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Original Article

Comparison of the effects of sliding-type and hinge-type joints of knee-ankle-foot orthoses on temporal gait parameters in patients with paraplegia

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ABSTRACT
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Objective: To determine the efficacy of sliding-type medial hip joint (Primewalk system) and a hinge-type medial hip joint (Walkabout system) of knee-ankle-foot orthoses in improving the temporal gait parameters in patients with paraplegia.
Methods: The subjects were 7 consecutively recruited patients with paraplegia (6 men and 1 woman; age, 20-45 years). All subjects had got used to the Walkabout system and were trained using the Primewalk system for at least 1 month before the measurements of the temporal gait parameters. The average gait velocity, cadence, and stride length were measured. The pelvic rotation angle was additionally measured in 1 patient.
Results: The average gait velocity was higher, cadence was faster, and stride was longer with the Primewalk system than with the Walkabout system. The value for the step length divided by the pelvic rotation angle was larger with the Primewalk system than with the Walkabout system.
Conclusion: The Primewalk system improved the gait efficiency by the sliding mechanism that set the virtual axis of the orthoses hip joint higher than that of the hinge-type joint.
Key words: paraplegia, gait, orthosis, medial hip joint

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Introduction

Knee-ankle-foot orthoses (KAFOs) and hip-knee-ankle-foot orthoses (HKAFOs) have long been used for the treatment of patients with paraplegia after thoracic and/or lumbar spinal cord injuries [1]. However, while these orthoses provide excellent stability during steady-state standing, they are not convenient for daily home use. As a result, the rate of continuous use of orthoses is low, and they tend to be worn only for standing and exercise in the home setting [2]. Even in the clinical setting, these orthoses are not frequently used because of problems associated with their weight, size, appearance, and comfortableness. Most patients with paraplegia use a wheelchair as the main equipment for transportation. Various types of wheelchairs with excellent function, utility, and design have been developed to meet patient needs. In addition, the patients' surroundings have been modified, and wheelchair accessibility to various facilities and locations has gradually improved. Accordingly, the rehabilitation of patients with paraplegia has focused on ensuring that the patient attains wheelchair skills for daily life at home or in the community.

However, in efforts to help patients expand their spheres of activity, a number of orthoses have been developed recently to aid in the restoration of standing and walking abilities [3-7]. The Walkabout unit invented in 1992 (Polymedic Co., Goldcoast, Queensland, Australia) functions as a single-axis hip joint connecting 2 KAFOs (Fig. 1). The unit is positioned and attached to the KAFOs between the thighs, under the perineum, but is also removable. In this article, the KAFOs connected with the unit are called Walkabout systems. Walkabout systems provide stability during standing and walking, are compatible with wheelchairs, have cosmetic benefits, and are easy to don/doff [8]. However, the Walkabout system has a hypothetical axis that is lower than the position of the physiological hip joint. Middleton et al [9]. suggested that this discrepancy would create a significant impediment to ambulation by increasing resistance to the movement of the legs. Therefore, they developed the Moorong Medial Linkage Orthosis (Moorong MLO), which uses an arcuate sliding link centered on the hip joints. On the basis of the results of a study with only 1 patient who wore the orthosis on various terrains (e.g., level footpath, grass, and up-down slope), they concluded that the use of this orthosis could improve gait efficiency in comparison with the Walkabout system.

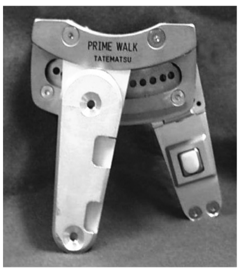
We have also reported that the walking speed achieved using the Walkabout system was low because the unit allows only a slow cadence and short stride [10,11]. In order to solve this problem, we previously developed an orthotic system by using KAFOs with another medial linkage device, the Primewalk (TIMS Co., Fukamiiwahana, Fujiko-cho, Nishikamo, Aichi, Japan), which has a virtual axis based on a sliding mechanism (Fig. 2). The Primewalk device used in this study was a sliding-type medial hip joint that had 12 embedded bearings in order to ensure smooth movement. It was made from duralumin and weighed 688 g. The permitted range of motion was 40 degrees. The height of the virtual axis was set to 80 mm above the apparatus in accordance with the results of a preliminary study performed using anthropometric matching between the hip joint and the virtual axis of the brace joint [11]. Similar to the Walkabout unit, it was possible to remove the Primewalk unit from KAFOs, and it was also possible to wear the Primewalk system on a wheelchair. In addition, the Primewalk system passed an engineering examination evaluation (a strength test and a durability test) and a clinical test, and it was adopted as a standard to set the Law for the Welfare of the Physically Disabled and the Child Welfare Law. It is now industrially mass-produced.

A

B

Figure 1. Walkabout (A) and Walkabout system (B).

A



B

Figure 2. Primewalk (A) and Primewalk system (B).

We hypothesized that the gait efficiency of the patients with paraplegia would be improved if there were less discrepancy of the position of the physiological hip joint and the hip joint of the device. In order to determine the efficacy of this device employing the sliding mechanism, we, unlike Middleton et al., thought that it requires testing with a number of patients with paraplegia. The purpose of this study was to determine the efficacy of the Primewalk system as compared with the Walkabout system in improving the temporal gait parameter of the patients with paraplegia.

Methods

Subjects

Six male patients and 1 female patient with paraplegia were consecutively recruited from those patients with paraplegia who were treated at the University hospital. The age range of the subjects was 20-45 years (mean ± standard deviation (SD), 34.1 ± 9.94 years). The level of paresis was thoracic T4 to T10 in these subjects. According to the American Spinal Injury Association (ASIA) impairment scale, 6 subjects were classified as grade A and 1 was classified as grade C. The time after the onset of paresis is shown in Table 1. All subjects had used the Walkabout system for at least 2 months (14.3 ± 7.8 months) and could walk using the orthoses at the beginning of this study. All subjects were trained using the Primewalk system for 1 month before the measurements of temporal gait parameters.

All the measurements were performed after the subjects were provided with a verbal and written explanation of the purpose of this study, and the subjects had given informed consent to participate.

Measurements of temporal gait parameters

KAFOs were made for each subject's use and the connecting parts of each KAFO were made to be able

Table 1. Comparison of the Walkabout and Primewalk

case	age (yo)	sex	ASIA	TAO (month)	velocity (m/min)*		cadence (steps/min)*		stride length (m)*	
					Walkabout	Primewalk	Walkabout	Primewalk	Walkabout	Primewalk
1	21	M	T4A	41	10.0	14.6	57.0	65.9	0.35	0.44
2	20	M	T4C	32	5.0	11.1	20.0	40.0	0.50	0.56
3	38	M	T6A	21	2.6	3.6	26.1	29.1	0.20	0.25
6	37	M	T6A	12	6.2	11.3	28.4	39.6	0.43	0.57
7	43	M	T9A	5	13.9	17.5	55.7	59.6	0.50	0.58
4	35	M	T10A	98	8.5	9.5	58.3	61.0	0.29	0.31
5	45	F	T10A	29	5.3	5.7	39.8	41.1	0.27	0.28
Average					7.4 ± 3.8	10.5. ± 4.8	40.8 ± 16.3	48.0 ± 13.9	0.36 ± 0.12	0.43 ± 0.15

ASIA; American Spinal Injury Association Impairment Scale *(p<0.05)
TAO; time after on set
NOTE. Values are mean or mean ± SD.

to attach with both the Walkabout unit and Primewalk unit.

During the familiarization session, the subjects walked using the Walkabout system first within parallel bars and then for several meters using Lofstrand crutches. After the familiarization session, they walked using the Walkabout system and Lofstrand crutches at their own comfortable speed thrice for 10 m. The time taken and the following temporal gait parameters were measured for each 10-m walk: gait velocity, cadence, and stride length. After the familiarization session and between each measurement, the subjects rested to ensure sufficient recovery. One week later, the same measurements were performed by using the Primewalk system for the same subject.

Data analyses were performed using the Wilcoxon signed-rank sum test. The results were considered statistically significant if $p < 0.05$.

Three-dimensional gait analysis

An additional gait analysis was performed for 1 subject who had mastered the use of both the Walkabout system and the Primewalk system. The track of the pelvis during locomotion was measured by a three-dimensional gait analysis system in the horizontal plane (Optotrack 3020: Northern Digital Inc., Waterloo, Ontario, Canada). The subject walked 3 times along a 5-m lane, after which the change in the location of each marker was measured. The change in the pelvic rotation angle was calculated from the data.

Results

Temporal gait parameters

As shown in Table 1, the average gait velocity with the Primewalk system (10.5 ± 4.8 m/min) was higher than that with the Walkabout system (7.4 ± 3.8 m/min). The average cadence was significantly faster and stride significantly longer with the Primewalk system (48.0 steps/min and 0.43 ± 0.15 m, respectively; $p < 0.05$ for both the values) than with the Walkabout system (40.8 steps/min and 0.36 ± 0.12 m, respectively).

Three-dimensional gait analysis

The average angle of pelvic rotation when the Primewalk system was used (45.1 ± 8.6 degrees) was smaller than that when the Walkabout system was used (45.8 ± 9.2 degrees); however, this difference was not statistically significant. The average step length with the Primewalk system (0.69 m) was longer than that with the Walkabout system (0.61 m). As measuring a measure of the ease of the swing of lower limbs per pelvis rotation angle, we divided the step length by the pelvis rotation angle. The average of this value was significantly higher when the Primewalk system was used (1.55 ± 0.14 cm/degree) than when the Walkabout system was used (1.36 ± 0.16 cm/degree).

In addition, there was no fall accident during the measurement; therefore, it was suggested that both systems showed sufficient stability during standing and walking.

Discussion

Many patients with paraplegia use an orthosis during the course of rehabilitation but rarely use such aids in daily life. One reason for this is that many orthoses are bulky and therefore are not compatible with wheelchair usage. Furthermore, the energy cost is higher than for wheelchair locomotion, and upper extremity fatigue is greater during daily use [12,13]. On the other hand, the restoration of standing and walking functions is considered to be valuable for patients with paraplegia in order to prevent comorbidities such as osteoporosis, contracture of the leg joints, and cardiovascular deconditioning as well as psychological problems [14-16].

Recently, a number of orthoses have been developed in order to restore the functions of standing and walking. Among these, the orthosis employing the WA, a medially hinged joint, confers several benefits such as wheelchair-compatibility and ease of donning/doffing, as compared with orthoses with laterally positioned hip joints [17]. Middleton et al. reported that the maintenance of joint mobility and psychological benefit were the most important outcomes of using the Walkabout system [18]. However, the Walkabout system has a problem related to its mechanical design. Middleton et al. had suggested this problem before we commenced the present study and had demonstrated it using a single-case analysis. While studies using single-case analysis are undoubtedly useful for detecting the incipient failure of newly developed industrial products, they do not address the effect of differences between individual user responses and cannot assess the validity of results to the same degree as studies using multiple cases. In addition, Middleton et al. did not adopt anthropometrical analysis to decide the position of the virtual axis of the medial linkage joint with the sliding system.

The results of our study using multiple-case design suggested that patients with paraplegia had improved walking ability, specifically in relation to temporal gait parameters, when the Primewalk system was used than when the Walkabout system was used. The high position of the rotational axis was responsible for the higher velocity, faster cadence, and longer stride length, even though these were produced virtually by using the sliding system. Harvey et al. compared temporal gait parameters with the Walkabout system with that of an isocentric reciprocal gait orthosis (IRGO) in persons with paraplegia [19]. The IRGO is one of the orthoses with laterally positioned hip joints that connects to a thoracolumbar corset and which allows the height of the hip joint to be adjusted to the level of the physiological hip joint. Harvey et al. reported that walking was significantly faster when the IRGO was used over flat surfaces and on ramps. This result suggests that even with a heavier system such as the IRGO, setting the hip joint rotational axis of the orthosis at a position adjacent to the physiological hip joint of the patient will improve the mechanical efficiency.

On the basis of clinical observations of the patient gait when the Walkabout system was used, we predicted that backward tilting of the pelvis and viscoelasticity of the soft tissue in front of the hip joint would be utilized when the patient swung the leg forward. The backward tilting movement of the pelvis would be delivered to the lower limb through distension of the soft tissue, including the capsule, ligament, and skin around the hip joint. Although the tightness of the soft tissue would vary among patients, it was conceivable that the loss of force would depend on the distance between the pelvis and the rotational center of the orthoses. The higher the rotational center, the easier the movement of the lower limb (Fig. 3). This was, in fact, reflected in the results of the rotational pelvic movement in the horizontal plane and step length; when the step length was divided by the angle of pelvic rotation, the average value for the Primewalk system was significantly larger than that for the Walkabout system.

We also assumed that the discrepancy in height between the physiological hip joint and that of the Walkabout system would decrease the effective length of the lower extremity with the Walkabout system as well as convey compensatory rotational pelvic movement in the horizontal plane. The greater the pelvis movement, the greater would be the trunk and shoulder girdle movement produced. While walking using the Walkabout system, patients with paraplegia would use their arms more in order to accommodate these movements and to aid balance. It might be easier to detect the existence of compensatory movements through the examination of energy expenditure, rather than by three-dimensional motion analysis. Middleton et al. reported lower energy expenditure when the Moorong MLO was used than when the Walkabout system was used during walking on various terrains [9]. In addition, Harvey et al. found that while

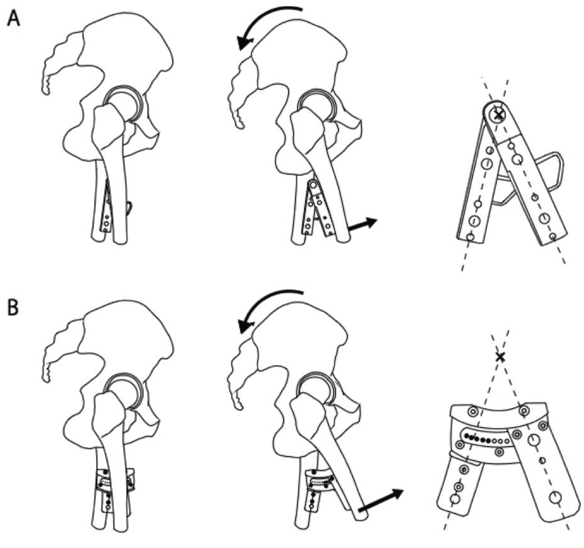


Figure 3. Difference in height of the rotational center between the Walkabout (A) and the Primewalk (B).
A. Users of medially hinged orthoses utilize backward tilting of the pelvis (indicated by the curved arrow) and viscoelasticity of the soft tissue in front of the hip joint while moving the lower limb (indicated by the straight arrow).
B. When the height of the rotational center (marked as X) is set at a higher position, the loss of force through the distension of the soft tissue is decreased, and the lower limb can be moved more easily.

comparing energy expenditure when the Walkabout system and IRGO were used in patients with paraplegia, the physiological cost index and oxygen cost were significantly greater with the Walkabout system [20]. This result suggested that the walking efficiency would be improved because the hip joint position of the orthosis was set near the physiological hip joint.

The effect of the Primewalk system might last for a short period because gait exercises with the system were performed 1 or 2 times a week for about 1 month. This is one of the substantial limitations in this study, and we thought that the subjects should be evaluated again after a substantial practice period. Furthermore, we believe that a reevaluation with the Walkabout system after the second evaluation with the Primewalk system should be performed; however, all subjects could not attend the reevaluation trial because they had personal reasons, and hence, we could not arrange another day for measurement. In fact, all subjects of this study did not anticipate continual use of the Walkabout system because they felt that it was easier to walk using the Primewalk system.

Although there were several limitations in the study, the Primewalk system conferred various advantages to patients with paraplegia, such as its lightweight structure, its use with a wheelchair, and reduction in the discrepancy of positions between the physiological joint and orthotic joint by the virtual axis. There still exists the problem that the walking efficiency when the system is used is much slower than that with normal gait. Assistance with the joint motion of the hip and knee by using a motor system [21] or functional electrical stimulation (FES) might offer a solution to this problem. Shimada et al. reported the effects of hybrid FES with medial linkage KAFOs in patients with complete paraplegia [22]. In their study, they suggested that FES provides sufficient propulsion to allow patients to walk and also showed that the Primewalk system produced a higher gait velocity than the Walkabout system under FES. Any motor device used in assisting joint motion must be light and easy to operate. For patients with paraplegia, we are currently developing a type of robotic system that will function as a controlled actuator to move the sliding medial hip joint and knee joints of the orthoses. If the system proves as useful as we anticipate, it could enable patients to recover walking ability not only in clinical settings but also in daily life.

Conclusion

The Primewalk system had the effect of improving gait efficiency by the sliding mechanism that set the virtual axis of the orthotic hip joint higher than the hinge-type joint.

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