CURRENT STATUS OF WALKING ORTHOSES FOR THORACIC PARAPLEGICS

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Spinal cord injury (SCI)[1] patients classified as paraplegics are confined to a wheelchair for a prolonged period of time, which they use as their sole mode of transportation. Prolonged sitting, however, results in compounded medical, physiologic, social, and psychologic problems that severely compromise the patient's health and quality of life. Pressures sores, decreased bone-density in the legs, increased risk of fracture, bowel and bladder stagnation, urinary tract infection, deteriorating cardiopulmonary and circulatory conditions, spasticity, and joint contractures are the most common problems of wheelchair-bound paraplegics.

Spasticity is a most debilitating problem, since it requires muscle relaxation for suppression. Muscle relaxants may cause generalized depression and reduce patients' ability to deal with the usual stress of daily living. This may ultimately result in the patient feeling detached from society. Unfortunately, at present, there is no practical orthosis that allows paraplegics to stand and walk independently for periods considered useful or even exercise.

A long leg brace (LLB), such as a rigid knee, ankle, and foot orthosis (KAFO) that requires significant consumption of energy for ambulation, provides limited walking function. Unfortunately, long-term evaluations have shown that this orthosis is soon abandoned by most patients, although a few use it for exercise.

The Reciprocating Gait Orthosis (RGO) developed at Louisiana State University (LSU) in the 1970s was first used in pediatric patients with severe musculoskeletal disabilities of the lower extremities (e.g. spina bifida, muscular dystrophy, sacral agenesis, osteogenesis imperfecta, and limited cases of cerebral palsy). During the late 1970s and through the 1980s, successful applications were made to SCI patients, mostly paraplegics, although some quadriplegics with residual upper extremity function also benefited. Since 1983, approximately 5,000 RGO units have been made and applied in the United States, Canada, Great Britain, The Netherlands, France, Israel, Australia, and South Africa. At present, the RGO is fully covered by Medicare/Medicaid, private insurers, and by the health authorities of the various countries.

Although initial results with the RGO in SCI patients were encouraging, the orthosis has several limitations, especially the high energy cost of ambulation compared with healthy subjects or wheelchair transportation. To reduce that energy cost, we developed (in 1983) a simple but effective and practical electrical muscle stimulation (MS) unit to power the RGO during walking.

Requirements for Simple Locomotion

Four distinct biomechanical factors are involved in the most simple human locomotion: standing upright, swinging one leg, simultaneously pushing off with the other while maintaining balance and stability.

The swing phase of one leg is a relatively complex function requiring activation of the hip, knee, and ankle in the flexion mode. For the most elementary swing phase, however, hip flexion is the minimal requirement for the "stiff-leg" walk (i.e., extended knee and rigid ankle). This type of stiff-legged locomotion, however, requires some lateral sway and an elevation of the trunk so that the foot clears the floor as the leg moves from the posterior (toe-off) to the anterior (heel-strike) position.

The contralateral push-off is accomplished by hip extension of that leg accompanied by knee extension and ankle plantarflexion. Considering the elementary "stiff-knee" gait, only hip extension is required. The isolated swing of one leg without a contralateral push-off, however, will result in zero forward progression (known as "wheel spinning"), which underscores the importance of hip extension.

The issue of balance and its stability requires that the trunk's center of gravity be positioned within a prescribed region between the feet, which allows a certain amount of anterior-posterior and lateral sway but preserves balance. Shifting the projection of the trunk's center of gravity out of that region will upset the balance and may cause a fall if not corrected fast enough.

Design Rationale for Muscle Stimulation Power

In our experience over the last ten years, we noted that most patients can achieve reasonable locomotion with the

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LSU-RGO alone (i.e., without MS). Why, then, employ MS power to complicate the system?

Isolated upper body work consumes much more metabolic energy per kilogram of body mass of active tissue than the combined work of the upper and lower body. This, added to the fact that the legs are paralyzed and the trunk muscles are very active during locomotion with the RGO alone (without MS), results in excessive energy expenditure and stress on the arms. By using MS to power the RGO, we can produce strong enough contractions of the large thigh muscles to provide the swing and push-off functions while simultaneously creating combined upper and lower body work, thereby reducing the overall energy cost of locomotion. An additional advantage is the reduction in work by and stress on the spinal and arm muscles produced by the swing/push-off in the absence of MS. This is very important to the design concept, as will become obvious when the system evaluation is considered.

The rationale for designing a practical hybrid locomotion system is, therefore, based on biomechanical, physiological, ergonomic, surgical/medical, and realistic factors. The design itself should allow for several other important factors that are the foundation of orthotics/prosthetics practice-i.e., function, ease of donning/doffing the device, safety, reliability, independence of assistance in operation, cost, and cosmesis. These factors are addressed in the following sections.

The LSU-RGO maintains upright posture and balance, and electrical muscle stimulation of the rectus femoris of one leg simultaneously with the stimulation of the contralateral hamstrings will provide hip flexion and extension, respectively, for successful locomotion.

The LSU-RGO

The Louisiana State University-Reciprocating Gait Orthosis (LSU-RGO) is a passive mechanical orthosis generally categorized as an HKAFO (hip, knee, ankle, foot orthosis). It consists of a polypropylene AFO splint that is custom-made to the size of the patient and worn inside the shoe. Its function is to give stability to the ankle joint to allow balanced upright posture. From each AFO, two aluminum uprights extend on the lateral and medial sides, terminating in bilateral knee joints. Two additional uprights extend from each knee joint, the lateral one terminating in a hip joint, while the medial upright extends only two-thirds of the way along the thigh. A polypropylene posterior cuff connects the medial and lateral thigh uprights, while anterior velcro straps insure that the thigh stays in position. An additional upright extends from each hip joint along the lateral aspects of the trunk to just below the axilla. Two velcro straps, one posterior and one anterior, connect the proximal ends of the uprights to insure proper placement of the trunk.

The knee joint was specifically redesigned for applications in SCI patients. Our experience shows that nearly all paraplegics suffer from significant hamstring contractures. Attempts to stand from a seated position with the aid of muscle stimulation or with arm strength alone does not result in full knee extension. To allow the patient to remain upright and prevent his collapse into the wheelchair, we incorporated a ratchet knee joint that would freely move into extension but not return into knee flexion. This important feature allows the patient to remain upright even when the knee is flexed 10° to 25°. After the first step, the shear force developed at the knee with heel strike fully extends the knee and locks the joint in position for the desired duration of locomotion. For sitting, specially designed posterior bales are engaged by the edge of the chair, which unlocks the ratchet mechanism and allows the knee to flex freely. The bales are spring-loaded, which causes the ratchet mechanism to be engaged as soon as they are removed from the edge of the chair. The patient does not have to use his arms for locking or unlocking the knee joint.

The hip joints of the RGO are connected to each other with two stainless steel cables guided inside a low-friction conduit. The cables function to satisfy two objectives: first, to prevent simultaneous hip flexion of both hips and consequent collapse of the patient (this allows the patient to remain upright with no energy expenditure and without using the upper extremities for support for prolonged periods of time); second, to force transmission from one hip to the contralateral one in order to make reciprocal movement of the legs possible. If one hip goes into flexion, force is transmitted via the cables to create a contralateral hip extension, a reciprocal motion identical to the swing of one leg simultaneously with contralateral push-off.

The reciprocal mechanism may be disengaged to allow simultaneous flexion of both hips for purposes of sitting down. This is accomplished by the patient pressing a small pin that disengages the reciprocal mechanism. The pin, however, is spring loaded and will engage the cables automatically if the patient stands and extends his or her hips sufficiently. The pin is also equipped with two locking positions, one at full hip extension and the second at 20° hip flexion. Hip flexion of 20° shifts the center of gravity forward so that the patient can walk up a handicapped ramp. This position of partial hip flexion also allows patients with some hip flexion contracture (which is common after prolonged sitting) to stand up in two stages. Standing or hip extension may easily be locked in the 20° position, relieving the patient's upper extremities from providing antigravity support. The patient can then attempt to extend the hip further into the fully extended position.

Principle of Operation

The RGO allows stable upright balance at minimal metabolic energy cost. As the patient starts to walk, several physical functions are taken in sequence, as follows:

- *Step 1.* The patient's weight is shifted over one leg (normally the stance leg that will execute the push-off function). This is accomplished by elbow extension with the contralateral arm, tilting the trunk toward the leg. This results in a slight elevation of one leg and allows it to clear the floor as the swing phase is initiated.

- *Step 2.* The patient exaggerates his lordosis, applying force against the posterior thoracic strap of the RGO. This force, acting on the lateral thoracic uprights of the RGO, creates a moment about the hip joint and forces the stance leg to undergo hip extension.

- *Step 3.* The dual-cable mechanism linking the two hip joints transmits part of the torque created about the hip of the stance leg to the contralateral hip in a reciprocal manner, initiating hip flexion. This results in the execution of the swing phase simultaneously with the contralateral push-off.

Needless to say, the above sequential steps require some coordination, which is easily learned by the patient, given appropriate guidance and instruction by a well-trained physical therapist and several hours of supervised practice.

The Stimulation System

As noted above, there are two objectives of muscle stimulation. The first is to initiate the swing of one leg simultaneously with contralateral push-off, thereby providing the power for locomotion while releasing the upper extremities and spinal muscles from that task. Second, because both the upper and lower extremities are active, stimulation reduces the energy expenditure per unit of body mass.

To stimulate the rectus femoris of one leg simultaneously with the hamstring of the contralateral leg, two channels are necessary. Furthermore, to initiate the next step, the cycle is reversed, which requires stimulation of the hamstrings of one leg with simultaneous activation of the contralateral rectus femoris. In all, four stimulation channels are required, with each pair active simultaneously.

The stimulation is accomplished with monophasic, charge-balanced pulses of 0.5 ms duration at a rate that varies from 18 to 26 pps, according to the individual patient. The objective of the rate adjustment is to generate a contraction of a strength near 50 to 70% of the maximal tetanic force without inducing fatigue. Lower rates may accomplish this. Individual adjustments can be made to accommodate the muscle fiber composition of each patient and the changes resulting from the MS therapy administered to reverse muscle atrophy.

The pulsed current is applied to the patient via conventional carbon-impregnated rubber electrodes covered with Karaya solid gel.

We have designed a flexible copolymer electrode cuff which is custom-made for each patient. The electrodes are placed in the cuff properly predistanced about the motor point. All electrode wires are passed between the outer shell and the internal foam cover and emerge from the cuff in a single cable with a plug connector. The connector can be inserted into the stimulator in only one way. The inside foam cover can be peeled off for washing or for replacing the Karaya gel; it also allows ventilation of the skin, absorption of sweat, and prevents temperature build-up. Velcro straps fasten the cuffs snugly about the thigh.

The stimulator is always in the "off" mode except when the patient decides to walk. By triggering a mini-switch mounted on each handlebar of the rolling walker, the patient activates the rectus femoris on the same side of the switch while stimulating the contralateral hamstrings. The trigger signal from the switch is transmitted to the belt-worn stimulator via a spiral cable from the walker.

REHABILITATION PROGRAM

Evaluation

There are no clear, universally accepted guidelines for accepting SCI patients to a rehabilitation program that includes locomotion with an orthosis or an MS-powered orthosis. The current criteria of Kralj et al is an initial attempt. Our aggressive, research-oriented experience has yielded additional important knowledge. Once the patient has been declared by the physician to have a stable spine and to be in general good condition, we have found that the major positive factor is motivation. Once the patient demonstrates motivation by requesting to join the program and by attending preliminary sessions, we proceed with the evaluation. To date, the characteristics of the patients who are in, or have completed, the training include:

- Injury level: C/5-6 incomplete to T-11;
- Age: 18-62 years;
- Time since injury: 11 months to 22 years;
- Spasms: None to severe;
- Contractures: None to severe (but not ossified joints);
- Weight: Normal to overweight;
- Pressure sores: None to some.

The reason for such liberal acceptance criteria is based on our initial need to gain experience. We have found that even severe spasticity will significantly diminish or even disappear with the application of muscle stimulation or with

locomotion in the RGO (with or without stimulation). This can result primarily from muscle stretching, range-of-motion exercise, or stimulation alone, as was reported by Kralj et al. Stimulation alone is important in reducing or eliminating spasticity and, consequently, the antispastic medication. The effect of electrical stimulation on spasticity, however, lasts only a short while, with a gradual return of spasticity three to four days following the last application.

Contractures of the hip, knee, and ankle joints were initially regarded as contraindications, but as long as the joints are not ossified, application of MS and/or locomotion with the RGO significantly decreases the contracture and increases the joints' range of motion. Continuation of the locomotion with the RGO powered by muscle stimulation consolidates the gains, but they can be quickly lost if the patient does not ambulate for two to three weeks.

Long periods of sitting in the wheelchair accelerate weight gain. We accept overweight, motivated patients who often lose weight rapidly as soon as they begin to walk. This could not be attributed to the MS alone, but rather to the locomotion and the high rate of metabolic energy consumption it requires. These patients are eventually good walkers despite the initial hardship.

Patients who begin locomotion relatively soon after injury have a rapid reversal of muscle atrophy. Patients who begin even two decades after injury can have equal improvements, but they require longer periods of MS therapy. The late-starting patients have greater initial difficulties to overcome because of deficiencies of their cardiopulmonary systems.

Patients with injuries at T-1 to T-11 are easier to rehabilitate, although we accept patients with lesions above and below the range. One patient had complete lack of sensory and motor function below T-1 and incomplete damage up to the C/5-6 level. After several weeks of arm-hand strengthening he was accepted to the program, and three years later, he was one of the best users. However, high lesions that completely affect the arms and hands are contraindications.

Patients with lesions below T-11 have partial or complete damage to the lower motor neurons and therefore do not respond to stimulation. Such patients are, as a rule, better walkers with the RGO alone, especially if some hip flexion is available.

The pre-existing pressure sores and some skin lacerations heal rapidly once stimulation and locomotion are initiated. We suspect that the improvement in the lower extremities is the result of stimulation, muscle hypertrophy, revascularization, and increased metabolism.

Experience shows that acceptance to the program should not be limited to certain patients but should be open to the general paraplegic population. Hardship and perseverance are required by some patients with severe deficiencies, but success is possible.

RGO Fitting and Training

Each patient undergoes three to four weeks of perambulatory training (three one-hour sessions per week) to develop trunk balance and to strengthen arm and shoulder girdle muscle, back extensors, and abdominal muscle. The object of this perambulatory training is to reduce contractures, maximize the strength and control of any innervated muscles, increase the strength of the arms and shoulders (essential for ambulation in the RGO), and retrain the patient to control the trunk's center of gravity-a function gradually lost after prolonged sitting in the wheelchair. Another purpose is to improve the patient's cardiopulmonary condition and endurance.

The importance of this perambulatory training can be gauged from the fact that patients who successfully complete it become good users of the RGO relatively quickly, whereas patients who do not participate have a low acceptance rate even after prolonged ambulatory training.

Our patients are fitted with a custom RGO by a certified orthotist who has prior experience with this orthosis. The RGO uprights and cables are properly calibrated so that, for at least one minute, the patient can stand fully balanced and stable without holding on to anything. Additional care is taken to align the leg uprights to that circumduction or scissoring is completely eliminated.

Following the initial fitting, each patient receives six weeks of training: three-hour sessions each day for three days a week learning to put on and take off the RGO, walk on level surfaces, sit and stand, and make corners and full turns. All training is provided by a registered physical therapist with extensive previous experience with the RGO.

Patients with injuries at T1 and/or incomplete damage to the low cervical levels receive an additional three weeks of arm strengthening before beginning RGO training.

The proper fitting and calibration of the RGO by an experienced orthotist is essential for its success. The alignment of leg members, symmetry, proper tension in cables, adjustment of thoracic straps, and other factors make an enormous difference in the ability of the patient to use and accept the orthosis.

Muscle Stimulation Therapy

Each patient receives six weeks of MS therapy to the quadriceps and hamstrings muscles. The therapy consists of three weekly sessions lasting up to 40 minutes each. The object is to reverse thigh muscle atrophy and increase strength. A pair of carbon-impregnated surface electrodes are placed over the hamstrings and another pair over the quadriceps of each leg. The patient is raised with a

specifically designed hydraulic lift while sitting on a narrow seat, similar to a bicycle seat, with free space around the legs. A specially designed, four-channel electrical stimulator delivers 0.5 ms rectangular pulses at a rate of 20 pulses per second to one quadriceps and the contralateral hamstrings. This results in a hip flexion, contralateral hip extension and knee flexion and simulates swing and push-off phases of the gait cycle. The stimuli are then switched to the contralateral muscles.

Initially, the stimuli are applied for one minute at a rate of 0.3 steps/sec (i.e., a swing and a contralateral push-off are held for three seconds before reversing the stimuli to the muscles of each leg). A ten-minute rest is given to the patient following another minute of the "walking-like" session.

The stimulation therapy is increased by two minutes per session as the muscles become conditioned. In the final two weeks of the stimulation therapy, the patients are given two 20-minute sessions around a ten minute rest period. A 25 N weight is wrapped around the ankles to load the movement and to improve strength and fatigue resistance of the thigh muscles. During the last two weeks of training, the stimulus cycle is increased to one step/sec-i.e., the patient performs swing and contralateral push-off 60 times per minute.

During therapy, patients' heart rates are monitored with an earlobe sensor to check for excessive stress. Some patients demonstrate a rapid increase in heart rate during the first week of MS therapy. If the heart rate increases over 140 beats per minute, the patient is lowered to the supine position and closely monitored for 20-25 minutes until the heart rate returns to normal. Occasionally, additional preconditioning is prescribed on the tilt table to allow the cardiovascular system to adjust to the upright posture.

Gait Training with MS-powered RGO

Once a patient completes the six weeks of gait training with RGO and the simultaneous MS therapy, an additional six weeks (three-hour sessions thrice weekly) of gait training with the MS-powered RGO is given to develop skill and improve performance in level walking when using MS for the thigh muscles.

ENERGY CONSUMPTION

Protocol

Instrumentation for patients consists of a nose clip and a mouthpiece from which two flexible tubes are connected to a volume spirometer containing oxygen mounted on a rolling cart. The cart is pushed along after the patient during locomotion. The tubes are mounted on a light-weight plastic shoulder harness to allow the patient to move his head freely during locomotion. Expired, excess O_2 consumption during each breath and overall 0_2 consumption are recorded.

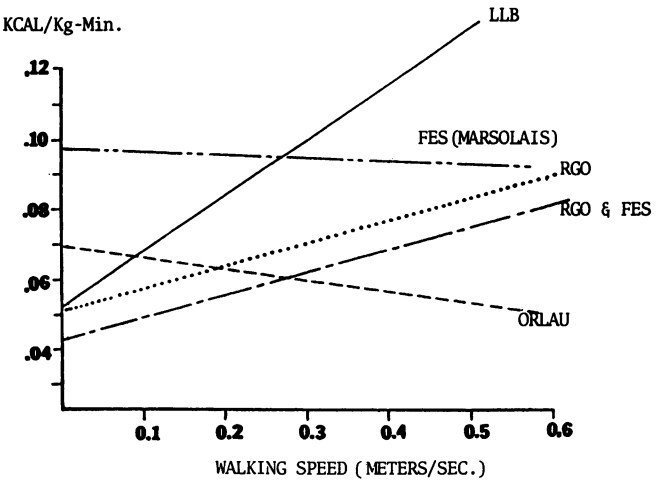

Figure 1

Initially, the patient stands quietly for five minutes to establish basal heart rate and energy consumption at rest. The patient is then instructed to walk a level, straight 30-meter track at a speed set by a metronome. At the end of the track, the final heart rate and total O_2 consumption is measured. Following a 20-minute rest, the metronome speed is changed and the procedure is repeated. Walking speeds are set at random to prevent bias errors. Before the next trial is initiated, the patients' heart rates must return to within ± 3 beats/min. of the original resting heart rate.

Patients are instructed not to eat for three to four hours before coming to the clinic and another hour and a half without food is allowed to elapse before the trial begins. Each patient is also instructed to walk a 30-meter distance at a comfortable speed. Two such trials are performed by each patient and are included in calculating the average preferred walking speed of all the patients. The preferred walking speed of a group of six patients with T-1 to T-10 injuries is 0.2 m/sec.

Results

The energy cost of a new orthotic device is meaningful only if it is compared to that of a well-known device, such as the LLB, that is available as an option for the same patient category. The data in figure 1 compares five systems. The energy expenditure in kcal/kg-min against walking speed is shown. The lowest energy cost is associated with the MS-powered RGO at walking speeds from 0 to 0.27 m/sec. Ranking second in energy expenditure per minute is the RGO, which displays a nearly parallel curve to the RGO and MS, but shifted 0.01 kcal/kg-min upward. The energy expenditure associated with the LLB climbs quickly as walking speed increases; it

is ranked third for walking speeds ranging up to 0.1 m/sec. The HGO demonstrates a rapid decline in energy cost as walking speed increases; it has a lower cost than the LLB at 0.1 m/sec and is even lower than the RGO and MS-powered RGO at 2.0 and 0.27 m/sec, respectively.

If 0.2 m/sec is the preferred walking speed for daily activities, a ranking of the five types of walking aids would put the RGO and the MS first, with the lowest energy cost, the RGO and HGO second and third, the LLB fourth, and the Marsolais FES, with the highest energy cost, fifth.

Heart Rate

Figure 2 displays the mean and standard deviation of the pooled pre- and post-trials heart rate for the RGO and MS-powered RGO, and the heart rate date for the LLB and the Marsolais FES as obtained from the literature. Heart rate data for the HGO are not available in the literature.

The mean pre-trial heart rate (HR) for patients using the MS-powered RGO was 88 beats/min (standing quietly) and the post-trial heart rate (HR) was 119 beats/min, a 35.2% increase. For the RGO, the HR rose from 86 beats/min at rest (standing) to 131 beats/min post-trial, a 52.3% increase. For the LLB and Marsolais FES systems, the comparable increases (from the seated positions) were 87.5% and 101.25%.

By the amounts indicated in Figure 2, the addition of MS power to the RGO resulted in lower HRs at the end of a walk of at least 30 meters, compared to the HRs of the same patients using the RGO alone, the LLB, and Marsolais FES system. The lower HR from walking in the MS-powered RGO reflects the low stress associated with this device, confirming the advantages of a walking aid in which a passive mechanical orthosis is coupled with MS of the leg muscles.

Cost

An important factor in the use of orthotic devices is cost. The RGO has been available commercially since the mid-1970s from Durr-Fillauer Orthopaedics, Inc., of Chattanooga, Tennessee. At present, its cost, including the hardware shipped from the manufacturer, assembly by a local orthotist, and custom fitting (casting, alignments, calibration, etc.), is $4,200. The cost of the rolling walker necessary for ambulation is $155, and the custom-built stimulator is $1,200. The total cost of the hardware is therefore $5,555.

The success of an orthosis, as determined by patient acceptance, depends on the quality of training in its use. In our experience, the training proved to be a most important element in acceptance. Well-trained patients became routine users; poorly trained patients (primarily those not from New Orleans who could spend only a limited time as

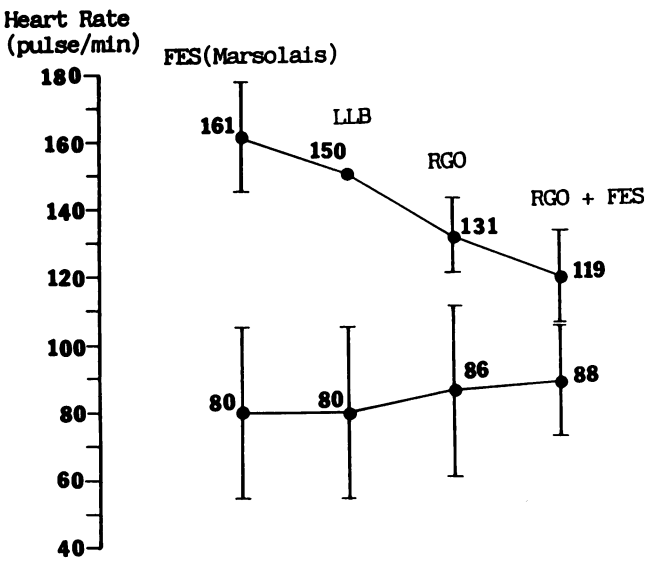

Figure 2

outpatients) were not frequent users. The training requires at least six weeks of supervised and guided ambulation by a physical therapist at the rate of three weekly sessions. The cost of this gait training averages $1,200, although it varies with the patient's age, weight, sex, level of injury, duration of disability, and motivation. Some patients need only two to three weeks of gait training; in difficult cases, up to 15 weeks is required. The latter cases involve patients with joint contractures, high level of injury, high levels of spasticity, weight problems, and advanced age (oldest patient: 62 years old at rehabilitation).

Therapy to reverse muscle atrophy adds to the costs: three weekly sessions that last for an average of six weeks cost an average of $2,500.

Overall, the average cost of the rehabilitation comes to $9,255, which is reasonable compared to other orthotic or prosthetic devices. A below-knee prosthesis, for example, costs between $1,800 and $4,000; an above-knee prosthesis costs between $3,200 and $10,000, excluding gait training.

Reliability-Maintenance

The RGO has become more reliable over the years. Based on experience with a large number of patients, the RGO, if used daily, requires approximately two service visits per year. Less frequent users require an average of one service visit every two years, a frequent equivalent to that of other prosthetic devices that are routinely applied, such as above- and below-knee prosthetics. Repairs normally occur during the gait-training period when the brace is new and occasionally needs calibration to optimize its performance. A broken cable or a fractured AFO are usually attributable to the patients' weight, and can be

immediately replaced with heavy-duty components that can last satisfactorily for many years.

Conclusions

Compared to other currently available options including mechanical or the MS orthosis, the use of the RGO powered by brief electrical stimulation of the thigh muscles to initiate the gait cycle of thoracic paraplegics results in a substantial reduction of energy expenditure. The advantages of such a hybrid orthosis, combined with the appropriate training, can provide selected paraplegics with an alternative to wheelchair transportation. It has added potential benefits of preventing osteoporosis and pressure sores, improving cardiopulmonary, kidney, bladder, and circulatory functions, as well as improving the patients' outlook.

To date, we have fitted 700 patients with the RGO and over 27 patients with the MS-powered RGO and followed them nearly three years. We had two failures, patients who abandoned the program before training was completed due to social problems. The remaining patients are regular users daily or at least three times a week. They use it in the workplace, in daily walking exercise or as a means of home ambulation for a total of 40 hours weekly. Others who do not use it daily will use it for such special occasions as going to church or social gatherings for at least 12 to 15 hours per week.

Patients are trained to don or doff the orthosis either in bed or when seated. This procedure normally takes 15 to 20 minutes when performed without help. This does not bother patients, but they are disappointed that the brace has to be taken off to perform bathroom functions. This requirement is the result of the RGO's inability to perform hip abduction; lack of this function also limits a patient's ability to get in and out of a car or bed without help. We have designed, and are now testing, a hip abduction joint that will remove this limitation, but many other limitations still exist: the inability to safely walk up stairs or on uneven surfaces of dirt, grass, or gravel. Current work indicates that improvements in function are possible and would increase acceptance of the orthosis as a routinely worn accessory.

The successes and failures of researchers over the decades have taught us invaluable lessons which have helped us develop a reasonably practical walking orthosis. We consider it practical as patients can use it without assistance in the home, workplace, school or other environments; it is commercially available and has a reasonable cost; and it was found useful by many outside of our group. This is the first time an orthosis with such features is available. Still, it is primitive when compared to healthy legs. Rather than frustrate us, this should motivate us to more aggressive research efforts.

We have relied heavily on the physiologic and engineering work of others and on the basis of recent developments in our laboratory, we see the potential for significant advances in control of muscles in a mode similar to that used in voluntary contraction. There is now good progress in obtaining basic information on how agonist and antagonist muscles coactivate or co-contract about a joint; we are studying the feasibility of using EMG as a force feedback in a closed-loop MS-control scheme. Completing this research and development will take many years, but the expected results will be worth the wait. In the meantime, a reasonable and practical orthosis is available as an alternative to the wheelchair.

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