Prosthetics and Orthotics International

Effects of a low-cost prosthetic knee on amputee gait over uneven and even terrains

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Abstract

Limited data are available related to using a low-cost prosthetic knee while walking. To address this gap, this study compared the performance of a low-cost prosthetic knee with 2 more advanced prosthetic knees while walking on even and uneven terrains. Two adult subjects with above-knee amputations completed walking trials using a low-cost prosthetic knee (ReMotion knee) and their personal prosthetic knees (Ottobock 3R60 Pro mechanical knee and Ossur Rheo microprocessor knee) over even and uneven terrains. Several measures of gait performance were obtained including step size, stability, energy expenditure, as well as user perception of ReMotion workload and performance during gait. Effects of the ReMotion knee were different between the mechanical and microprocessor knee user. In addition, subjects perceived the positive aspects associated with the ReMotion knee to be its lightweight feature and their perceived increased in stability during walking while both subjects disliked the inability of the ReMotion knee to adjust to preferred walking speeds. This study provided an understanding of low-cost prosthetic technology among lower-limb amputees compared to prosthetic technology with more technologically advanced assistance. These findings may help guide future low-cost prosthetic knee design considerations for use on various terrains.

Keywords

lower limb amputees, prosthetic knees, gait, developing countries, uneven terrain

Date received: 4 May 2023; accepted 29 July 2024.

Background

Low-cost prostheses have the potential to improve mobility and quality of life for the estimated 40 million amputees in developing countries.[1,2] Only 5% of amputees in developing countries have access to prosthetic services[1] because of high cost of most prostheses[3] and limited accessibility of prostheses maintenance.[3,4] Low-cost prostheses provide a cost-effective solution, yet some remain susceptible to reduced robustness for use on varied terrain often found in developing countries.[5]

The effects of low-cost prosthetic knees on amputee gait is not well characterized.[2] Previous studies comparing gait using a low-cost knee with more technologically advanced knees found that a low-cost stance-control knee produced similar walking energy expenditure on even terrain,[6] while the low-cost ReMotion knee produced decreased clinical mobility scores, balance confidence scores, and comfort compared to a more advanced prosthetic knee.[7] Although these studies provide insight into the performance of low-cost prosthetic knees, further understanding of their gait performance, especially on uneven terrain that is often encountered in developing countries, is needed.[2]

The goal of this exploratory study was to compare gait performance between the low-cost ReMotion knee and more advanced prosthetic knees on both even and uneven terrain. The ReMotion knee was investigated because of its successful dissemination in developing countries[5] where 79% of 141 users reported still wearing the knee 2 years after first receiving it, and 95% reported no failures.[8] Identifying differences in gait between these knees may help guide improvements to the ReMotion knee.

Case report

One mechanical knee user and one microprocessor knee user, both with at least 1 year of experience using their prosthesis and similar mobility and activity levels, completed the study (see Supplemental Digital Content—Table S1, http://links.lww.com/POI/A275). The mechanical knee used a Ottobock 3R60 Pro hydraulic-based system that allowed for flexion and extension dampening while the microprocessor knee used a Ossur Rheo microcomputer system to continuously control flexion and extension of the knee. The ReMotion knee uses a four-bar linkage design for flexion stability with swing assistance provided by flexible, embedded

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Associate Editor: Jan Andrysek

DOI: 10.1097/PXR.0000000000000400

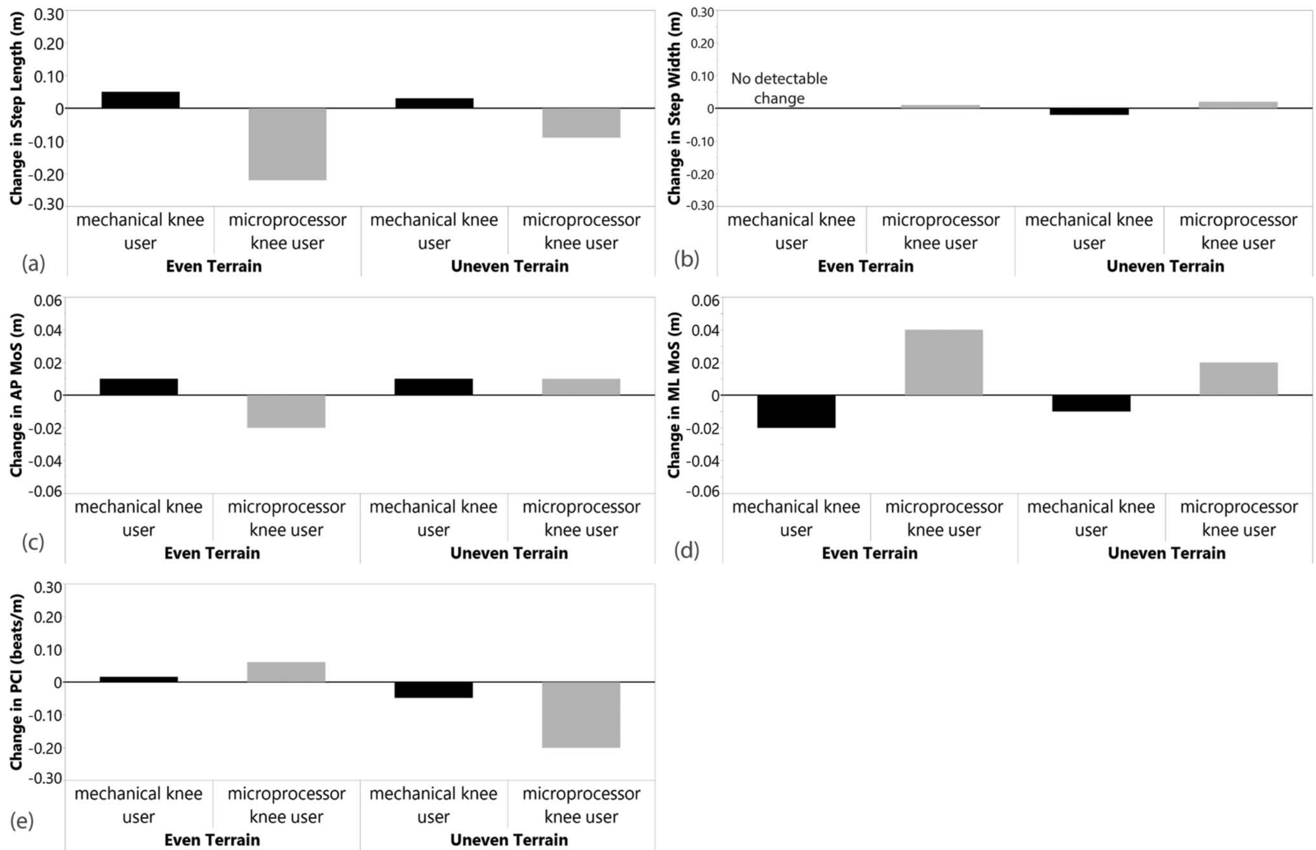

Figure 1. Changes (ReMotion knee—personal knee) in step size, gait stability, and energy expenditure measures across terrain types indoors and outdoors including (a) step length, (b) step width, (c) AP MoS, (d) ML MoS, and (e) PCI for the mechanical knee user and microprocessor knee user.

metal strips.[8] This study was approved by the university's Institutional Review Board, and subjects signed informed consent forms before participating.

A repeated measures design was used for this study. Subjects completed one session consisting of several walking trials on even and uneven terrains (counterbalanced order) using their personal then ReMotion knees. The even terrain was a flat, tiled walkway, whereas the uneven terrain was also flat but with varied wooden blocks glued in place to mimic a rocky outdoor terrain (see Supplemental Digital Content—Figure S1, http://links.lww.com/POI/A276).

During the session, subjects completed four 5-minute walking trials along a laboratory walkway (12 m × 1.2 m) on both terrains at their preferred gait speed. Walking trials were 5 minutes to allow for the rate of energy expenditure to stabilize while minimizing fatigue, and preferred gait speed was controlled to minimize confounding effects related to gait speed. For each terrain type, preferred gait speed (measured with a stopwatch) was calculated as the average speed during the first 2 minutes of walking. For the remainder of the trial and subsequent trials, subjects were verbally asked to speed up or slow down if their gait speed deviated by more than ±10% of their preferred speed to standardize subject's gait speed across all trials. When donning the ReMotion knee, a custom-sized pylon was used to ensure consistent prosthesis height, and alignment of the knee followed manufacturing guidelines (eg knee/foot abduction/adduction angle) to the extent possible given preexisting hardware. After a 20-minute familiarization period, subjects completed walking trials on both terrains.

Throughout all trials, heart rate was monitored using a chest band (Polar H10, Polar Electro Oy, Kempele, Finland), and body kinematics were sampled at 60 Hz using 17 inertial measurement units (IMUs) (Xsens Technologies B.V., Enschede, the Netherlands). Step size (width and length), anterior-posterior (AP) and mediolateral (ML) gait stability (Margin of Stability [MoS]), and energy expenditure (Physiological Cost Index [PCI] using heart rate and walking speed)[9] were determined during the last 2 minutes of each trial (see Supplemental Digital Content for additional details, http://links.lww.com/POI/A274). A change in MoS toward negative infinity was viewed as a decrease in stability and has been associated with increased fall risk.[10] Values for step size and gait stability are only reported for the amputated limb. At the end of each walking trial, subjects completed the NASA TLX,[11] and rated the ReMotion knee's stability (or resistance to buckling) and overall performance. NASA TLX scores for the microprocessor knee user on uneven terrain are missing because of clerical errors (missing data entry); therefore, only NASA TLX change scores for even terrain are reported for both subjects.

Findings and outcomes

When the mechanical knee user walked with the ReMotion knee, step length increased 0.03–0.05 m, AP MoS increased, indicating increased stability by 0.01 m, and ML MoS decreased 0.01–0.02 m across both terrains (Figure 1). Interestingly, PCI increased

Table 1. Results from the postsession quantitative and qualitative interview administered to subjects to observe their perceptions of the ReMotion knee including numerical and verbal responses.

	Mechanical knee user		Microprocessor knee user	
How would you rate the stability of the ReMotion knee? 1 = very stable 10 = very unstable	3	Very similar to current knee	2.5	Own knee is more stable
How would you rate the ease of use of the ReMotion knee? 1= very easy to use 10 = very difficult to use	6.5	Timing is very slow, so it takes more thinking Swinging of current knee is easier, ReMotion knee is easier to flex, but it is slow	1.5	Easier to use because it is lighter
How would you rate the overall performance of the ReMotion knee? 1 = best 10= worst	5	Likes current knee better because it is (1) Better at walking at different speeds (2) Easier to bend (3) Does not have to fire contralateral muscles as much If the ReMotion knee was faster and if it returned energy, it would be better	2.5	No comment
What did you like about the ReMotion knee?	Very stable Easy to flex Does not require much force to move		Lightweight— made it easy to use Lightweight—did not pull down their prosthetic liner when walking. In current knee, prosthetic liner slides down when they start to sweat It would be a good knee for someone who is more active	
What did you dislike about the ReMotion knee?	Extension of the knee is very slow Knee flexion takes more effort (on even terrain) Inability of ReMotion knee to keep up with gait and pace of walking		Does not bend easily Seems to hold you back when you walk Believes it would be difficult to use going down on steps There was a lag in the timing of the knee, but believes they could get used to it	

0.02 beats/m on even terrain but decreased 0.05 beats/meter on uneven terrain (Figure 1). NASA TLX showed increased workload (1–5 points out of 10) across all categories with physical workload and frustration showing the largest change (Figure 2). The mechanical knee user reported that the ReMotion knee's stability was similar to their own knee and that it was easier to flex than their own but disliked the speed of it while walking (Table 1).

When the microprocessor knee user walked with the ReMotion knee, step length decreased 0.09–0.22 m and ML MoS increased 0.02–0.04 m (Figure 1). Interestingly, PCI increased 0.06 beats/m on even terrain but decreased 0.20 beats/meter on uneven terrain (Figure 1). NASA TLX showed decreased (2–3 points out of 10) physical and temporal workload but slightly decreased (+1) performance (Figure 2). The microprocessor knee user also reported that the ReMotion knee was less stable their own, its lightweight feature was seen as beneficial for ease of use and not pulling down their prosthetic liner but disliked the speed of it while walking (Table 1).

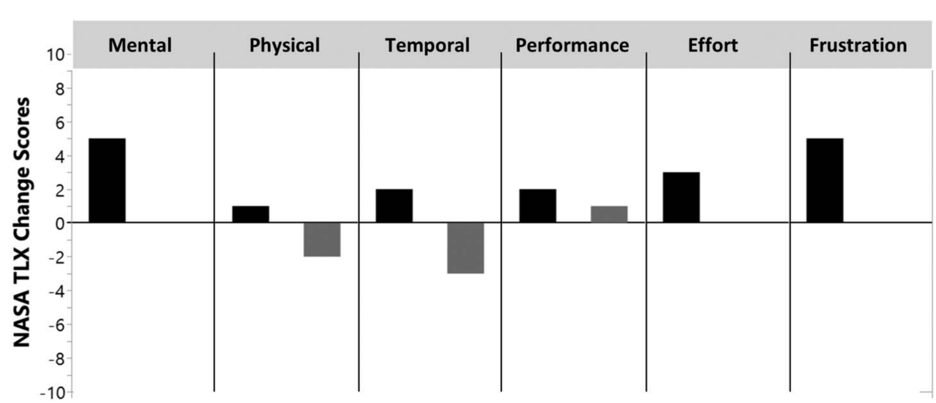

Figure 2. Raw NASA TLX ratings on even terrain when using the ReMotion knee and subject's personal knee. TLX ratings were on a 0–10 scale with higher numbers reflecting greater demands or effort and poorer performance. NASA TLX scores for the microprocessor knee user on uneven terrain are missing because of clerical errors (missing data entry); therefore, only NASA TLX change scores for even terrain are reported for both subjects.

Discussion

Gait stability and energy expenditure findings may highlight favorable attributes of the ReMotion knee that could be considered for future designs. Gait stability was expected to decrease with the ReMotion knee because of its reliance on gait modifications to prevent buckling while subjects' personal knees had hydraulic and computer technology to help prevent excessive knee flexion. AP MoS improved among both subjects, but ML MoS only improved among the microprocessor user. Other case studies found a 10% decreased ML MoS[12] and decreased perceived stability[13] when walking with a mechanical compared to a microprocessor knee, which aligns with the decreased ML MoS and decreased perceived stability when using the less technologically advanced ReMotion knee. Energy expenditure was expected to increase with the ReMotion knee because of its limited assistance. Interestingly, PCI improved on uneven terrain when using the ReMotion knee with a greater improvement among the microprocessor knee user. Other studies demonstrated increased net oxygen consumption when using the 3C1 hydraulic knee compared with the C-Leg electronic knee,[14] which aligns with the increased energy expenditure findings on even terrain when using the ReMotion knee.

User perceptions of the ReMotion knee identified characteristics that may help guide future technology. The mechanical knee user's reported increased mental workload and frustration may be related to their comments about the ReMotion knee being slow. The microprocessor knee user's reported decreased physical and temporal workload may be related to their comments about the ReMotion knee being lightweight. Both subjects found it difficult for the ReMotion knee to adjust to the required gait speed. This finding is similar to decreased performance with the ReMotion knee on the L test that measures time required to stand, walk 20 m with 4 turns, and sit down.[6] Together, these findings support that future low-cost prosthetic knee designs should consider easy walking speed adjustments and remain lightweight.

A few limitations of this study are worth noting. First, the small sample size limits generalizability, but the findings may help guide future designs. Second, ReMotion familiarization was limited to 20 minutes to mitigate fatigue and large residual limb volume fluctuations, and our findings may be dependent upon experience with the knee. We note that short familiarization periods are not uncommon in end-user field settings because of time constraints.[5] Third, although the ReMotion knee was mounted and aligned with the subjects' prosthesis according to manufacturer instructions, it was not performed by a licensed prosthetist. However, this may match underdeveloped countries where the availability of trained prosthetist can be limited.

Conclusions

Gait performance with the ReMotion knee exhibited both advantageous and disadvantageous changes from more advanced knees. Advantageous changes in energy expenditure and gait stability may be associated with its lower mass, whereas disadvantageous changes in gait speed adjustments and perceived mental workload may be associated with its simplistic control and limited assistance. These findings may help guide future low-cost prosthetic knee design considerations for use on various terrains.

Funding

This work was supported by a Virginia Tech Graduate Research Development Program grant (to J.A.). The funding source had no involvement in any part of this study.

Declaration of conflicting interest

The author(s) disclosed no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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