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Oxygen Uptake During Walking in Three Types of Microprocessor-Controlled Prosthetic Knee Joints in a Middle-Aged Male with Bilateral Transfemoral Amputation

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1. Abstract

Individuals with bilateral transfemoral amputations experience great difficulty in prosthetic ambulation in their community because of high energy consumption during walking. We present the case of a 47-year-old male with bilateral transfemoral amputation who gradually became more fatigued when walking with prostheses 11 years after completing his first prosthetic training. We provided 8 weeks of prosthetic rehabilitation and evaluation with three types of Microprocessor-Controlled Knee joints (MPKs), Hybrid knee, Kenevo, and C-leg. As a result, he regained stable ambulation with the least fatigue and oxygen uptake in the C-leg. Appropriate MPKs suitable for the physical functions of bilateral transfemoral amputees could reduce the physical burden of prosthetic walking and allow amputees to continue ambulation in their community.

2. Introduction

Few amputees with bilateral transfemoral amputations continue to walk with prostheses in their community [1,2]. One reason for this is the extremely high energy consumption of prosthetic walking. It has been reported that the oxygen uptake of bilateral transfemoral amputees walking with prostheses is much greater than that of healthy individuals walking or amputees moving in wheelchairs [3-6]. Energy expenditure or fatigue during walking is an important factor that prevents individuals with bilateral transfemoral amputations from using prostheses as a means of mobility in their community.

In recent years, microprocessor-controlled prosthetic knee joints (MKPs) have been increasingly used in transfemoral prostheses, and their effectiveness has been reported in unilateral transfemoral amputees. MPKs have been reported to consume less energy during walking than Nonmicroprocessor-Controlled Prosthetic Knee joints (NMPKs) [7] and provide greater stability and safety during walking on level ground, uneven terrain, slopes, and stairs [8, 9]. Furthermore, it has been reported that the MPK, which controls both the stance and swing phases, consumes less energy during walking than the MPK, which is computer-controlled only during the swing phase and mechanically controlled during the stance phase [10]. However, there have been very few reports on energy expenditure during gait using MPKs in bilateral transfemoral amputees, and most have been conducted on a limited group of subjects, such as young adults and soldiers with combat-related amputations [11, 12]. In addition, few studies have been conduct-

ed on energy expenditure during walking with prostheses in middle-aged and older bilateral transfemoral amputees, and no studies have examined the differences in oxygen uptake during walking in individuals with bilateral transfemoral amputations with multiple MPKs.

Here, we report the case of a middle-aged man with bilateral transfemoral amputation who underwent prosthetic training with three types of MPKs. In this patient, using an MPK appropriate for his physical function reduced energy expenditure while walking, which resulted in less fatigue and less fear of falling. This study was conducted according to the Declaration of Helsinki, and written consent was obtained from the patient.

3. Case Presentation

A 47-year-old male underwent bilateral transfemoral amputation due to a work-related accident at 34 years. After 18 months of inpatient rehabilitation, he was discharged and returned to work as an office worker after gaining the ability to walk on a bilateral transfemoral prosthetic leg with two canes. At the time of discharge from the hospital, his prosthetic prescription was as follows: bilateral Ischial-Ramel-Containing (IRC) suction socket, Hybrid knee (an MPK with pneumatic computer control for the swing phase and hydraulic mechanical control for the stance phase: Nabtesco, Tokyo, Japan), and an energy-storing foot (Freedom foot, Freedom innovations, Irvine, CA, USA). Subsequently, he continued to walk with his prosthesis for about 30 minutes every day on weekdays and about 1–2 hours on weekends. However, as he aged, he gradually became increasingly fatigued and unsteady when walking and began to feel a fear of falling. Shortly before readmission to our hospital, he used a wheelchair most of the time, but he wished to continue walking with his prosthetic leg. He was admitted to our hospital for 8 weeks, 11 years after discharge for prosthetic rehabilitation, to reacquire a stable gait.

On physical examination, the stump length was 26 cm on the right side and 25 cm on the left, with no abnormalities in the stump skin. There was no flexion or abduction contracture in the bilateral hip joints, and bilateral hip muscle strength was five on manual muscle testing. During the first 3 days after admission, the patient underwent physical therapy and self-training with a Hybrid knee that he used daily before admission to confirm gait movement and improve basic physical fitness.

Physiotherapy and Progress with Kenevo

We considered that Kenevo (an MPK with hydraulic computer control for both the swing and stance phases; Ottobock GmBH, Duderstadt, Germany), which is suitable for individuals with low/middle activity levels, would provide gait stability in this case. Kenevo has been reported to be safe and reduce the risk of falls in low-activity individuals undergoing unilateral transfemoral amputation [13,14]. On day 4, the bilateral knee joints were replaced with Kenevo, and physiotherapy was performed. Kenevo has four control modes that can be selected based on walking stability. To evaluate stability in walking with physiotherapy, the patient started Kenevo training with the most stable A/A (both the swing and stance phase fixed) mode, then progressed to swing phase hydraulic computer-controlled and stance phase fixed (B/B) mode, B+/B+ (swing phase hydraulic computer-controlled and stance phase computer-controlled bouncing) mode, and C/C (swing phase hydraulic computer-controlled and stance phase hydraulic computer-controlled yielding) mode. After 1 week of training with Kenevo, the patient could walk stably on level ground with two canes. The patient was also trained to walk on uneven terrain, ramps, and stairs, and within 3 weeks, he acquired stable ambulation using Kenevo with two canes indoors and outdoors. The oxygen uptake during walking with the hybrid knee and Kenevo was measured in the fourth week of hospitalization (Table 1; Figures 1 and 2).

Figure 1: Measurement of oxygen uptake

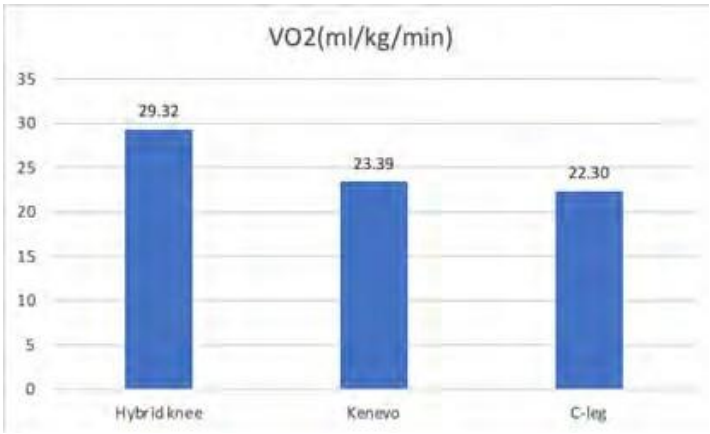

Figure 2: Oxygen uptake during walking

Kenevo reduced oxygen uptake by 20% compared to the hybrid knee. The C-leg revealed a 24% reduction in oxygen uptake compared to the hybrid knee. C-leg decreased oxygen uptake by 4.7% relative to that of Kenevo.

Table 1: Walking speed

	6MD(m)	Spped(m/min)	Speed(km/h)
Hybrid knee	357	59.5	3.6
Kenevo	354	59	3.5
C-leg	387	64.5	3.8

Walking speed was the fastest in C-leg; however, the difference was small.

Physiotherapy and Progress with C-leg

The patient successfully achieved stable ambulation with Kenevo, and his walking speed exceeded Kenevo's maximum speed of 3 km/h (50 m/min; Table 1). At this point, we determined that the C-leg (Ottobock GmBH: swing phase hydraulic computer-controlled and stance phase hydraulic computer-controlled yielding), an MPK indicated for more active individuals than Kenevo, should be appropriate for this case [15,16]. The bilateral knee joints were then changed to the C-leg, and physiotherapy was performed. Within 3 weeks, indoor and outdoor activities, including level and uneven terrain walking, slopes, and stairs, were stabilized with two canes. Oxygen uptake during walking with the C-leg was measured in the eighth week of hospitalization (Table 1, Figure 2).

4. Protocol for Measuring Oxygen Uptake During Walking

K5 (Cosmed, Rome, Italy) was used to measure oxygen uptake (VO2; ml/kg/min) [17]. Walking distance was measured by performing a 6-minute walking test (6MD) [18] on a 90 m indoor, flat rectangular course. Measurements were performed according to a previous report by Chin et al. [10] (Figure 1). Heart rate was measured before and after the measurement of oxygen uptake, and subjective fatigue was assessed after walking, using the modified Borg scale (mBS) [19]. When the Hybrid knee and Kenevo assessments were performed, 15-minute rest periods were taken between each knee joint assessment. The oxygen cost (ml/kg/m) was calculated using the average walking speed (m/min) during the 6-minute walk.

4.1 Results of Oxygen Uptake Measurement, Oxygen Cost, and Progress

Regarding the oxygen uptake measurement, the 6MD, walking speed, and heart rate at the time of measurement were almost the same among the three types of MPKs, and the walking speed was more than 3 km/h in all joints (Tables 1 and 2).

The mBS was the lowest for the C-leg at five, and we discovered that the C-leg could reduce fatigue while waking (Table 2). Oxygen uptake was 20% lower for Kenevo and 24% lower for C-leg compared to the Hybrid knee (Figure 2). Oxygen cost was also improved by 18% for Kenevo and 29% for C-leg compared to the Hybrid knee (Figure 3).

The patient stated that walking with the C-leg was the most stable and reduced the instability and fear of falling during prosthetic ambulation. Therefore, the C-leg was prescribed as the new prosthetic knee joint. The new prosthetic prescription was: bilateral IRC suction socket, C-leg knee joint, and energy-storing foot (Taleo, Ottobock GmBH). For safety reasons, the patient continued to use two canes after discharge. At the three month follow-up after discharge, his walking time improved to almost the same degree as 11 years ago, when he was discharged from the first prosthetic rehabilitation.

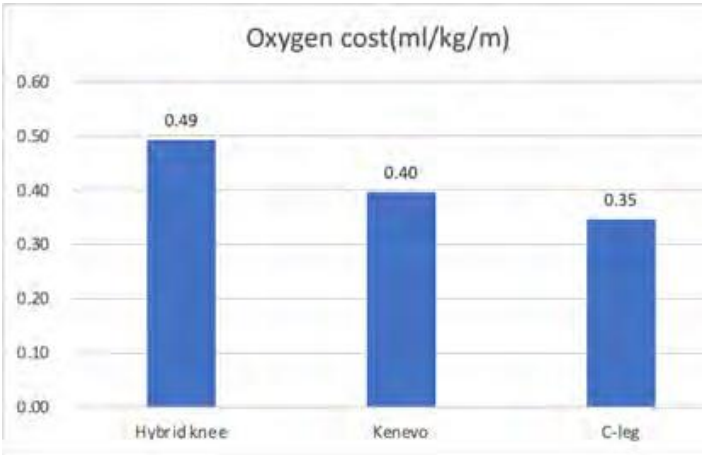

Figure 3: Oxygen cost
Kenevo improved oxygen cost by 18% compared to the Hybrid knee. C-leg improved oxygen cost by 29% and 13% of the Hybrid knee and Kenevo, respectively.

Table 2: Pre- and post-walking heart rate and subjective fatigue

	HR before (beats/min)	HR after (beats/min)	mBS
Hybrid knee	97	139	7(very strong)
Kenevo	95	139	7(very strong)
C-leg	100	136	5(strong)

Heart rates before and after walking were similar among the MPKs. The C-leg revealed the smallest mBS, and the hybrid knee and Kenevo were comparable.
mBS; modified Borg Scale

5. Discussion

We measured oxygen uptake during prosthetic walking with three different MPKs in a middle-aged male who underwent bilateral transfemoral amputation. We revealed that Kenevo and C-leg reduced walking oxygen uptake by over 20% compared to Hybrid knee, and oxygen cost was improved with Kenevo and C-leg compared to Hybrid knee. The walking speeds of all three MPKs were similar, over 3 km/h, and post-walking heart rates were also similar; however, subjective fatigue was the lowest with C-leg, and C-leg was the most comfortable for the patient.

The lower energy expenditure during ambulation in individuals with bilateral transfemoral amputation with Kenevo and C-leg could have important implications for the continuation of community ambulation in bilateral transfemoral amputees with prostheses. Several reports have revealed high-energy expenditure during prosthetic walking in bilateral transfemoral amputees. Wu et al. measured oxygen uptake and oxygen cost during ambulation in a wheelchair and NMPK in a 40-year-old female with bilateral transfemoral amputation; they reported that ambulatory oxygen uptake in the NMPK was 143% of that in the wheelchair, movement speed was 31%, and oxygen cost was 466% of that in the wheelchair [3]. Huang et al. reported that oxygen consumption during walking with a prosthesis in young males with bilateral transfemoral amputation was 280% of that in healthy adults [4]. Hoffman et al. reported that the comfortable walking speed of bilateral transfemoral amputees was 21% slower and oxygen consumption 149% greater than that of healthy adults of the same age [5]. Crouse et al. stated that only the most physically fit individuals with bilateral transfemoral amputations could walk with their prosthetic leg owing to the high energy consumption during walking [6]. These reports suggest that walking with a prosthetic leg is challenging for middle-aged bilateral transfemoral amputees.

However, a few reports have revealed that MPKs could reduce energy expenditure during prosthetic walking in unilateral or bilateral transfemoral amputees. Jarvis et al. measured energy expenditure during prosthetic walking in young soldiers with combat-related transfemoral amputations. They discovered that the walking speed of bilateral transfemoral amputees with MPKs was only 13% slower than that of normal subjects (1.12 m/s), and oxygen uptake was 16.2 ml/kg/min, 143% of normal subjects [11]. Perry et al. also reported that the C-leg improved walking speed by 70% compared to short prosthetic legs (stubbies) and NMPKs in a young bilateral knee-disarticulated patient, allowing him to walk at 70% of the speed of normal individuals, and improved oxygen cost from 212–314% of normal subjects with stubbies and NMPKs to 120–167% with the C-leg [12]. These reports have revealed that young amputees could reduce energy expenditure during walking when using MPKs compared to conventional NMPKs; however, no studies have measured energy expenditure during walking using MPKs in middle-aged and older individuals with bilateral transfemoral amputation. In our study, oxygen uptake and cost during prosthetic walking were improved in a middle-aged bilateral transfemoral amputee using Kenevo or C-leg compared to Hybrid knee. In particular, the C-leg also reduced subjective fatigue, as measured by the mBS. The oxygen uptake and cost during walking were greater than those reported by Jarvis et al., and Kenevo and C-leg revealed remarkable improvement compared to Hybrid knee; however, the walking speed was similar to this report [11]. These results suggest that with appropriate MPKs, prosthetic walking in the community could be achieved in bilateral transfemoral amputees for a long time after amputation with advancing age.

In this case, walking speed and 6MD with the three types of MPKs were almost equivalent. These results imply that all three types of MPKs used could achieve stable gait with appropriate physiotherapy and training; however, C-leg was the best in terms of oxygen uptake and cost. Chin et al. reported that the C-leg, which is computer-controlled for both stance and swing phases, was superior in energy consumption compared to MPK in which the stance phase is mechanically controlled [10]. In this case, the stance phase of the Hybrid knee was mechanically controlled, and its energy consumption may have been higher than that of the C-leg with computer-controlled mechanism of the stance phase, which is consistent with a previous report by Bellman et al. [20]. The control mechanisms of Kenevo (C-mode) and C-leg are almost identical; however, the results for the C-leg were superior in this case. This may be because Kenevo is a knee joint intended for low-activity amputees and has a maximum walking speed of 3 km/h (50 m/min) [13, 14]. In this case, the walking speed of Kenevo was 3.5 km/h (Table 1), which was faster than that in subjects with good indications for Kenevo. Therefore, comparing C-leg and Kenevo, which have equivalent control mechanisms, the results may indicate that the C-leg is appropriate based on the physical ability of the subject. In contrast, Kenevo may be suitable for amputees with lower exercise tolerance than in this case, for example, amputees with a walking speed slower than 3 km/h. It has been reported that older or vascular etiology transfemoral amputees with reduced physical function have lower maximal oxygen uptake and reduced exercise tolerance capacity [21, 22]. These results imply that appropriate evaluation of physical function and specific physiotherapy for prosthetic walking are critical to selecting prosthetic knee joints in bilateral transfemoral amputees. The ability to walk faster than 3 km/h may be a criterion for deciding whether Kenevo or the C-leg is appropriate. However, further studies are needed to determine whether the Kenevo or C-leg is appropriate.

The C-leg was also excellent at reducing the fear of falling in this patient. For lower-limb amputees, a sense of stability in walking and reduced fear of falling are important for continuing walking with a prosthetic leg in their community [23]. Compared with the Hybrid knee, where the stance phase is mechanically controlled, the C-leg has computer control in the stance phase, which may have provided a better balance and sense of security in walking. In addition, in the comparison between Kenevo and C-leg, the patient's physical function was relatively high; therefore, it may have been better matched in the C-leg than in Kenevo. The results of this case may highlight the importance of matching the physical function and prosthetic knee function, and the appropriate evaluation of physical function and physiotherapy for prosthetic knee joint selection in bilateral transfemoral amputees.

Appropriate prosthetic knee joint selection, physiotherapy for prosthetic walking, and follow-up are necessary for individuals with bilateral transfemoral amputations to continue walking with

their prosthetic legs in the community. This case demonstrates that walking ability declines with age in bilateral transfemoral amputees and can be improved with appropriate knee joint selection and training. Further studies are needed to gain knowledge on selecting appropriate prosthetic knee joints and establish optimized prosthetic training protocols for individuals with bilateral transfemoral amputations.

6. Conclusion

Oxygen uptake during walking with three different MPKs in a middle-aged male with bilateral transfemoral amputation revealed the C-leg provided the best energy expenditure and reduced the fear of falling. The patient continued to walk with his prosthesis using C-leg in the community after discharge from the hospital. This case may imply that using appropriate MPKs for individuals with bilateral transfemoral amputations might be effective for continuing community ambulation with their prostheses, even in middle age.

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