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Unlockable Knee Joint Mechanism for Powered Gait Orthosis

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Walking with the knee joint locked increases the amplitude of pelvic tilt and results in an unnatural gait. This paper introduces a powered gait orthosis with a moveable knee joint designed to improve the gait speed of patients with spinal cord injury (SCI). The unlockable knee joint powered gait orthosis (UKJ-PGO) uses a gas spring cylinder and a solenoid locking device to enable flexion of the joint, while the rigidity of the hip-joint device is enhanced using air muscles. A gait analysis was conducted to evaluate the performance of the UKJ-PGO, and the kinematic parameters obtained were compared with those of a standard PGO. In the gait of SCI patients using the UKJ-PGO, the new knee-joint device enabled flexion during the swing phase and showed a decrease in pelvic tilt compared with the standard PGO gait. As greater flexion was possible at the knee joint, the duration of the stance phase substantially decreased to near to the normal value, and the duration of the swing phase increased accordingly. In addition, the gait using the UKJ-PGO was faster than that with the standard PGO.

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NOMENCLATURE

UKJ-PGO = unlockable knee joint powered gait orthosis
RGO = reciprocating gait orthosis

1. Introduction

Paraplegics have abnormal kinematic and sensory functions due to spinal cord damage, which may be caused by traffic accidents, falls, industrial hazards, or sports injuries. They are often people with high activity levels who lose their sensory and kinetic nerves along with autonomic nervous functions as a result of their accidents.

Existing rehabilitation treatment methods for these patients rely on physical therapies with aiding devices or gait-aid orthoses. Gait training using an aiding device is most often used to prevent various complications that occur with paralysis patients. The training enhances kinematic functions to form joints, prevent muscle weakening and dropsy in the lower body, improve colon function, and maintain the functional actions required for a normal gait. Before the 1960s, knee-ankle-foot orthosis (KAFO) was used for rehabilitation treatment, but in 1968, the Ontario Crippled Children's Centre in Canada introduced the concept of a reciprocating gait orthosis (RGO) for children. Douglas *et al*.[1] developed the Louisiana State University RGO (LSU-RGO) with a double cable. The link at the hip joint was improved by Beckman *et al*.[2] in 1987, and an LSU-RGO for adults was developed in 1989 by Salter *et al*.[3] Hugh Steeper Ltd. in the United Kingdom developed the advanced RGO (ARGO) in 1990. This improved device had a pair of crossed Bowden cables along the center of the hinge axis on the hip joint, enabling cross-walking as the two axes of the hip joint rotated in opposite directions when walking.[4] This ARGO was heavy because of the additional components, and it required a lot of time to put on. The ARGO was improved in the late 1990s by Lissens[5] and Ijzerman *et al*.[6] and in 1993, the isocentric RGO (IRGO) was developed by Motloch *et al*.[7] The IRGO eliminated the crossing axes of the ARGO and instead has the central axis of rotational movement located at the rear center of the pelvic band. The IRGO operates by a rotational link device at the hip joint that links to the rotational movement in the central axis of the pelvic band. The aiding device connected to the single-body pelvic band by a link has high stability in posturing, and the structure is simple and light so that the patient does not become exhausted so easily.[8,9]

Mechanical RGOs developed for gait aid require a large amount of physical energy because they depend on the movement of the body; this results in limitations on the time and distance of their use. Therefore, new hybrid RGOs are being developed that use outside power or electrical stimulation of the paralyzed muscles. Solomonow *et al*.[10] created a hybrid RGO in 1989 that combined functional electrical stimulation (FES) with an RGO, and also investigated muscle reaction and decrease in muscle rigidity in patients with spinal damage. Using FES, however, resulted in rapid muscular exhaustion, which made the device unsuited for long walks.

In 1997, Ruthenberg *et al*.[11] developed a powered gait orthosis (PGO) powered by a DC motor with one degree of freedom. A two-degree version with an additional small DC motor in the knee joint was developed by Ohta *et al*.[12] in 2007. These PGO systems use mechanical links and motors with a speed reducer, but they are not practical in real life because of their large volume, their weight due to complex machinery, and the high power consumption of the motors that requires a separate cable. To aid flexion at the hip joint and decrease energy consumption, an air-pressure PGO using fuzzy logic control[13] was developed, but its success was limited due to the locked knee joint.

The aim of this study was to develop a PGO with two degrees of freedom while increasing the material rigidity of the structure with artificial muscles and enabling flexion at the knee joint with a gas spring cylinder and solenoid. The UKJ-PGO was compared with both the PGO and RGO to assess the quantitative kinematic improvements.

2. UKJ-PGO System

2.1 Hip Mechanism

Since powered RGOs rely on outside power for movement of the hip joint in paraplegics, the balancing posture must be very stable. In this study, the IRGO linked by a single-body pelvic band was used, with very strong titanium (TiAl6V4) in the design of the hip joint to improve the effect of orthosis rigidity.[14]

An air-compression muscle provides flexion strength at the hip joint. The structural mechanism of the hip joint positions the C-shaped pelvic band at the center of the waist region on the spinal orthosis, and both ends of the band are connected to the ball joint in the middle of the hip joint device. The device consists of a rotating device, a KAFO, and a connecting upright bar in a single component positioned at the center of the body. When the body is rotated for walking, the pelvic band also rotates, and during the stance period, the hip joint device on each side extends the hip joint by ball joint links. The interaction between the hip joint device and the ball joint connected to the pelvic band crosses the flexions in the rotating direction, inducing gait (Fig. 1).

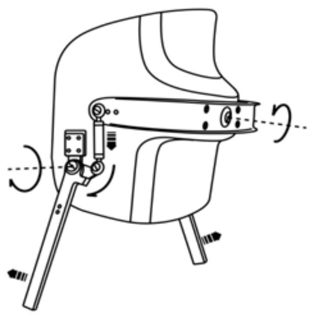

Fig. 1 RGO hip-driving mechanism

The air muscle is a power device that uses air pressure to function in a manner similar to biological muscles. Its strength lies in its relatively large power relative to its weight.[15]

The new PGO includes an air muscle (weight, 40 g; diameter, 20 mm; length, 210 mm; contraction force, 200 N; Shadow Robot Co., UK) between the rotating axes of the hip joint to enable flexion. From the origin of rotational center at the hip joint, a metal bracket is used between the metal link that connects to the thoracic spinal aid device and the upright bar that connects to the long-leg brace for fixation (Fig. 2). The PGO complements body rotation by using the air muscle to rotate the pelvic band while walking, decreasing energy consumption by the user. A method introduced by Colbrunn[16] was used in the mathematical modeling of the air muscle. The kinetic power balance equation, added to the viscosity effect of the air and the attenuating effects of friction from woven material, has the relationship described in Eq. (1).

$$F = \frac{P_g b^2}{4\pi n^2}\left(\frac{3L^2}{b^2} - 1\right) \cdot Eff(P_g) + c \cdot v \pm Q \cdot k \quad (1)$$

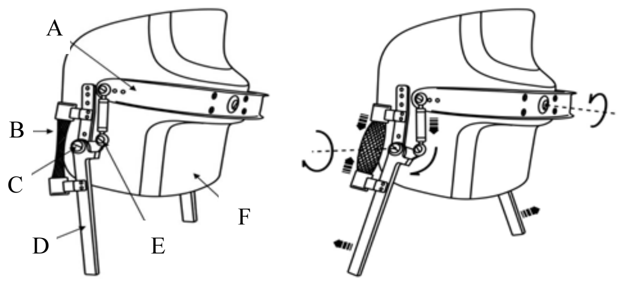

Fig. 2 Schematic diagrams of the air compression-powered hip joint: A, pelvic band; B, air muscle; C, hip joint; D, upright bar; E, ball joint link; and F, spinal orthosis

2.2 Unlockable Knee Mechanism

A ring lock device that completely locks the joint is used for the knee joint to prevent flexion during RGO- or PGO-aided gaits. Complete locking of the knee joint provides stability during the stance period, but it also prevents flexion, causing the feet to drag and requiring greater movement in the pelvic region to lift the legs, which leads to rapid exhaustion. There have been trials using linear motors or electromagnets as brake devices to solve this problem, but these could not be made sufficiently lightweight, and heavy knee-joint devices contribute to fatigue.

To address this weakness, a gas spring cylinder (maximum repulsion force, 45 N; weight, 70 g; outer diameter, 15 mm; length, 130 mm; stroke, 30 mm; Sangyun Co., Korea) and a small solenoid (voltage, 24 VDC; stroke, 15 mm, weight, 45 g; Dong-A Co., Korea) were used to enable flexion and extension at the knee joint (Fig. 3).

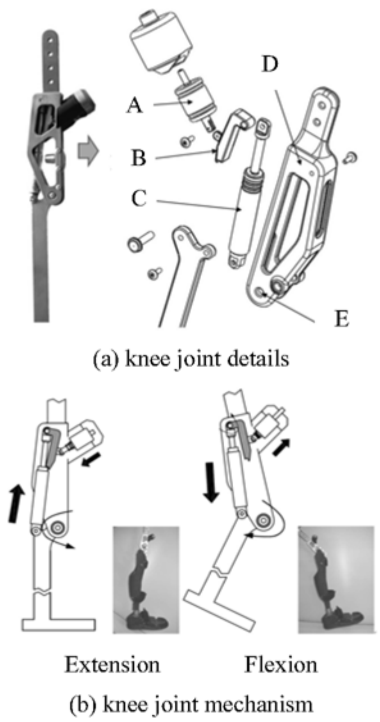

Fig. 3 Schematic diagrams and photographs of the lockable/ unlockable knee joint: A, solenoid; B, stopper; C, gas spring cylinder; D, body (TiAl6V4); and E, knee joint

Flexion prevention in the stance period uses a metal locking device with a gas spring attached to a solenoid to hinder movement, even when the moment of the stance phase occurs. As the phase moves on from stance to swing, the lock is disabled by the solenoid, and the knee joint naturally bends by canceling the repulsion of the spring cylinder with rear inertia for the leg, applied by Edward.[17] When the heel contacts the floor during the swing phase, the gas spring cylinder restores the conserved compressed energy to help the extension. When the knee joint is completely straightened by extension, the solenoid operates to lock the joint and stabilize the stance phase. Figure 3(b) shows the extension and flexion shapes using the knee joint locking device. The unlocking knee joint has a gas cylinder fixed to the metal body of the joint axis by bolts, and the stopper is located on the same line as the axis.

The assembled stopper hinders the straight movement of the cylinder. The stopper is operated by a solenoid fixed on the body, and the solenoid returns to its original position under the force of the built-in spring when power is removed. The hole in the metal body is assembled in line with the upright bar, which is connected to the ankle joint on the axis line. The body is also installed with a stopper block that limits the flexion region according to the stage of walk; adjusting the gap can control the maximum flexion angle. A solenoid unlocks the knee joint when toeing off (solenoid is on) and locks it just before the heel contacts the floor (Fig. 4).

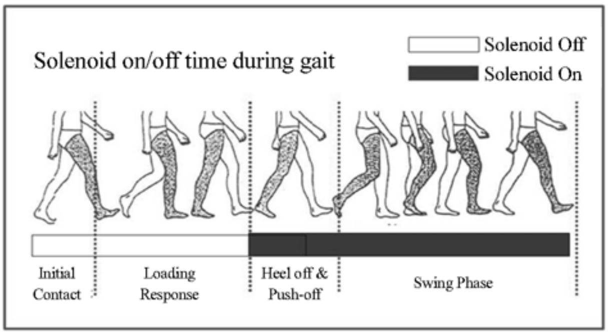

Fig. 4 Solenoid on/off time during gait

The ground repulsion force (F_T) and center of pressure (COP) shown in Eqs. (2) and (3) can be acquired by using four pressure sensors on the sole of the foot to measure the ankle pressures (Fig. 5).

$$F_T = F_{00} + F_{x0} + F_{0y} + F_{xy} \tag{2}$$

$$\begin{aligned} COP_x &= \frac{x}{2}\left[1+\frac{(F_{xo}+F_{xy})-(F_{oo}+F_{oy})}{F_T}\right] \\ COP_y &= \frac{y}{2}\left[1+\frac{(F_{oy}+F_{xy})-(F_{oo}+F_{xo})}{F_T}\right] \end{aligned} \tag{3}$$

The solenoid for the knee-joint movement is on during the swing phase when the ground repulsion force is zero, and it is off during the stance phase when the ground repulsion force is generated. Because flexion at the knee joint is required in the swing phase during the whole gait, the knee joint is unlocked by operating the solenoid when the ground repulsion force is zero. After this, the repulsion force is generated in the stance phase section of the heel contact, and the solenoid turns off, locking the knee and preventing flexion.

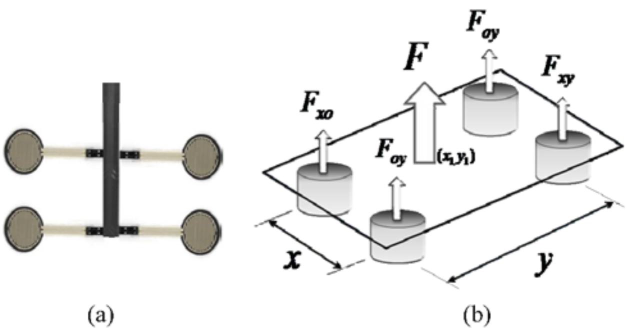

Fig. 5 Illustration of force-sensing resistors (FSR) for COP measurement: (a) four-FSR sensor array; (b) measurements of COP

In the stance phase of the gait, flexion and extension are both limited due to stability issues, and they enable clearance of the ground in the swing phase. To determine the magnitude of repulsion required in the gas spring cylinder, the moment created during flexion and extending of the knee joint during the swing phase[18] can be calculated using Eq. (4).

$$M_{knee} = I_{0\alpha} - R_{x1} \times x_{procc} + R_{y1} \times y_{procc} - R_{x2} \times x_{proccknee} + R_{y2} \times y_{proccknee} \tag{4}$$

For a body weight of 60 kg, 2.02 N•m is acquired as the flexion moment at the swing phase. The Automatic Dynamic Analysis of Mechanical Systems software was used to calculate the extending moment of the cylinder acting on the knee joint. The moment enacted by the cylinder for flexion using rear inertia was calculated to reach a value of 60%.

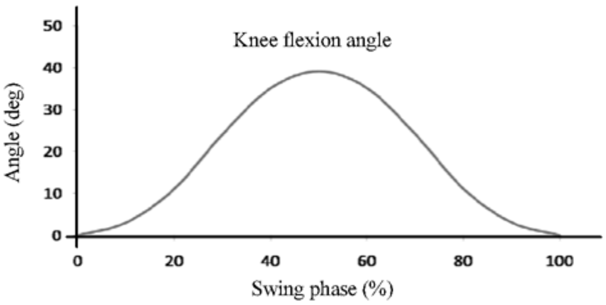

Fig. 6 Knee flexion pattern

The repulsion force of the cylinder at this moment was 45 N. In the experiment, three different types of cylinders were used according to body weight: 45, 60, and 75 N. The maximum flexion angle of the knee joint was set to 40 (Fig. 6).

2.3 Driving system

The control system for the UKJ-PGO is composed of a solenoid valve (LCP35A; MAC Valve Inc., U.S.A.), an air pump (voltage, 24 VDC; maximum [something], 2.5 kg/cm^2; weight, 805 g; Korea Pneumatics Co., Korea), a battery (Li-ion, 4400 mAh, 11.1 V, 450 g; Samsung Co. Ltd., Korea) and a real-time controller.[19,20]

The real-time controller has a high operational speed and uses a microprocessor (ATMega-128; ATMel Co.), which has integral features such as input/output ports, analog to digital conversion, and pulse-width modulation output (Fig. 7). The signals for the gait are generated by electromyogram sensors attached to both arms, and sensors on the foot aid the walk. The total weight of the control system is 2.2 kg, and it runs for three hours of continuous use on a fully charged battery.

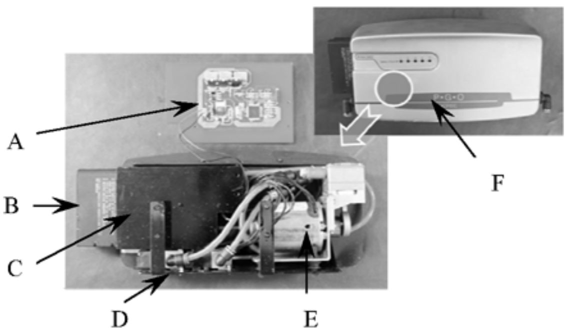

Fig. 7 Photographs of the PGO driving system: A, controller; B, battery; C, inner chassis; D, solenoid valve; E, compression pump; and F, case cover

3. Gait Analysis

An analysis of the kinematic variation and gait was conducted to analyze the gait effects of paraplegics using the UKJ-PGO. The participants were male patients with spinal damage in T11 (Table 1), resulting in complete paralysis of the lower body.

Table 1 Details of subjects included in the study

Subject	Sex	Age	Weight (kg)	Time since injury (months)	RGO use (months)
A	M	37	56	30	10
B	M	41	67	18	2

The kinematic traits of the participants were measured with a Vicon 370 (Oxford Metrics, UK) data-processing device, and data were captured with six infrared motion-capture cameras (Oxford Metrics, UK), four force plates (Kistler, Switzerland) and a 25-mm reflective marker.[21]

The knee joint was locked for the gait experiments using the UKJ-PGO (Fig. 8) and the PGO. The participants donned the PGO at the parallel bars and warmed up for 10 minutes (Fig. 9). When their heart rates had stabilized after 20 minutes of rest, they each underwent five repetitions of the gait analysis wearing the PGO. There was a 20-min rest between each use of the orthosis.

In the case of the RGO or PGO with a locked knee joint, the gait was very forced due to the lack of movement in the joint, and was significantly different than normal gait.[22,23] In the case of the UKJ-PGO, flexion and extension were enabled during the swing phase, which can be observed in Fig. 10(b).

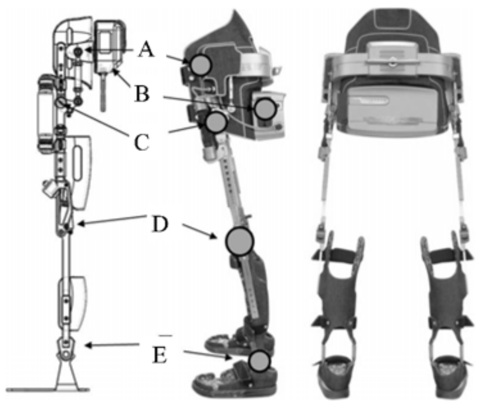

Fig. 8 Air-muscle powered gait orthosis: A, pelvic band; B, controller; C, hip joint; D, knee joint; and E, ankle joint (double Klenzak)

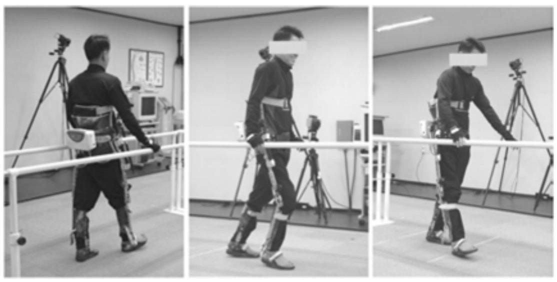

Fig. 9 Gait training

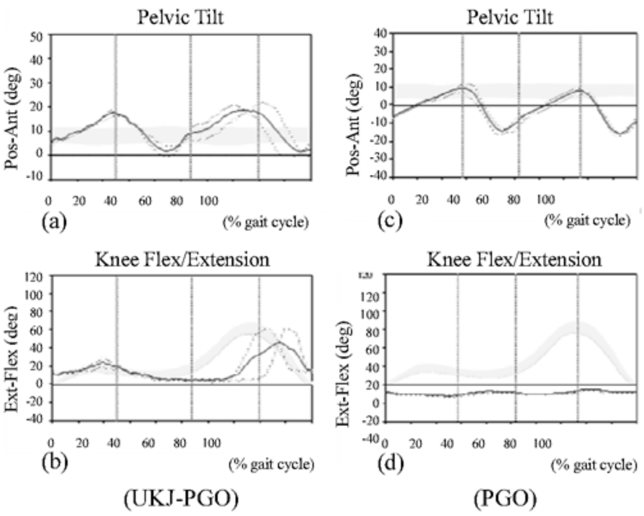

Fig. 10 Angular pattern of paraplegic gait assisted by UKJ-PGO and PGO: (a) pelvic tilt with UKJ-PGO, (b) knee flexion/extension with UKJ-PGO, (c) pelvic tilt with PGO, and (d) knee flexion/extension with PGO

The flexion angle of the PGO with the knee joint locked was 8±1° due to deformation of the orthosis, depending on its rigidity. The UKJ-PGO with the flexible knee joint had a value of 43±5°, displaying good flexion in the joint (Fig. 11a).

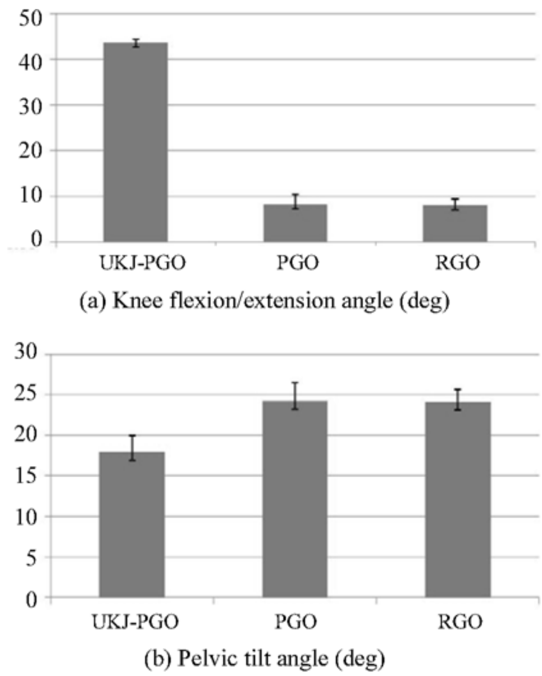

Fig. 11 Gait angles

The RGO and PGO required a large pelvic slope for walking. In the UKJ-PGO gait, the knee joint could be bent in the swing phase, creating flexion in the hip joint with the air muscle, which resulted in a smaller pelvic slope for walking. The pelvic slope angle with the PGO was 24±2°, while with the UKJ-PGO, it was 18±2 (Fig. 11b).

In the conventional gait of a normal adult, the stance phase takes up 60% of the gait cycle while the swing phase takes up the other 40%.[24,25] However, as walking speed increases, the ratio shifts as the swing phase increases and the stance phase decreases. In UKJ-PGO-aided gait, the stance phase was 70±1% of the gait cycle, and for the PGO, it was 74±2% (Fig. 12a). The percentage of the swing phase was 29±1% of the gait cycle for the UKJ-PGO and 25±2% for the PGO (Fig.12b). The UKJ-PGO-aided gait had a shorter stance phase and a longer swing phase, a pattern more similar to that of an uninjured person. An improvement in the gait cycle of paraplegics can create a more natural gait pattern and improve walking speed.

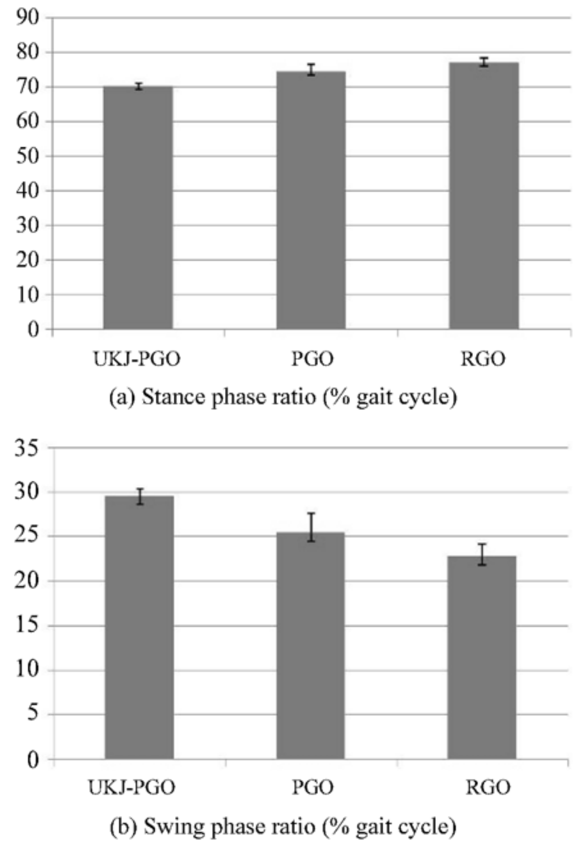

Fig. 12 Gait cycles

The walking cadence for a normal adult is in the range of 100±10 steps/min, with variations according to physical attributes and personal walking habits.[26] In orthosis-aided gaits of paralyzed patients, the rate was lower than this due to the effects of paralysis. When the new device was tested, an increase was observed in the cadence of UKJ-PGO-aided gaits along with a change in the walking speed (Fig. 13). In the PGO-aided gait, the average cadence of the patients was 33±2 steps/min; this increased by about 10% to 36±2 steps/min when using the UKJ-PGO.

The walking speed was faster using the UKJ-PGO, in which the movement is caused by the body, compared to that obtained using the PGO, in which only the air muscle is used. The walking speed with the PGO was 26±2 cm/s, identical to that of RGO. The UKJ-PGO-aided gait was about 16% higher, 31±2 cm/s (Fig. 14). This shows that flexion in the knee joint enables patients to cover distance in a shorter time.

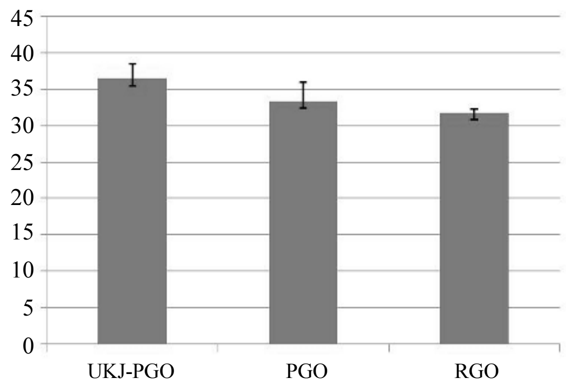

Fig. 13 Gait cadence (steps/min)

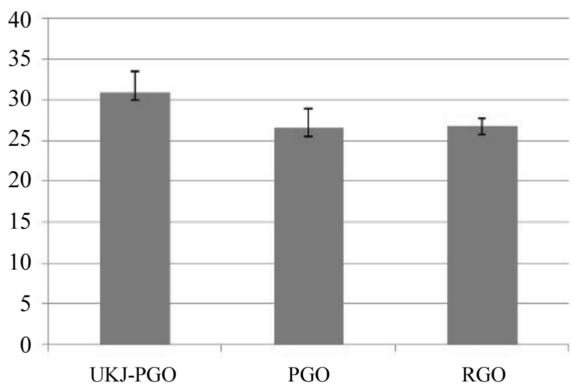

Fig. 14 Gait velocity (cm/s)

4. Conclusions

The UKJ-PGO developed in the course of this study had flexion and extension at the knee joint and enhanced rigidity at the hip joint device to allow a paraplegic to walk. A gait analysis conducted to evaluate its kinematic performance gave the following results.

An RGO or a PGO, in which the knee joint is locked for the patient's safety, allows no movement at the knee joint, forcing an unnatural walk that is much different than the normal adult gait. The UKJ-PGO introduced in this paper uses a gas spring cylinder and solenoid locking device to enable flexion in the knee joint during the swing phase, and the pelvic tilt was less than that of PGO-aided gait. With flexion at the knee joint, the abnormally excessive ratio of the stance phase in the gait cycle that occurs with other orthosis models decreased and the percentage of the swing phase increased, improving the patients' gait cycles. Use of the UKJ-PGO resulted in improvements in both cadence and walking speed compared to previous RGOs and PGOs due to the flexion at the knee joint.

ACKNOWLEDGMENTS

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