Influences of Joint Motion Restriction on the Performance of Normal Subjects and Their Implications on Development of Orthosis for Spinal Cord Injured Individuals

Eklem Hareket Kısıtlamasının Normal Deneklerde Performansa Etkileri ve Bunların Omurilik Yaralı Hastalarda Ortez Geliştirmeye Katkıları

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ABSTRACT

Objective: Different types of orthoses have been designed for paraplegic subjects in order to enable them to walk again. However, patients experience some problems in donning and doffing the orthosis and expend high energy during walking.

Methods: A new type of Reciprocal Gait Orthosis (RGO) was designed to solve some of the problems of the previous orthoses. The functional performance of normal subjects was evaluated while standing and walking with the new orthosis with different hip joint configurations and was compared with that of the Hip Guidance Orthosis (HGO).

Results: The results of this research study showed that the performance of the new orthosis can be better than that of the HGO orthosis. Moreover, it has no medial thigh bars and it is much easier for the subjects to donn and doff the orthosis independently.

Conclusion: The performance of the subjects in walking with the new design of the RGO orthosis was better than that with the HGO orthosis.*(J PMR Sci 2010;13:122-31)*

Keywords: Spinal cord injury, walking, orthosis

ÖZET

Amaç: Paraplejik hastaların tekrar yürüyebilmesi için farklı tipte ortezler tasarlanmıştır. Ancak hastalar ortezleri giyip çıkarmak konusunda bazı problemler yaşamakta ve yürüme sırasında çok fazla enerji harcamaktadırlar. Bu çalışmada daha önce kullanılan ortezlerin problemlerini çözmek amacıyla yeni bir resiprokal yürüme ortazi (RYO) tasarlandı ve kalça yönelimli ortezle karşılaştırıldı.

Yöntem: Normal deneklerin fonksiyonel performansı farklı kalça eklem konfigürasyonlarında ayakta durma ve yürüme sırasında değerlendirildi ve kalça yönelimli ortezle (KYO) karşılaştırıldı.

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Received/Geliş Tarihi: *25.12.2010*
Accepted/Kabul Tarihi: *26.01.2011*

Bulgular: Bu araştırmanın sonuçları yeni ortezin performansının KYO’dan daha iyi olabileceğini gösterdi. Ek olarak bu ortezin medial uyluk barı yoktur ve denekler tarafından giyilip çıkarılabilmesi daha kolaydır.

Sonuç: Yeni tasarlanan RYO ile deneklerin yürüme performansları KYO’den daha iyiydi. Paraplejik hastalarda bu yeni ortezi uygunluğunun araştırılması gereklidir. *(FTR Bil Der 2010;13:122-31)*

Anahtar kelimeler: Omurilik yaralanması, yürüme, ortez

Introduction

Spinal Cord Injury (SCI) is damage to the spinal cord resulting in loss of function and mobility. Such patients use different methods in order to transfer themselves from place to place. Using an orthosis is one of the mobilization methods selected by these patients. Although, various orthoses have been designed for paraplegic subjects the HGO orthosis (Hip Guidance Orthosis) has been reported to provide the best performance (1-15). The main feature of this orthosis in contrast to other types is its greatest lateral rigidity which plays a significant role in increasing the performance of paraplegic subjects during walking (3,16).

The gait performance of the HGO orthosis was evaluated in various research studies (3, 8, 12-14,17-26). It has been shown that although the performance of paraplegic subjects is better with the HGO orthosis than with other orthoses; most subjects prefer to use Louisiana State University Reciprocal Gait (LSU RGO) orthosis instead, as it is more cosmetically appealing (2, 3). So it was too important to design an orthosis in order to overcome the problems associated with the HGO orthosis.

The function of various orthoses for paraplegic subjects was also analyzed by energy consumption test, stability analysis during quiet standing and while undertaking some hand tasks (9,10,27-32). The results of energy consumption test done by Stallard to evaluate the effect of increasing the lateral stiffness of the HGO orthosis on performance of paraplegic subjects showed that the physiological cost index (PCI) decreased from 1.4 to 0.98 beats/m (16, 33). In contrast in the research carried out by Yano et al (1997) it was 3.6 beats/m.

As can be seen from the aforementioned research studies, there is no information in the literature to show what is the best performance of the SCI patients during walking with an orthosis and how much room remains to improve the orthosis. The aims of this research were to assess the performance of normal subjects in walking and standing with the HGO and a new RGO orthosis, which represents the best performance of SCI subjects can be hopefully achieved and, also to compare the function of two orthoses. Moreover, evaluation of the effect of setting the orthosis in abduction on its function during walking and standing was another aim of this research.

Method

Equipment: A new RGO orthosis was designed, based on the HGO orthosis principle, which allows easier independent donning and doffing by the user. The components of this orthosis were designed to be capable of being aligned with respect to each other. It has an open structure, i.e. without medial thigh bars, similar in design to the ARGO, but with increased lateral stiffness and custom moulded body section. It allows alignment of the orthosis when the user is wearing the orthosis, and the modularity of the orthosis allows easy transportation.

The orthosis was made of three main parts, the AFO (Ankle Foot Orthosis), Torso and lateral bars with the hip and knee joints. Special attachment components were to be inserted above the hip and below the knee joints for changing the alignment of the orthosis in different planes. The lateral bar was attached to the hip and knee attachment components by using some pins. Figure 1 shows the new RGO orthosis.

Figure 1. The new RGO (Reciprocal Gait orthosis) orthosis

The HGO orthosis, which was obtained from the ORLAU (Orthotic Research and Locomotor Assessment Unit) centre, consists of three main parts, the hip joints, the calipers and body section (34). Figure 2 shows the HGO orthosis used in this study. The sizes of body and leg sections of the orthosis were made to suit the size of the participants.

Kinematic and kinetic assessments were performed in the gait lab using an 8 camera 3D gait analysis system (Vicon motion system, Ltd Oxford UK) and four force plates (Kistler instrument Corp, USA). The data were analyzed by using a biomechanical model developed by body builder software (body builder for biomechanics developed by Vicon motion analysis system Ltd). This software allows calculations of the forces and moments of the different joints from the raw data collected.

The energy consumption test was carried out using the Physiological Cost Index (PCI) which is a reliable, easy to use and a repeatable parameter especially for handicapped subjects (35). For this test a Polar Accrue Plus Monitor, was used which is also known as Polar Electro, Finland. It consists of a transmitter embedded in an electrode belt. The receiver and recorder are located in a specially designed wrist watch. The data were collected by the receiver in the wrist watch with 5 seconds interval. A Polar Interface Plus was used to transfer the collected data from a wrist watch to a personal computer.

The stability of the participants during standing with and without the orthosis was evaluated during quiet standing and while undertaking various hand tasks. A force plate was used to measure the excursion of centre of pressure (COP) both in the anteroposterior and mediolateral planes. For the functional stability test, the excursion of COP while performing various hand tasks, and simultaneously the time necessary to undertake different hand tasks were measured. For this task, a table (width 80 cm, depth 60 cm) with a height equal to 5 to 10 cm below the anterior superior iliac spine (ASIS) was used. Five cylindrical weights having the same size and weight marked with five different colours (with 0.25 kg weight, 5 cm height and 5 cm diameter) were selected for this test. They were positioned approximately 15 cm apart from left to right on five different coloured circles.

Subjects

For the first part of this project, which was evaluation of the first generation of the RGO orthosis, 3 normal subjects participated. However, for the second part of the project, which was evaluation the performance of the subjects during walking with the new RGO and HGO orthoses, 5 normal subjects were recruited. Table 1 shows the characteristics of the subjects who participated in this study. For undertaking this research project an ethical approval was obtained from Strathclyde University ethics committee. Before starting the tests, a consent form was signed by each participant. Different gait parameters such as the angular excursion of the hip joint motions in the sagittal and coronal planes, the spatio-temporal gait parameters and the moments applied on the hip joint complex were determined.

Procedure

The subjects were trained for 8 hours (4 hours for each orthosis) to donn the orthosis independently and to stand and walk with the orthosis using two sticks. In the first part of the project the subjects were asked to walk and stand without the orthosis and then with the orthosis with different hip joint configurations which included:

1) Hip joint with free flexion and extension (25 and 10 degree of flexion and extension, respectively) and without abduction (configuration 1)

2) Hip joint with free flexion and extension and with 5 degrees abduction (configuration 2)

3) Hip joint with flexion and extension restricted (15 and 5 degrees of flexion and extension, respectively) and without abduction (configuration 3)

4) Hip joint with flexion and extension restricted with 5 degrees abduction (configuration 4)

Gait Analysis

The prefabricated markers used in this research were 14 mm spheres covered with a reflective sheet that was recognized by the cameras. The marker placement protocol was the preferred method of marker adhesion and subsequent identification used in Bioengineering Unit of University of Strathclyde (36,37). Fourteen markers were attached on the right and left anterior superior iliac spine (ASIS), right and left posterior superior iliac spine (PSIS), medial and lateral malleolus, first and fifth metatarsal heads. Moreover, four clusters, comprising four markers attached on rhomboid plates, were used. They were attached on the anterior surfaces of the legs and thighs using extensible Velcro straps, Figure 3. The marker attachment process was begun from the most distal segment of the lower extremity, i.e. foot. Markers were placed on the foot when the subject was in sitting position. The location of the knee joint markers in the medial and lateral sides was determined by using a pointer (38) on the fully marked up subject standing on the force plate area, during static calibration.

The subjects were asked to walk with a comfortable speed along the gait lab. The tests were repeated 5 times and the force applied on the foot and crutch were collected at the same time.

Table 1: Characteristics of the subjects who participated in this study

Parameters	Age	Number of subject	Weight	Height
First part of the research	20±3.46	3	78±15.28	1.77±0.01
Second part of the research	24±6.04	5	76.15±11.3	1.76±0.023

For stability analysis during quiet standing, the subjects were asked to stand on the force plate; they were instructed to look straight ahead, with their head erect and their arms at their sides in a comfortable position. The tests were recorded for one minute and were repeated 5 times for each subject. Analogue signals were sampled at a frequency of 120 Hz with an analogue to digital convertor and were stored on a computer. The signals of the force plate were filtered with a Butterworth low-pass filter at 10 Hz (39,40). The first and last 15 seconds of the data were deleted and only 30 seconds of the data were used for the final analysis. The 30 seconds of the data was used to show the absolute sway of the centre of pressure (COP). The mean values of all parameters obtained from 5 successful trials were used for final analysis.

For functional stability tests the subjects were asked to stand on the force plate in front of the table and after becoming stable were asked to move the cylindrical weights from left to right to the corresponding coloured circles on the back row as quickly as possible and back again from right to left. For the second part of the test they were asked to move the weights and put them on the top of a small table which was located 25 cm behind the edge of the main table and then returning them to the original position. The functional stability tests were also repeated for 5 times. The excursions of the COP and the time necessary to carry out these tasks were recorded for the final analysis.

For the energy consumption test, the heart rate during walking and resting were collected using the Polar Electro. The test was done according to the following procedure:

a) Heart rate monitor worn by subject

b) Five minutes resting heart rate collected

c) Standing up and then remaining in this position for two minutes

d) Ten minutes of walking with a self selected walking speed around a 30.4 meter figure of eight path, during which data collection was continued

e) Five minutes of resting during which data was collected

The energy consumption during walking based on the PCI can be determined using the following equation which was developed by MacGregor (41).

$$PCI=\frac{\text{Heart rate during walking}\left(\frac{\text{beats}}{\text{mean}}\right)-\text{Heart rate during resting}\left(\frac{\text{beats}}{\text{mean}}\right)}{\text{Walking speed}\left(\frac{\text{m}}{\text{min}}\right)}$$

The validity of this method was evaluated in various studies (35,42-45).

Data Analysis: The normal distribution of all mentioned parameters was tested by using the Shapiro-Wilk test. Since the parameters had a normal distribution the parametric statistical test was used to evaluate the difference between the mean values. The difference between the mean values of all mentioned parameters, namely stability, gait analysis and energy consumption during standing and walking with orthoses with various hip joint configurations and without orthosis was compared by using pair-t test. The significance point (α point) was 0.05 for all parameters. All statistical analysis was performed using statistical package for Social sciences (SPSS).

Results

The results of the first part of this study showed that there was a significant difference between the performance of the subjects during walking with and without the orthosis. Tables 2 and 3 shows some results of the first part of the study. Figures 4 and 5 show the flexion/ extension motions of the hip joint during walking with and without orthosis (Subject 1).

As can be seen, the energy consumption during walking with the orthosis increased significantly in contrast to that in normal walking, p-value was 0.007, (Table 2, and Figure 6).

The results of the second part of the research showed that the performance of the subjects while walking with the new orthosis could be better than that of the HGO orthosis, although the results of the paired sample T test showed that the difference between the mean values of the many parameters was not significant (tables 4). The mean values of the COP excursions in the mediolateral and anteroposterior directions were 8.03±3.28 and 11.5±3.5, respectively while standing with the RGO and 10.67±6.34 and 28.1±26.8 while standing with the HGO orthosis. Stability of the subjects while undertaking different hand tasks improved in the new orthosis in contrast to that in the HGO orthosis. Table 5 summarizes the results of functional stability tests while standing with the two orthoses. The flexing /extending moments of the hip joint during walking with the new RGO and HGO orthoses are shown in figures 7 and 8.

Discussion

In the following discussion, application of the results of the current study which was done on normal subjects to paraplegic walking in an orthosis is considered with caution, as normal subjects has muscular power around the joints. Moreover, they used crutches especially for balance which differs from paraplegic subjects who use it for both balance and propulsion.

It is not too practical to compare the performance of paraplegic subjects with the healthy subjects during normal walking. Although, the orthosis stabilizes the paralyzed joints and help the handicapped subjects to walk again, it restricts other motions, which are necessary for normal walking, such as the pelvic motion. It could be a good idea to compare the functional performance of normal subjects in walking with the orthosis with that of paraplegic subjects. This not only will show the negative effects of using the orthosis on the normal walking but also will show the importance of other motions which are restricted by the orthosis. Moreover, it will represent the best performance that can be achieved by paraplegic subjects in walking with the orthosis which would be the same as the function of normal subjects in using the orthosis. This can show the gap between the normal and handicapped subjects' performance, which can be decreased by designing a suitable orthosis. The results of the research undertook by Greene and Granat and Yang et al showed that the results of testing the orthosis on normal subjects can be used for SCI individuals (8, 46).

The stability of the subjects improved during standing with the orthosis as it restricted the motion of the hip joint during standing. The mean value of COP excursion in the anteroposterior plane was founded to be between 35.22 and 37.97 millimeters for paraplegic subjects standing with the ARGO orthosis [10]. It varied from 35.53 to 41.72 millimeters for the mediolateral plane. In contrast to the stability of the normal subjects, there is a huge gap between the normal and the SCI subjects. This represents the effect of musculoskeletal system on the standing stability.

The functional performance of the normal subjects during walking with the orthosis decreased significantly in contrast to normal walking. The velocity decreased by more than 50% in walking with the orthosis. Decreased stride length and cadence was the main reason for the decrease of the walking

Figure 2. The HGO (Hip Guidance Orthosis) orthosis

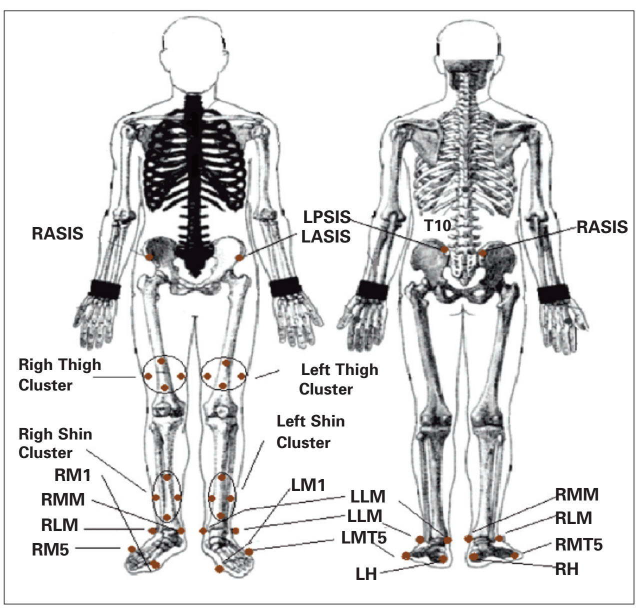

Figure 3. The location of the markers used in this research study

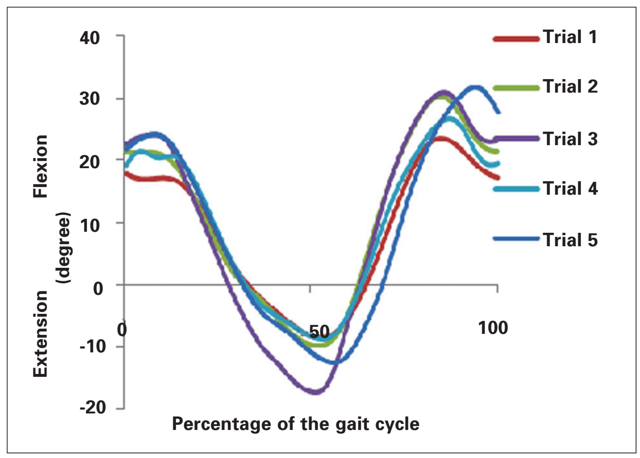

Figure 4. The flexion extension of the hip joint as a percentage of gait cycle during normal walking (no orthosis), subject 1

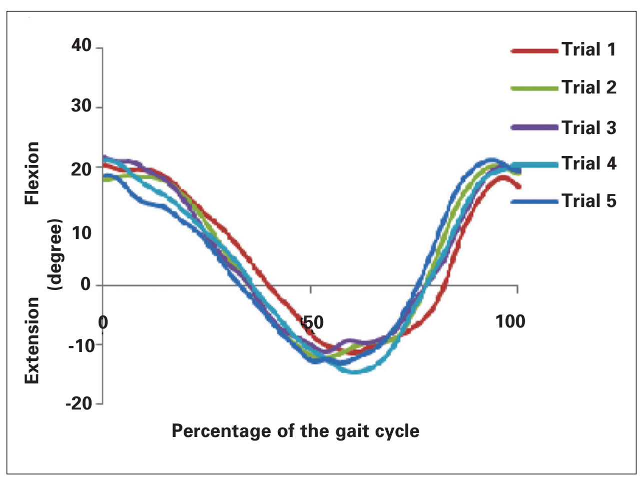

Figure 5. The flexion extension of the hip joint as a percentage of gait cycle while walking with orthosis, configuration 1 (subject 1)

velocity (Tables 2 and 3). Restriction of the internal/ external rotational movement and abduction/adduction of the hip joint was the first reason for the decrease of the performance of the subjects in walking with the orthosis. The second reason related to the use of crutches during walking; the subjects had to move the crutch and foot reciprocally and this decreased the walking velocity.

In contrast to the velocity of the normal subjects that participated in research carried out by Yang et al (1996) (46), which was between 0.262 and 0.563 m/s, the subjects in the current study walked faster with this orthosis (Table 2). Paraplegic subjects walked with a velocity between 8 and 18 m/min with the HGO orthosis (12,19,25), which is significantly less than that of the normal subjects in this study. The velocity of the normal subjects in this study was nearly 2.5 times more than that of paraplegic subjects, evidently shows a huge difference between them.

The cadence of the normal subjects decreased by half when walking with the orthoses. It reported that this was 37

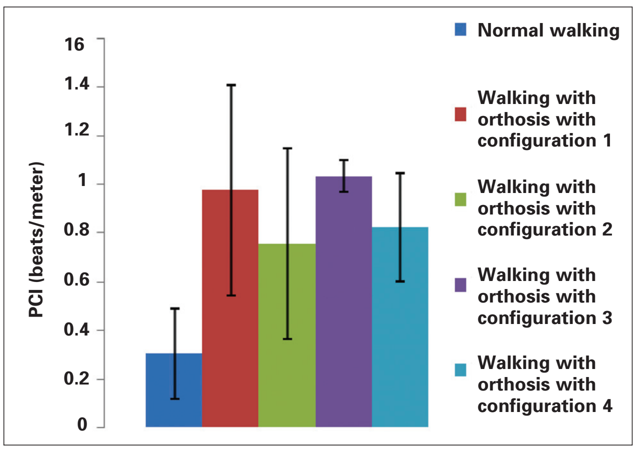

Figure 6. The mean values of the PCI during walking with and without orthosis

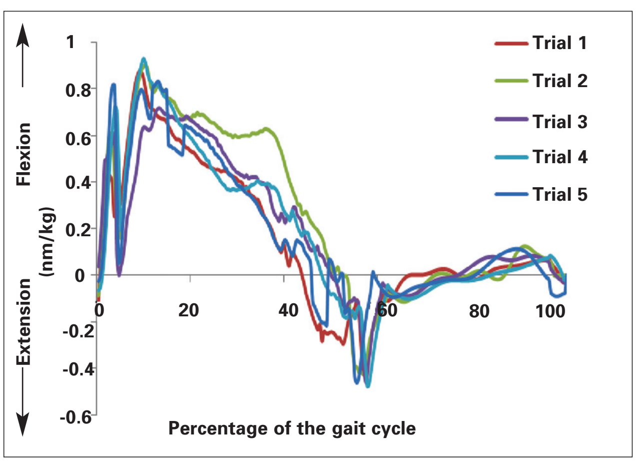

Figure 7. The flexion extension of the hip joint as a percentage of gait cycle while walking with orthosis, configuration 1 (subject 1)

steps/min for the paraplegic subjects (1). The percentage of the stance phase was nearly the same during normal walking and walking with the orthosis however, it was found to be between 72 and 79% of the total gait cycle in walking of the paraplegic subjects with the HGO orthosis. The difference between the performance of the paraplegic subjects and the normal subjects in walking with this orthosis shows that a huge gap exists which can be decreased by designing an improved orthosis.

The force applied on the crutch is transmitted to the countralateral side and helped the subject to lift the swinging leg off the ground. The maximum value of the crutch force for the SCI subjects has been reported to be between 0.24 and 0.4 N/BW (25). In contrast in this study it varied from 0.185 to 0.223 N/BW for the normal subjects walking with the orthosis. It means that the paraplegic subjects have to apply more force to take the swing leg off the ground than that of the normal subjects. However, both the handicapped and normal subjects have to use crutches to increase their stability and to improve their function during walking with the orthosis. Inserting some degrees of abduction and restricting the flexion/extension motion of the hip joint (configurations1 and 4) decreased crutch force and FTI during walking with the new orthosis, which is the same as the results of the research undertook by Ijzerman et al (1997). It was much easier for the subjects to take the swinging leg off the ground when it was aligned in slight abduction. Moreover, the subjects had to use the crutch further laterally from the body in walking with an abducted orthosis and as a result the force applied on the crutch decreased (47).

The flexing/extending moments at the hip joint complex decreased during walking with the orthoses. The flexing moment reached to a zero value at 30% of the gait cycle in normal walking however, it occurred at 45 % of the gait cycle during walking with the orthosis (Table 2). The main reason for

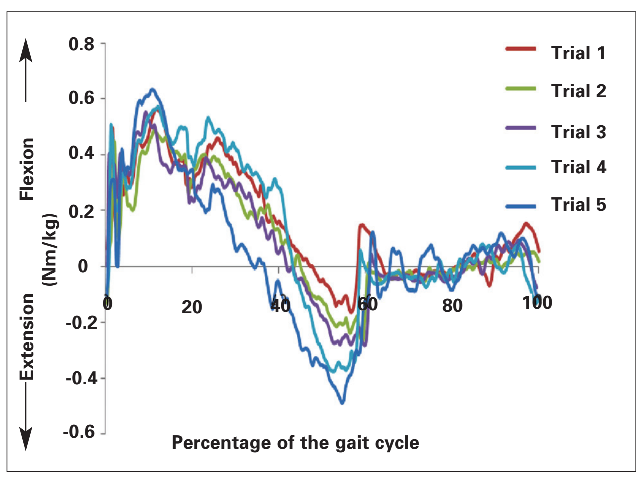

Figure 8. The flexing/extending moments of the hip joint as a percentage of gait cycle during walking with the HGO orthosis (subject 1)

that may be the force of the contralateral crutch which was transferred to the hip joint but with some delay (16,19,27). In comparison with the paraplegic subjects the pattern and the mean values of the flexing and extending moments of the hip joint was the same as those of the normal subjects in walking with the orthosis.

Table 2: The mean values of the gait and energy consumption parameters during walking with and without orthosis

Parameters	Normal walking	Number of subject	Walking with orthosis with configuration 1	Walking with orthosis with configuration 2	Walking with orthosis with configuration 3	Walking with orthosis with configuration 4
Stride length (m)	1.66±0.235	3	1.2±0.258	1.275±0.188	1.075±0.176	1.093±0.054
Cadence (steps/min)	105.2±5.87	3	52.95±3	58.6±1.6	59.63±1.45	58.36±3.34
Foot force (N/BW)	1.188±0.021	3	0.993±0.076	1.005±0.07	1.02±0.058	1.0167±0.066
Crutch force (N/BW)	--------	3	0.223±0.11	0.185±0.05	0.2±0.063	0.19±0.066
FTI (Ns)	--------	3	167.6±115	96±36.2	106.7±57.4	116±36.9
Stance phase %	60.8±2.46	3	62.62±4.4	61.6±2.22	62.36±3.73	63.28±0.97
Walking speed (m/min)	88.8±19.2	3	35.8±7.5	40.94±3.82	35.39±2.9	35.34±1.28
PCI (beats/min)	0.311±0.185	3	0.85±0.168	0.74±0.381	1.087±0.31	0.83±0.24

M: metre, min: minute, N: Newton, BW: Body Weight, Ns: Newton second, FTI: Force time integral, PCI: Physiological cost index

Table 3: Comparison between the performance of the subjects during walking and standing with orthosis with various hip joint configurations and without orthosis

Parameters	Normal walking and configuration1	Configurations 1 and 2	Configurations 1 and 3	Configurations 2 and 4
Stride length	0.021	0.642	0.101	0.271
Cadence	0.006	0.024	0.094	0.935
Foot force	0.071	0.857	0.497	0.64
Crutch force	--------------	0.041	0.703	0.524
FTI	--------------	0.045	0.526	0.005
Stance phase	0.535	0.659	0.89	0.429
Walking speed	0.024	0.141	0.903	0.163
PCI	0.007	0.538	0.187	0.584
COP sway in AP	0.203	0.941	0.17	0.45
COP sway in ML	0.324	0.503	0.973	0.61
Flexion extension excursion	0.04	0.022	0.02	0.485
Abduction adduction excursion	0.011	0.006	0.314	0.483
Flexing moment	0.078	0.75	0.126	0.709
Extending moment	0.244	0.979	0.994	0.165
Adducting moment	0.423	0.102	0.064	0.091

PCI: physiological cost index, M: meter, N: Newton, COP: Centre of Pressure,
AP: Anteroposterior, ML: Mediolateral, HGO: Hip Guidance Orthosis,
RGO: Reciprocal Gait Orthosis

The range of motion of the hip joint during walking with the orthosis with configurations 3 and 4 was more than the design value (17 degrees). It means that the TLSO (Thoraco Lumbo Sacral Orthosis) of the orthosis acts as a reciprocal link which transmits the motion from one side to other side.

In the second part of the study the performance of the normal subjects was evaluated during walking and standing with the HGO and new RGO orthoses. The flexion/extension excursion of the hip joint was almost the same in both orthoses (Table 4) however, it was more than expected. It means that the motion of the hip joint from one side was transferred to the contralateral side.

The walking performance of the subjects (walking velocity, stride length, cadence and the crutch force) improved in the new RGO orthosis in contrast to that in the HGO orthosis however, the difference was not significant (Table 4). The excursion of the hip joint in the coronal plane in walking with the new RGO orthosis was significantly less than that with the HGO orthosis (Table 4). It means that the new orthosis is stiffer than the HGO, especially in the frontal plane. It was shown that the lateral stiffness of the orthosis plays a significant role on improving the performance of the subjects and decreasing the loads applied on the upper limb in walking with orthoses.

The difference between the stability of the subjects in standing with the new orthosis and the HGO was significant. The stiffness of the new orthosis improved the stability of the subjects. Moreover, inserting some degrees of abduction in the hip joint of the orthosis increased the base of support and improved the mediolateral stability.

Table 4: The mean values of the gait parameters while walking with orthoses

Parameters	Number of subjects	HGO orthosis	New RGO orthosis	P-value of the difference
Velocity (m/min)	5	33.6±11.2	35.6±6.3	0.688
Stride length (m)	5	1.1±0.22	1.03±0.24	0.121
Cadence (Steps/min)	5	50.12±12.8	57.61±3.65	0.296
Flexing moment (N.m/kg)	5	0.474±0.2	0.54±0.28	0.417
Extending Moment (N.m/kg)	5	0.44±0.05	0.437±0.11	0.946
Adducting moment (N.m/kg)	5	0.89±0.43	1.056±0.29	0.282
Flexion extension excursion (degree)	5	30.5±4.24	29.4±3.6	0.41
Abduction adduction excursion (degree)	5	10.8±5.5	5.61±2.15	0.179
Crutch force (N/BW)	5	0.179±0.067	0.163±0.04	0.496
Foot force (N/BW)	5	1±0.05	1±0.03	0.82
FTI (N.s)	5	121.3±94.4	93.2±29	0.04

M: meter, min: minute, N: Newton, BW: Body Weight, FTI: Force Time Integral,
N.s: Newton second

Table 5: The mean values of the functional stability parameters during standing with the HGO and new RGO orthoses

Parameters	New RGO orthosis	HGO orthosis	P-value of the difference
Time transverse (second)	9.53±2.1	9.64±1.97	0.899
Time vertical (second)	9±1.54	9.074±1.99	0.874
COP sway , AP transverse (mm)	76.94±11	85.3±9.96	0.227
COP sway , ML transverse reaching (mm)	244.4±88.2	213.2±66.4	0.644
COP sway, AP vertical reaching (mm)	58.1±15.9	72.6±14.5	0.047
COP sway, ML vertical reaching (mm)	56.1±10.8	72±29.4	0.02

RGO: Reciprocal Gait Orthosis, HGO: Hip Guidance Orthosis, COP: Centre of Pressure, AP: anteroposterior, mm: millimeter, ML: Mediolateral

Limitations of the current study and suggestion for further research

There were some limitations that need to be acknowledged regarding the present research study. These included:

1) The sample size of the first part of this research study was small. It was impossible to increase the number of the participants, since it took considerable time and funding to prepare the orthosis specifically for each subject

2) The training and data collection time restricted the possibilities to do the tests with many hip joint configurations

3) Testing the orthosis on paraplegic subjects was impossible in Strathclyde University, as obtaining the ethical approval for undertaking the research was very time consuming

It is suggested that the new orthosis be tested during walking and standing of paraplegic subjects by employing the same procedures used in this research project. Moreover, it is suggested to measure the absolute value of the loads applied on the orthosis during walking of SCI individuals which can be used for further development of the orthosis

Conclusion

The results of this study showed that the performance of the normal subjects in walking with the orthosis decreased significantly in contrast to that in the normal walking. In contrast to the performance of the paraplegic subjects there is a huge gap which can be decreased by designing an improved orthosis. The results of this study showed the performance of normal subjects in using an orthosis which is the best performance that paraplegic subjects can hope to achieve in walking with an orthosis. Inserting a few degrees of abduction improved the functional abilities of the orthosis and decreased the energy consumption during walking. The new designed RGO orthosis could be better than other available orthoses.

As the orthosis was tested on normal subjects, the results of this research can be used with caution. It is suggested to test the new orthosis on paraplegic subjects by employing the same procedure used in this research project.

References

1. Jefferson RJ, Whittle MW. Performance of three walking orthoses for the paralysed: a case study using gait analysis. Prosthet Orthot Int 1990;14:103-10.
2. Whittle MW, Cochrane GM, Chase AP et al. A comparative trial of two walking systems for paralysed people. Paraplegia 1991;29:97-102.
3. Stallard J, Major RE. A review of reciprocal walking systems for paraplegic patients: factors affecting choice and economic justification. Prosthet Orthot Int 1998;22:240-7.
4. Scivoletto G, Mancini M, Fiorelli E, Morganti B, Molinari M. A prototype of an adjustable advanced reciprocating gait orthosis (ARGO) for spinal cord injury (SCI). Spinal Cord 2003;41:187-91.
5. Ohta Y, Yano H, Suzuki R, Yoshida M, Kawashima N, Nakazawa K. A two-degree-of-freedom motor-powered gait orthosis for spinal cord injury patients. Proc Inst Mech Eng H. 2007;221:629-39.
6. Dall PM, Muller B, Stallard I, Edwards J, Granat MH. The functional use of the reciprocal hip mechanism during gait for paraplegic patients walking in the Louisiana State University reciprocating gait orthosis. Prosthet Orthot Int 1999;23:152-62.
7. Cuddeford TJ, Freeling RP, Thomas SS et al. Energy consumption in children with myelomeningocele: a comparison between reciprocating gait orthosis and hip-knee-ankle-foot orthosis ambulators. Dev Med Child Neurol Suppl 1997;39:239-42.
8. Greene PJ, Granat MH. A knee and ankle flexing hybrid orthosis for paraplegic ambulation. Med Eng Phys 2003;25:539-45.
9. Kagawa T, Fukuda H, Uno Y. Stability analysis of paraplegic standing while wearing an orthosis. Med Biol Eng Comput 2006;44:907-17.
10. Baardman G, Ijzerman MJ, Hermens HJ, Veltink PH, Boom HB, Zilvold G. The influence of the reciprocal hip joint link in the Advanced Reciprocating Gait Orthosis on standing performance in paraplegia. Prosthet Orthot Int 1997;21:210-21.
11. Shimada Y, Hatakeyama K, Minato T et al. Hybrid functional electrical stimulation with medial linkage knee-ankle-foot orthoses in complete paraplegics. Tohoku J Exp Med 2006;209:117-23.
12. Yano H, Kaneko S, Nakazawa K, Yamamoto SI, Bettoh A. A new concept of dynamic orthosis for paraplegia: the weight bearing control (WBC) orthosis. Prosthet Orthot Int 1997;21:222-8.
13. Genda E, Oota K, Suzuki Y, Koyama K, Kasahara T. A new walking orthosis for paraplegics: hip and ankle linkage system. Prosthet Orthot Int 2004;28:69-74.
14. Dall PM. The function of orthotic hip and knee joints during gait for individuals with thoracic level spinal cord injury [Thesis (Ph.D.)]. Glasgow: University of Strathclyde; 2004.
15. Middleton JW, Fisher W, Davis GM, Smith RM. A medial linkage orthosis to assist ambulation after spinal cord injury. Prosthet Orthot Int 1998;22:258-64.
16. Stallard J, Major RE. The influence of orthosis stiffness on paraplegic ambulation and its implications for functional electrical stimulation (FES) walking systems. Prosthet Orthot Int 1995;19:108-14.
17. Major RE, Stallard J, Farmer SE. A review of 42 patients of 16 years and over using the ORLAU Parawalker. Prosthet Orthot Int 1997;21:147-52.
18. Rose Gk, Sankarankutty M, Stallard J. A clinical review of the orthotic treatment of myelomeningocele patients. J Bone Joint Surg 1983;65:242-6.
19. Major RE, Stallard J, Rose GK. The dynamics of walking using the hip guidance orthosis (hgo) with crutches. Prosthet Orthot Int 1981;7:19-22.
20. Butler P, Engelbrecht M, Major RE, Tait JH, TStallard J, Patrick JH. Physiological cost index of walking for normal children and its use as an indicator of physical handicap. Dev Med Child Neurol 1984;26:607-12.
21. Butler PB, Major RE. ParaWalker: a rational approach to the provision of reciprocal ambulation for paraplegic patients. Physiotherapy 1987;73:393-7.
22. Nene AV, Major RE. Dynamics of reciprocal gait of adult paraplegics using the Para Walker (Hip Guidance Orthosis). Prosthet Orthot Int 1987;11:124-7.
23. Woolam PJ, Lomas B, Stallard J. A reciprocal walking orthosis hip joint for young paediatric patients with a variety of pathological conditions. Prosthet Orthot Int. 2001;25(1):47-52.
24. Stallard J, Woollam PJ, Miller K, Farmer IR, Jones N, Poiner R. An infant reciprocal walking orthosis: engineering development. Proc Inst Mech Eng H 2001;215:599-604.
25. Ferrarin M, Pedotti A, Boccardi S. Biomechanical assessment of paraplegic locomotion with hip guidance orthosis (HGO). Clin Rehabil 1993;7:303-8.
26. Rose GK. The principles and practice of hip guidance articulations. Prosthet Orthot Int 1979;3:37-43.

27. Minato T, Shimada Y, Sato K et al. Standing stability of the medial linkage KAFOs using functional electrical stimulation in complete paraplegia. Strathclyde University 1998:3.
28. Cybulski GR, Jaeger RJ. Standing performance of persons with paraplegia. Arch Phys Med Rehabil 1986;67:103-8.
29. Middleton JW, Sinclair PJ, Smith RM, Davis GM. Postural control during stance in paraplegia: effects of medially linked versus unlinked knee-ankle-foot orthoses. Arch Phys Med Rehabil 1999;80:1558-65.
30. Ulkar B, Yavuzer G, Guner R, Ergin S. Energy expenditure of the paraplegic gait: comparison between different walking aids and normal subjects. Int J Rehabil Res 2003;26:213-7.
31. Hirokawa S, Solomonow M, Baratta R, D'Ambrosia R. Energy expenditure and fatiguability in paraplegic ambulation using reciprocating gait orthosis and electric stimulation. Disabil Rehabil 1996;18:115-22.
32. Massucci M, Brunetti G, Piperno R, Betti L, Franceschini M. Walking with the advanced reciprocating gait orthosis (ARGO) in thoracic paraplegic patients: energy expenditure and cardiorespiratory performance. Spinal Cord 1998;36:223-7.
33. Stallard J, Major RE. The case for lateral stiffness in walking orthoses for paraplegic patients. Proc Inst Mech Eng H 1993;207:1-6.
34. Stallard J, Major RE, Poiner R, Farmer IR, Jones N. Engineering design considerations of the ORLAU Parawalker and FES hybrid system. Eng Med 1986;15:123-9.
35. Nene AV, Patrick JH. Energy cost of paraplegic locomotion with the ORLAU ParaWalker. Paraplegia 1989;27:5-18.
36. Agustsson A. Two-dimensional Versus three-dimensional kinematics in normal and pathological gait. Glasgow: University of Strathclyde; 2002.
37. Malizos NK. A study of the optimization of lower extrimity gait analysis. Glasgow: University of Strathclyde; 2006.
38. Erdemir A, Piazza SJ. Simulation-based design of a pointer for accurate determination of anatomical landmarks. Proceedings of the American Society of Biomechanics. Pittsburgh 1999.
39. Santos BR, Delisle A, Larivière C, Plamondon A, Imbeau D. Reliability of centre of pressure summary measures of postural steadiness in healthy young adults. Gait Posture 2008;27:408-15.
40. Lafond DF, Corriveau H, Hebert R, Prince F. Intrasession reliability of center of pressure measures of postural steadiness in healthy elderly people. Arch Phys Med Rehabil 2004;85:896-901.
41. McGregor J. The objective measurement of physical performance with long term ambulatory physiological surveillance equipment (LAPSE). Proceedings of the third international sysmposium on ambulatory monitoring. Academic press 1979;28-38.
42. Nene AV. Physiological cost index of walking in able-bodied adolescents and adults. Clin Rehabil 1993;7:319-26.
43. Nene AV, Patrick JH. Energy cost of paraplegic locomotion using the ParaWalker--electrical stimulation "hybrid" orthosis. Arch Phys Med Rehabil 1990;71:116-20.
44. Nene AV, Jennings SJ. Physiological cost index of paraplegic locomotion using the ORLAU ParaWalker. Paraplegia 1992;30:246-52.
45. Bar-On Z, Nene AV. Relationship between heart rate and oxygen uptake in thoracic level paraplegics. Paraplegia 1990;28:87-95.
46. Yang L, Condie DN, Granat MH, Paul JP, Rowley DI. Effects of joint motion constraints on the gait of normal subjects and their implications on the further development of hybrid FES orthosis for paraplegic persons. J Biomech 1996;29:217-26.
47. IJzerman MJ, Baardman G, Hermens HJ, Veltink PH, Boom HB, Zilvold G. The influence of the reciprocal cable linkage in the advanced reciprocating gait orthosis on paraplegic gait performance. Prosthet Orthot Int 1997;21:52-61.