# A Neuromuscular Algorithm for a Powered Foot-Ankle Prosthesis Shows Robust Control of Level Walking and Stair Ascent

Hessel AL*, Tahir U*, Petak J*, LeMoyne RC*, Han Z **, Tester J* and Nishikawa KC*
* The Center for Bioengineering Innovation, Northern Arizona University, Flagstaff, USA
** iWalk, Inc. Bedford, MA, USA
alh385@nau.edu

## 1 Introduction

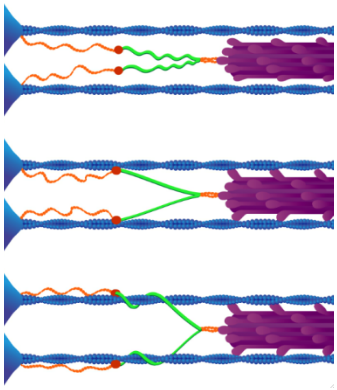
Currently, three types of lower limb prosthetic devices are available commercially for persons with a lower limb amputation: passive, energy storage and return, and powered prostheses (Zelic 2012). These types of prostheses offer benefits for persons with different levels of function and activity. The mechanical complexity varies from effectively stationary passive prostheses, to energy storage and return devices that include deflecting components and moving parts, to more complex electro-mechanical powered prostheses that provide actuation during plantarflexion and/or dorsiflexion (Au et al. 2007).

The iWalk BiOM is a powered foot-ankle prosthesis for persons with trans-tibial amputation (Markowitz et al. 2011). Provision of motor power permits faster walking than can be produced using only the spring-like behavior provided by passive devices. However, the use of active motor power raises the issue of control (Farrell & Herr 2011). The control approach exhibits no inherent adaptation to varying environmental conditions. Instead, algorithms generate positive feedback torque control for all intended activities and variations of terrain. Although the current BiOM performs well across a range of level and ramp walking speeds, more robust control algorithms could potentially improve users' experience for all terrain walk. It is possible that bio-inspired algorithms could offer that robustness.

Current drawbacks to neuromuscular controllers lie in the use of Hill-type muscle models, which lack the ability to predict history dependent muscle properties (such as residual force enhancement or depression). These properties enable the muscles in our body to adapt instantaneously to changes in load without requiring sensory feedback, an intrinsic property that has remain unexplained for decades (Nishikawa et al. 2013).

Our laboratory has spent the last several years investigating intrinsic muscle properties. We recently developed a "winding filament" hypothesis for muscle contraction that incorporates a role for the giant titin protein in active muscle (Nishikawa et al. 2012, fig. 1). The winding filament hypothesis (WFH) fills important gaps while building on the sliding filament theory. The hypothesis proposes that N2A titin (red dot, Fig. 1) binds to actin (blue) upon Ca2+ influx in skeletal muscle (Fig. 1, middle), and that PEVK titin (green) winds on thin filaments during force development (Fig. 1, bottom) because the cross-bridges (purple) not only translate but also rotate the thin filaments (for supporting evidence, see Nishikawa et al. 2012).

**Figure 1**



Schematic of a muscle half sarcomere, showing thin filaments (blue), thick filaments (purple) and titin filament (green and red). The winding filament hypothesis proposes that, upon $Ca^{2+}$ influx, N2A titin (red) binds to thin filaments (blue), and that the cross bridges (purple) wind PEVK titin (green) on the thin filaments.

The WFH accurately predicts intrinsic muscle properties (Nishikawa et al. 2012). This new hypothesis could allow us to develop robust control algorithms for control of powered prostheses. Our goal was to develop a WFH-based control algorithm for the BiOM prosthesis and test its function during level walking, stair ascent and descent, and backwards walking.

## 2 Methods

We developed a bio-inspired control algorithm for the BiOM foot-ankle prosthesis (iWalk, Inc.), based on the winding filament hypothesis. The control algorithm incorporates a pair of virtual muscles that emulate the subject's shank muscles prior to amputation: an anterior tibialis anterior muscle, which contracts to effect ankle dorsiflexion; and a posterior muscle based on the soleus and gastrocnemius, which contracts to effect ankle plantarflexion. The force produced by each virtual muscle is calculated using a model inspired by the winding filament hypothesis (Fig. 1). In our model, a contractile element represents myosin cross-bridges, a pulley represents actin thin filaments, a spring represents titin, and a second spring represents tendons. In each time step, the simulation calculates the length of the anterior and posterior muscles based on ankle angular position.

The muscle model estimates the torque produced by each muscle based on its length and level of activation. The length of each muscle is determined at each time step from a sensor on the prosthesis that measures the ankle angle. The muscles are activated in a simple pattern: the dorsiflexor is activated at 50% of its maximum force during swing, and the plantarflexor is activated at 50% of its maximum force during stance. The control algorithm calculates the net ankle torque at each time step.

The net ankle torque from the model determines the current applied to the motor, and therefore the torque produced by the prosthesis. We tested subjects under a variety of conditions including level walking, stair ascent, descent, and backwards walking.

## 3 Results

Our results indicate that the WFH-based control algorithm for the BiOM prosthesis is capable of producing ankle torque profiles during level walking that are similar to the BiOM stock controller and human ankle (Herr & Grabowski 2011). The WFH-based control algorithm is also capable of reproducing ankle torque profiles that match those of able-bodied individuals during stair ascent (Sinitski et al. 2012) with minimal sensing (i.e., ankle angle) and no change in activation or model parameters. Preliminary data indicate that stair descent and backwards walking are limited in success due to mechanical constraints of the BiOM design.

## 4 Discussion

Our research demonstrates successful implementation of a neuromuscular controller for a powered foot-ankle prosthesis based on the winding filament hypothesis. By implementing a control algorithm that, like muscle, adapts instantaneously to changes in load, we have achieved more robust prosthesis control. Our work will continue to test the WFH controller's robustness on ramps, uneven terrain and on compliant substrates. Ongoing studies also include metabolic cost of transport.

## Literature Cited

Au SK, Herr H, Weber J, Martinez-Villalpando EC (2007) *Conf Proc IEEE Eng Med Biol Soc* 2007:3020-6.

Farrell MT, Herr H (2011) *Conf Proc IEEE Eng Med Biol Soc* 2011:6041-6.

Markowitz J, Krishnaswamy P, Eilenberg M., Endo K, Barnhart C, Herr H (2011) *Phil Trans Roy Soc B* 366: 1621-31.

Nishikawa KC, Monroy JA, Uyeno TA, Yeo SH, Pai DK, Lindstedt SL (2012) *Proc Roy Soc B* 297:981-90.

Nishikawa KC, Monroy JA, Powers KL, Gilmore LA, Uyeno TA, Lindstedt SL (2013) *Adv Exp Med Biol* 782:111-25.

Sinitski EH, Hansen AH, Wilken JM (2012). *J Biomech* 45:588-94.

Zelić KE (2012) PhD Thesis, University of Michigan.

Acknowledgements – We thank Zhixiu Han from iWalk for his assistance with the implementation of the WFM in the BiOM. This work was supported by NSF IOS 0742483, IOS-1025806, and IIP-1237878.