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A Physiologic Rationale for Orthotic Prescription in Paraplegia

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INTRODUCTION

A difficult clinical decision to be made when treating a paraplegic patient is deciding if walking is a realistic goal, if orthoses should be prescribed, and what the functional outcome will be. It has been demonstrated that the energy expenditure for paraplegics, utilizing a crutch assisted swing-through gait pattern, is markedly elevated. Many patients have learned to walk with crutches and orthoses, but discontinued their use after discharge from a rehabilitation center.[2,3,4] Studies of other forms of bracing also reveal elevated energy expenditure.[12]

In this review, we will describe the indications for prescribing ankle-foot orthoses and knee-ankle-foot orthoses. We will then outline the criteria used at Rancho Los Amigos Medical Center to determine whether or not a paraplegic is a candidate for ambulation. These criteria are based on the results of energy expenditure measurements of 150 patients with traumatic paraplegia.[10] Further investigation of the data collected revealed that the proprioception level or pattern seemed a reliable indicator of which patients would achieve ambulation, while muscle function seemed to determine the quality of their ambulation. These results have helped us to develop guidelines for projecting the functional outcome of ambulation of paraplegics.

ORTHOTIC PRESCRIPTION

The goal of orthotic management in paraplegia is to provide the external support necessary to compensate for the motor and sensory deficits. Joint range of motion, muscle strength, proprioception, sensation, and spasticity are evaluated when determining the orthotic prescription.

Knee-Ankle-Foot Orthosis (KAFO)

Quadriceps strength less than "Fair+" on manual muscle testing is the most common indication for a KAFO. The KAFO is locked at the knee while walking. Although some patients with less than "Fair+" strength are able to ambulate a short distance without a locked knee (knee stabilization), knee instability usually occurs after a few steps. The exception is the patient with severe quadriceps spasticity which maintains the knee in extension, eliminating the need for external support.

Another indication for a KAFO is impaired or absent knee proprioception. The lack of proprioception can result in knee instability even when the quadriceps strength is "Fair+" or greater, as the patient is unable to monitor joint position. If light touch sensation is present on the front of the thigh, a KAFO which allows knee flexion is usually sufficient to control the knee. The anterior stop of the knee mechanism limits extension at 180 degrees and the patient feels pressure from the anterior thigh cuff. In this regard, the brace serves as a transducer that converts proprioception (which is not perceived) into pressure (which is perceived).

The final indication for extending bracing above the knee is a severe hyperextension thrust during stance. Paraplegics whose gait is characterized by a hyperextension thrust may develop ligamentous instability, due to attenuation of the posterior cruciate ligament and posterior knee capsule resulting in hyperextension deformity.

Range of motion at the hip from 0 degrees of extension to 110 degrees of flexion should be present. In the absence of hip extensor muscles, full hip extension range is necessary to allow the patient to lean backwards and move the center of gravity of the trunk posterior to the hip joint (Figure 1). Hip flexion to 110 degrees, with the knee extended, enables the patient to come to standing with locked KAFO's and rise from the ground after a fall. Full knee extension is required for optimal fit.

Ten degrees of dorsiflexion at the ankle is the minimum necessary for unassisted upright balance (Figure 1). Normal proprioception in at least one hip also facilitates unassisted standing.

Inability to meet the joint range requirements described above commonly occurs and is most often due to spasticity or contracture. If satisfactory orthotic fit and posture cannot be achieved, a physical therapy regime that includes stretching exercises or serial casting is often successful when spasticity is mild and the deformity is not longstanding. When severe spasticity or deformity is present, or the deformity has been present for an extended time, the patient should be referred to an orthopedic surgeon.

Good trunk strength is necessary to maintain an erect posture in the standing position without excessive weight bearing in the arms. High level paraplegics without adequate trunk strength must exert a strong upwards force by the arms throughout the entire gait cycle to prevent forward collapse and accomplish forward progression. This contributes to the high energy demand. (All swing-through gait candidates are required to perform 50 consecutive dips on parallel bars to insure they have sufficient upper extremity strength and endurance.)

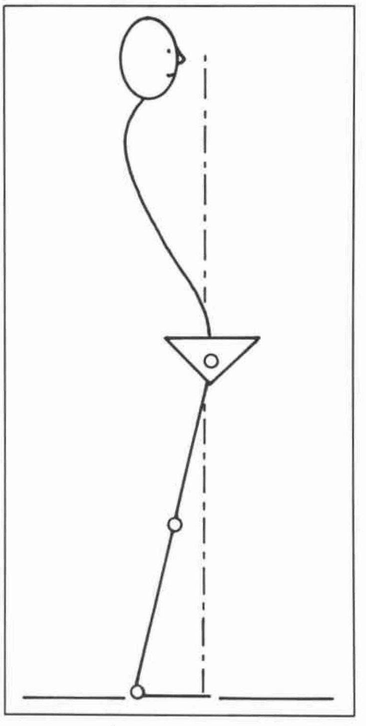

Figure 1. Standing posture.

Ankle-Foot Orthosis (AFO)

Quadriceps strength greater than "Fair" should be present to stabilize the knee if an AFO is prescribed. The patient must also have adequate hip flexion strength to swing the leg forward to achieve a reciprocal gait pattern. The indications for AFO are numerous and include any or all of the following: plantarflexion strength less than "Good," dorsiflexion strength less than "Fair," impaired ankle proprioception, and moderate to severe plantarflexion spasticity.

During normal walking, the plantarflexors are active during the stance phase of gait to prevent excessive forward advancement of the tibia. As a result of forward momentum, the knee passively extends as the body advances forward over the stabilized tibia, and the demand placed on the quadriceps is minimal. Customary manual muscle testing methods fail to place a sufficient load on the plantarflexors to evaluate the force required during gait. The strength required to provide ankle and knee stability is present in patients who can perform 15 to 20 toe raises on one leg. Failure to provide adequate orthotic stabilization of the ankle in patients with inadequate plantarflexion strength may result in ankle instability and knee instability, if the quadriceps and/or hip extension strength is also inadequate.

Knee wobble can be a sign of impaired ankle proprioception and/or weakness. This can be eliminated by an AFO with a rigid ankle or anterior ankle stop, which provides distal stability and kinesthetic information via the calf cuff.

An AFO may be utilized to hold the ankle in the neutral position when dorsiflexion strength is impaired or there is excessive plantarflexion spasticity. When spasticity is severe, it may not be possible to maintain the foot in neutral, and the patient should be referred to an orthopedic surgeon if non-operative measures prove inadequate.

When the ankle is held in a rigid orthosis, ankle stability is gained during midstance. However, a forward thrust is imposed, forcing the knee into flexion at the moment of heel contact. (This knee flexion torque is generated because the rigidly immobilized ankle rotates forward about the point of heel contact.) During normal gait, this torque is avoided by ankle plantarflexion, minimizing the effect of the heel lever.

There are two courses of action available to provide ankle stability during stance, while still maintaining knee stability at heel strike. If the patient has "Fair+" or better ankle dorsiflexion strength and intact proprioception, we fit a metal AFO with a double adjustable ankle joint. A set screw in the anterior channel provides an adjustable stop that prevents excessive dorsiflexion. The posterior stop is left open to allow free ankle plantarflexion. Springs can be added posteriorly if dorsiflexion strength is less than "Fair+." The advantage gained is that restriction of motion during terminal stance is maintained while the normal plantarflexion motion during heel contact is preserved, avoiding the undesired knee flexion torque. If the patient has less than "Fair" dorsiflexors or absent proprioception at the ankle, then the ankle is locked and either metal or plastic is used. To avoid the excessive knee flexion torque when the AFO is locked, the heel of the shoe is undercut. This decreases the heel lever and, thus, the knee flexion torque.

ORTHOSIS WEIGHT

Weight is an important factor to some patients, as is the availability of joint motion of the orthotic system. Plastic, because of its potential to be lighter than metal, is sometimes preferable. For the patient with weak hip flexors, efforts to minimize weight are warranted since any extra weight at the end of the limb will make it more difficult to lift the foot and advance the leg. Lehneis, et al.[8] found that improving orthotic stability at the ankle reduces energy costs. It follows, then, that in any orthotic design, stability (control about a joint) should not be sacrificed merely to achieve lighter weight.

EXERCISE PHYSIOLOGY

It is necessary to understand several fundamental principles of exercise physiology to interpret the results of energy expenditure measurements in paraplegic patients.[1] The use of oxygen consumption is based on the fact that during sustained exercise, most of the ATP for muscle contraction is generated by aerobic metabolic pathways. After several minutes of exercising at a constant submaximal workload, the rate of oxygen consumption rises until it reaches a level sufficient to meet the metabolic demands of the exercising muscle. Measurement of the rate of oxygen consumption at this time reflects the energy cost of the activity and indicates the exercise intensity. The oxygen cost per meter walked determines the efficiency of ambulation.

The principle fuels for aerobic metabolism are carbohydrates and fats. The oxidation of glucose can be summarized by the following equation:

$$\text{GLUCOSE} + 36\ \text{ADP} + 6\ O_2 \rightarrow 6\ CO_2 + 44\ H_2O + 36\ \text{ATP}$$

During exercise, the extent to which anaerobic pathways contribute to the production of energy depends upon the intensity of the effort. In mild to moderate exercise (approximately 50 percent of the maximal aerobic capacity for untrained individuals), the oxygen supplied to the tissue for the aerobic energy producing reactions is usually sufficient to meet energy requirements. During more strenuous exercise, anaerobic oxidation processes also occurs.

The amount of energy that can be produced by anaerobic means is limited. Nineteen times more energy is produced by the aerobic oxidation than by anaerobic oxidation. Also, accumulation of lactate in muscle and blood leads to acidosis, limiting the extent to which intense exercise can be performed. From a practical standpoint, anaerobic oxidation provides an extra supply of energy for sudden bursts of strenuous effort, but these pathways cannot be routinely utilized for a prolonged time. In contrast, when exercise is performed below anaerobic threshold, an individual can sustain exercise for many hours without exhaustion.

MAXIMAL AEROBIC CAPACITY

The maximal aerobic capacity (VO_2 max) is the single best indicator of physical work capacity and fitness. It measures the individual's maximum energy production capability. Generally, an individual is able to reach the VO_2 maximum within two to three minutes of instituting strenuous exercise. Any disorder of the respiratory-cardiovascular muscle or metabolic systems that restricts the supply of oxygen to the muscle decreases the VO_2 max. A physical conditioning program can increase aerobic capacity by several processes which include improving cardiac output, increasing the capacity of the muscle to extract oxygen from the blood, increasing the level of hemoglobin, and increasing the muscle mass. On the other hand, the maximal aerobic capacity can be reduced due to blood loss, paralysis, surgery, negative nitrogen balance, or bed rest.[1] The important clinical implication is that the paraplegic patient is usually severely deconditioned as a consequence of the injury. The prescription of orthoses and a walking program should not be initiated until the patient has sufficient strength and maximal aerobic capacity to meet the required energy demand. The deconditioned paraplegic patient will respond to a physical conditioning program just as an able bodied subject with respect to increased strength, endurance, and maximal aerobic capacity.[5]

In able bodied subjects, the VO_2 max also depends on the type of exercise. During lower limb exercise, the VO_2 max is greater than the VO_2 max for the upper limbs. Since paraplegic patients rely on the upper extremities to walk with the aid of crutches, their energy production capability is inherently limited. The problem in paraplegics is further compounded by the effects of the spinal injury. The upper extremity VO_2 max for paraplegics is lower than for able bodied subjects, presumably due to the effects of paralysis and interruption of the autonomic neurological pathways which regulate blood flow and cause venous pooling in the lower extremities.[6,11] For the typical adult male paraplegic, we establish a VO_2 max of 20 ml/kg-min during upper arm cranking as the minimal criteria acceptable for entering gait training if a swing-through crutch assisted gait pattern will be required.

ENERGY EXPENDITURE

Wheeling Versus Normal Walking

On a hard, level surface paraplegic wheelchair use is as efficient as normal walking. A comparison of the data in Figure 2 indicates that when propelling a chair around a 60.5 meter circular track, the speed was almost as fast as normal walking (72 versus 80 m/min).[10] The oxygen rate was approximately the same (11.5 versus 11.9 ml/kg/min) (Figure 3), as was the oxygen cost (.16 versus .15 ml/kg/min). The heart rate was higher in paraplegics using the wheelchair than in normal walking (123 versus 100 BPM) (Figure 4). As previously mentioned, this relates to the lower upper maximal aerobic capacity in paraplegics during arm exercise. From a clinical standpoint, it may be concluded that the wheelchair is a highly efficient means of transportation whose speed and energy requirements are comparable to that of normal walking.

Swing Through Gait

Crutch walking with a swing-through gait requires the arms and shoulder girdle to lift the entire weight of the body and swing it forward with each step. The average speed in paraplegics trained to use a swing-through crutch assisted gait was 64 percent lower than normal walking (20 versus 80 m/min) (Figure 2); the rate of oxygen consumption was 38 percent greater (16.5 versus 11.9 ml/kg/min) (Figure 3); the oxygen cost was 560 percent greater (.84 versus .15 ml/kg/min); and the heart rate was increased 46 percent (145 versus 99 BPM) (Figure 4).[10] This rate of energy expenditure requires most of the aerobic capacity of the typical adult male paraplegic with a complete T12 lesion and is well above the anaerobic

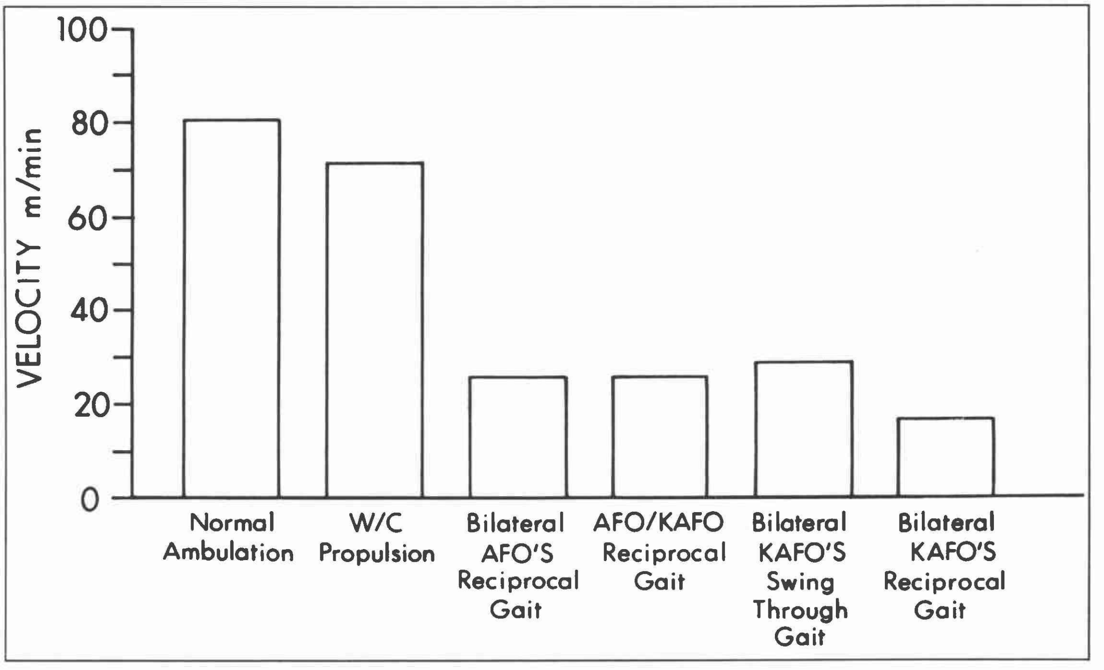

Figure 2. Average velocity in normal subjects and in patients using wheelchairs or orthoses.

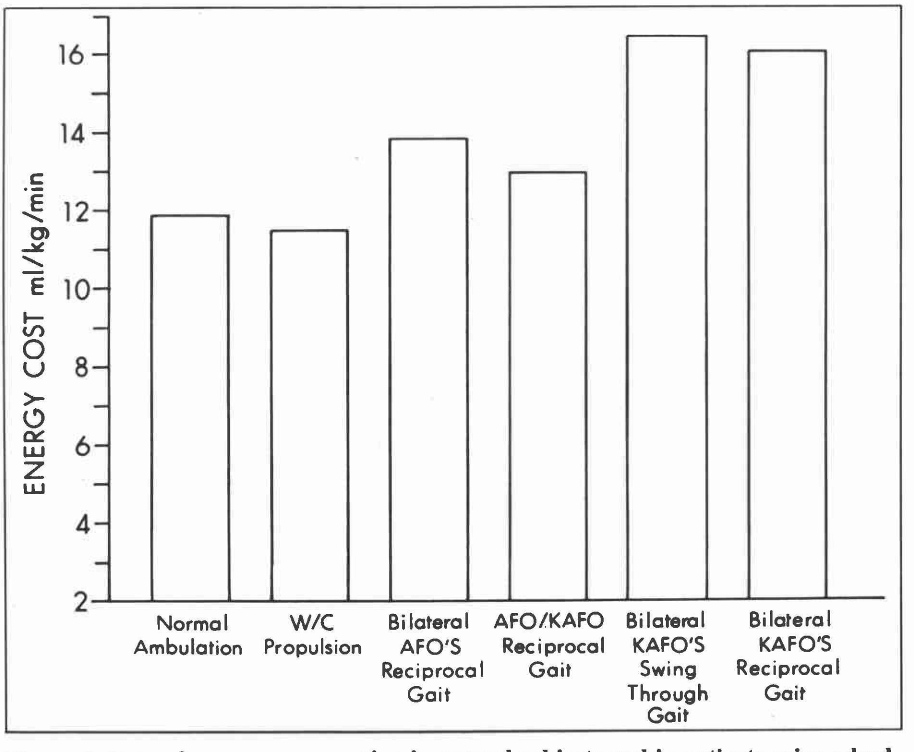

Figure 3. Rate of oxygen consumption in normal subjects and in patients using wheelchairs or orthoses.

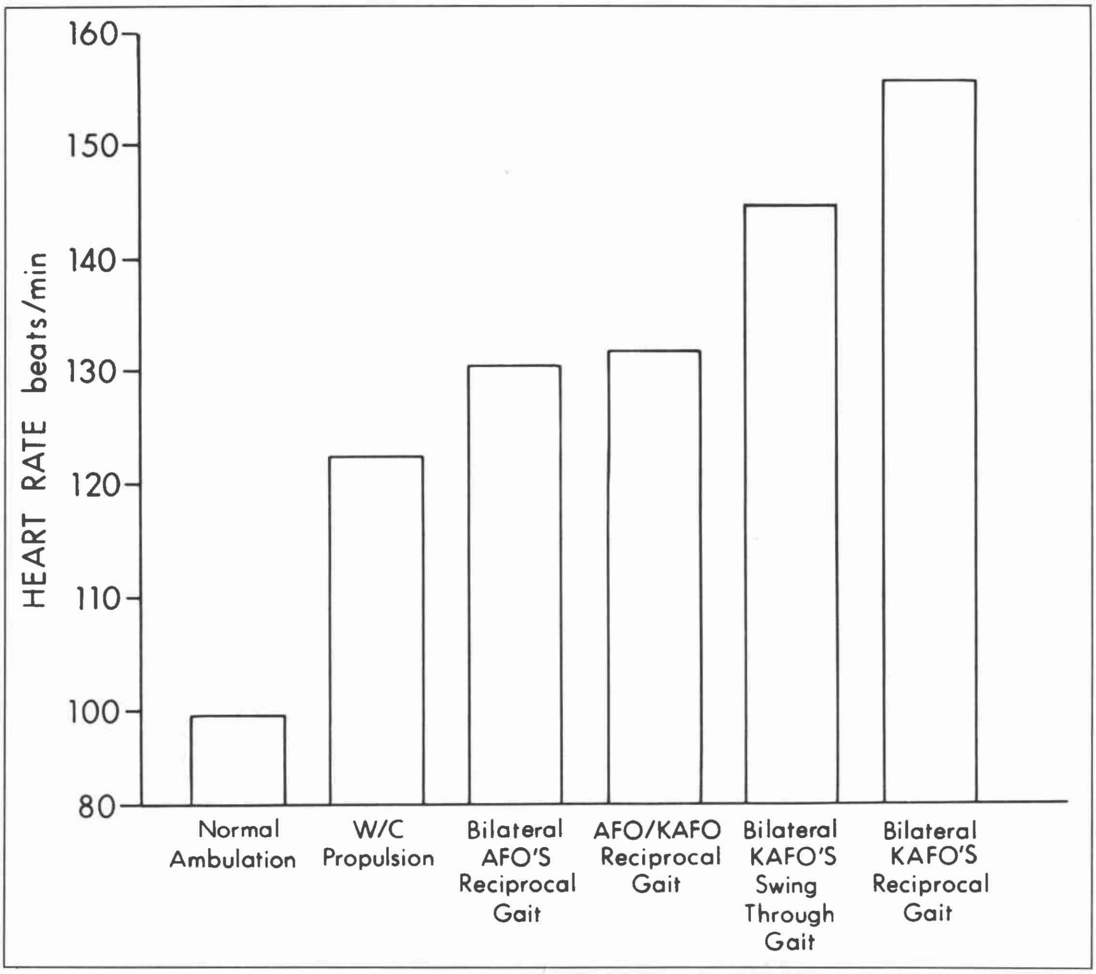

Figure 4. Heart rate in normal subjects and in patients using wheelchairs or orthoses.

threshold. The extreme exertion required for a swing-through gait demands a greater intensity of physical effort than a normal individual customarily expends on sports activity such as recreational jogging. Consequently, it is not surprising that while the athletic paraplegic may be willing to expend this level of exertion for recreational purposes, he is unwilling to sustain these efforts for normal activities of daily living. Even those patients, who are physiologically capable of sustaining the intense physical effort of a swing-through gait for a sustained time period to travel longer distances, find tachypnea (rapid breathing), tachycardia (rapid heart rate), and hidrosis (sweating), unacceptable for routine activities of daily living.

We believe that the highly motivated paraplegic who is willing to exercise strenuously should not be discouraged from walking, but a more realistic approach should be taken for the average patient. The average patient should be given walking training and bilateral knee-ankle-foot orthoses only if walking is necessary for psychological reasons, for purposes of exercise, or because of architectural barriers in the living environment. It should be clearly explained that the wheelchair should be considered as the primary means of mobility.

We have tested three patients with "Fair+" hip flexors who used bilateral KAFO's and preferred a reciprocal gait pattern.[10] Interestingly, the effort expended by these patients was just as great as in swing-through gait (Figures 2, 3, and 4).

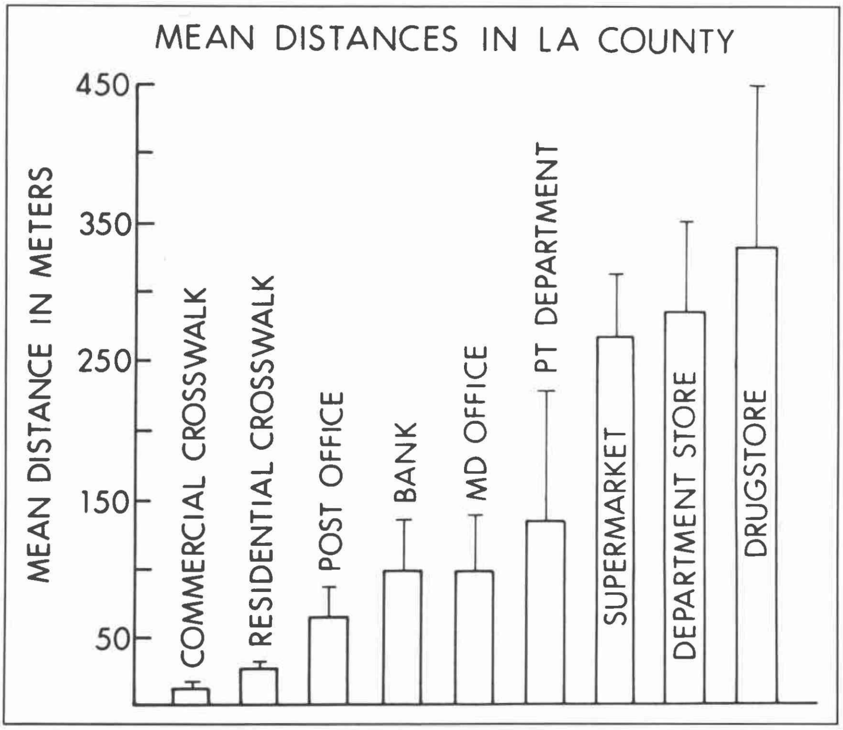

Figure 5. Average distances necessary to perform customary activities of daily living.

Energy Expenditure: Reciprocal Gait

In a review of spinal cord injured patients, Hussey and Stauffer found that those patients who were able to walk in the community had pelvic control with at least "Fair" hip flexor strength and at least "Fair" extensor strength in one knee so that a maximum of one KAFO was required, enabling the patient to achieve a reciprocal gait pattern.[6] Having "Fair+" or greater quadriceps strength sufficient to stabilize one knee eliminates the need for one KAFO and enables the patient to walk with a crutch assisted reciprocal gait pattern at a rate of energy expenditure and heart rate that are significantly below that required for a swing-through gait pattern (Figures 3 and 4). Surprisingly, we found no difference in the speed and rate of energy expenditure in patients with one free knee or two free knees and requiring bracing only below the knee (Figures 2 and 3).

Nevertheless, paraplegics who have intact hip flexion and knee extension bilaterally require orthoses only below the knees, and those who use a reciprocal crutch assisted gait pattern are still severely impaired (Figures 2, 3, and 4). Compared to normal walking, the rate of oxygen expenditure is 20 percent greater (16.3 versus 11.9 ml/kg/min) (Figure 3), the heart rate 31 percent greater (131 versus 100 BPM) (Figure 4), and the speed 67 percent slower (80 versus 20 m/min) (Figure 2).[10] The typical paraplegic who uses crutches and a reciprocal gait still exerts a force of 25 to 50 percent of total body weight on the crutches with each step, accounting for the increased rate of energy expenditure. The only spinal cord injured patients we have tested whose energy expenditure during walking does not exceed normal values are those patients with minimal involvement who have intact sacral function (in addition to lumbar function) and a sufficient hip abductor and extensor strength to maintain an erect posture without crutches.

The average distances necessary to perform different daily living activities are listed in Figure 5 and were obtained from numerous measurements made in different types of urban areas in Los Angeles.[8] Since the average speed of walking in low lumbar paraplegics who used bilateral ankle-foot orthoses and a reciprocal crutch assisted gait pattern was only 26 m/min, it would take more than five minutes to travel 150 meters. Because five minutes of walking will require a strenuous effort, it is apparent why even the typical low lumbar paraplegic is a limited walker outside the home and is not able to routinely ambulate comfortably for activities which require walking a longer distance. In this regard, clinicians are justified in prescribing a wheelchair to any spinal injury patient who requires crutch assistance. The patients should be encouraged to use the wheelchair as necessary and be reassured that reliance on the wheelchair, when necessary, should not be considered a failure.

AUTHORS

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