Technical note

A new walking orthosis for paraplegics: hip and ankle linkage system

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Abstract

For paraplegics, two major disadvantages of hip-knee-ankle-foot orthotic systems that have a medial single hip joint are the short stride and horizontal rotation of the pelvis. The authors consider the pelvic rotation is caused by two factors; one is the lack of a mechanism to assist hip flexion, and the other is fixed ankle joints that cause instability when the step length becomes longer. Users must rotate their pelvis to initiate a swing in their legs and to achieve stability by making their two legs as parallel as possible in order to avoid losing balance. To overcome those disadvantages, the authors developed a new orthosis named “HALO” (Hip and Ankle Linked Orthosis), which has a linking mechanism that connects both ankle joints with a medial single hip joint. This new orthosis allows users to keep both feet always parallel to the floor while walking, and assists the swinging of the leg when the contralateral ankle is flexed dorsally by loading.

Gait analysis revealed that the pelvic rotation with “HALO” either in parallel bars or with Lofstrand crutches was within 20°, which was within the physiologically normal level.

Introduction

Although advances in wheelchairs have conferred many benefits on paraplegics, standing and walking remain the ultimate goals for them. Standing and walking provide not only another option of transport, but also many benefits for health; prevention of muscle contracture, reduction of spasticity, reduction of bone mineral loss, improvement of lower limb blood circulation, prevention of pressure sores, and improvement of bladder and bowel function. Many efforts have been devoted to realising these aims, and the goal is coming closer step by step. Hip-knee-ankle-foot orthotic (HKAFO) systems such as the hip guidance orthosis (HGO) (Rose, 1979; Moore and Stallard 1991) and reciprocating gait orthoses (RGOs) (Douglas et al., 1983, Jefferson and Whittle, 1990) have been developed to enable paraplegics to achieve reciprocal gait. Many researchers (Nene and Patrick, 1990; Hirokawa et al., 1990; Bernardi et al., 1995; Feleci et al., 1997; Massucci et al., 1998) reported that such reciprocal walking systems have a lower energy cost than KAFO systems. However, as Stallard and Major (1988) commented, it is not realistic to expect that any of these systems will achieve the same efficiency of locomotion as wheelchairs on a flat surface. Thus, both wheelchairs and orthoses are likely to be used alternatively, depending on the situation. However, orthoses are bulky and difficult to use with a wheelchair, and many patients abandon them because they are too bulky or difficult to don/doff (Merati et al., 2000).

In 1992, Kirtley and McKay invented a new compact orthotic system named “Walkabout” that has a medial single hip joint (MSH-KAFO). It consists of a bilateral knee-ankle-foot orthosis (KAF0) and a Walkabout unit. It has advantages in terms of being lightweight, easy to don and doff and usable with a wheelchair. However, a short stride (37% of normal value) (Saito et al., 1996) and horizontal rotation of the pelvis are 2 major disadvantages of this system. These disadvantages were considered to be caused by a structural problem of the system: the discrepancy of height between the axis of the
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Fig. 1. Comparison of ankle motions with a conventional orthosis (a) and the new orthosis (b). In the new orthosis, the foot is always parallel to the floor during walking.

Saito et al., (1997) invented a new medial side hip joint called "Primewalk" which used a sliding mechanism and brought the orthotic hip joint centre close to the physiological hip joint centre. Consequently, the structural problem that disrupted a long stride and caused pelvic rotation seemed to be resolved. However, although the stride length became longer, the pelvic rotation remained. The authors consider that the pelvic rotation has 2 causes in addition to hip centre dissociation; one is the lack of a mechanism assisting hip flexion, and the other is fixed ankle joints that cause instability when the step length becomes longer (Fig. 1). The users must rotate their pelvis to help their legs start swinging, and to achieve stability by making their 2 legs as parallel as possible in order to avoid losing balance.

To resolve those problems, a linking mechanism that connects both ankles and hip joint was adopted. This mechanism enables the user to keep both feet always parallel to the floor while walking and assists leg swinging when the contralateral ankle is flexed dorsally by loading.

The objectives of this study are to introduce this new concept in orthosis for paraplegics and compare the gait with that of Primewalk.

Methods

Mechanism of the new orthosis

The new orthosis consists of three parts: a medial single hip joint and two knee-ankle-foot orthoses (KAFO) with lockable knee joints and movable ankle joints. The heels of both feet are connected with the hip joint by steel wires (Fig. 2). The hip joint has 2 pulleys that have the same axis and move independently. The right side pulley is connected with the left UFO, and the left side pulley is connected with the right KAFO. A steel wire connects the heel of one foot with the other in the forefoot.

Fig. 2. Overall view of the new orthosis (a), the hip joint (b) and the ankle joint (c). The orthosis consists of three parts: a medial single hip joint and two knee-ankle-foot orthoses (KAFO) with lockable knee joints and movable ankle joints. The hip joint has two pulleys that have the same axis and move independently. The right side pulley is connected with the left KAFO, and the left side pulley is connected with the right KAFO. A steel wire connects the heel of one foot with the same side pulley at the hip joint. Another steel wire connects one foot with the other in the forefoot.
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Fig. 3. The mechanism of the new orthosis: (1) when weight is applied in the dorsal direction on one foot, (2) the ankle flexes dorsally and the wire connected to the heel is pulled, (3) the pulley of the hip joint that connects to the contralateral leg is rotated, and (4) the contralateral leg is extended relatively, and (5) the wire pulls the contralateral heel and the ankle is planterflexed. (6) The ipsilateral leg is extended relatively, and (7) the wire that connects the forefeet on both sides prevents dorsiflexion of both ankles at the same time. The knee joints are locked during walking. Figure 3 explains the mechanism of this orthosis. When dorsal flexion of the left ankle occurs with loading, the wire connected to the heel is pulled and rotates the pulley of the hip joint that connects with the right KAFO, then assists the right leg in swinging forward. The left leg extends relatively to the right leg and then the left pulley rotates to pull the wire that connects with the right heel to allow the right ankle plantar flexion. These motions occur alternatively and a reciprocating gait process is continued. The rotation ratio between the ankle and hip joint was set at 1:2 so that the feet are always parallel to the floor during walking. This linking mechanism does not allow both ankles to flex in the same direction; therefore, the standing stability is the same as that of MSH-KAFO. The authors named this new orthosis “HALO” (Hip and Ankle Linked Orthosis).

Gait analysis
To evaluate the gait with HALO, a 33 year old man (height 1.63m, weight 53kg), with complete paraplegia at the level of TH12, was selected for the subject.

A VICON 250 (Oxford Metrics, UK) was used for motion analysis. Ten (10) markers were attached to the lateral side of each orthosis at the level of the hip, knee, ankle, heel and forefoot. Two (2) more markers were attached to both anterior-superior iliac spines to obtain pelvic motion. The sampling rate was 120Hz, and the subject walked in parallel bars or using Lofstrand crutches twice each.

To determine the general gait parameters (cadence, stride length, velocity), the subject was asked to walk a 10m distance as fast as possible with HALO and Primewalk using a walker or Lofstrand crutches. Trials were performed twice each.

Results
Pattern of movement
Figure 4 shows one right leg step with HALO. The feet were always parallel to the floor and little pelvic rotation was observed.

Figure 5 shows a sagittal plane representation of the left leg (a, c) and a transverse plane representation of the pelvis (b, d) plotted at 15Hz during a single gait cycle from heel strike to heel strike with HALO (a, b) and Primewalk (c, d) using Lofstrand crutches. Notable features are:
(i) Pelvic rotation was much smaller with HALO (b) than with Primewalk (d).
(ii) Horizontal right and left movement of the pelvis was almost the same with both orthoses (b, d).
(iii) Foot to floor angle was almost constant with HALO (a) through one gait cycle.
(iv) Stride length with both orthoses was almost the same (a, c).

Pelvic rotation
The pelvic rotation angle was measured by two markers attached to the bilateral anterior-superior iliac spine. The pelvic rotation with HALO was within 20° both in parallel bars and when using Lofstrand crutches. This is within the physiologically normal level. In comparison, the pelvic rotation of Primewalk was around 50° (Fig. 6). As a result, the subject’s gait with HALO looked more natural than that with Primewalk.
Fig. 4. One right leg step with HALO. Feet are always parallel to the floor and little pelvic rotation was seen.

Fig. 5. Left leg motion of one gait cycle in the sagittal plane in the two orthoses: (a) HALO, (c) Primewalk. Pelvic motion of one gait cycle in the transverse plane in the two orthoses: (b) HALO, (d) Primewalk.

-General gait parameters

The stride length was not significantly different between the two orthoses, however, HALO was superior to Primewalk in the cadence and the velocity both with a walker and Lofstrand crutches (Table 1).

Discussion

In normal walking, ankle joints are flexed dorsally or plantarly depending on the phase of the gait cycle. In the double support phase, after heel contact occurs, the ankle is plantar flexed in order to achieve foot flat. During single limb stance, the ankle is gradually dorsiflexed to maintain foot flat. Such ankle motions contribute stability when shifting from double support to a single limb stance. However, either orthosis with lateral or medial hip joints has fixed ankle joints; therefore, both feet are flat only when both legs are parallel.
Table 1. General gait parameters with the two orthoses.

<table>
<thead>
<tr>
<th></th>
<th>Stride length (cm)</th>
<th>Cadence (steps/min)</th>
<th>Velocity (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>With a walker</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primewalk</td>
<td>100</td>
<td>58.9</td>
<td>29.1</td>
</tr>
<tr>
<td>HALO</td>
<td>103</td>
<td>74.1</td>
<td>36.0</td>
</tr>
<tr>
<td>With Lofstrand crutches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primewalker</td>
<td>69</td>
<td>45.5</td>
<td>15.5</td>
</tr>
<tr>
<td>HALO</td>
<td>66</td>
<td>56.6</td>
<td>19.2</td>
</tr>
</tbody>
</table>

If a user swings his leg a short distance, the flexibility of the brace keeps his foot flat to the floor. However, if a user swings his leg a greater distance, his foot is no longer flat to the floor, and he will lose his balance. This is one reason why a long stride is impossible. He must rotate his pelvis to keep his legs as parallel as possible to avoid falls. In double support phase, especially, there is no method for a fixed ankle to achieve foot flat from heel strike without pelvic rotation.

The pelvic rotation with Primewalk was around 50° in this analysis, and that with HGO or RGOs was reported to be 33° or 23-26°, respectively. The pelvic rotation with HALO, which was within 20°, was still smaller than that with RGOs or HGO. These results indicate that the main cause of pelvic rotation is fixed ankle joints.

The ankle joint motion of the new orthosis HALO not only gives stability in walking, but also utilises the dorsiflexion moment of the ankle to assist the swing of the contralateral leg. As a result, the leg is so easily swung that assistance by pelvic rotation is not needed. For these 2 reasons, pelvic rotation becomes smaller, and thus the gait with HALO becomes more natural than that with conventional orthoses. This mechanism is also applicable for HKAFOs that have lateral hip joints such as HGO and RGOs by linking the ankle joint with the contralateral hip joint.

The standing stability with both legs parallel is the same as that with MSH-KAFO, because a mechanism in which both ankles are flexed in the same direction is made impossible. This mechanism also makes standing without both legs parallel possible.

There was no significant difference between the 2 orthoses in stride length even though the hip centre of HALO is lower than that of Primewalk. This means that the hip centre dissociation is not closely related to stride length.

Both walking stability and the swing assisting mechanism of the new orthosis make a wide stride and larger cadence possible. This might make walking with HALO more efficient than...
with Primewalk, although such improved efficiency must still be proved through an energy consumption study. The authors believe this new concept in orthotics will be another step forward in approaching the goal of paraplegics.

REFERENCES


