Speed and Efficiency in Walking and Wheeling with Novel Stimulation and Bracing Systems After Spinal Cord Injury: A Case Study

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▪ ABSTRACT

To compare various novel and conventional systems for locomotion, a 25-year-old man was studied with motor complete spinal cord injury at the T4/5 level. He used various devices in the community, and changes in speed, physiological cost index (PCI), and oxygen consumption were measured periodically. Speed was fastest with a conventional manual wheelchair (nearly 120 m/min in a 4-min test). Speed was about 30% less, but the PCI was lowest (highest efficiency) using functional electrical stimulation (FES) of the quadriceps and hamstring muscles to propel a novel wheelchair. He walked with knee-ankle-foot orthoses (KAFO) at much lower speed (8.8 m/min) and higher PCI. He walked with an alternating gait using a new stance-control KAFO with FES. The speed was still slow (5 m/min), but he prefers the more normal-looking gait and uses it daily. Walking with FES and ankle-foot orthoses (AFO) was slowest (3.5 m/min) and had the highest PCI. In conclusion, the leg-propelled wheelchair provides a more efficient method of locomotion. A new stance-controlled KAFO with FES may provide a more acceptable walking system, but must be tested on other subjects. ▪

KEY WORDS: functional electrical stimulation, locomotion, orthosis, spinal cord injury

INTRODUCTION

Restoration of walking after complete spinal cord injury (SCI) with FES has been a research goal for many years (1,2). The U.S. Medicare system has now approved one FES walking system for reimbursement (Parastep; Sigmedics, Inc, Chicago, Illinois, USA). However, only a few hundred people worldwide with complete SCI use FES systems for walking. In comparison, the number of persons who cannot walk as a result of SCI without assistive devices is in the hundreds of thousands. The vast majority of these people use wheelchairs, even when the major leg muscles required for walking and the nerves innervating them are intact. There are a

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number of reasons for the slow acceptance of FES systems by this population.

1) Some of the important muscles are deep enough that they are only poorly stimulated with electrodes on the surface of the skin. Systems using percutaneous and fully implanted electrodes have been tested in research for a number of years (3–5). None of these systems has yet been submitted to regulatory agencies for sale or reimbursement to our knowledge.
2) Energy efficiency is a problem with both implanted and surface FES systems. An able-bodied person standing quietly will balance over the bones using feedback from many sensory systems so as to reduce the effort needed. The FES systems to date are largely lacking in feedback from the lower body, although subjects use visual and other feedback from the intact, upper body as much as possible. Systems for standing with feedback (6) have improved performance markedly, but are not available for walking systems. Another approach is to use bracing to enhance stability. Reciprocal gait orthoses (RGO) and other bracing systems have been used for some years and have been combined with FES systems to improve efficiency (7–9). These braces are quite bulky and restrictive in that the hip, knee, and ankle are all regulated. Some less-restrictive systems have been developed (WalkAbout (10)) in which the hips are relatively free but effort must be exerted with the upper body to stabilize them. As in the RGO, the knees remain locked in extension, which makes it difficult to swing the leg through. Recently, stance-control, knee-ankle-foot orthoses (KAFO) have been developed, which also leave the hips free, but have a knee that can be unlocked by mechanical pressure or switches. These novel braces are being tested here for the first time in a person with a motor-complete paraplegia, although a related type of mechanism for locking the knee has been tested in a laboratory setting (11).
3) In the absence of feedback, muscles are overstimulated to maintain balance and rapidly fatigue. The leg muscles in paraplegics are already more fatigable from disuse, although electrical stimulation of 1–2 hr a day can increase the fatigue resistance substantially (12). In a stance-control KAFO, stimulation of the quadriceps is only needed to lock the brace. Once locked, the brace can support the body weight as in the RGO and the WalkAbout systems.

In contrast to the high consumption of energy in FES systems, wheelchairs are more efficient than walking (13). Recently, we have developed a leg-propelled wheelchair (13,14) that is even more efficient than a wheelchair propelled in the usual manner by the arms. The footrests of a conventional wheelchair are replaced with ones that can rotate. The lower leg is attached to the footrests and flexion and extension of the knee is coupled to a gear system that turns the wheels.

Despite the many types of FES and non-FES systems for locomotion of paraplegics, they rarely are compared in the same subject. This paper presents a case study of a single person who had a motor complete SCI at the T4/5 level in 2001. He is a 25-year-old man, who has had a limited return of sensory function (ASIA C) and no major medical problems other than his SCI. This paper extends a preliminary report at the IFESS conference in Australia (15) and compares performance with a wide range of systems for locomotion (speed, endurance, changes in heart rate, physiologic cost index) as well as his subjective reaction to each system.

MATERIALS AND METHODS

The subject has used a variety of systems for locomotion including: 1) a conventional wheelchair; 2) a leg-propelled wheelchair with FES of quadriceps and hamstring muscles (13); 3) conventional long-leg braces with forearm crutches or a walker; 4) a surface FES system using stimulation of the quadriceps muscles (for stance), the common peroneal nerve to elicit a flexor reflex for swing, and ankle-foot orthoses (AFO) to maintain stability around the ankle (1,16); and 5) the FES system above with advanced KAFOs incorporating knee joints that can be locked and unlocked automatically (Stance Control, Horton Technology, Little Rock, Arkansas, USA). He uses the systems in 4) and 5) with a walker having wheels in the front and legs in back that lock when supporting weight. In the past, he has used a commercially available FES cycle ergometry system (Ergys, Therapeutic Technologies, Inc, Dayton, Ohio, USA) and an FES-rowing machine (17) to exercise and condition his legs. All systems have been tested on at least several occasions over a period of time and the values presented are means of all trials for a standard 4-min exercise period. For some modalities, where possible, trials were conducted over longer distances (up to several kilometers) and longer periods of time.

Cardiorespiratory Measurements

A Parvo Medics TrueMax 2400 metabolic measurement cart (Sandy, Utah, USA) was used to collect and analyze the expired gases via a Hans Rudolf facemask and valve assembly (Kansas City, Missouri, USA). Oxygen and other respiratory parameters were measured every 15 sec. In the exercise trials over longer distances, a portable power supply unit was used to power the system while following the subject on a 200-m track. The metabolic system was calibrated with known gas concentrations (O_2 and CO_2) before and after each assessment. Volume of air was also calibrated before each test according to the manufacturer's instructions. Each subject wore a heart rate monitor (Polar Electro, Finland) and heart rate was also measured every 15 sec. Physiological cost index (PCI) is well accepted as a measure of the efficiency of producing locomotor movements (18) and is obtained by dividing the change in heart rate between rest and steady activity (beats/min) by the velocity (m/min) of the movement. PCI was measured as described previously (13). Essentially, each subject spent 2 min at rest, 4 min in the activity, and at least 4 min for the heart rate to return to rest after the activity. Resting heart rate and oxygen consumption were calculated by averaging the values for the 2 min before the activity and the final 2 min after the activity. The active heart rate and oxygen consumption were averaged over the last 2 min of activity.

Leg-Propelled Wheelchair

Three 5 × 10-cm surface electrodes (Unipatch, Wabasha, Minnesota, USA) were placed over the quadriceps muscles to stimulate rectus femoris, vastus lateralis, and vastus medialis, and three electrodes over the distal and proximal hamstrings. A rule base automatically switched stimulation to the quadriceps muscles when a flexion threshold was exceeded and stimulation of the hamstring muscles when an extension threshold was exceeded (19).

Surface FES

Electrodes were placed over the quadriceps muscles as described above and over the common peroneal nerve, where it passes the head of the fibula (1). Hand switches were mounted on the walker and the subject pressed the left or right switches to elicit a flexor reflex of the left or right legs. The quadriceps muscles were stimulated on each side except when the corresponding switch was depressed. Pressing both switches simultaneously activated quadriceps muscles on both sides for the sit to stand transition and this stimulation continued after releasing the switches to maintain the standing state. Pressing both switches again turned off the stimulation of the quadriceps after a delay for the subject to sit down.

Hybrid FES System with Advanced Braces

Two carbon fiber, long-leg braces were constructed (Fig. 1). Each leg contains a switch on the medial

Figure 1. System incorporating a stance-controlled KAFO and FES to stimulate the quadriceps muscles and common peroneal nerve for walking. Note that the electrodes are built into the straps, so they are automatically applied when the subject dons the braces.

and lateral aspects of the knee that can be in an unlocked, locked, or automatic position (Stance Control, Horton Technology). In the automatic position the knee locks when the ankle extends and weight is supported by the leg, as occurs at heel strike. To unlock, the ankle must flex and the knee must be extended, as occurs when the weight of the body moves over the foot late in the stance phase of a normal gait cycle. The same electrodes were used as for the surface FES system above, but were mounted on the straps of the braces for ease of application. The rule base was also modified as follows. Pressing the hand switch first produces a brief activation of the quadriceps muscles to unlock the knee, followed by the flexor reflex stimulus to produce the swing of the leg. Releasing the button produces another brief activation of the quadriceps muscles to straighten the knee, so it will lock at the beginning of stance after heel strike. The stimulation is then turned off until the switch is pressed again.

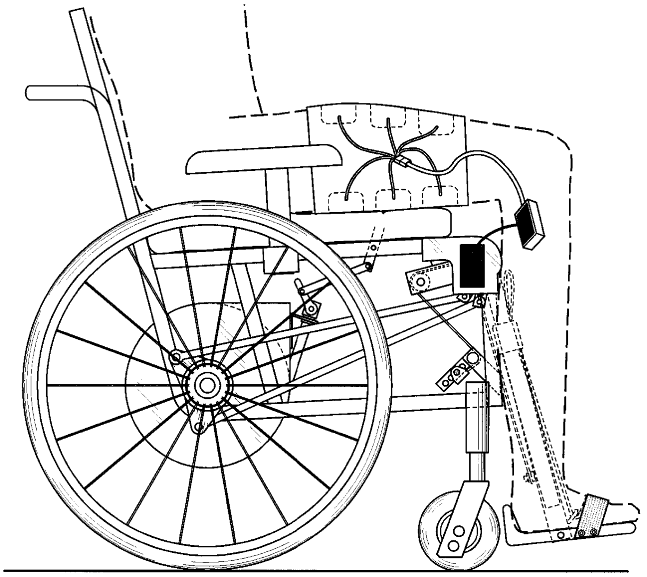

Figure 2. Diagram of the leg-propelled wheelchair. Extension or flexion of the knees moves the footrest and causes forward movement of the chair through separate drive levers. The subject with an FES system (dashed lines) stimulates quadriceps and hamstring muscles to produce the knee extension and flexion. Modified from James (14).

RESULTS

Like the vast majority of paraplegics, this subject uses a conventional wheelchair for most activities, so the values for this mode of activity were measured as a basis for comparison with the other methods of locomotion. Measurements were made on a 200-m indoor track. He can wheel long distances with little fatigue. His heart rate increased from 87 to 137 beats/min on average during the exercise while he wheeled at 119 m/min (about 2 m/sec or 7.2 km/ hr). The value of PCI was 0.42, which is typical for healthy young SCI subjects (mean = 0.40) and comparable to the value for walking in a control population (mean = 0.33) (13). Recently, we developed a new type of wheelchair that can be propelled by flexion and extension of the knee (13,14). One or both knee movements can be coupled to the rotation of the wheels to produce forward movement of the wheelchair (Fig. 2). A model has been developed that allows the coupling to be optimized, based on the relative strength of the knee flexor (hamstring) and knee extensor (quadriceps) muscle groups for each subject (19). With these optimal settings the subject was able to wheel for several kilometer around the indoor track (Fig. 3).

The velocity declined slowly from 85 to 40 m/min as he wheeled more than 2.5 km over a period of 52 min. Note that the heart rate increased only from 93 beats/min at rest (distance = 0) to about 110 beats/

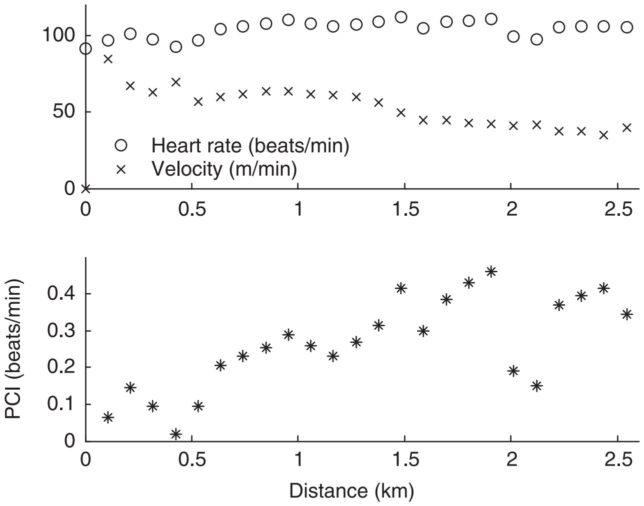

Figure 3. Heart rate and velocity (top) while a subject used the leg-propelled wheelchair with FES over a distance of 2.5 km. The heart rate increased very little from rest (distance = 0) throughout the period of test (52 min) while the velocity was quite well maintained. The physiologic cost index (PCI) was initially very low, but gradually increased (bottom).

min over this whole period. The PCI was initially about 0.1 for the first 500 m and gradually increased, but remained more efficient than arm wheeling. In a 4-min trial on another day, his PCI was 0.07. The average value for motor complete SCI subjects is 0.18, which is more than twice as efficient as for arm wheeling (13). The subject liked the leg-propelled wheelchair, but had a strong desire to walk.

He had been fitted with conventional KAFOs and used these from time to time for exercise. He could use the braces with forearm crutches or a walker. He achieved an average speed of 8.8 m/min using a "swing-to" gait in which he moves the walker forward and then supports his weight with both arms. The legs are then brought up to the new walker position. The heart rate increased from 88 to 119 beats/m on average for a PCI of 3.5. Thus, the speed and efficiency was an order of magnitude less than for wheeling with comparable effort. His endurance for walking was less than 100 m with the long-leg braces. Figure 4 compares the speed, PCI, and changes in heart rate for all modes of locomotion. Measurements were made for each mode over a standard 4-min exercise period on at least three occasions (see Methods) and average values are plotted.

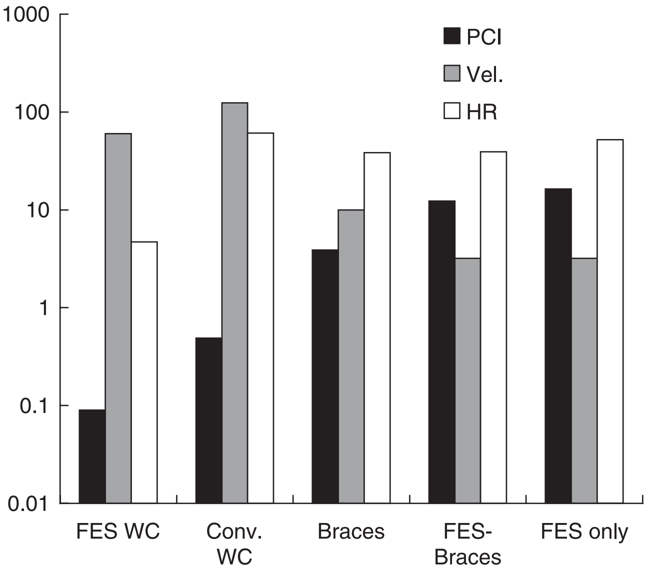

Figure 4. Comparison of PCI (beats/min), velocity of locomotion (m/min) and change in heart rate (beats/min) for five different methods of locomotion. The values are on a logarithmic scale because of the wide range. Note that the effort (PCI) is least for the leg-propelled wheelchair using FES while the velocity is highest with the conventional wheelchair. The change in heart rate is comparable using FES only (with AFOs) and arm wheeling, but the velocity is much smaller using FES only.

We also tested the subject with a surface FES system (see Methods). AFOs were used to provide additional stability at the ankle joints, together with a walker. With this system he was only able to walk at a speed of 3.5 m/min and had to sit down after less than 3 min of use. The active heart rate increased to a mean near 140 beats/min over the last 2 min and the PCI was 16. He had not been extensively trained with this FES system and the distance and efficiency would presumably increase, if training were provided over a period of time. Nonetheless, the effort was so high and the speed and efficiency so low that he felt he would not use such a system on a regular basis, except perhaps for exercise.

Recently, advanced KAFOs have become available commercially (see Methods) that have a stance-control, orthotic knee joint that can be locked and unlocked automatically during walking. When the knee is locked, no further stimulation is needed, which reduces the fatigue and effort required. Initially, his walking speed was very slow (2.5 m/min), and the PCI high (13). Nonetheless, he was able to walk up to 100 m at a time and did not fatigue to the same extent as with the FES system alone, since he could stand without stimulation to "catch his breath" (6). He reported that his arms and palms got tired from the weight they support. This is now the limiting factor, rather than the legs fatiguing. He likes the fact that he is walking with an alternating gait in a "normal" fashion, rather than using a "swing-to" gait or a wheelchair. The subject reported no negative medical consequences (e.g., pressure sores, injury) with any of the systems tested.

Over the 2 years since he took the braces home his gait speed has improved considerably (Fig. 5). The trend was highly significant ($p < 0.0001$) although the speed remains slow. The PCI had more variability from day to day, but also showed a statistically significant trend ($p < 0.05$). Because of his limited movement capabilities and proprioceptive feedback, he sometimes had difficulty loading and unloading the right leg correctly to lock and unlock the brace. Horton Technologies has supplied a switch-controlled system with electrically operated solenoids on a

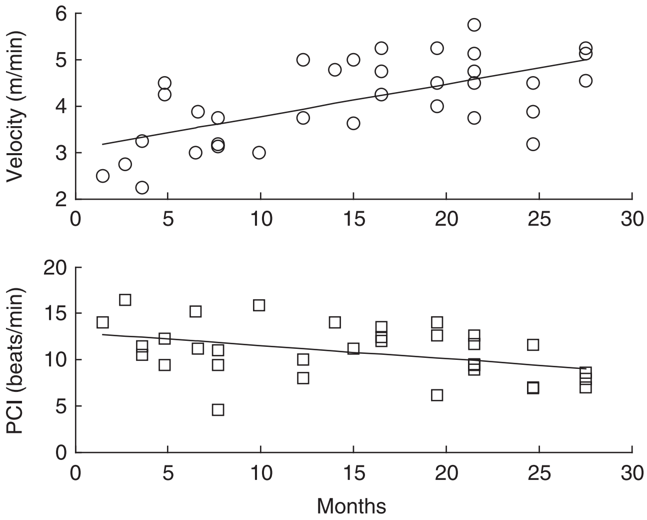

Figure 5. Velocity (m/sec) over a 4-min exercise period and physiologic cost index (PCI; beats/m) using the FES-brace system described in the text for over 2 years since it was fitted. Despite some variability, the trend line shows a highly significant increase in speed and a significant decrease in PCI over time.

trial basis and the subject finds this system more reliable. The prototype is somewhat bulky, but a smaller system has been developed.

We have used PCI as a measure of the effort to do the various tasks, because it is easier and more convenient to measure on moving subjects than oxygen consumption. For example, when he is walking, the subject watches his feet to ensure that placement is correct, since he has little sensation. This is difficult to do with the mask used for expired air collection over his face. Nonetheless, oxygen consumption remains the "gold standard" for energy cost and in a few experiments we measured both oxygen consumption and heart rate, as shown in Figure 6. Although there is a statistically significant linear relationship between the two variables, substantial deviations can be seen. For example, there was little change or even a negative change in heart rate during leg wheeling. Increasing the FES levels too high can produce autonomic dysreflexia in which blood pressure increases and heart rate decreases. The oxygen consumption increases under these conditions (+), although the increase is still modest compared to that during arm wheeling (*). Also, when the subject stands the heart rate goes up substantially (squares), with only a small increase in oxygen consumption. The increased heart rate was associated with a modest decrease in blood pressure (postural hypotension) in this subject, compared to a small increase we measured in control subjects for comparison (unpublished observations). Thus, the PCI measured during walking in the paraplegic subject overestimates the energy consumption, because part of the increase is an effect of the postural hypotension. Similarly, the PCI measured during leg wheeling can underestimate energy consumption, because of autonomic dysreflexia. In conclusion, changes in PCI should be confirmed with direct measures of oxygen consumption, particularly in subjects with SCI.

DISCUSSION AND CONCLUSIONS

One must be careful about drawing conclusions from single case studies, but some of the differences are so large that the values were more appropriately plotted on logarithmic scales (Fig. 4). The subject can wheel fastest and farthest with his arms and continues to use this mode of transportation for daily activity. However, the subject locomotes most efficiently with a leg-propelled wheelchair that uses an FES system to flex and extend his knees. He has traveled several kilometer with less change in heart rate than when propelling the wheelchair conventionally with his arms. Yet, when offered the option, he expressed

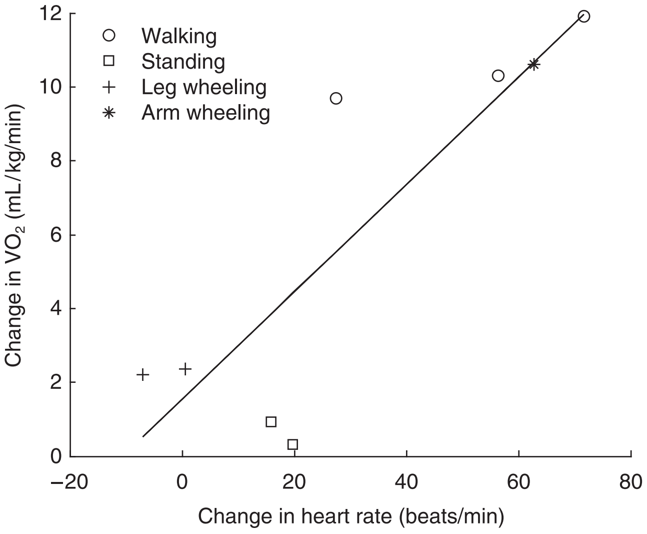

Figure 6. Changes in oxygen consumption (mL/kg/min) and heart rate (beats/min) are generally correlated, but can show substantial deviations from proportionality. See further details in text.

a strong desire to walk and urged us to develop better walking systems.

As a result we developed the new system combining FES with a stance-control KAFO. He has been enthusiastic about this new system and has used it on most days for over 2 years. For example, last year he used it to stand in a bridal party at the altar during a marriage ceremony. Scientifically, we thought it important to compare this system with conventional KAFOs that he had used previously and a more conventional surface FES system. The slow speed and high energy required are presumably reasons why conventional surface FES systems have only been accepted by a small number of people with SCI. His performance continues to increase and he is able to walk faster, further, and with less effort using the new system compared to a conventional surface FES system. The stress placed on his upper body is a concern, but we have been working with him to maintain a more upright stance with more weight supported by the legs, since overuse injuries of the shoulders and arms are a frequent problem after SCI (20,21).

The change in heart rate from initial to final values when walking with the stance control brace and FES was 54 beats/min, compared to 39 beats/min for a conventional KAFO. These values can be compared with average values of heart rate change in the literature (KAFO, 70 beats/min; RGO, 51 beats/min; RGO with FES, 42 beats/min) (22). Solomonow et al. (23) also reported oxygen consumption in kCal/kg/min. Converting back to mL/kg/min, as reported here for a walking speed of 5 m/min, they found differences between standing and walking of 8.3 mL/kg/min with an RGO alone and 5.8 mL/kg/min with an RGO and FES. The corresponding value for our subject was 9.8 mL/kg/min. The values will vary enormously between subjects depending on the level of injury and other factors. Our subject had less heart rate change than average using KAFOs, but was unable to walk more than a few steps when fitted with an RGO.

Our subject is still slower and less efficient with the new stance control brace plus FES than when using a conventional KAFO system without FES. However, he prefers the new system and uses it, while the conventional KAFOs remain in the closet. When asked the reasons for his preference, he replied that he can walk using an alternating gait with knee flexion and extension, rather than a stiff-legged gait. The unnatural gait may explain why he and most other motor-complete paraplegics do not frequently use long-leg braces, except for exercise over short distances. He can don and doff the new system easily while seated in a wheelchair and the stimulation of both quadriceps muscles allows him to stand up easily. He also appreciates the benefits of using FES to build up his muscles and strengthen his bones (24), while obtaining a good cardiovascular workout. He is a very motivated individual and it remains to be seen whether others will have similar preferences and determination (24). Nonetheless, we are encouraged by his positive reaction to this new FES walking system with stance-control KAFOs.

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