ACRM
AMERICAN CONGRESS OF REHABILITATION MEDICINE

Archives of Physical Medicine and Rehabilitation

journal homepage: www.archives-pmr.org

Archives of Physical Medicine and Rehabilitation 2016;97:1100-6

ORIGINAL RESEARCH

# Improved Weight-Bearing Symmetry for Transfemoral Amputees During Standing Up and Sitting Down With a Powered Knee-Ankle Prosthesis

Ann M. Simon, PhD,[a,b] Nicholas P. Fey, PhD,[a,b] Kimberly A. Ingraham, BS,[a]
Suzanne B. Finucane, MS, PTA,[a] Elizabeth G. Halsne, CPO,[a] Levi J. Hargrove, PhD[a,b,c]

*From the [a]Center for Bionic Medicine, Rehabilitation Institute of Chicago, Chicago, IL; [b]Department of Physical Medicine and Rehabilitation, Northwestern University, Chicago, IL; and [c]Department of Biomedical Engineering, Northwestern University, Evanston, IL.*

**Abstract**

**Objective:** To test a new user-modulated control strategy that enables improved control of a powered knee-ankle prosthesis during sit-to-stand and stand-to-sit movements.

**Design:** Within-subject comparison study.

**Setting:** Gait laboratory.

**Participants:** Unilateral transfemoral amputees (N=7; 4 men, 3 women) capable of community ambulation.

**Interventions:** Subjects performed 10 repetitions of sit-to-stand and stand-to-sit with a powered knee-ankle prosthesis and with their prescribed passive prosthesis in a randomized order. With the powered prosthesis, knee and ankle power generation were controlled as a function of weight transferred onto the prosthesis.

**Main Outcome Measures:** Vertical ground reaction force limb asymmetry and durations of movement were compared statistically (Wilcoxon signed-rank test, $\alpha=.05$).

**Results:** For sit-to-stand, peak vertical ground reaction forces were significantly less asymmetric using the powered prosthesis (mean, 19.3%±11.8%) than the prescribed prosthesis (57.9%±13.5%; $P=.018$), where positive asymmetry values represented greater force through the intact limb. For stand-to-sit, peak vertical ground reaction forces were also significantly less asymmetric using the powered prosthesis (28.06%±11.6%) than the prescribed prosthesis (48.2%±16%; $P=.028$). Duration of movement was not significantly different between devices (sit-to-stand: $P=.18$; stand-to-sit: $P=.063$).

**Conclusions:** Allowing transfemoral amputees more control over the timing and rate of knee and ankle power generation enabled users to stand up and sit down with their weight distributed more equally between their lower limbs. Increased weight bearing on the prosthetic limb may make such activities of daily living easier for transfemoral amputees.

Archives of Physical Medicine and Rehabilitation 2016;97:1100-6



Lower-limb amputation affects an individual's ability to efficiently perform activities of daily living.[1,2] For individuals with high levels of amputation (eg, knee disarticulation, transfemoral amputation), this affect can be much greater because they must rely on a mechanical substitute for their knee and ankle joints. When using mechanically passive microprocessor or non-microprocessor prosthetic devices, these individuals often walk with gait asymmetries[3-5] and expend more energy[6,7] than non-amputees. These gait deviations and compensatory mechanisms can lead to secondary physical conditions (eg, back pain, osteoarthritis, other musculoskeletal problems), potentially because of overuse of the intact limb.[8,9] Newly commercialized mechanically active microprocessor prostheses aim to reduce these asymmetries and compensatory mechanisms by providing knee and/or ankle joint torques near physiological values.[10-12] Although most

Presented as an abstract to the World Congress of Biomechanics, July 7, 2014, Boston, MA.

Supported by the U.S. Army Telemedicine and Advanced Technology Research Center (contract no. WW81XWH-09-2-0020) and the U.S. Army Joint Warfighter Program (contract no. W81XWH-14-C-0105).

Disclosures: L.J.H. has a patent pending for an ambulation prediction controller for assistive device invention (patent no. 13/925,668). N.P.F. and A.M.S. have a patent pending for impedance parameter power control lower limb assistive device (patent no. 14/070,150). The other authors have nothing to disclose.

0003-9993/16/$36 - see front matter © 2016 by the American Congress of Rehabilitation Medicine
http://dx.doi.org/10.1016/j.apmr.2015.11.006

**Table 1** User demographics

| User | Sex | Age (y) | Time Postamputation (y) | Weight (kg) | Etiology | Amputation Level | Prescribed Knee |
|---|---|---|---|---|---|---|---|
| TF1 | Male | 65 | 38 | 86.2 | Right traumatic | Transfemoral | C-Leg[a] |
| TF2 | Female | 22 | 6 | 52.2 | Left sarcoma | Transfemoral | C-Leg |
| TF3 | Male | 29 | 17 | 86.2 | Left sarcoma | Knee disarticulation | Hydraulic KX06[b] |
| TF4 | Female | 46 | 24 | 65.8 | Right traumatic | Transfemoral | Rheo[c] |
| TF5 | Male | 65 | 4 | 86.4 | Left sarcoma | Transfemoral | C-Leg |
| TF6 | Female | 28 | 15 | 62.2 | Right sarcoma | Transfemoral | C-Leg |
| TF7 | Male | 29 | 4 | 79.7 | Right infection/other | Transfemoral | 3R80[a] |

NOTE. TF indicates the list of transfemoral amputee participant numbers (numbers are arbitrary).

powered prosthesis research focuses on the control and functional performance of various modes of ambulation (eg, level ground walking, incline walking, stair climbing),[10,13-17] other activities of daily living (eg, standing up from a seated position) must be improved as well.

A typical healthy adult performs an average of 60 sit-to-stand movements each day.[18] This common but demanding activity is necessary for independence and requires more leg strength and greater ranges of motion[19,20] than walking[21] or stair climbing.[22,23] Although the sit-to-stand movement can be subdivided several ways,[19,24,25] the movement consists of a forward trunk lean to shift the center of gravity over the feet, weight transfer to the legs, extension to achieve the upright position, and stabilization. Individuals must maintain sufficient postural control throughout the entire movement.

Able-bodied control subjects often perform this task with minor asymmetries in lower-limb kinematics and kinetics.[26] In contrast, individuals with lower-limb amputation who use mechanically passive devices rely heavily on their intact limb to perform sit-to-stand movements, likely because their devices cannot generate net positive mechanical work to assist with the sit-to-stand movement.[27-29] For individuals with a unilateral transfemoral amputation—who must compensate for the absence of muscles that formerly spanned their knee and ankle—mechanically passive prosthetic knees and ankles often only provide a small amount of balance support during sit-to-stand; most of the user's weight is transferred to the intact limb for most movements.[29]

Although mechanically active powered prosthetic knees and ankles have the potential to improve lower-limb symmetry during the sit-to-stand movement, studies have yet to produce conclusive biomechanical evidence justifying the use of these devices for sit-to-stand. Individuals fit with the Power Knee[c] showed only small improvements in limb symmetry while standing up compared with those fit with passive microprocessor or nonmicroprocessor knees,[30-32] possibly because of incorrect synchronization of knee power generation with the user's intention. However, little is published about the control of power generation using the Power Knee. Further, a powered knee-ankle prosthesis designed and tested at Vanderbilt University[11] has been recently configured to assist users during sit-to-stand and stand-to-sit movements.[33] Although more information is published regarding this control strategy—the amount of power generation at the knee was dependent on knee position—it was only tested with 1 unilateral transfemoral amputee, and individual ground reaction forces were not reported. Therefore, although the potential of these devices to provide improved biomechanical function during sit-to-stand follows logically from their underlying structure, no studies have provided sufficient control strategies and compelling evidence for their use.

This study's purpose was to develop a strategy to encourage users to bear more weight through their prosthetic side during sit-to-stand movements. In the control strategy, the timing and amount of knee and ankle power were controlled as a function of weight transfer onto the prosthesis. We hypothesized that this user-modulated strategy would result in more equal ground reaction forces while standing up from a seated position. This study includes a detailed description of the prosthesis configuration and reports performance results from 7 transfemoral amputees. Further, a control strategy to enable stand-to-sit movements is also presented and tested.

# Methods

## Participants

A convenience sample of 7 individuals (table 1 lists all transfemoral amputee [TF] participants' demographics) was recruited using the following inclusion criteria: a unilateral above-knee or knee-disarticulation amputation and capable of community ambulation with Medicare functional classification levels K3 or K4.[34] The exclusion criteria were as follows: >113kg or affected by cognitive deficits or visual impairments. This study was approved by the Northwestern University Institutional Review Board. All individuals provided informed consent and had previous experience walking on the powered prosthesis (mean, 21.4±10.5h).

## Powered knee-ankle prosthesis

A certified prosthetist fit users with a powered knee-ankle prosthesis designed by Vanderbilt University.[11] Two brushless direct current motors with belt-driven transmissions provided up to 90Nm of torque at the knee and 100Nm at the ankle. Onboard sensors measured joint angles, joint velocities, motor current, and axial shank force. Knee and ankle joint torque ($\tau$) were modulated according to an impedance-based model:

$$\tau_i = -k_i(\theta_i - \theta_{ei}) - b\dot{\theta}_i$$

Where $i$ corresponded to the knee or ankle joint, $\theta$ was the joint angle, and $\dot{\theta}$ was the joint angular velocity. Impedance parameters,