A new hip-knee-ankle-foot sling: Kinematic comparison with a traditional ankle-foot orthosis

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Abstract—In this study, we performed a kinematic analysis of a new, low-cost sling for the lower limb, compared to a common ankle-foot orthosis (AFO). Gait with no orthosis, with the AFO, and with the new sling was analyzed in one hemiplegic subject. Both the AFO and the sling reduced the mean angle and ROM (range of movement) of the ankle and the vertical displacement of the center of mass. The sling, but not the AFO, restored the normal sequence heel-strike, forefoot contact of the affected side. The sling, but not the AFO, reduced the affected limb stance and stride duration, increased stride length, and improved walking speed. In conclusion, the proposed sling for the lower limb equally improved the affected ankle kinematics in contrast to the traditional AFO, and it also improved some gait variables in this hemiplegic subject.

Key words: AFO, gait, hemiplegia, kinematic, lower limb, orthosis, sling.

INTRODUCTION

Hemiplegic patients always show alterations of walking pattern kinematics [1,2] and slow walking speed, even if the gait is tripod- or cane-assisted [3]. Ankle-foot orthoses (AFO) are often prescribed to those patients to obtain a better heel-strike, a more dynamic and balanced gait, and a lower energy expenditure during walking [4–7]. Knee-ankle-foot orthoses (KAFO) are rarely used in hemiplegic patients, because of their weight and their supposed disturbance of walking patterns [8]. While AFOs are mainly used to counteract the foot plantar flexion, they are also reported to enhance the paretic quadriceps muscle activity [6] and lower-limb swing in hemiplegic subjects [9].

This study developed a device for the lower limb that could correct the abnormal foot posture, while simultaneously facilitating the swing phase of the lower limb. In our opinion, this could be done by “linking” the patient’s affected lower limb and the opposite body side. Following this idea, we developed a strap-based linkage system, which is a “sling-like” product. We then performed a kinematic analysis of the new, simple, low-cost sling in one representative hemiplegic patient and compared the analysis of the sling to a commonly prescribed AFO.

Abbreviations: AFO = ankle-foot orthosis, ANOVA = analysis of variance, ASIS = anterior superior iliac spine, COM = center of mass, KAFO = knee-ankle-foot orthosis, LSD = least significant difference, RGO = reciprocating gait orthosis, ROM = range of movement, SD = standard deviation.

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METHODS

A single-case study design was chosen, avoiding intersubject variability and confounding factors. One subject was evaluated: a 74-year-old male who suffered from ischemic stroke and subsequent right-side hemiplegia without aphasia, apraxia, or spatial neglect. The ischemic lesion was located in the left-middle cerebral artery territory, and it was documented by a computed tomography (CT) scan. Walking analysis was performed 30 days after stroke and 3 weeks after the beginning of the rehabilitation program, which was performed according to Bobath principles.

At the moment of the walking tests, the subject presented an upper-limb recovery classified as Phase 1, according to Brunnstrom [10]:

1. A spasticity of affected triceps surae muscle was present (Ashworth score = 2) with no equinus deformity.
2. No limitation in the range of motion (ROM) of the lower-limb joints was present.
3. The lower limb presented flexion and extension synergies without capability of isolated movements.
4. The walking pattern was classified as Phase 2-A, according to Winters et al. [1,11].

The custom-made sling consisted of inextensible textile stripes, as shown in Figure 1(a) and 1(b):

1. A belt with a stripe across the shoulder.
2. A connecting stripe lying on the anterior face of the lower limb, consisting of (Figure 1(a)) an upper segment, connected to the belt in correspondence to the anterior superior iliac spine (ASIS), and a lower segment, which is connected to the upper segment by means of a buckle and fixed by little straps around the knee and around the metatarsal heads.

All the parts of the sling are buckle-adjustable to fit patient’s body size. The AFO, also custom-made, was a commonly prescribed type (posterior leaf spring, (Figure 1(c))), which was already in use at the time of the rehabilitative treatment. Like the AFO, the sling counteracts the plantar flexion, while allowing the “normal” foot dorsal flexion during gait. The sling was used by the patient for the first time during this test. The patient was not able to put on the AFO or the sling without help. The walking test was performed either without the orthosis, with the AFO, and with the sling. The sling was set on the patient in an upright position, with the ankle at an approximately 90° angle.

Experimental Procedure

In a single session, three conditions were tested (use of no orthosis, use of AFO, and use of sling), with a total of six walking tests and 2 min intervals between tests. Every test consisted of the patient walking alone for a distance of 6 m, with the paretic upper limb supported and a tripod on the unaffected side. Two tests at the same walking condition were necessary to collect a sufficient number of steps for the analysis. The first two consecutive tests were performed with no orthosis, two consecutive tests with the spring AFO, and the last two consecutive tests with the sling. The subject was placed at the beginning of the 6 m line, previously traced on the laboratory floor. At the operator’s signal, the patient started walking at his own spontaneous speed, and data recording started.

Data Acquisition and Analysis

The walking tests were recorded by the ELITE movement analysis system (BTS, Italy). This system
consisted of six infrared cameras (100 Hz frequency) positioned at the vertexes of an hexagonal space surrounding the line used for the walking tests. Infrared-reflecting markers were positioned on the following points of body sides: acromion, ASIS, trochanter major, head of fibula, lateral malleolus, fifth metatarsal head. The last marker was attached to the shoe, corresponding to the fifth metatarsal head. The patient wore his shoes under all conditions tested. The position of the markers was acquired throughout the 6 m walking test. Data were recorded on electronic media and later analyzed with the use of the standard ELITE system software. The following variables were recorded and measured:

1. Hip, knee, and ankle mean angle and ROM.
2. Frontal and horizontal displacement of the mean point between the ASIS markers approximately corresponding to the subject’s center of mass (COM).
3. Temporal sequence of the heel-strike forefoot contact and heel-off-forefoot-off, calculated on the basis of the time course of the position of the markers on the malleolus and fifth metatarsal bone.
4. Duration of stance phase.
5. Stride length.
6. Stride duration, calculated for both limbs from the temporal succession of heel strikes.
7. Walking speed.

Statistical Analysis

Mean values and standard deviations (SDs) of the variables were recorded during the patient’s walking with no orthosis, with the spring AFO, and with the new sling. The statistics were compared with the use of a one-way analysis of variance (ANOVA) and a posthoc Neumann-Keuls Multiple Comparison test, with \( p < 0.05 \) considered for significance. To evaluate the effect of the devices on the heel-strike-forefoot-contact and heel-off-forefoot-off intervals, on both the affected and the unaffected side, we used a two-way ANOVA (no orthosis, AFO, sling on the affected and unaffected side), followed by Fisher’s Least Significant Difference (LSD) tests. Fisher’s LSD tests were chosen because of the small size of samples; \( p < 0.05 \) was considered significant.

RESULTS

We evaluated a total of 12 steps with no orthosis, 10 steps with the AFO and 10 steps with the sling. The hip, knee, and ankle mean angles showed only little differences across no orthosis, AFO, and sling conditions. The ankle ROM with the sling showed a significant decrease compared to the use of no orthosis (–30.5%, \( p < 0.001 \)). It also showed a considerable decrease with the AFO compared to the use of no orthosis (–31.6%, \( p < 0.001 \)), while there was no statistical difference between ankle ROM with the AFO and with the sling (Figure 2(a)). The COM vertical displacement showed a sizeable decrease (–34.2%, \( p < 0.001 \)) with the sling compared to the use of no orthosis. The AFO also had a substantial decrease compared to no orthosis (–33.2%, \( p < 0.001 \)), and no significant difference existed between COM vertical displacement with the AFO and the sling (Figure 2(b)).

No noteworthy difference was found in the subject’s COM mediolateral displacement with either the AFO, sling, or no orthosis. During free walking on the affected side, the normal sequence heel-strike forefoot contact was inverted (forefoot landing before heel-strike), and a negative value resulted from the difference between the instants of heel-strike and forefoot contact (Figure 2(c)). This abnormal value turned to normal (heel-strike before forefoot contact) with the sling, compared to no orthosis (\( p < 0.001 \)), and the difference between the affected and unaffected side turned to a nonsignificant value (\( p = 0.607 \), posthoc test).

With the AFO, the timing difference between heel-strike and forefoot contact sizeably diminished (\( p < 0.001 \)) and was almost canceled. However, this difference was still abnormal compared to no orthosis, most likely because of the large compliance of the AFO material, which did not fully support the foot weight or oppose the plantar flexors muscles spasticity [9]. Although much improved, the sequence was still appreciably different between the affected and unaffected side (\( p < 0.05 \), posthoc test). The improving effects produced by the sling on the foot contact sequence proved to be almost significantly different (\( p = 0.05008 \), posthoc test) from those obtained with the AFO (Figure 2(d)). The temporal sequence of the heel-off-forefoot-off did not show any measurable difference with the AFO, sling, or no orthosis (Figure 2(d)).

The stance duration on the affected side was noticeably smaller with the sling (–20.8%, \( p < 0.001 \)) compared to no orthosis, and the AFO also considerably decreased stance duration (–22.7%, \( p < 0.05 \)) compared to no orthosis, but no difference was found between the AFO and sling (Figure 2(e)). The stride length of the affected side increased sizeably with the sling (+18.5%, \( p = 0.024 \)), but not the
(a) Mean ± standard deviations (SDs) of hip, knee, and ankle range of motion (ROM). ROM “0” represents no variation of articular angle during locomotion. Both AFO and sling significantly limited mobility of affected side ankle. 

(b) Mean ± SDs of vertical displacement of subject’s center of mass (COM). Both AFO and sling significantly limited elevation of affected pelvis side (* = p < 0.05). 

(c) Mean ± SDs of heel-strike forefoot contact temporal sequence. Negative value indicates forefoot landing before heel. 

(d) Heel-off-forefoot-off temporal sequence: sling induces a trend toward normalization of sequence. 

(e) Mean ± SDs of stance duration, calculated for unaffected and affected lower limb: both AFO and sling orthoses significantly reduced stance duration on affected lower limb (* = p < 0.05), with minor effects on unaffected side. 

(f) Mean ± SDs of stride length, calculated for unaffected and affected lower limb: with sling, but not AFO, significantly increased stride length of both affected and unaffected lower limb (* = p < 0.05). 

(g) Mean ± SDs of stride duration, calculated for unaffected and affected lower limb: with sling, but not AFO, significantly diminished stride duration of both affected and unaffected lower limb (* = p < 0.05). 

(h) Mean walking speed with no orthosis, AFO, and sling. Walking speed with sling increased 64.7% and 29.4% with AFO.
AFO, compared to no orthosis (Figure 2(f)). The stride duration of the affected leg was significantly smaller with the sling (−26%, p = 0.002), but not the AFO, compared to no orthosis (Figure 2(g)). The mean walking speed increased with both the sling (+64.7%) and the AFO (+29.4%), compared to no orthosis (Figure 2(h)).

**DISCUSSION**

The findings indicate that both types of orthoses produced similar effects on hip, knee, and ankle ROM. Both the sling and the AFO equally limited the subject’s plantar flexion during walking. The analysis of COM vertical displacement shows a diminished need for elevation of the affected pelvis side with both the AFO and the sling. Despite the similarity in kinematic data for both devices, the walking speed was substantially higher with the sling. Therefore, the reduction in the affected ankle ROM alone does not seem to be sufficient to explain the subject’s increase in walking speed [12]. An element of explanation could be derived from the change in the interval of heel-strike forefoot contact. During the subject’s walking without orthosis, as well as with the AFO, the normal heel-strike forefoot-contact sequence was inverted (the affected limb forefoot hit the ground before the heel did). The AFO significantly improved the timing of the foot stance phases; in particular, it changed the foot-strike from a first-forefoot contact to an almost flat-foot contact. Using the sling, the subject resumed a correct and a close-to-normal pattern sequence interval (the heel-strike was performed before forefoot contact), with no significant difference compared to subject’s unaffected lower limb. Even if the mechanism of action is not simple to elucidate, the “linkage” between normal body side and the affected lower-limb may be another explanation of the increase in walking speed [12]. An element of explanation could be derived from the change in the interval of heel-strike forefoot contact. During the subject’s walking without orthosis, as well as with the AFO, the normal heel-strike forefoot-contact sequence was inverted (the affected limb forefoot hit the ground before the heel did). The AFO significantly improved the timing of the foot stance phases; in particular, it changed the foot-strike from a first-forefoot contact to an almost flat-foot contact. Using the sling, the subject resumed a correct and a close-to-normal pattern sequence interval (the heel-strike was performed before forefoot contact), with no significant difference compared to subject’s unaffected lower limb. Even if the mechanism of action is not simple to elucidate, the “linkage” between normal body side and the affected lower-limb may be another explanation of the increase in walking speed. The sling may also enhance the effects of the inward hip rotation of the unaffected limb. As the affected side ASIS rotates forward toward the midsagittal plane, the sling tightens and pulls forward the whole limb through its foot attachment. This recalls the action of reciprocating gait orthosis (RGO), with a difference. In this case, the RGO action turns the extension of the stance leg into the flexion of the swinging leg [13], while pelvic thrust and inward rotation on the supporting unaffected limb are presumably the main mechanism of action of the sling.

**CONCLUSIONS**

The results indicated to us that the proposed sling improved the affected side’s ankle kinematics equally to the traditional AFO. In addition, the sling also improved some variables of walking pattern in this hemiplegic subject, leading to a greater increase of walking speed than the AFO. These data could contribute to a background for future studies that would evaluate the possibility of clinical application of the proposed sling.

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