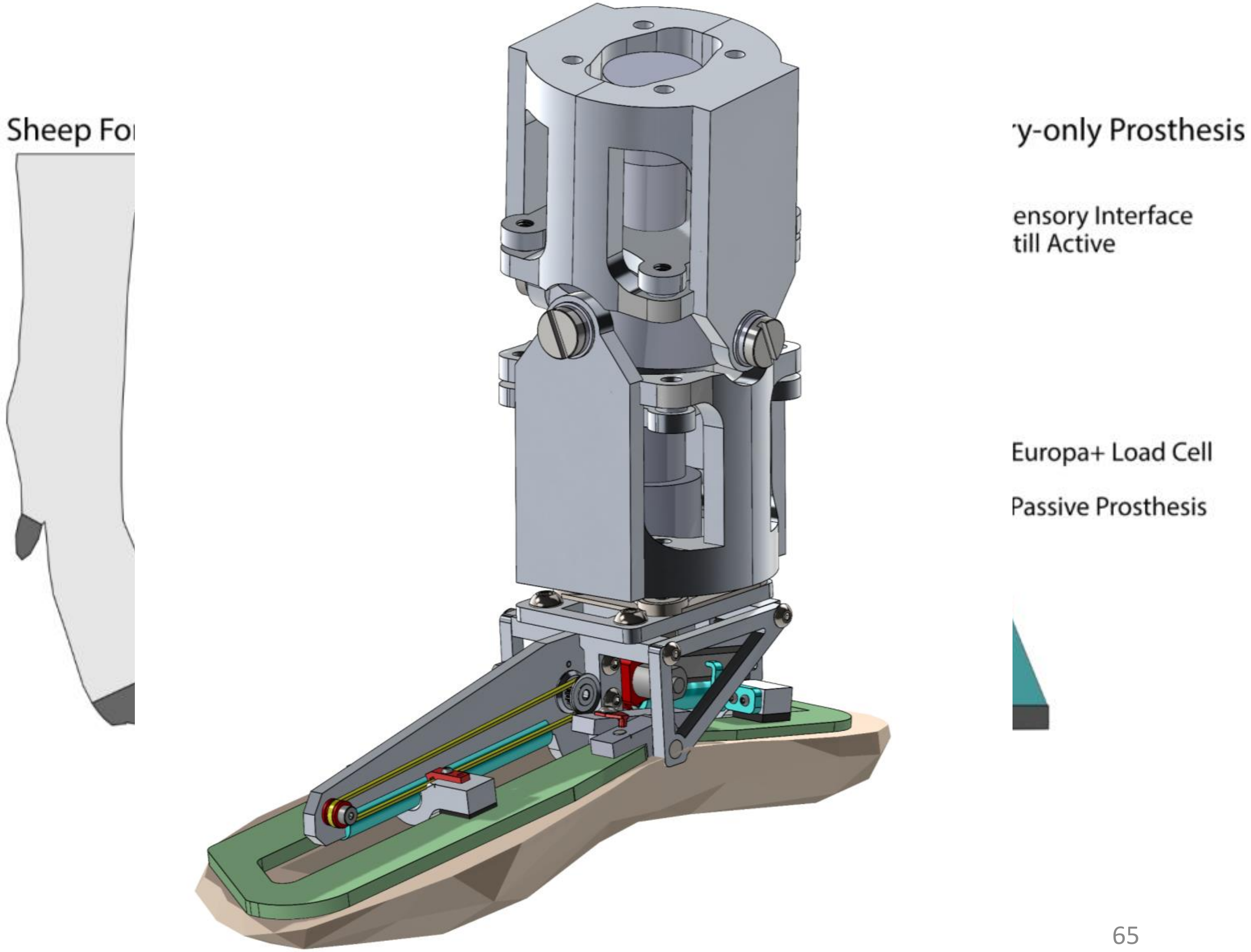
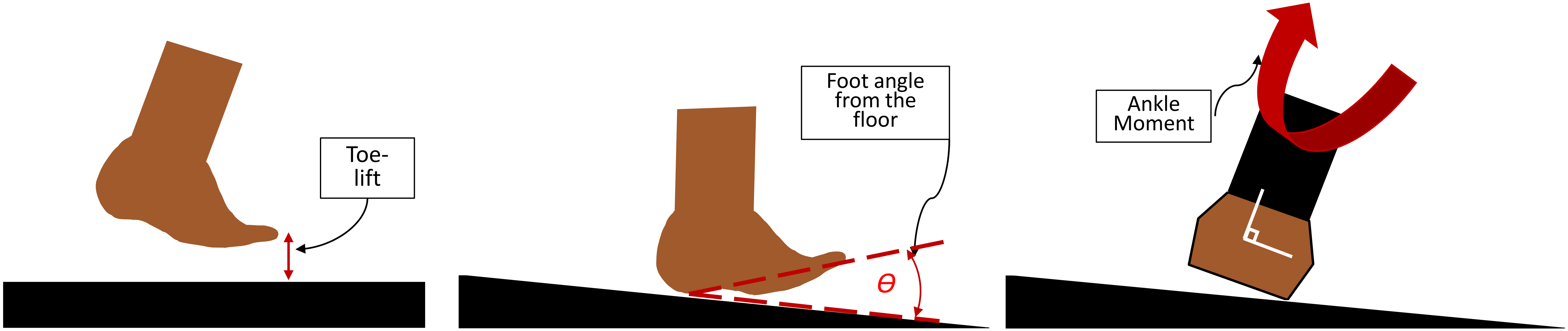


Figure of STADA: Congressionally Directed Medical Research Programs (CDMRP) Search Awards. https://cdmrp.army.mil/search.aspx?LOG_NO=DM190827.

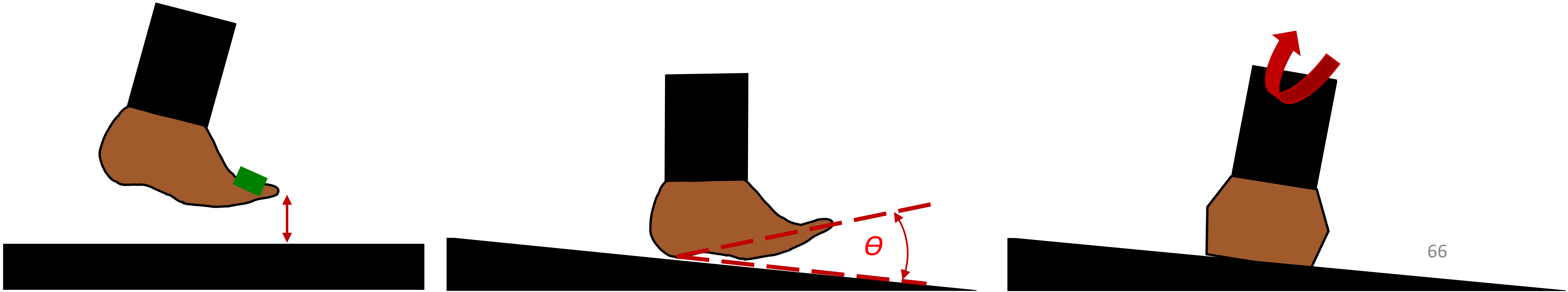
Current and Future Work: Specific Aim 1



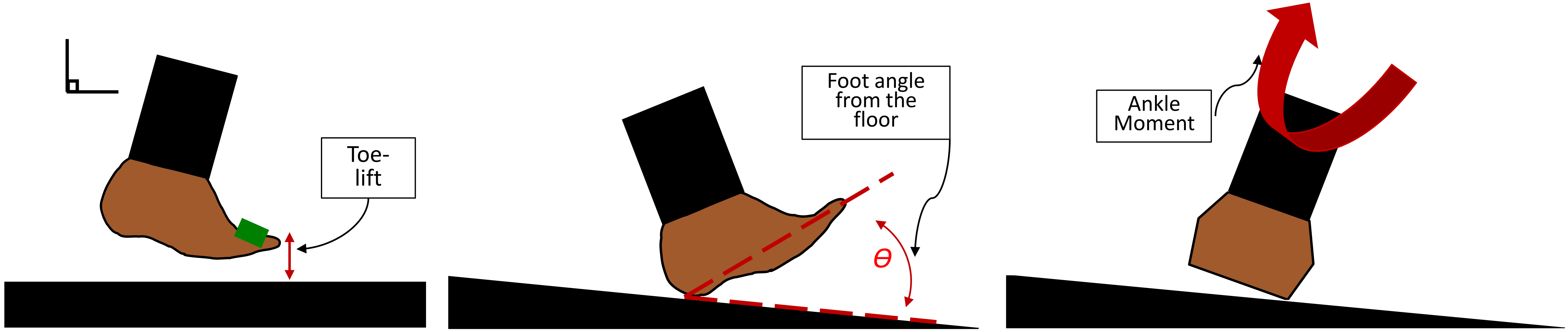
Same Toe-lift and ankle angles during swing

Same difference between foot and ground angles during stance

Less ankle moments during stance



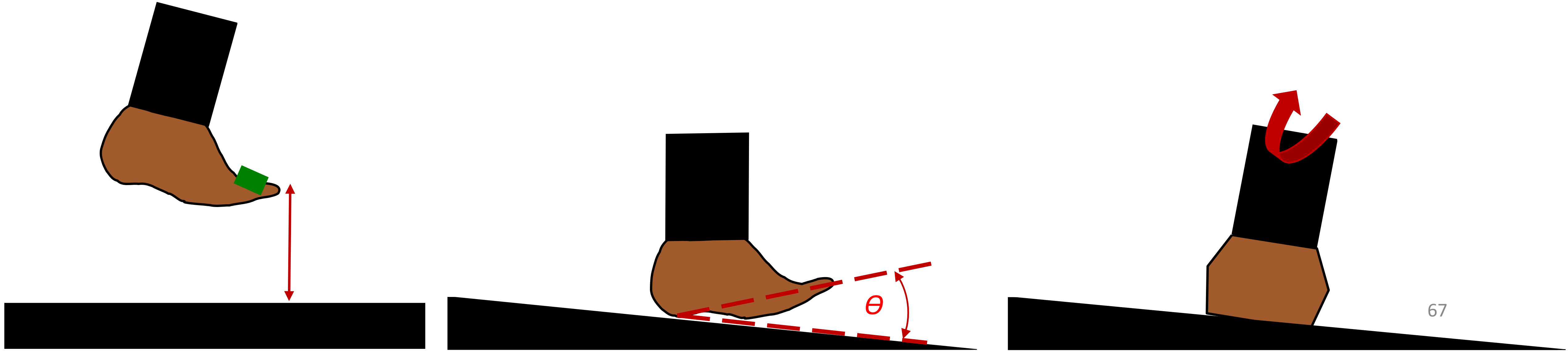
Current and Future Work: Specific Aim 2



More Toe-lift at first then less over time

Less difference between ankle and ground angles

Less ankle moments

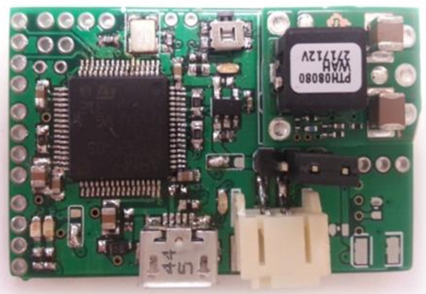


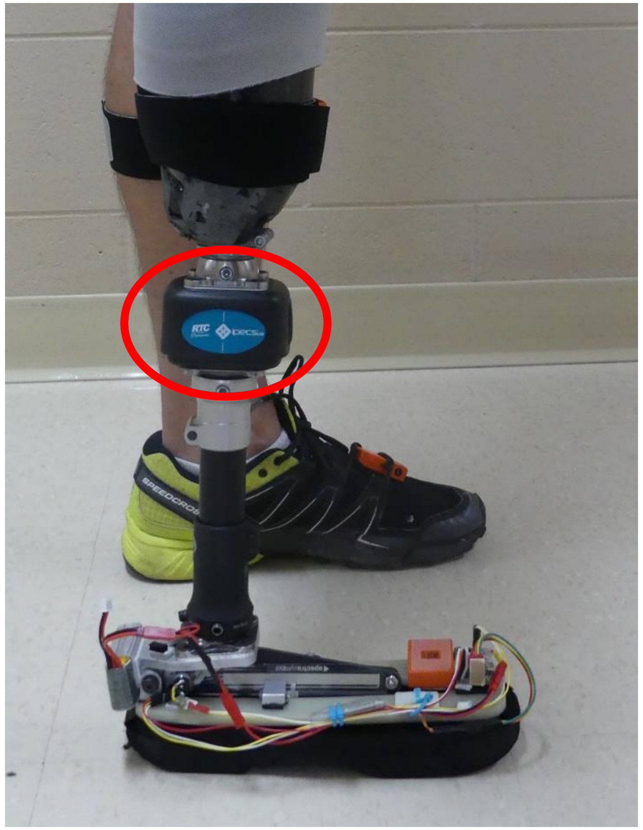
Sensors

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