Evaluating the Mechanical Design of a Transfemoral Powered Prosthesis through Metabolic Cost

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Abstract

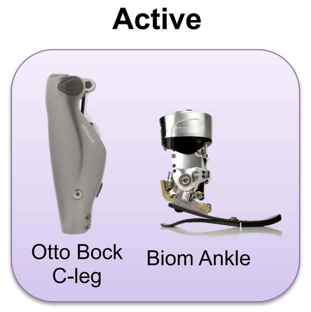
The objective of this research is to investigate the effects that mechanical components of a transfemoral powered prosthetic platform, AMPRO3, have on safe, stable, efficient locomotion for amputees. Specifically, mechanical designs were implemented to allow for multi-contact walking. Metabolic cost experimentation was used to quantify the effect of prosthetic walking on human energy expenditure. Initial results showed that while multi-contact walking was possible due to new designs, it had a higher metabolic cost than flat-foot walking on able-bodied subjects. Future work hopes to test an energy capturing foot design and continue exhaustive metabolic testing with a transfemoral amputee subject.

Introduction

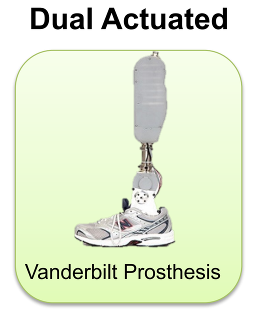
There are two different kinds of prostheses: electrically passive and active. Currently, there is only one commercial powered knee prosthesis, one commercial powered lower limb prosthesis, and only one dual actuated powered transfemoral prosthesis.

Electrically Passive

Active



Dual Actuated



Yet despite the scarcity in commercialized powered prostheses, electrically passive devices expend up to 60% more metabolic energy [1].

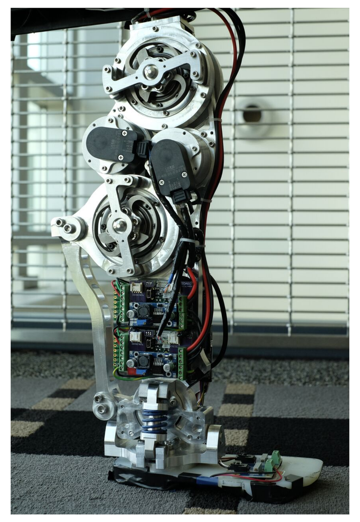
The lack of advancement in powered prostheses is even more troubling considering the fact that there are more than 300,000 transfemoral amputees in the U.S [2] , with approximately 30,000 new transfemoral amputees each year [2].

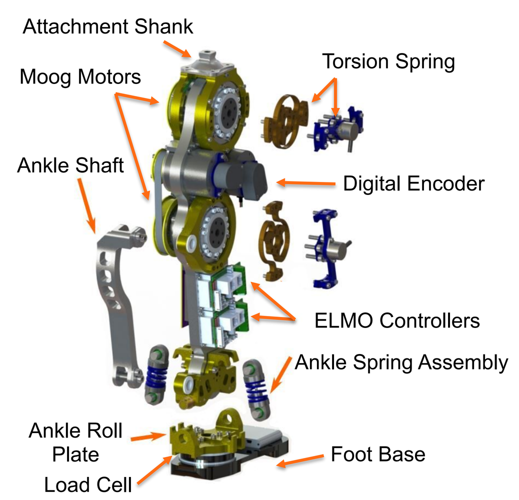
AMPRO3 Prosthesis

The AMBER Lab has extensive previous work with humanoid bi-pedal robots. The control and mechanical design knowledge from these robots was implemented to create a new transfemoral prosthesis to serve as a platform for control and design testing

Control

Mechanical

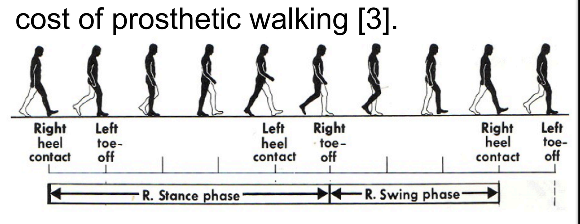




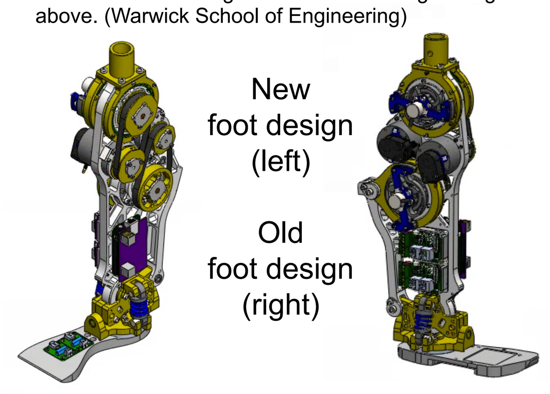
The images above show the transfemoral prosthesis, AMPRO3, with the original flat-foot design

Foot Design for Multi-Contact Walking

A new prosthetic foot was designed to allow for multi-contact walking. Multi-Contact walking has been shown in previous studies to reduce the metabolic cost of prosthetic walking [3].

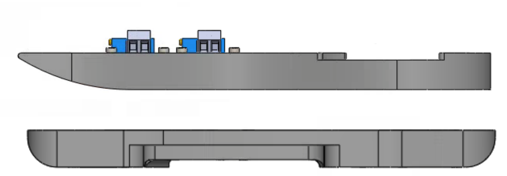


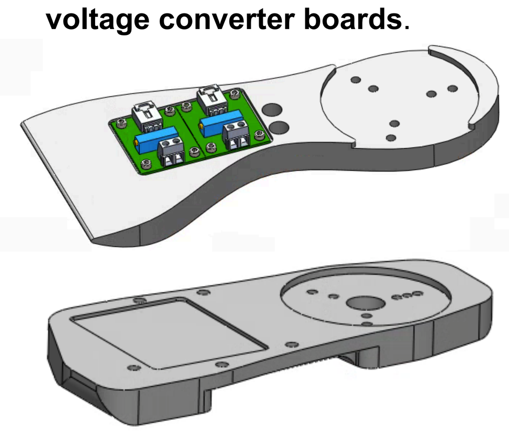
Multi-Contact walking can be seen in the gait diagram above. (Warwick School of Engineering)



New foot design (left)

Old foot design (right)



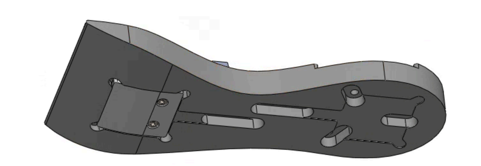


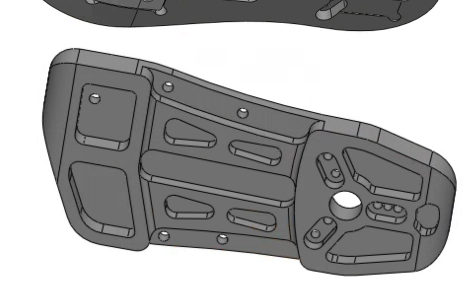
The new foot design can be seen in the top image, compared to the old design in the bottom image.

The profile of the new design is shaped in a way that will **allow for toe/ground contact throughout the toe-roll** during push-off. This enables for a higher torque push off and thus has the potential to decrease metabolic cost.

The new foot design can be seen in the top image, compared to the old design in the bottom image.

The contoured shape of the new design allows the **foot to be placed inside of a sneaker.** The new design also includes features to **secure the force sensor voltage converter boards**.





The new foot design can be seen in the top image, compared to the old design in the bottom image.

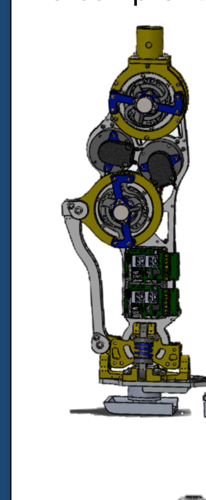
The bottom of the new design includes features to **mount flat force sensors**. These force sensors allow the prosthetic to sense which phase of the gait it is in (stance verse swing).

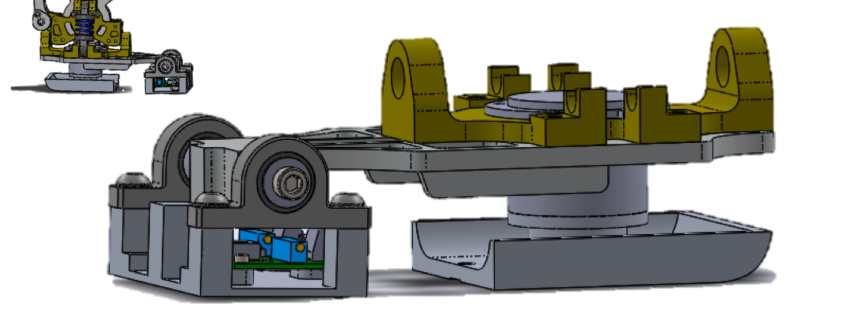
Foot Design for Energy Capture

Studies have found that energy capturing prosthetic feet help to reduce the metabolic cost of transfemoral prostheses [5,6]. Thus, a new foot was designed for AMPRO3 to implement a compliant spring that captures and redirects energy throughout the gait.

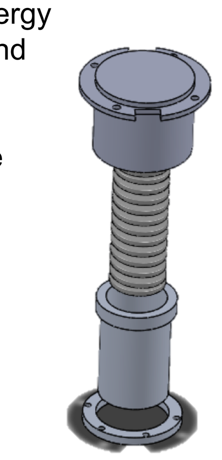
The design objectives for this new foot were the following:

1. Low profile to avoid adding height to AMPRO3
2. Use of a spring to add compliance and to capture energy
3. A toe that can pivot to maintain contact with the ground during the "push-off" phase of the walking gait
4. Designs that are easy to manufacture and low cost
5. Curved heel to assist in the heel contact phase of the walking gait





The foot design above was created in order to implement energy capture for AMPRO3 and meet all of the design objectives



The image above shows the exploded view of the spring mechanism

Methods

Metabolic Cost Experiment

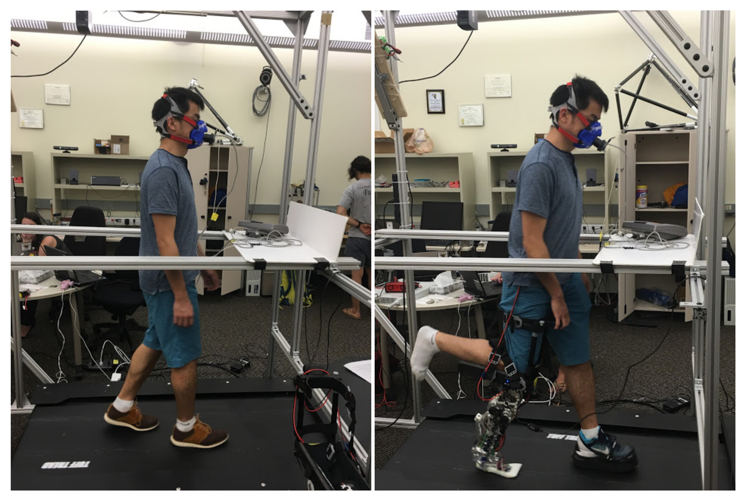
1. **Obtained IRB Approval**
2. **Set up Experiment**
   - 4 conditions (Resting, Human walking, Flat-Foot walking, Multi-Contact walking)
   - Each walking condition has 6 minutes of walking
   - Only the last 2 minutes of data are used in the calculation
3. **Analyze Data**
   - Metabolic Mask output is VO2 (ml/kg/min)
   - Need to convert VO2 into Metabolic cost (W/kg)

$$\frac{W}{kg} = VO2 * \frac{5}{1000}\left(\frac{kcal}{ml\ O2}\right) * 4186\left(\frac{J}{kcal}\right) * \frac{1}{60}\left(\frac{min}{s}\right)$$

4. **Obtain comparable data**

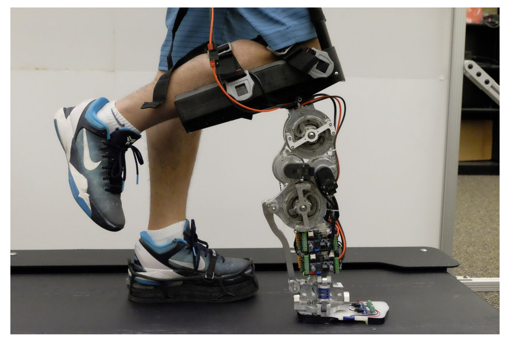
$$\text{Metabolic Cost of Walking} = \text{Metabolic Cost} - \text{Resting}$$

$$\text{Metabolic Cost of Transport} = \frac{\text{Metabolic Cost of Walking}}{\text{Speed of Walking}}$$



Human Walking experimental condition (left) and Prosthetic Walking experimental condition (right)

Metabolic Mask used for experiment



Bi-Pass Device used for able-bodied testing subjects

Preliminary Results

Metabolic Cost for Various Walking Conditions

	Speed (m/s)	VO2 Weighted (ml/kg/min)	Metabolic Conversion (J/kg/min)	Metabolic Cost (W/kg)	Metabolic Cost of Walking (W/kg)	Metabolic Cost of Transport (J/kg/m)
AMBER Resting (Average)	0	4.66	97.46	1.62		
Human Walking	0.49	9.68	202.59	3.38	1.70	**3.46**
	0.63	10.47	219.23	3.65	2.09	**3.33**
AMPRO3 Flat-Foot Walking	0.49	16.35	342.17	5.70	4.02	**8.21**
	0.63	17.05	356.95	5.95	4.38	**7.00**
AMPRO3 Multi-Contact Walking	0.63	19.87	415.82	6.93	5.36	**8.57**
AMPRO3 Multi-Contact Walking (Increased Torque)	0.49	16.79	351.43	5.86	4.18	**8.52**
	0.63	19.00	397.60	6.63	4.95	**7.85**

The preliminary results obtained from metabolic testing can be seen in the table above. The various walking conditions are separated by colors and into the different walking speeds.

Potential Reasons why Multi-Contact walking has a higher metabolic cost to Flat-Foot walking include:

- Multi-Contact walking has a more complex gait and is thus more cumbersome for a subject that is not fully comfortable with the prosthetic device
- Testing subject is able-bodied, and thus the bi-pass used for testing is not fully conducive for prosthetic walking.
- The controls for multi-contact walking are newly developed and need to be optimized

When AMPRO3 is compared to the leading prostheses [4], shown in the table below, the metabolic cost of walking is similar, but metabolic cost of transport is much higher for AMPRO3.

	Speed (m/s)	Metabolic Cost of Walking (W/kg)	Metabolic Cost of Transport (J/kg/m)
AMPRO3 Flat-Foot Walking	0.63	4.38	7.00
AMPRO3 Multi-Contact Walking (New Gait)	0.63	4.95	7.85
C-leg (amputee)	1.3	5.44	4.18
MIT Active Knee (amputee)	1.3	5.07	3.9

Conclusions

The preliminary results suggest

- Multi-contact walking does not currently have a metabolic cost advantage to flat-foot walking.
- When the torque was increased in a second iterative testing, the metabolic cost of multi-contact walking decreased
- Further testing needs to be done when multi-contact walking has been optimized for maximal toe push off.

Future Work

- Further exhaustive metabolic testing needs to be done on AMPRO3
- Additional metabolic testing with the new energy capturing foot
- Metabolic testing with an amputee subject once the controls of AMPRO3 are robust.

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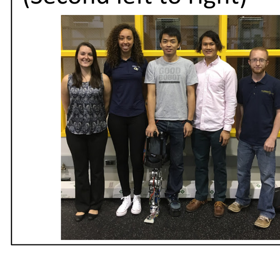

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