Technical note

A new concept of dynamic orthosis for paraplegia: the weight bearing control (WBC) orthosis

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Abstract

A new concept of device, termed the weight-bearing control (WBC) orthosis, has been designed with three major needs in mind; a rigid frame that supports the user's body weight, a special hip joint device that reciprocally propels each leg forward, a gas powered foot device that varies the sole thickness of the device for foot/floor clearance, and control system of the orthosis.

A paraplegic (T7 level complete paraplegia, sensory evoked potential silent, response to electro-stimulation on the cortical area of the brain also silent) who has tested this WBC orthosis has been able to walk without fatigue at a high speed for a greater distance than before. In walking tests of this WBC orthosis, he achieved a maximum walking speed of 34.1 m/min for a distance of 10 metres. The walking distance reached 521 m with an average walking speed of 21.2 m/min without rest on one small tank of CO2 liquid gas, measuring 10 cm in length and 3 cm in diameter.

Introduction

In the past, many devices have been developed to assist the paraplegic to walk, but these devices have fallen short of the paraplegic's wishes (Hahn, 1969; Scott, 1971; Rosman and Spira 1974; Silber *et al.*, 1975). Huang *et al.* (1979) examined the energy cost of orthotic gait of paraplegia. This test measured the 0_2 consumption in paraplegic walking with the Craig-Scott brace. This orthosis did not provide practical assistance for walking in severe cases, so he used in this test walking a special reciprocal walker instead of the brace for paraplegia of T4 level. In the biomechanical field, many authorities have devoted effort to the design and manufacture of a walking orthosis with an external power source (Corcoran *et al*, 1968; Nojima, 1972; Miyamoto *et al.*, 1984), but these ideas have not been realized. In most recent times, the ORLAU group, Rose (1979), Major *et al.* (1981), Butler *et al.* (1984) and Stallard *et al.* (1986) have developed the Parawalker, which to come extent, enables paraplegics to attain better walking speed and provides greater stability to protect the user's safety.

The Parawalker, like custom-made orthotic devices of the past, had no external power source, but it had several innovations; a rigid frame to support the user's walking posture, eliminating the requirement for muscle force of arm and shoulder for handling crutches, thus facilitating the swing forward that each step requires by shifting the weight of the trunk and tilting the Parawalker forward.

A special device that provides hip joint mobility, termed the hip guidance orthosis (hgo), permitted a straight swing forward and the leg braces are reinforced to protect them from damage by the force of a sudden twist or bend.

In spite of these innovations, however, the Parawalker did not fulfil the desires of paraplegics, since its basic design did not permit a more normal walking speed on account of the necessity of lateral body shift on each step.

The reciprocal gait orthosis (RGO) and the advanced type (ARGO), respectively developed by Douglas *et al.* (1983) and Beckman (1987),

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were new orthotic devices that enabled the user to walk in the following manner. During the initial stance phase, a hip joint torque provides a propulsive force to swing the limb forward; after this was accomplished, a succession of these reciprocal actions enabled the user to walk, lifting the user's weight at each step with his muscle power. Yet, despite this improvement in forward propulsion, a major problem must still be solved, the lack of sufficient foot/floor clearance for the swinging limb to move forward during walking.

Thus, the Parawalker and the RGO caused fatigue. Nene and Patrick (1990) and Phillips and Hendershot (1991) have tried to construct a hybrid orthosis using electrical stimulation of the gluteal muscles and others to produce a force to sustain an erect position of the whole body and swing the leg forward. This innovation has been useful to some extent, but the energy reduction was limited to within a few percent of the total energy needed in paraplegic walking. A better, fatigue-free, reciprocal walking orthosis still waits to be developed.

With this in mind, a new type of device, termed the weight bearing control (WBC) orthosis, has been designed.

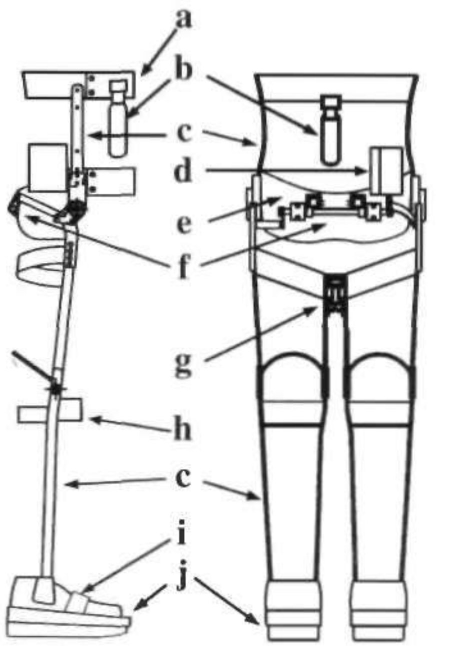

Fig. 1. Structure of the WBC orthosis
a) thoracic girdle, b) CO, gas tank, c) rigid exoskeletal frame, d) control box, e) pelvic girdle, f) reciprocal link system on rear pelvic girdle connected through bilateral hip joints, g) reciprocal link divide, h) bail lock device and strap for knee, i) ankle strap, j) variable sole plate.

Structure of the WBC orthosis

The WBC orthosis incorporated several major innovations in relation to the design and theory of the Parawalker and the RGO. The structure of the WBC orthosis consists of the following four main parts: 1) an exoskeletal frame with joints for supporting body weight, 2) a reciprocal link device for normal walking and for providing the optimum step length during walking, 3) a variable sole-plate for foot/floor clearance, with energy supplied from a gas tank, 4) the control system for the dynamic orthosis. Each part is described below.

1) The exoskeletal frame with joints consists of two main parts, a thoracic girdle and two long leg braces with hip and knee joints and with reciprocal connection. The thoracic and pelvic girdle are made of acrylic resin reinforced with glass-fibre, and the two long leg braces and each foot device are of duralumin and aluminium. The hip and knee joints of this exoskeletal frame are free and the ankle is fixed, but in walking, the range of hip joint motion is restricted by a locking device permitting 6° of extension and 18° of flexion, whereas the knee joint is fixed with a bail lock (Fig. 1).

2) The reciprocal joint system has two parts, one is a reciprocal link system that connects both hip joint axes through a steel bar on the back of the pelvic girdle (Fig. 2), the other is a

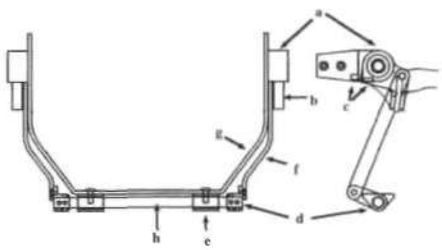

Fig. 2. The reciprocal hip joint system of pelvic rear girdle
a) hip joint axis with a radial bearing and a thrust bearing that connects leg orthosis, thoracic orthosis and pelvic girdle, b) lock device for limited motion of hip joint, c) control limits for the range of hip motion, d) reversal link device for converting the direction of hip joint rotation, e) limit switch for sensing the angular position of the hip, f) inner bar of pelvic girdle, g) lateral outer bar, h) posterior steel bar for transmitting rotational force of hip joint.

reciprocal link device that connects the medial uprights of the long leg brace at the medial proximal aspect and assists the reciprocal motion of the formerly described reciprocal link system. The level of the rotation axis of the reciprocal link device corresponds to the level of the axis of hip joint rotation of both long leg braces. This reciprocal link device reinforced the exoskeletal frame of the bilateral leg orthosis and contributed to the strength to weight ratio of the WBC orthosis (Fig. 3). The role of the reciprocal joint system is an essential feature of the reciprocal walking of the WBC orthosis. The extension force produced by the extension movement of one side produced the flexion force transmitted to the other side of the long leg brace, so that the user can swing forward the leg by the extension movement of the contralateral hip joint of the supporting leg. The user can easily achieve reciprocal swing forward of each long leg brace by the special dual design of these reciprocal joint systems.

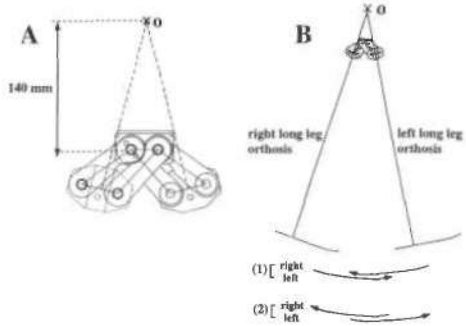

Fig. 3. The reciprocal link device
Special double link device for reverse motion of leg orthosis. It assists the role of the reciprocal hip joint and reinforces the strength of the two leg orthosis.

3) Each variable sole plate consists of two metal plates at the base of each long leg brace that extend or retract by a gas powered piston supplied from a $C0_2$ liquid air gas tank strapped to the user's back to provide the foot and floor clearance while walking.

These sole plates can shorten by 4 cm, to allow each leg to easily swing forward in preparation for the next step without an excessive lateral body sway (Fig. 4).

4) The control system consists of the hardware and software systems. The hardware consists of the following sensors which provide the control signals. The force sensor beneath the sole detects the magnitude of contact force between the sole plate and the floor. The limit switches attached to goniometers around each hip joint axis signal the angular displacement during the hip joint motion (Fig. 5). The software of the control system for the WBC

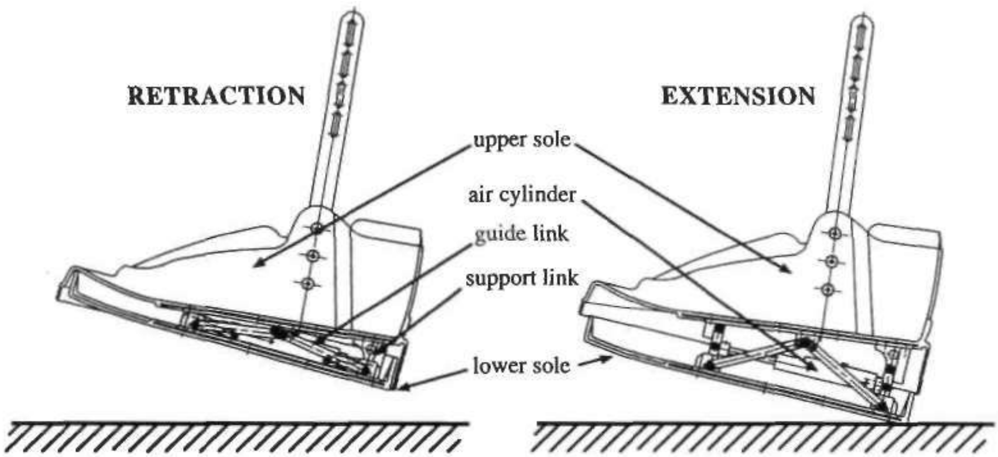

Fig. 4. Variable sole plate system
The cylindrical piston supplied $C0_2$ gas expands and extends the sole against gravity force by means of a linkage mechanism between the double sole plates. The signal from the control box opens the electromagnetic valve exhausting the gas from the cylinder permitting the sole to retract.

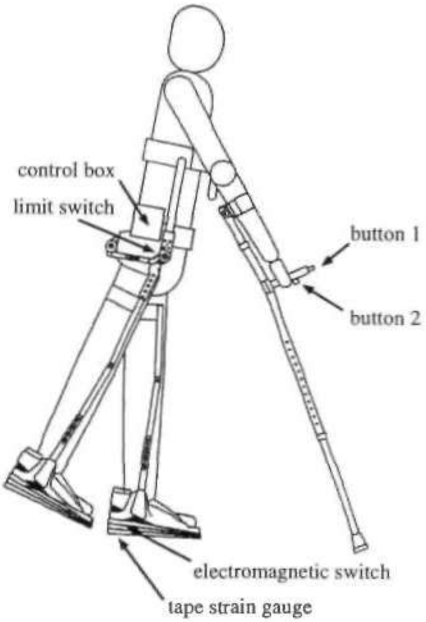

Fig. 5. The sensor system
A manual mode or automatic mode is selected by the operating button 1. In manual mode the sole plate retracts by operating button 2 and extends by releasing it. In automatic mode, pressing button 1 starts a successive retraction and extension action. The signal from the limit switch indicates the position of the leg. The limit switch actuates the electromagnetic switch on the piston thus actuating the sole mechanism. The force signals from tape strain gauge operate the fail safe programme.

orthosis contains four main programmes as follows, a) sequential operating programme, b) fail safe programme, c) buzzer system for alarm, d) count programme of step number.

The sequential programme regulates the opening or closing of exhaust gas valves by an on-off signal of an electromagnetic switch, which is on the cylindrical piston of the sole plates. Opening of exhaust gas valves results in shortening of the cylindrical piston and retraction of the double sole plate. Conversely, closing of the valve produces a lengthening of the piston due to supply of gas resulting in an extension.

The software of the sequential programme of the WBC orthosis has two modes related to the retraction and extension of the double sole plate: a manual mode and an automatic mode (Fig. 6).

The manual mode is used to initiate or to reverse the direction of walking, whereas the automatic mode is used in progressive walking. In the manual mode, retraction or extension of the sole plate thickness is done by pushing a button attached to the grip of each crutch. When the user pushes on the button of the right side crutch, the sole plate thickness is reduced on the left side of the user, and this reduction is maintained until the user releases the button. In the automatic mode, when the button is pushed on, regardless of whether the button pushed is on the left side or right side, the thickness of the sole plate starts to reduce on the required side for forward swing. However, for safety, the thickness of the sole plate does not reduce for the next phase of walking until the signals are received from the limit switch at the rotatory steel bar of the pelvic rear girdle and from the

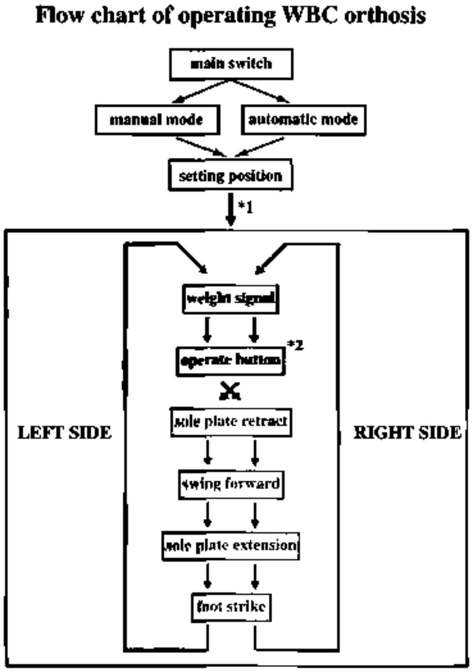

Fig. 6 Flow chart of operation of the WBC orthosis. In manual mode, the subject starts with both legs in a crossed position, for example, right leg forward and left leg backward He moves his body weight to right forward leg (*1). He presses right button 2, causing the left sole plate to retract. Next, the left leg swings forward by extension of the right hip joint. The sole plate is extended by releasing button 2 when the angle of the left hip joint reaches the permitted flexion of about 18° producing foot strike. The second step cycle is performed by pressing left button 2, when the body weight has been transferred to left foot (*2). Automatic mode, is initiated by pressing button 1(*2).

force sensor attached under the sole plate. The signal from the limit switch provides rotatory information from the goniometer on the axis of each hip joint, about leg position with regard to forward or backward, and the signal from the force sensor indicates whether the weight on the rear leg had been reduced to under 5 kg. The fail safe programme always watches whether the sequential programme runs correctly or not. This information on gait is constantly evaluated and relayed to achieve a fast, safe progression.

The WBC orthosis gait

The walking pattern using the WBC orthosis is shown in Figure 7.

Firstly, standing erect with the orthosis and selecting manual mode, the user pushes the "on" button on the right crutch, thereby shortening the left sole plate by 4 cm, which permits the left leg to swing forward by extending the right hip joint and tilting the pelvis and trunk forward simultaneously using two crutches. On reaching an angular displacement of about 18° of flexion of the left hip joint, which is the full flexion permitted in the limited range of motion, the left sole plate extends 4 cm by releasing the button. The left leg strikes the floor, after which the user shifts his or her weight to the left leg. The user then pushes the left crutch button "on" to shorten the right sole plate 4 cm. This shortening causes the right leg to swing forward by extending the left hip joint and tilting the pelvis and trunk simultaneously as before. On reaching about 18° of flexion of the right hip joint, the right leg is extended 4 cm by releasing the left crutch button. The right leg strikes the floor. The first full step forward is thus completed.

Successive steps are a repetition of these same movements. However, after the first two or three steps, the user changes the walking mode from manual to automatic, thereby enabling a faster pace for greater distances without fatigue. It should be noted that the safety features previously described still protect the user from accidents during the automatic mode.

Results

The paraplegic subject studied is a 27 years old male, who had the injury at 23 years of age. The injury is complete paraplegia at T7 level with sensory evoked potential from the bilateral sural nerve of the foot silent and the response of magnetic electrostimulation on 23 regions of the cortical area of the brain was also silent. Voluntary EMG response was silent on the gluteal muscle group, and erector spina muscles below the T7 level. He had lost completely voluntary motion below his pelvis.

The above mentioned paraplegic subject achieved a maximum walking speed of 34.1 m/min on average for a distance of 10 metres, and a maximum walking speed of 23.5m/min on average for a distance of 50 metres.

With practice, the patient's successful walking distance of 521m was achieved with an average walking speed of 21.5 m/min without rest and on one small tank of CO, liquid gas, measuring 10 cm in length and 3cm in diameter.

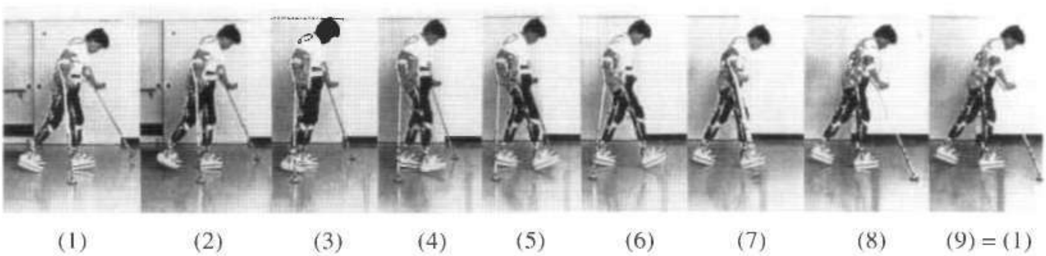

Fig. 7. Walking pattern in manual mode.

(1) The left leg is forward and the right leg backward in double support phase, (2) the right sole plate is retracted by pushing on left button 2, and swing forward of the right leg, initiated (3) and (4) the swing phase of the right leg, (5) extension of the right sole plate, (6) foot strike of right leg, (7) and (8) Moving the body weight to the right foot, (9) start of next step.

The charateristic pattern of WBC orthosis gait is seen in figure (3) to (5) where the left hip joint is fully extended after which it moves towards flexion and transmits an extension movement to the right hip joint. The subject was able to walk at high speed taking successive steps from double support phase to single support phase without losing forward momentum even when the step was long.

Table 1. Results of walking test (T7 complete paraplegia, 27yrs, male)

Parameter	WBC orthosis	Parawalker
Maximum walking speed 10m distance (m/min)	34.1	16.5
Average walking speed 50m distance (m/min)	23.5	11.5
Successive walkling distance (m)	521.0	82.0
average walking speed (m/min)	21.2	8.0
average step length (cm)	55.2	33.1
average cadence (step/min)	38.4	24.2
PCI (beat/m)	1.9	3.6

The average step length and cadence in the successful walking 521m was 55.2 cm and 38.4 steps/min respectively. The PCI as energy cost index was 1.9 (Table 1).

In spite of having a great amount of walking exercise using the Parawalker for the last two years. The results using the WBC orthosis were far better for this subject. In the course of training, achieving 12,600 steps in two months, the data showed the unexpected improvement of about fifty percent in all walking parameters.

Conclusion

The WBC orthosis proposes a new concept of dynamic orthosis for paraplegia providing the user with the low energy tool "variable sole plate" activated by supplying a small amount of CO_2 liquid energy from a gas tank as an extra-power source. The results of test walking using this WBC orthosis proved that even though the supply of external energy was small if the sequential control is adequately matched for the flexion and extension pattern of the whole body in paraplegic walking, it is able to provide power for erect reciprocal walking.

It points the way to harmonizing the provision of power and the residual biomechanical abilities of the disabled person.

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The authors wish to thank the members attending meetings of the Research and Development Committee of the Weight Bearing Control (WBC) orthosis organized by the Japanese Government in The Technical Welfare Institute. This Research and Development Committee received a grant in aid of project research from the foundation of the Industrial and Trade Ministry of Government.

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