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Equipment specifications for supported treadmill ambulation training

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Abstract—Supported Treadmill Ambulation Training (STAT) is a mode of therapy for gait retraining for patients with spinal cord injuries or other upper motor neuron dysfunction. The STAT program involves simultaneously supporting a portion of the patient's weight while gait training on a treadmill. STAT has been successful in improving the gait of many research subjects, but has not been widely applied in clinical practice. The goal of this study was to acquire practical, clinically useful information regarding this therapeutic intervention in order to remove barriers to its use. This manuscript enumerates equipment specifications for the treadmill, body weight support (BWS) system, and harness. The ergonomics of the work space are also considered, since the therapist(s) will need access to the patient's legs during therapy. The specific recommendations were determined through prior clinical experience, consultation of anthropometric tables, and application of engineering principles. The guidelines listed are intended to facilitate safe and effective application of the therapy at minimum hardware cost.

Key words: *gait training, rehabilitation, spinal cord injuries, stroke.*

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INTRODUCTION

Achieving functional ambulation is a goal unmet by many people who have sustained a spinal cord injury or other upper motor neuron dysfunction. By exploring new therapies, researchers have begun to challenge some of the conventional wisdom about the recovery potential of the spinal cord. One such therapy, the supported treadmill ambulation training (STAT) program, involves unloading a portion of the patient's weight while gait training the subject on a treadmill. By participating in this therapy many people have experienced substantial gains in ambulatory abilities (1–3).

Earlier research has shown that mammals such as cats have been trained to improve their gait on a treadmill even after a complete spinal cord transection (4,5). Cats who received treadmill training improved their maximum gait speed by a factor of eight, while those who did not participate in the training only improved their gait speed by a factor of three (4). These results suggest that the spinal cord is capable of learning and have motivated researchers to try treadmill training with humans who have sustained a spinal cord injury or other upper motor neuron dysfunction.

Wernig, Nanassy, and Muller found these gains could be maintained for extended periods of time (1). They categorized the patients on an ordinal scale of zero

Journal of Rehabilitation Research and Development Vol. 37 No. 4 2000

to five based on their ambulatory abilities (**Table 1**). The higher scores corresponded with greater functional ability in independent ambulation. Patients with scores of zero through two were considered wheelchair bound while those with higher scores were considered non-wheelchair bound. The patients were divided into a chronic group, who began STAT more than 6 mos after injury, and an acute group, who began therapy as soon as they were stabilized. Of the 35 patients in the chronic group, 25 began the study wheelchair bound. By the end of the 3 mos of therapy, only 5 patients remained in the wheelchair bound group. When evaluated in a follow-up exam conducted 6 mos to 6 y after the conclusion of therapy (median 20 mos) only 5 patients continued to be classified as wheelchair bound. **Figure 1** shows the distribution of the chronic patients before therapy, after therapy, and at the follow-up exam (1). The data for the 41 acute patients showed similar success. Before therapy, 37 of the patients were wheelchair bound. After therapy, eight remained in this group. At the follow-up exam, only six were considered wheelchair bound.

Table 1.
Functional scale for ranking ambulatory abilities, adapted from Wernig et al. (1).

Ranking	Explanation
Wheelchair-bound	
0	Lower limbs cannot support body weight for standing or walking even with moderate help by two therapists
1	Capable of standing and walking only with the help of two therapists
2	Walking at railing with the help of one therapist
Not wheelchair-bound	
3	Walking with rollator/walker or reciprocal frame
4	Walking with two regular canes or four-point canes
5	Walking without devices (free walking) for more than five steps

The success of the STAT program depends on many factors: a commitment by the patient to the protocol, trained therapists, and appropriate equipment. One of the reasons STAT has not been implemented in clinical practice is that there is a great deal of confusion among clinical practitioners regarding the equipment required to successfully train patients. This technical note is presented primarily in an attempt to identify key hardware and the features needed for a successful application.

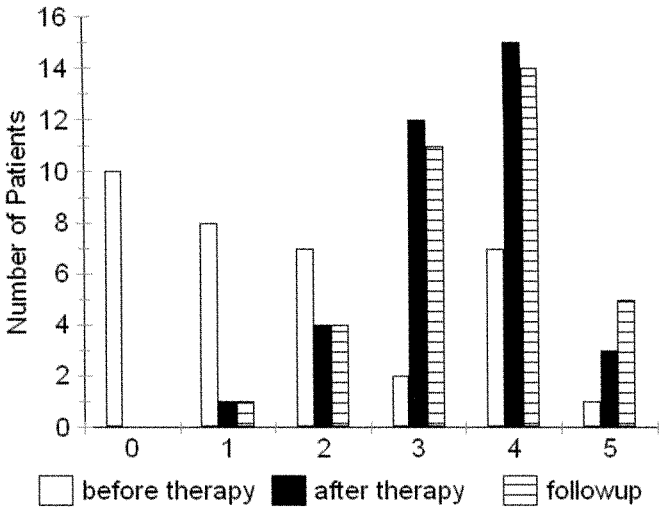

Figure 1.
Results of STAT for chronic patients. Adapted from: Wernig A., Nanassy A., Muller, S. Maintenance of locomotor abilities following Laufband (treadmill) therapy in para- and tetraplegic persons: follow-up studies (1).

METHODS

Patient Selection Criteria

Preliminary studies done with three patients at the VA Hospital in Houston, TX, provide objective data to quantify the successes of the patients. Three patients participated in STAT therapy for 12 wk, 5 d/wk. The volunteers were drawn from a pool of patients with chronic spinal cord injuries or who recently had experienced strokes. To participate, patients needed to meet criteria to ensure safety and maximize the efficacy of this therapy. Subjects were required to have range of motion of the lower extremities, sufficient to allow upright posture and stability for weight bearing, and sufficient arm strength (bilateral grade of three or above for triceps brachii).

Spinal cord patients with an American Spinal Injury Association (ASIA) impairment scale of C or D were eligible for the study, while those with scores of A or B were not. Those patients without quadriceps or Achilles tendon reflexes bilaterally, or those with spasticity that would interfere with standing were not eligible.

Eligible stroke patients were those who were able to stand and take at least one step without assistance, but

were not able to walk at a speed greater than 36 m/min. The three volunteers for this study were all patients with spinal cord injuries. Complete inclusion and exclusion criteria are available from the authors.

Therapy Assessment: Gait Speed, Endurance and Efficiency

The therapy began with approximately 40 percent body weight support (although patients who are able to should begin with less), which was diminished as the patients improved. The subjects progressed to overground walking as soon as possible. These three subjects were evaluated every 4 wk for progress in gait speed, endurance, and efficiency.

Gait speed was measured by timing a 5 m walk and dividing the distance by the time. Gait endurance was determined by allowing the subjects to walk as far as possible within a 5 min. period. Gait efficiency was quantified in terms of energy expenditure, measured in ml oxygen/kg body weight/m walked.

Equipment Specifications

The standard features of STAT were enumerated by applying standard engineering principles to the feedback from researchers and therapists. Required and recommended features for each piece of equipment (treadmill, unloading system, and harness) were determined through interviews, literature review, and consultation with anthropometric tables.

Treadmill

The treadmill is an integral part of the STAT program for patients with an upper motor neuron dysfunction. Many brands and models of treadmills are commercially available, but not all are effective in this application. An appropriate treadmill must be able to operate at a very slow speed and allow for speed increases in small increments. A minimum speed of 0.1 km/hr (0.06 mi/hr) is allowed on the treadmill used by the Wernig group (7). Ambulation training at the VA Hospital in Houston, TX was done at speeds ranging from 0.3 km/hr (0.2 mi/hr) to 1.3 km/hr (0.8 mi/hr). Speed increments of 0.15 km/hr (0.1 mi/hr) are recommended.

It is also important for the treadmill to be able to maintain this slow speed without stalling. Any treadmill can be stalled or stopped with enough resistance, especially at these slower speeds. The treadmill must be powerful enough to overcome the force of friction due to the subject's weight, internal friction, and any additional resistance provided by the subject. Patients may provide some resistance by pulling on the handrails, but this resistance will be more than counteracted by the decrease in weight of the patient due to the body weight support system. Therefore, the sum of the resistances due to the patient will be lower than the product of body weight×the coefficient of friction. If this coefficient of friction, the amount of internal friction, and the radius of the treadmill wheel are known, the required torque can be calculated.

Without knowing these specifications or doing any calculations, one can use a quick and easy test to determine the efficacy of a given treadmill. Position a weight on the walking surface (for resistance) and then set the treadmill to 0.3 km/hr. The treadmill must be able to move a static weight of 140 kg (300 lb), an amount equal to the weight limit for patients of 115 kg (250 lb) plus a margin of error of 20 percent.

The walking surface of an appropriate treadmill must be long enough to allow the subject to complete a normal stride and allow for missteps; the width must be sufficient for patient comfort. Minimum appropriate dimensions for the walking surface are a length of 150 cm (60 in) and a width of 60 cm (25 in). The length is based on the average stride length to leg length ratio of 1.57 (8). If a subject 2 m in height (6 ft 8 in) had a leg length of 53 percent of his height (106 cm) (7), his stride length would be about 166 cm. Dividing by two, to calculate the step length, yields 83 cm. Adding 30 cm for foot length brings the total length to 113 cm. Leaving 10 cm behind the subject to prevent slippage, and factoring in 20 percent for safety, a reasonable length of 150 cm is recommended.

The width of the treadmill must not be excessive, or else the accessibility of the subject's legs by the therapist is compromised. The maximum acceptable width of the treadmill will depend on the body dimensions of the therapist, the seating system used by the therapist, and the gait of the patient. A minimum width of 60 cm allows the patient to stand with feet placed shoulder width apart (95 percent anthropometry data for shoulder width equals 50 cm (9)) and allows 20 percent (10 cm) for comfort and outliers. Since a wider treadmill offers few advantages (unless it is to be used for a specific patient population), it is recommended that the treadmill width be limited to no more than 75 cm. This width allows a therapist who corresponds in stature to the 5 percent female anthropometric data to reach the patient (**Figure 2**). This therapist would have a functional reach of about 50 cm (9), allowing her access to the midline of the treadmill without straining to her maximum reach.

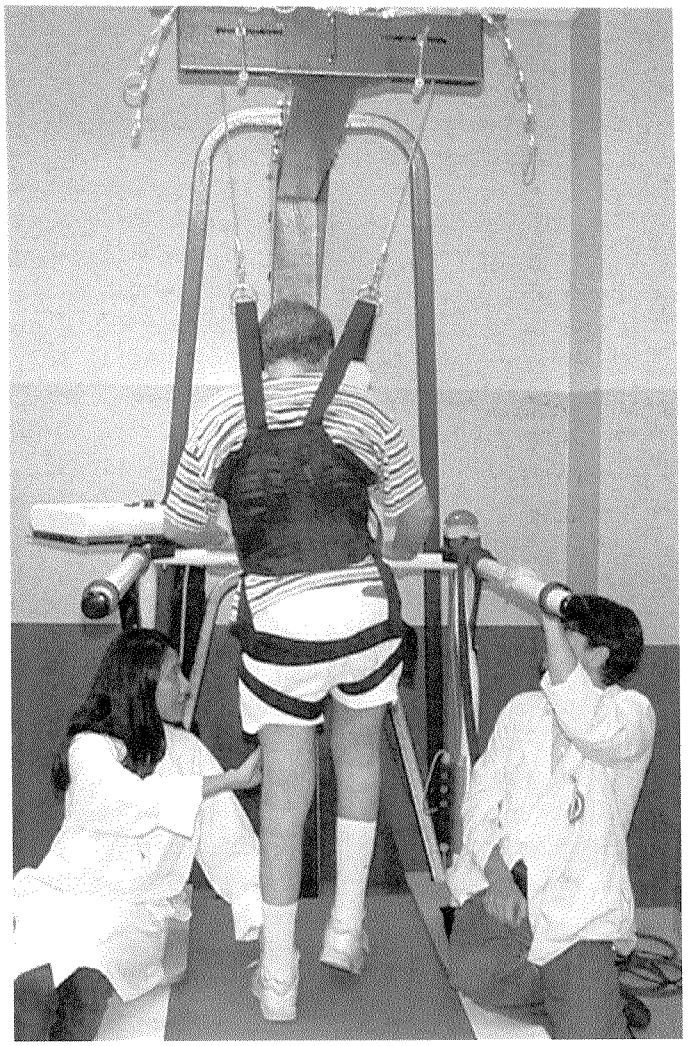

Figure 2.
Therapists' access to patient's legs while on the treadmill.

The treadmill should include handrails to assist the patient in balance, a reliable display reporting the speed of the walking surface, and a safety stop in case of emergency. In addition, the ideal treadmill would include a ramp to allow wheelchair access to the walking area.

Another important consideration in the proposed training is the accessibility of the subject's legs for manipulation by the therapist. The ideal treadmill would include a lift to raise the treadmill's walking surface to an ergonomically appropriate working height for the therapist. However, many facilities do not have ceilings high enough to accommodate the raised treadmill with the subject and unloading system above it. If a room with less than an 11 ft ceiling is used, the lift system must be sacrificed. Nevertheless, the therapist should not be forced into odd contortions in order to facilitate the patient's gait; rather, the treadmill should have a sufficiently wide region, approximately 25 cm (10 in), on each side of the walking surface for a therapist to sit. The therapist should also be provided a back support with which to brace while manipulating the lower extremities of the patient. This support can be a simple firm cushion molded to be compatible with the human back.

Unloading System

The harness/unloading system provides relief to decrease the amount of weight the patient must uphold. The unloading system must be able to support 40 percent of the subject's body weight during a training session. However, for safety reasons, the body weight support (BWS) must also prevent patient injury due to falls. To halt the acceleration due to gravity that a person experiences when falling, it is necessary to provide support in excess of body weight. The BWS system also must allow enough vertical movement of the subject's center of gravity to permit normal gait, but not enough to allow the patient to lose posture. Five cm (2 in) of vertical displacement is often reported as necessary for normal gait (10). A study of 25 healthy men and 25 healthy women measured the average displacement as 2.7±0.6 cm for females and 3.7±0.9 cm for the males (11).

Using the larger figure (3.7, males) and adding two standard deviations gives a value of 5.5 cm, which can be used as the vertical displacement ceiling for normal gait. Although an individual could certainly ambulate with more vertical movement than 5.5 cm, this gait would certainly be classified as abnormal and, therefore, not the goal of gait training. For this reason, the BWS system should allow vertical displacements up to 5.5 cm. To stop a fall in a reasonable amount of time and space, the fall prevention system must provide 150 percent of body weight. If the patient was in free fall for the entire 5.5 cm of normal travel, applying 150 percent of body weight as a fall prevention will stop the fall in just over 0.2 sec. This amount of time is enough to counteract the momentum of the falling person and bring them to a stop over a distance of 11.2 cm (approximately 4.5 in).

To increase the safety of this therapy, a safety factor of two is used to double the support of the fall prevention system from 150 percent to 300 percent. Using a limit of 115 kg (250 lb) for the heaviest subject, the BWS system must be able to unload 45 kg (100 lb) for gait training and provide up to 345 kg (750 lb) of support to prevent falls.

The unloading system must also report reliably to ensure the correct degree of unloading. A key element of the training paradigm is the progressively increased load on the

musculoskeletal system, brought about by reductions in the percentage of body weight support by the unloading system. There is no specific schedule for lessening the body weight support; rather, a general goal of reducing the support. For this reason, accuracy of the measurement of BWS can be sacrificed as long as consistency is maintained. Finding the exact percentages of body weight support used is not nearly as important as the paradigm of decreasing that support, so reproducibility of measurements is vital for the purpose of quantifying improvement.

The unloading system must also have controls that are easily accessible and support levels that allow for easy adjustments to the amount of BWS as the subject improves or fatigues during a training session.

It is also important that the unloading system supports the harness (and the patient) by two supports, separated by approximately shoulder width, to allow for a more natural weight shift than a one-point suspension permits. A single point support leads to excessive twisting movements and instability in patients with diminished voluntary postural control. A suspension lacking in appropriate width results in a pivoting effect foreign to normal gait. Use of the 95th percentile for male shoulder width from anthropometric data (9) sets the minimum distance between the two supports at 50 cm (20 in).

Two types of unloading systems exist. The first is a counterweight system, which is relatively simple and provides a constant amount of body weight support over a large range of vertical displacements. The disadvantage of this approach is that the inertia of the counterweight mass causes perturbations in the support force, particularly prominent when the subject undergoes rapid vertical accelerations. These large "jerks" are unsettling to the patient and interfere with the therapy. For this reason, the counterweight system is not recommended.

The other option is a spring-based system, which can be further subdivided by the type of spring used. The systems are categorized based on function; therefore, this group is not limited to simple springs, per se, but also includes pneumatic, elastic, and other systems that exhibit similar behavior. A constant force spring allows for the possibility of a relatively constant degree of body weight support over a range of vertical displacements of the body. The major disadvantage is the unstable feeling the patients report, especially early in training. A separate fall prevention system would be required, which would jerk the patient when activated.

A conventional Hooke's Law spring will provide a varying amount of support directly proportional to its stretch from equilibrium. The increase in support when the spring is stretched provides more feedback and reassurance to the patient. This system also has the advantage of a smoother fall prevention "catch", since the patient will already be decelerating due to the increased upward support as the fall is initiated. Thus, when the separate fall prevention system engages, the impulse on the patient will not be so great, since his velocity will be decreased due to the increased force from the spring. Since changes in BWS throughout the gait cycle have not been proven to be beneficial or detrimental, the conventional spring system is recommended.

The specifications of the spring are dependent upon the patient population to be served. If an adult population of patients weighing between 45 kg (100 lb) and 115 kg (250 lb) is expected, the spring constant may be calculated as follows. First, the lightest patient must be considered. To allow for the necessary vertical travel when this patient is in advanced stages of therapy (at about 10 percent BWS), the spring must provide 4.5 kg (44 N) of force over the displacement of 5 cm. Using Hooke's Law, the spring constant is calculated to be about 880 N/m. Again, since absolute accuracy is not the utmost concern, this exact number is not critical. For the heaviest subject at any early stage of therapy (40 percent BWS), the spring must provide 46 kg (450 N) over the 5 cm displacement. This could be accomplished by stretching the original spring about 50 cm (20 in). A simple system to accomplish this stretching would be a hand powered winch geared down by ten-to-one, to allow a therapist to crank up or down the support provided by this one long, but soft, spring.

Other systems which may appear to use a different mechanism are often only spring systems in disguise. For example, some researchers have found success using a winch system with a steel cable. Similar to how the weakest link in a chain will break, the most elastic element in series will stretch. The use of a spring gauge in series with the cable will allow this unit to function like a spring system. To achieve normal gait, there must be enough stretch in the system to accommodate the vertical displacements of the center of gravity of the subject. If the system does not allow for these vertical movements, gait is markedly distorted. The subject may still be able to move on the treadmill, since the walking surface is moving below him, but this unnatural form of gait is not the goal of therapy.

Harness

The harness should have support across the buttocks and around the thighs, as well as around the rib

Journal of Rehabilitation Research and Development Vol. 37 No. 4 2000

cage, while allowing free movement of the arms and legs. It is important for the harness not to interfere with normal gait, as that is the goal of the therapy. It must fit snugly enough to minimize upward slipping of the harness during unloading. It should also be comfortable to the subject, even when maximal support is provided by the BWS. The harness must avoid impinging on the brachial plexus of any subject and the pectoral area of female subjects. Additionally, it should be quick and easy to don and doff for those with limited mobility. Above all else, the most important consideration for the harness is that it promote an upright stance. Many commercially available harnesses are currently in use in this therapy, but other alternatives exist. The use of modified rock-climbing harnesses has shown potential for this application.

For feasibility studies, a Black Diamond® BOD (model) harness (Salt Lake City, Utah) was used to provide support to the lower portion of the body. A Black Diamond® vario chest harness (Salt Lake City, Utah) provided the support for the torso. The chest and BOD harnesses were coupled with one-inch nylon, which also provided the attachment to the unloading system (**Figures 3, 4**). By providing the majority of support to the pelvic region and applying to the torso only sufficient force for stabilization, this harness avoids high pressure to the brachial plexus and allows for more gender neutrality than the thorax harnesses.

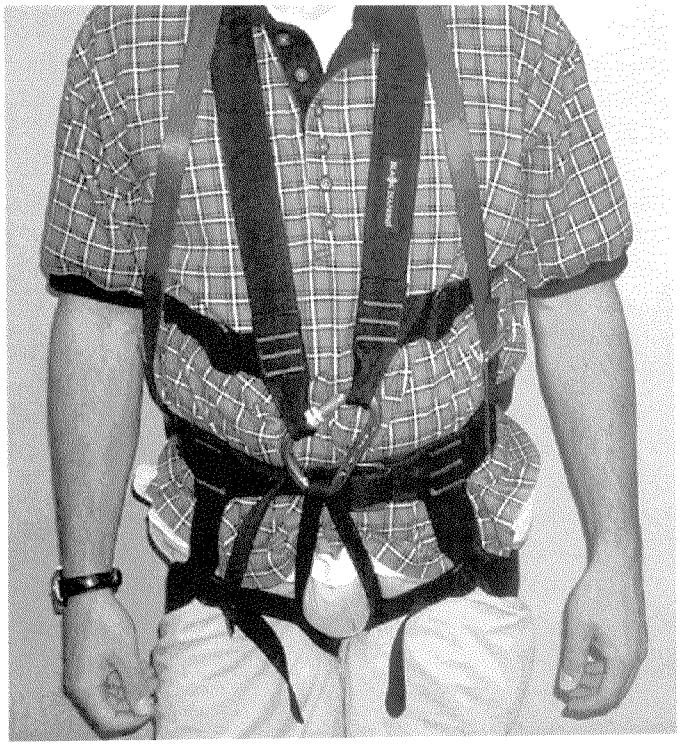

Figure 3.
Front view of the modified harness.

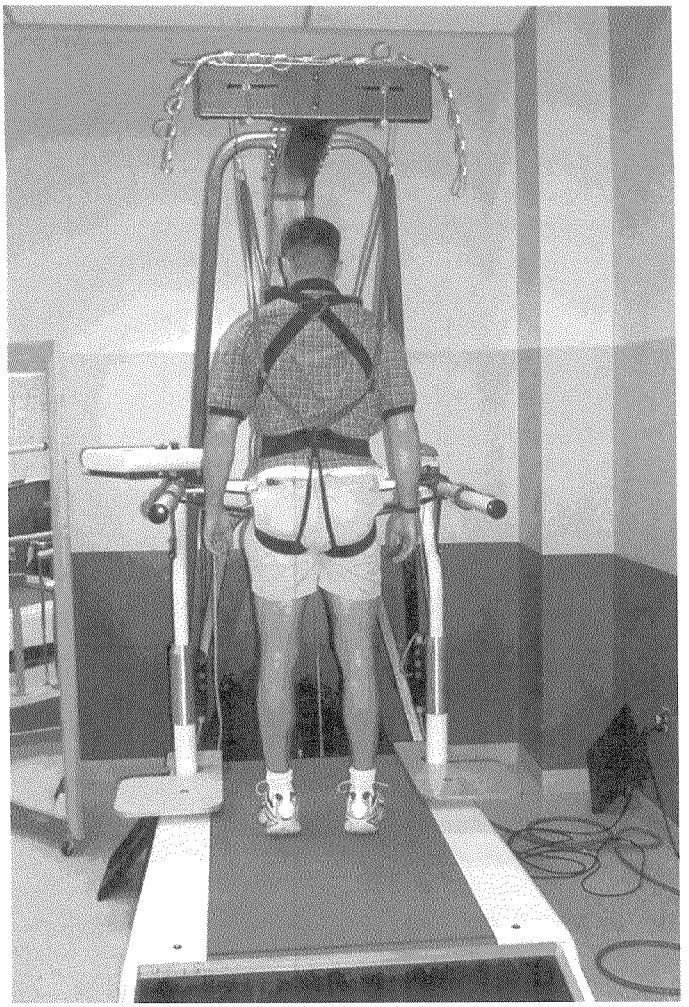

Figure 4.
Rear view of the subject wearing modified harness with unloading force applied.

Another novel approach involves the use of positive air pressure inside an inflatable skirt to reduce the effective body weight. The Differential Pressure Walking Assist is topped by a neoprene waist which interfaces with the subject and provides a seal for the inflatable skirt (12).

RESULTS AND DISCUSSION

Assessment of Gait Speed, Endurance and Efficiency

By the end of the 12 wk period each subject had improved in each of the categories (**Figure 5**) and the

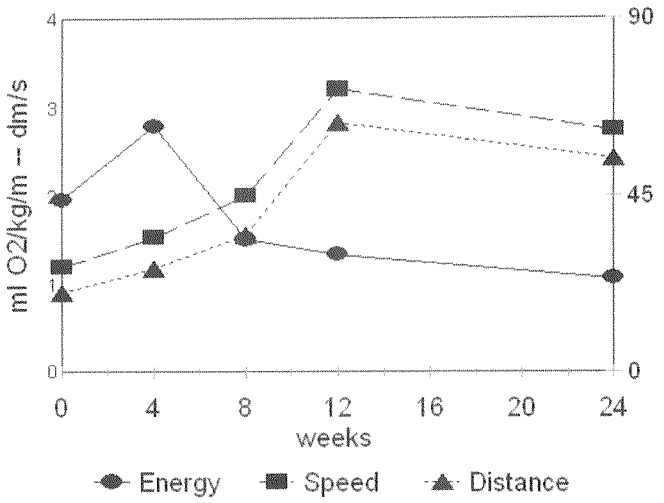

Figure 5.
Gait speed, gait endurance (distance), and energy expenditure of patients. Adapted from: Protas AJ, Holmes SA, Qureshy H, Johnson A, Rodriguez G, Moussavi M, Sherwood AM. Supported treadmill ambulation training after spinal cord injury (6).

improvements were largely maintained after an additional 12 weeks post-training. Detailed presentation of the results, and the discussion thereof, have been provided in a previous publication (6). **Table 2** enumerates the required and recommended equipment features for use in obtaining optimal therapeutic outcomes, as described fully in the Methods section.

Table 2.
STAT equipment specifications.

Required Features	Recommended Features
Treadmill	*Treadmill*
Minimum walking surface: 140 × 60 cm	Ramp for wheelchair access
Maximum walking surface width: 75 cm	Speed increments of 0.15 km/hr
Minimum speed: 0.3 km/hr	Cantilever handrails
Power to move 140 kg @ 0.3 km/hr	
Handrails	
Safety stop apparatus	
BWS	*BWS*
Spring support system	Hooke's Law spring system
Unloading up to 40% body weight	
Accessible controls to adjust support	
Fall prevention system	
Reliable reporting of unloading	
Two-point suspension (50 cm apart)	
Allow 5 cm of vertical displacement	
Harness	*Harness*
Promote upright posture	None
Two points for attachment to BWS	
Easy to don and doff	
Maintains comfort during unloading	
Therapist Space	*Therapist Space*
Adequate seating space (25 cm width)	Lift system to raise walking surface
Back support	
Adequate access to patient's legs	

CONCLUSION

Without appropriate equipment, this strategy for ambulation training with upper motor neuron lesion patients could be frustrating, sub-optimal, and perhaps dangerous. Additionally, extraneous features can make the costs for STAT prohibitive. Therefore, much care must be taken to ensure the treadmill, harness, and body weight support system are effective for this application. Although no specific treadmill, unloading system, or harness is endorsed, any models chosen should conform to the specifications herein.

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