Peak Physiological Responses to Electrically-Assisted Ambulation in SCI Paraplegics

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PURPOSE: The purpose of this study was to examine the peak physiological responses in SCI paraplegics using a transcutaneously applied FNS ambulation system in comparison with the peak responses to arm ergometry (AE) testing within the same subjects. METHODS: Nine persons with SCI (T_4-T_{10}), previously trained with a commercial FNS ambulation system (Parastep-1®), completed a series of ambulation bouts along a 10m runway at incremental walking pace to the point of volitional exhaustion. The subjects also completed peak incremental AE testing on a Monarch arm ergometer in three-minute stages to the point of exhaustion. Subjects were continuously monitored during both tests to metabolic activity via open circuit spirometry and to heart rate activity with a 12-lead EKG. Peak physiological responses were compared between the two testing modes with one-way ANOVAs, and the level of statistical significance was accepted at the $p<0.05$ level. RESULTS: There were no significant differences between FNS ambulation and AE in peak values of oxygen uptake (VO_2) or other metabolic measures. However, at matched subpeak levels of VO_2, significantly greater endurance was observed with the FNS walking. CONCLUSION: While FNS ambulation is limited in walking pace and energy efficiency, it may allow persons with SCI to engage in purposeful exercise for extended periods otherwise impossible with voluntary AE.

Index Terms—electrical stimulation, ambulation, spinal cord injury, neuroprosthesis, exercise

I. Introduction

Complete spinal cord injury (SCI) is a catastrophic event experienced by over ten thousand persons per year [2]. Survivors of complete injuries typically find themselves restricted to wheelchair locomotion as both a means of transportation and a mode of exercise. It is well established that upper extremity training is limited in comparison to leg exercise training due to the relatively smaller size, peripheral resistance, and fatigue characteristics of the upper extremities [4]. Persons with SCI are further limited in their capacity for cardiovascular training subsequent to decreased venous return from the paralyzed lower extremities. Decreased values of stroke volume require compensatory acceleration of heart rate (HR) in order to supply adequate cardiac output for the necessary oxygen transport to the exercising arms and torso muscles [3] [5] [8].

It has been suggested that functional neuromuscular stimulation (FNS) ambulation may offer the potential for positive physiological adaptations to persons with SCI. The utilization of FNS walking systems has been demonstrated to allow certain individuals with SCI to stand and ambulate limited distances. Beneficial training adaptations have been reported in SCI paraplegics following participation in a 12-week FNS walking program [7] [11]. After the walking training period, subjects were able to reach significantly higher peak power outputs of arm ergometry with greater values of peak oxygen uptake [7]. The heart rate (HR) responses to arm ergometry at matched levels of power output were significantly lower following training. Lower extremity muscular mass increased dramatically during the training period as did measures of local circulation [9] [11]. The average arterial inflow volume through the common femoral artery increased from initial values of 417 to 650 ml/min following training with enhanced circulatory responses to occlusion [11].

The significance of these reported beneficial adaptations to participation in a program of FNS walking must be determined in reference to the training accommodations that can be expected from traditional arm exercise, such as arm cranking. Therefore, it is necessary to examine the acute and chronic responses of persons with SCI to these very different modes of activity. The purpose of this study was to compare the peak physiological responses to FNS walking in SCI paraplegics with the peak responses of the same subjects to arm ergometry (AE) testing.

II. Methods

Nine persons (7 male, 2 female) with SCI (T_4-T_{10}) participated in this study. The subjects ranged in age from 23.0 to 45.2 years and in bodymass from 60.6 to 83.5 kilograms (72.6 ± 6.7 kg). All subjects had been previously trained in FNS ambulation with a commercial system and had completed a minimum of five months of consistent training immediately prior to the testing sessions. The testing procedures were explained to the subjects and a written consent was obtained in accordance with the University of Miami Medical Sciences Subcommittee for the Protection of Human Subjects.

The commercially available FNS device used in this study was the Parastep-1® device (Sigmedics, Inc. Northfield, Illinois) which was designed by Daniel Graupe, Ph.D. to allow certain persons with SCI to stand and

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ambulate limited distances. This battery-powered system administers six channels of electrical stimulation under microprocessor control to the quadriceps and gluteal muscles for knee and hip extension and near the common peroneal nerve to effect a flexor withdrawal stepping action. Finger switches located on the handles of an adapted walker frame allow experienced users to independently control the system and adjust the stimulation intensity of each channel as well as the walking pace.

Each subject completed peak exercise testing with both the FNS ambulation system and AE. These exercise tests were performed in random order with 48 to 96 hours between testing sessions. Subjects were continuously monitored to metabolic activity in both test modes via open circuit spirometry with a SensorMedics Horizon system. Heart rate (HR) activity was measured during AE with a 12-lead electrocardiogram and during the FNS walking tests via direct palpation of the carotid artery. Termination points for each exercise test procedure were in accordance with the Guidelines for Graded Exercise Testing and Prescription published by the American College of Sports Medicine [1]. Peak AE testing using a progressive protocol was performed on a Monarch arm ergometer. The initial three- minute exercise interval was executed with unloaded cranking and subsequent three-minute intervals were performed with power output progressively increased 10 watts per stage. Subjects were guided with a metronome to the proper cranking pace of 50 rpm. The AE tests were continued to the point of volitional exhaustion or until the subjects were unable to continue arm cranking at the assigned pace.

Peak FNS ambulation testing was performed along a 10-meter runway. Three minutes of resting data was collected with the subjects seated in their wheelchairs at the beginning of the runway. Subjects were then directed to activate the FNS system and rise into a standing position, remaining stationary in that position for one minute during which HR was measured. The subjects were then asked to begin walking along the runway at a controlled pace. At the end of the runway, the subjects stopped (while HR was measured) and then turned in place. The second pass was performed at a slightly faster pace of walking. This procedure was continued with the ambulation pace increasing on each subsequent pass. The FNS tests were terminated at the point of volitional exhaustion or when the subject was unable to increase the walking pace.

III. Results

Each of the nine subjects completed peak AE and FNS testing without complication. Analysis revealed a trend, though not statistically significant ($p=0.06$), for lower peak HR values during AE. The FNS testing produced a mean HR_{peak} of 189.0 bpm while the subjects reached 178.2 bpm at peak effort of AE. There were no significant differences between FNS and AE in any of the metabolic measures. Peak oxygen uptake was 1.652 and 1.634 l/min for FNS and AE respectively. Minute ventilation at peak exertion of FNS was 67.8 l/min while subjects reached a peak flow of 69.2 l/min during AE.

IV. Discussion

Persons with SCI are generally restricted to exercise activities involving the spared musculature above the point of lesion. In general, upper extremity exercise is limited to approximately 70% of the work capacity of leg exercise within the same person without disability [4]. Paralyzed persons are further limited in upper extremity work capacity due to vasomotor dysregulation which results in lower extremity blood pooling and diminished venous return [3] [6] [8]. Heart rate responses at rest and at matched levels of work efforts are higher in order to compensate for reduced stroke volume levels. Persons with paraplegia also reach significantly lower peak power outputs than non-disabled cohorts. Additionally, these persons are at risk for chronic upper extremity overuse injuries. Injuries of the shoulder and elbow can dramatically limit the ability of persons with SCI to perform activities of daily living such as transfers, weight shifts, and wheelchair locomotion.

Functional neuromuscular stimulation has been demonstrated to allow thoracic-level paraplegics to attain a standing position and take steps. The emphasis of research on this topic has concentrated on such aspects as control system and hardware issues. The few studies examining the acute physiological responses to FNS walking have been performed to assess gait efficiency and/or energy cost [6] [10]. The results of those studies implied that FNS walking was limited in application due to high energy consumption as compared with normal gait. The elevated energy requirements actually may result in beneficial exercise training effects. The high energy uptake required and the artificial muscle pump effected with FNS may provide a very productive exercise modality for persons with SCI.

Peak metabolic responses to FNS ambulation, as indicated in this study, are similar to the peak responses to AE. Walking using FNS may be an exercise option with reduced potential for the upper extremity overuse injuries previously associated with stressful AE or wheelchair ergometry training. Anecdotal reports have suggested that the capacity for training may be greater with FNS ambulation due to increased fatigue resistance characteristics of the lower extremities. Future research efforts are recommended to examine specific characteristics of prolonged endurance training with FNS ambulation systems.

V. Conclusions

The findings of this study demonstrate that FNS ambulation provides a physical activity which rivals that of arm ergometry in peak oxygen uptake. Therefore, FNS ambulation should be considered as a possible exercise alternative for persons with SCI. Further research is required to determine the subpeak exercise characteristics of FNS ambulation training prior to recommendation of this mode as a training method.

VI. REFERENCES

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