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Changes in Blood Volume Pulse During Exercise Recovery in Activity-Based Therapy for Spinal Cord Injury

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Abstract—**This paper presents the results of cardiovascular changes that occur during a novel rehabilitation strategy called activity based therapy (ABT). Blood volume pulse (BVP) signals were measured during functional electrical stimulation (FES)-induced cycling in adults with spinal cord injury (SCI) persons and results were compared to a passive cycling task and able-bodied controls performing normal cycling. BVP signals were compared during three conditions, a baseline pre-exercise condition, 5 minutes after exercise and after 30-minutes rest following exercise. Exercise recovery was evaluated using normalized inner products values in BVP signals. The results showed that FES-induced cycling in SCI participants resulted in a significantly greater peripheral resistance level and longer time to recover from exercise compared with passive cycling and normal cycling in able-bodied controls.**

I. Introduction

Spinal cord injury (SCI) is a neurological disorder whereby the cord is lacerated, bruised or severed during a traumatic injury or damaged as a result of disease. As a major consequence of a lesion to the spinal cord, there is a disturbance in the flow of sensorimotor neural traffic between the brain and the peripheral musculature, usually resulting in loss of motor and sensory function [1]. Living with SCI and adapting to the restricted lifestyle and concomitant reduction in community participation is challenging and for many it is a devastating sequel of neurotrauma [2]. One major goal to improve the quality of life for SCI persons is to improve function recovery. Activity based therapy (ABT) is a rehabilitation strategy designed to maximize the recovery of the neuromuscular system, through exercise such as standing and locomotion or training on a functional electrical stimulation (FES) bicycle. By using FES-induced exercise adults with SCI are able to contract specific muscle groups through depolarization of the muscle cell membranes using electrical stimulation [3]. The ABT strategy is based upon "activity-dependent plasticity" whereby changes in the nervous or muscular systems are driven by repetitive activity [4]. ABT has recently come into prominence due to its success in improving the motor and sensory function of SCI persons even when it was thought that no more functional recovery was possible [5]. In a N=1case report of a tetraplegic male persons with a break at the cervical region (C2) and classified as American Spinal Injury Association (ASIA) Grade A, that is, no sensory or motor function preserved in sacral regions (S4-5) function recovery was observed. His ABT training consisted of 1 hour of activity per day for three days a week, on a FES bicycle. Early results showed physical benefits such as enhancement of muscle mass and bone density, increased cardiovascular endurance and decreased spasticity [5]. After three years of therapy, function improvements included recovery of sensory function to 66% of his body and 20% of normal motor function, that is a recovery through two ASIA grades from A to C [5].

Although ABT is a promising rehabilitation strategy, very little is known about the cardiovascular effects from ABT training in SCI persons. Given the physical benefits of exercise from ABT such as an enhancement of muscle mass and increased cardiovascular endurance, this study aimed to investigate the cardiovascular effects of an ABT session, such as recovery from exercise, using plesthysmographic blood volume pulse (BVP). The BVP signal reflects changes in the volume of blood pumped with every heart beat and has been traditionally used to measure heart rate [6]. It has also been reported that the BVP feature called the 'Dicrotic Notch' which is the peak on the falling edge of the BVP signal, is a good marker for the status of cardiac activity and has been used to evaluate the amount of change in peripheral resistance of the cardiovascular system when people are subjected to physical stress [7]. This paper will assess circulatory changes using BVP signals, that occur from exercising with FES-induced cycling during ABT in SCI persons. Comparisons will be made against SCI persons undergoing passive cycling (that is, machine driven cycling) as well as compared with a matched able-bodied control group performing normal cycling. Normalized inner products from the BVP signal was also used to assess how well each group recovered from the exercise sessions.

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II. Methods

A. Participants

Sixteen participants (14 males, 2 females), 8 with SCI and 8 able-bodied controls were included in this study. The able-bodied control group was matched to the SCI group by age (± 5 years) and sex. The mean age of participants was 41 years (SD=13.4). SCI persons were recruited from the Clinical Exercise and Research Unit (CERU) at The University of Sydney, Australia. It was a requirement for SCI participants to be chosen through convenience sampling as they needed to be trained in ABT to be included in this study. It was not possible to used SCI persons who were naïve to ABT as the cycling training is gradual and takes about 2-3months to work to the levels employed in this study. All SCI participants were paraplegics (T4-T10 injuries) and graded as either ASIA A or B, that is, there were no motor function preserved in all participants. The average time since injury was 9 years (SD=7.8). The study was approved by the institutional research ethics committee and participants were only entered into the study after informed consent.

B. Procedure

The design of the study consisted of a matched repeated measures cohort design. This design allows comparisons between groups as a function of the conditions over time. This controlled experimental factorial design involved two groups (SCI and able-bodied controls) across four testing conditions, that is, before cycling (baseline), cycling, just after cycling and after rest). For the SCI participants cycling was performed twice on the same participants (FES induced active cycling and passive cycling) over two days within a 3 day period. The active or passive cycling on either day 1 or day 2 was randomly assigned. Plesmythographic BVP was measured throughout the testing conditions. During the four conditions participants were instructed to keep their hand still, head facing forward and not to talk.

C. FES Bicycle ABT

All ABT recordings were conducted at the RRC, The University of Sydney. Cycling was done on an isokinetic Motomed cycle by Multi-Tems Pty Ltd (see Fig 1). Isokinetic cycling involves muscle contraction at the maximum tension being generated at a constant speed over the full range of motion of the joint. For SCI persons, lateral leg guard were applied to the thighs to prevent lateral movement of the legs, without hindering the sagittal movements needed for effective cycling. The Motomed cycles are built with motor power and the cycling can be set to cycle passively. During the FES-induced cycling (active cycle), to start the FES the bicycles must be cycling passively at the start to assist the SCI persons and allow the FES stimulation to start activating the muscles. The stimulation is then worked up to 100% output, which is the equivalent cycling power of between 2 to 10W for the SCI person. The able-bodied controls were expected to cycle normally without any passive cycling assistance. Cycling power for the able-bodied control group was between 30 to 50W. Both power outputs are comparable in terms of muscle contraction especially considering the influence of the spinal injury such as muscle atrophy[8].

Fig. 1. SCI persons performing FES-induced cycling on the Motomed cycles.

D. BVP

The BVP signals were acquired from a Biosemi electrophysiology acquisition system (www.Biosemi.com). BVP data was collected from an auxiliary channel using an infrared plethysmograph with photoelectric sensors to detect changes in tissue blood volume. The plethysmograph works best where light can reflect from the bone beneath the tissue, therefore in this study we strapped the plethysmograph onto the index finger of the left hand in all participants.

BVP signals were acquired at a sampling rate of 2048Hz but was down sampled to 128Hz for the analyses. During FES-induced cycling very high electrical artifact signals from the electrical stimulation flooded the signals and the BVP signal was unable to be retrieved due to a high noise to signal ratio, therefore analyses of data occurred only in the three conditions, that is, baseline (Stage A), just after cycling (Stage B) and after 30-minutes rest (Stage C). Five minutes of data was used in each of the three stages.

E. Method to evaluate recovery from exercise

In this paper we examined the effects of ABT in adults with SCI using a procedure similar to that employed by Mann and Barreto (2009) [7], which involved the evaluation of the normalized inner products of each vector in Stage A, B and C, with the vector in Stage A. This procedure evaluates when recovery occurs after exercise. The details of the procedure is as follows:

(1) The 5 min data used in Stages A, B and C of each subject was segmented into ‘n’ number of 5 sec segments. The initial 10s and the final 15s of BVP data were discarded due to artifacts. Each segment in Stage A was grouped with a corresponding 5s segment in Stages B and C. These 5s segments in Stages B and C were chosen at the same corresponding point of the 5s data that occurred in the Stage A. Thus we have ‘n’ groups of 5 s segments of data from Stages A, B and C.

(2) Wavelet decomposition of the BVP signal was then applied using the Daubechies wavelet db3 at level 6 and the

approximation and details were extracted. The variances of the details D6, D5 and D4 were then evaluated on each of these 5 sec segments in stages A, B and C. The mean and the standard deviation of the variances of D6, D5 and D4 were then obtained from all the 5s segments in stages A, B and C.

(3) In order to remove segments that may contain artifacts [9], the following procedure was adopted. Since D6 is the major contributor to the variance of each segment, segments where the variance differed by 1 standard deviation from the mean value were eliminated. This resulted in a reduction in the number of groups from 'n' to a number 'm'.

(4) The normalized inner products of each vector in stage A, B and C for each of the participants is then computed with the vector in stage A. The mean and the standard deviation of the inner product values in stages B and C in the 'm' groups were evaluated.

Let $\{1, b_i, c_i\}$ be the inner product values of each group *i*. Thus for each group we have a triad of numbers $\{1, b_i, c_i\}$. Let b_m, c_m be the mean and s_b, s_c the standard deviation of $\{b_i\}$ and $\{c_i\}$ respectively.

(5) To classify recovery from exercise we propose the following:

(i) If $(1-b_m) \le s_b$ then recovery has occurred at Stage B. This was denoted by the number 1 (see Tables in results).

(ii) If $(1-b_m) > s_b$ but $(1-c_m) \le s_c$, then recovery has occurred at Stage C. This was denoted by the number 2.

(iii) If $(1-b_m) > s_b$ and $(1-c_m) > s_c$ then recovery has not been not reached in these two stages. This was denoted by the number 0.

(iv) If $(1-b_m) \le s_b$ but $(1-c_m) > s_c$, recovery was seen as temporary. This was denoted by the number 3.

III. Results

The analyses using the inner product normalization technique was carried out on all the participants, however, the BVP signals of one able-bodied person, and one SCI person involved in active exercise and two SCI subjects in passive exercise were contaminated with artifact so that their data could not be used in the analysis.

Table 1 shows the normalized inner product results of the able-bodied participants. In all cases except for Subject no. 5 recovery was reached in Stage B. The results in Subject no. 5 suggest that the inner product value was further decreased in Stage C and has moved away from the pre-exercise (baseline) state. This is possible if the pre-exercise state A is not the usual state of the participant, that is, the person was in a more excited or anxious state during baseline measurements.

Table 2 shows the results of the SCI subjects after FES-induced cycling (active exercise). The results are different from that of able bodied subjects. The inner product values at b_m was significantly reduced in SCI persons after active exercise when compared to able-bodied controls (t=2.7, p=0.02). However, there were no significant differences between the c_m values of the SCI group compared to the able-bodied controls. Only 3 out of 4 reach recovery in stage B. Three reached recovery in Stage C and one did not reach recovery even in stage C.

TABLE I
EXERCISE EVALUATION OF ABLE-BODIED SUBJECTS INVOLVED IN CYCLING EXERCISE

Subject No.	a_m	b_m	c_m	s_b	s_c	Exercise Recovery
1	1	0.983	0.991	0.021	0.012	1
2	1	0.990	0.989	0.009	0.011	1
3	1	0.999	0.999	0.001	0.002	1
4	1	0.992	0.990	0.011	0.011	1
5	1	0.987	0.928	0.015	0.036	3
6	1	0.984	0.988	0.026	0.023	1
7	1	0.988	0.990	0.015	0.011	1

TABLE 2
EXERCISE EVALUATION OF SCI SUBJECTS INVOLVED IN FES-INDUCED CYCLING EXERCISE

Subject No.	a_m	b_m	c_m	s_b	s_c	Exercise Recovery
1	1	0.951	0.966	0.043	0.029	0
2	1	0.946	0.982	0.025	0.021	2
3	1	0.984	0.989	0.022	0.014	1
4	1	0.942	0.985	0.054	0.015	2
5	1	0.945	0.986	0.035	0.019	2
6	1	0.995	0.992	0.007	0.009	1
7	1	0.989	0.991	0.017	0.011	1

Table 3 shows the results of the SCI subjects involved in passive cycling. It shows that the recovery pattern is similar to the able-bodied controls. All participants showed recovery from passive exercise at stage B. The inner product values b_m and c_m was not significantly different between SCI persons after passive exercise when compared to able-bodied controls .

TABLE 3
EXERCISE EVALUATION OF SCI SUBJECTS INVOLVED IN PASSIVE CYCLING EXERCISE

Subject no	a_m	b_m	c_m	s_b	s_c	Exercise Recovery
1	1	0.982	0.985	0.022	0.018	1
2	1	0.977	0.989	0.034	0.009	1
3	1	0.995	0.991	0.006	0.009	1
4	1	0.998	0.997	0.003	0.004	1
5	1	0.998	0.995	0.002	0.003	1
6	1	0.994	0.986	0.007	0.014	1

IV. Discussion

This paper evaluated the cardiovascular effects of ABT training on SCI persons. Cardiovascular activity was evaluated using the normalized inner product values in the BVP signal. This procedure is based on the assumption that morphological changes in the BVP signal from Stage A to Stages B and C are derived from changes in the proportionality that exist between the variances which span the three different frequency bands. If there is no change then the inner product will result in a value of one. Changes in the dicrotic notch such as a less prominent dicrotic notch will result in the value of the inner product being reduced. Monitoring the changes in the inner product will therefore provide information regarding recovery of the cardiovascular circulatory system [7].

The results showed that compared to both able-bodied controls cycling normally and SCI persons experiencing passive cycling, FES-induced cycling resulted in a greater amount of peripheral resistance as seen by the significantly greater reduction in the normalized inner product value at Stage B. This dip in Stage B is representative of the drop in amplitude of the dichrotic notch just after exercising and can be dependent on factors such as the fitness level of the individual [7]. In the case of the SCI participants, it is known that the sympathetic brain stem control of the vascular bed below the level of injury is deficient [10], and this may be the reason for the greater peripheral resistance especially after FES-induced cycling in ABT. The sympathetic nervous system controls cardiovascular responses during exercise [11] and it has previously been shown that vasoconstriction following a single burst of sympathetic activity has a longer duration in SCI persons when compared to able-bodied controls [10]. This may also explain the longer time for recovery from exercise in the FES-induced cycling group. Only 3 of the 7 SCI FES cycle participants recovered in Stage B, of those remaining, 3 recovered at Stage C, and 1 did not show recovery even by Stage C. The recovery levels were similar to that seen in able-bodied controls as there were no significant differences between the normalized inner product values of c_m in the SCI active exercise compared to able-bodied controls.

The results also show that the FES based ABT had a much greater cardiovascular effect on SCI persons when compared to passive exercising. All SCI participants had recovered by Stage B during passive cycling and had similar normalized inner product values at Stage B and Stage C. This could explain the physical benefits of FES-induced ABT as a rehabilitation strategy with benefits such as the enhancement of muscle mass and bone density, increased cardiovascular endurance and decreased spasticity.

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