Optimizing prosthesis design to maximize user satisfaction using a tethered robotic ankle-foot prosthesis

Joshua M. Caputo*, Peter G. Adamczyk** and Steven H. Collins*
* Carnegie Mellon University University, Pittsburgh, USA
joshua.m.caputo@gmail.com, stevecollins@cmu.edu
** Intelligent Prosthetic Systems, LLC, Ann Arbor, USA
p.g.adamczyk@gmail.com

1 Motivation

Lower-limb prostheses are designed based on observations of how users on average respond to different design features. Prostheses are then marketed on the basis that certain features are appropriate for certain types of individuals, with few options for user customization. This process is unlikely to provide individual users with devices that best suit their needs since it is unclear how to best categorize users and which design features are most important [1, 2]. This process is also slow to accommodate disruptive technologies since it requires time to develop a body of observations about new devices that practitioners are hesitant to prescribe. Prosthesis designs could instead be optimized for individual users, producing customized designs that are likely to be preferable to off-the-shelf designs. Using a traditional design approach, this would require costly rapid prototyping and evaluation of candidate designs. Instead, we demonstrate the use of a tethered robotic ankle-foot prosthesis [3] as a tool for rapid exploration of candidate designs. We devised a strategy for systematically exploring a space of possible device behaviors and identifying which are user preferred. The resultant optimized designs could then be sent to prosthesis manufacturers for physical implementation using traditional processes.

2 Methods

We parameterized a spring-like (net-zero work) ankle-foot prosthesis behavior using three parameters: rest angle or 'alignment', stiffness, and shape (stiffening vs. softening) of the virtual spring (Fig. 1). This behavior was optimized to maximize user satisfaction through a series of treadmill walking trials. Each trial consisted of three successive parameter optimizations wherein each parameter was adjusted in isolation. Parameters were adjusted incrementally once per stride and subjects were instructed to inform the experimenter when they noticed a decrease in their level of satisfaction with the device behavior. Upon receiving this feedback, the experimenter reversed the direction of adjustment, repeating the process for a total of three reversals. Upon reaching the final reversal of the trial, the optimal parameter value was taken to be the midpoint between the nearest reversals in search direction. For some parameters we observed coupled effects on satisfaction during pilot tests with some users, so the procedure was repeated four times to ensure convergence to the globally optimal parameter values. The order of parameter optimizations was randomized for each subject, and remained consistent across repetitions. Initial parameter values were

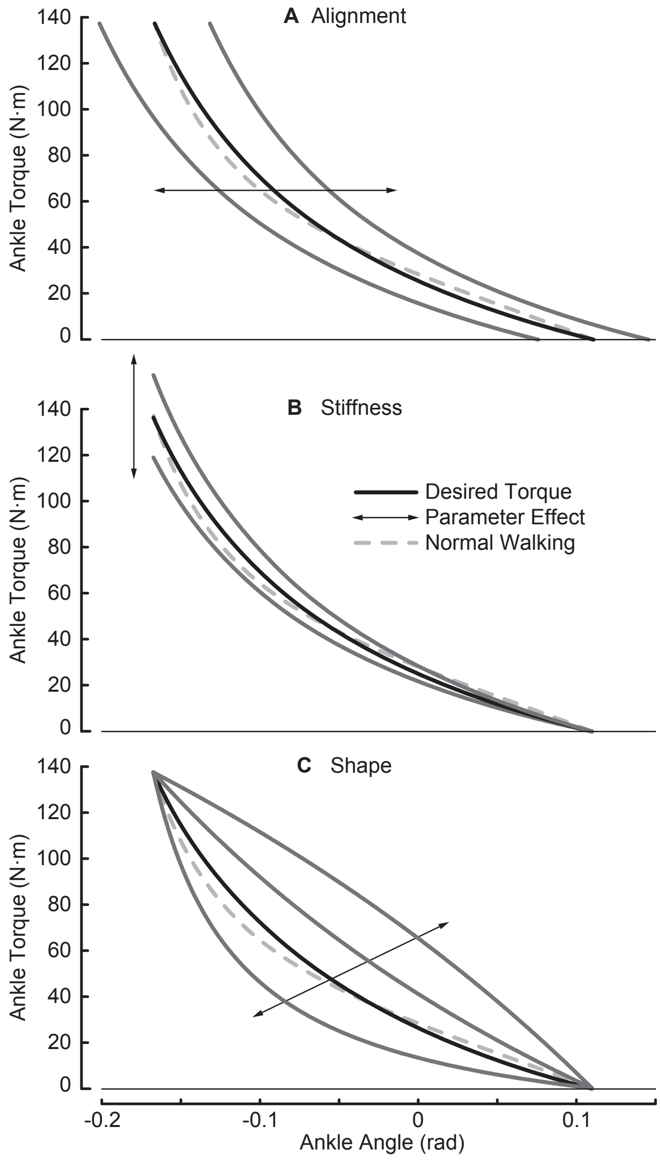

Figure 1: Prosthesis behavior was adjusted by varying three parameters: **A** alignment, **B** stiffness, and **C** shape.

randomly selected for the first trial, and then updated with the most recently measured optimal value for subsequent trials (as in hill climbing [4]).

The resultant optimized behavior (OPT) was then validated against alternative device behaviors, mimicking four typical reference conditions: an average healthy ankle (NORM), the user's prescribed prosthesis (PRE, a dynamic elastic response prosthesis), the user's intact ankle (INT), and an average solid ankle cushioned heel prosthesis (SACH). These different behaviors were compared based on measurements of metabolic rate, heart rate, maximum sustainable walking speed, and user satisfaction (measured on a scale from -10 to 10) taken during a 1.25 m·s treadmill walking trial.

3 Results

Three unilateral transtibial amputees have participated in the experiment. Representative optimization (Fig. 2) and validation (Fig. 3) data are provided for one subject.

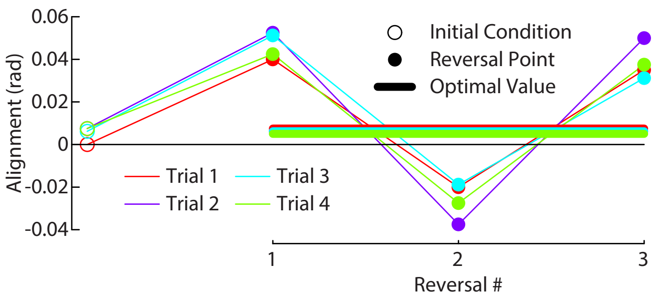

Figure 2: Optimization of the alignment parameter for a representative subject over the course of four trials, each with three reversals of the parameter search direction.

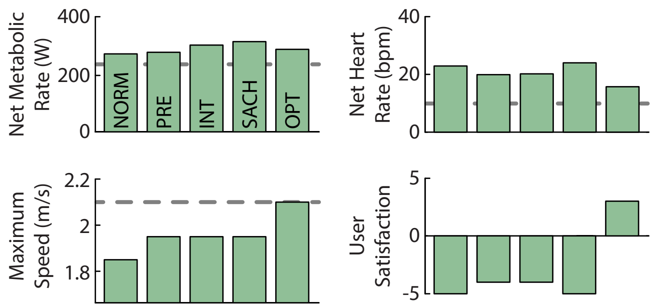

Figure 3: Comparison of the effect of candidate prosthesis behaviors on a representative subject's metabolic and heart rates, maximum walking speed, and satisfaction.

4 Discussion

The demonstrated approach differentiates users based on their perceived needs and results in designs that are user-preferred over typical design alternatives. Such an approach to user-optimized device design could address longstanding difficulties in clinical practice with device design and prescription while also helping to realize the promise of, e.g., powered robotic ankle-foot prostheses.

User satisfaction is but one of many possible design optimization objectives, and it is unclear which objectives are most appropriate. Effort related measures, such as metabolic rate, could be measured in real time to discover behaviors that minimize walking effort [5]. Other outcomes such as maximum walking speed, stability, or comfort could also be optimized. It is likely that some combination of these outcomes are relevant to the quality of life of amputees, but it is unclear what weighting of these outcomes is most appropriate. User satisfaction is quick to assess and it presumably includes some meaningful combination of the possible outcome metrics, so it appears to be a useful optimization criterion for real-time user-specific design optimization.

The optimization procedure demonstrated here is well-suited for optimization of user satisfaction, but other methods may be more appropriate for other optimization criteria. For example, in our first attempt to optimize user satisfaction we performed a grid search optimization, with users providing absolute measures of satisfaction on a scale of -10 to 10 for each behavior. Noise and drift in subjects' scores over time made it difficult to assess which behaviors were optimal, but for other optimization criterion, such a method could provide more detailed information about how behavior affects the outcome of interest.

The tethered robotic ankle-foot prosthesis used here is a versatile platform for design optimization, but the approach could also be applied using different types of devices. Behavior of mobile prostheses with easily swappable components [6] or programmable behavior [7] could be similarly optimized. These devices have more limited capabilities, but would allow design optimization to occur during activities and over time scales that are not feasible with a tethered device (e.g. walking throughout a user's home over the course of a normal day). Design optimization through computer simulation is another promising approach [8], but it is not yet clear if mathematical models can accurately predict an individual's response to changes in device behavior.

References

[1] C. Hofstad, H. Linde, J. Limbeek, K. Postema, "Prescription of prosthetic ankle-foot mechanisms after lower limb amputation," The Cochrane Database of Systematic Reviews, vol. 1, no. CD003978, pp. 1-42, 2015.

[2] J. M. Caputo, P. G. Adamczyk, S. H. Collins, "Informing ankle-foot prosthesis prescription through haptic emulation of candidate devices," IEEE International Conference on Robotics and Automation, in press, 2015.

[3] J. M. Caputo, S. H. Collins, "A universal ankle-foot prosthesis emulator for human locomotion experiments," Journal of Biomechanical Engineering, vol. 136, no. 3, p. 035002, 2014.

[4] S. Russell, P. Norvig, "Artificial Intelligence: A Modern Approach," Prentice Hall, pp. 122-5, 2010.

[5] W. Felt, J. Selinger, J. M. Donelan, C. D. Remy, "Body-in-the-Loop Optimizing Actual Human Walking," Dynamic Walking, 2014.

[6] P. G. Adamczyk, M. Roland, A. B. Sawers, M. E. Hahn "The Effects of Independent Variations in Rearfoot and Forefoot Prosthesis Stiffness on Amputee Gait," Annual Meeting of the Amer. Soc. of Biomechanics, 2013.

[7] M. F. Eilenberg, H. Geyer, H. M. Herr, "Control of a powered ankle-foot prosthesis based on a neuromuscular model," IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2010.

[8] W. van Dijk, H. van der Kooij, "Optimization of human walking for exoskeletal support," IEEE Inter. Conf. on Rehabilitation Robotics, 2013.