Fitness improved for individuals post-stroke after virtual reality augmented cycling training

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ABSTRACT

A virtual reality (VR) augmented cycling system was developed to address motor control and fitness deficits. In this paper we report on the use of the system to train fitness for individuals (N=4) in the chronic phase post-stroke who were limited community ambulators. Fitness was evaluated using a sub-maximal bicycle ergometer test before and after training. There was a statistically significant 13% ($p = .035$) improvement in VO_2 (with a range of 6-24.5 %). For these individuals, VR augmented cycling, using their heartrate to set the avatar's speed, fostered training of sufficient duration and intensity to promote fitness.

1. INTRODUCTION

Virtual reality environments for rehabilitation of individuals post-stroke have focused primarily on improving movement, whether of the upper extremity, lower extremity or in the context of mobility and ADL. The most recent Cochrane review that summarized the state of the evidence on virtual reality (VR) for stroke rehabilitation found that upper extremity VR applications were favored when compared to a control condition. (Laver et al. 2011) Lower extremity and mobility studies favored VR but did not reach significance. This in part may be explained by a lack of power, as only a few studies (n=3) were included in the lower extremity and mobility section of the Cochrane review. Alternatively, gait and mobility rehabilitation may require not only motor control training, but also fitness training.

It is well established that individuals post-stroke experience fitness deficits. Aerobic capacity post-stroke is reduced. (Mackay-Lyons and Makrides 2004, Severinsen et al. 2011) In a longitudinal study of individuals post-stroke it was reported that while mean peak Vo_2 (a measure of aerobic capacity) increased from one to six months post-stroke it was only 73% of the capacity measured in sedentary healthy controls. (Mackay-Lyons and Makrides 2004) Similar decreases in cardiorespiratory fitness were found in individuals who are chronic post-stroke. Reduced aerobic capacity is associated with walking limitations. (Courbon et al. 2006, Patterson et al. 2007)

Training to reverse fitness deficits post-stroke has been approached in a variety of ways. These include an 8 week water-based exercise program, (Chu et al. 2004) 10 and 14 week cycling ergometer programs, (Potempa et al. 1995, Lee et al. 2008, Rimmer et al. 2009) walking programs ranging from three to six months, (Macko et al. 1997, Macko et al. 2001) which have used BWSTT for acute (Texeira Da Cunha Filho et al. 2001, Mackay-Lyons and Makrides 2004) as well as chronic post-stroke individuals, (Macko et al. 2005)' (Patterson et al. 2008)' (Jorgensen et al. 2010) progressive adaptive physical activity (Michael et al. 2009) and 19 weeks of community based mobility training. (Pang et al. 2005) The consistent finding is that cardiovascular fitness measured with peak VO_2 can be improved with training. While it is recognized that fitness training is important challenges to engaging in such training include adherence, motivation and access to equipment.

We have developed a virtual reality augmented cycling system to address some of the limitations in fitness training for individuals post-stroke. The system is intended for both motor control and fitness training. The objectives of this project were to determine if 1. heartrate could be used as an input variable to drive the exercise intensity in a the virtual reality augmented cycling system, 2. individuals could train for a long duration (up to an hour), and if 3. training in the cycling virtual environment (VE) would result in improvements in cardiovascular and pulmonary fitness. We hypothesized that coupling of the VR assets s (Rizzo and Jounghyun Kim 2005) for sound exercise physiology principles would result in fitness benefits.

2. VIRTUAL REALITY AUGMENTED CYCLING

We have designed a virtual reality augmented cycling kit (see Figure 1) to concurrently promote mobility and fitness training. The kit is modular with sensorized pedals and handlebars that control the behavior of the rider in the park-like VE. The kit was designed to convert any bicycle into a virtually augmented cycle. The system is more detail elsewhere. (Ranky et al. 2010, Ranky et al. In Review) There are multiple inputs into the VE including the force generated at the pedals and the heartrate from the polar monitor. In this paper we focus on the heartrate input, however the pedal kinetics which promote riding symmetry are important for the recruitment of the stroke affected lower extremity. The ideal cycling pattern will recruit both lower extremities rather than promoting compensation by having the less affected limb dominate the pattern.

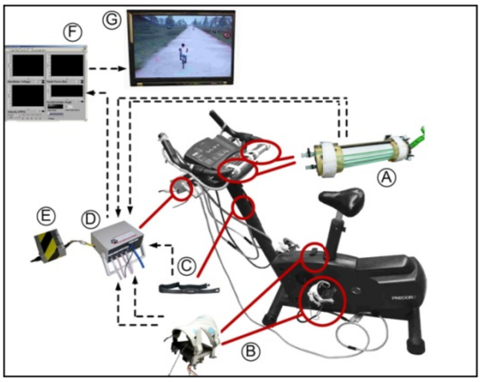

Figure 1. *Virtual Reality Augmented Cycling Kit (VRACK): A: Sensorized handle bars, B: Sensorized pedals, C: Heart Rate sensor and monitor D: Controller E: Power source F: Practitioner interface (where the target heart rate is set) G: Virtual Environment.*

The VE is a riding simulation with two avatars, one for the rider (in red) and the second for the pacer in blue (see Figure 2). The pacer cycles based on a target heart rate (THR) which is set by the therapist, is displayed inside a heart. The rider catches the pacer by working at an intensity that matches their target heart rate. If the rider exceeds the target heart rate the heart beats louder and gets larger indicating that riders need to exert themselves less in order to stay within their safe training range. The VRACK integrates with the bikes functionality. This permits the rider's workload to be adjusted by changing settings on the bike such as the work rate (in watts) and the resistance mode (constant or isokinetic). In this study the VRACK was attached to a biodex recumbent bicycle in which the work rate and resistance mode were adjustable.

Figure 2. *Virtual Environment: Rider in red (insert figure on left) uses exercise intensity based on his measured heartrate to catch the pacer (in blue) who is far ahead. At the start the rider and pacer are together, the rider's trajectory in the VE is displayed in the right upper corner.*

3. METHODS

3.1. Participants

Four individuals in the chronic phase post-stroke (one female and three males; ranging in age from 47 to 65) and one healthy sedentary control (male 48 year old) participated in this study. The individuals post-stroke presented with residual lower extremity (LE) impairments (LE Fugl Meyer scores ranged from 24-26; were house-hold to limited community ambulators (walking speed ranged from .56 to 1.1 m/s); and reported residual walking deficits such as limitations with walking distances. Participants were approved to participate by their primary care physician. One of the participants was engaged in a regular exercise program walking on a treadmill several times a week (S4) and second was swimming several times a week (S3). The other two participants did not have a regular exercise routine (S1 and S2). Participants were asked to maintain their regular exercise activities and not modify them during training.

3.2 Testing

Participants were consented and oriented to the protocol. Characterization of the subjects post-stroke sensorimotor impairment was performed with the lower extremity Fugl Meyer, which is valid and reliable (Duncan et al. 1983, Gladstone et al. 2002) (Sullivan et al. 2011) and related to gait pattern and speed. (Dettmann et al. 1987) Walking speed was collected using three walking trials at self-selected speed over the Gait Rite mat. Validity, reliability and MCID are well established. (Perry et al. 1995, Evans et al. 1997, Richards et al. 1999, Fulk and Echternach 2008) Cycling ergometry testing was used to assess fitness. An exercise pre-testing session using ACSM/YMCA sub-max VO_2 bike stress test was performed. (ACSM Guidelines: 8th Edition). Subjects were instrumented with a polar heart rate monitor and outfitted with a mouthpiece. Testing was conducted using a Cosmed K4B2 metabolic stress testing system. Subjects pedaled at 50 revolutions per minutes (rpm) (paced by a metronome), and reported their rate of perceived exertion (RPE) and exercised until they achieved 75-85% of maximum heart rate or needed to stop the test because of fatigue. Upon completion of training the post-test bike stress test was performed. Two participants reached their maximum heartrate and two participants stopped the test because of leg pain.

3.3 Intervention

Training on the virtual reality augmented cycling system took place over eight weeks. Participants attended two times a week and cycled between 20-30 minutes in the first session with increases until they achieved 60-minute sessions. Recommendations for cardiorespiratory fitness training in individuals post-stroke published by the American Heart Association range from 2-5 days a week for 20-60 minutes a session between 2 and 12- weeks (Gordon et al. 2004). The rate at which subjects increased their training time varied as did their total training time. See Figures 3 and 4. Training intensity was set to between 20 and 30 beats per minute above their resting heart rate. This HR set the pacers' rate in the virtual environment. A variety of features were manipulated in the simulation: path width, complexity and perturbations to increase immersion. The gain was also manipulated to change the rider's pedaling rate. Parameters on the bicycle, as well as on the VRACK, were varied to provide intervals of training that had greater resistance or speed. This was achieved primarily by changing the bicycles workload. The polar monitor tracked heartrate, which was displayed on the practitioner interface. Cycling included a warm and cool down period as well as time in the target heart rate zone. Intervals of cycling with attention to force generation were interleaved during the target heartrate training period. Blood pressure was recorded manually using a sphygmomanometer at ten-minute intervals. Concurrent with heart rate and blood pressure measurements subjects rated their perceived exertion. Exercise progression was based on heart rate response, reports of neuromuscular fatigue and perceived rate of exertion. The workload on the bike was increased as the heart rate response and neuromuscular fatigue tolerated it.

To ensure safety during training HR will be monitored continuously and BP every five minutes. American Congress of Sports Medicine guidelines were followed for exercise responses: a) HR did not exceed target HR; b) BP did not exceed 200/100 during exercise.

3.4 Data Analysis

Training time data were summarized and binned by week and as totals. Metabolic testing data were summarized descriptively. A non-parametric paired t-test with an alpha level of .05 was use to test the hypothesis that training in VR improved aerobic capacity. The dependent variable was sub-maximal VO_2 acquired pre and post the training.

4. RESULTS

All of the participants completed the eight-week training program. There was 100% adherence and no adverse events related to the training program were recorded. With the aid of a binding system at the foot all participants were able to use both lower extremities to bicycle. The virtual reality augmented cycling system accurately read the heart rate parameters throughout the training. Post-stroke participants achieved between 90 and 125 minutes of bicycling each week (see Figure 3) with a total of 800 to 1,000 minutes (see Figure 4) over the total training period. There was not a direct relationship between average training time and changes in aerobic capacity were not significant.

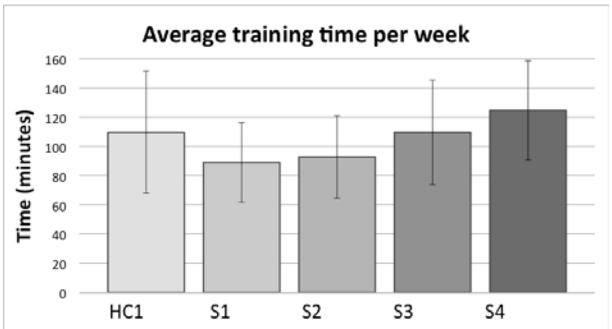

Figure 3. *Average Training Time per week* .

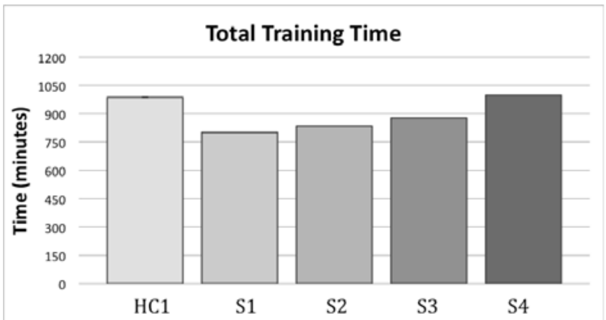

Figure 4. *Total Training Time by Subject.*

All participants post-stroke increased their aerobic capacity as measured by their oxygen consumption. There was a statistically significant 13% ($p = .035$) mean improvement in sub-maximal VO_2 (with a range of 6-24.5 %). Please see table one for a summary of the pre and post training values for time of exercise testing, workload achieved, heart rate, VO_2 and reported rate of perceived exertion. Two individuals post-stroke (S1 and S3) increased their exercise test time and workload, while the other two (S2 and S4) who had the symptom limited exercise test, did change their time and their workload either did not change (S2) or decreased (S4). Two out three out of four subjects did not have a change in their RPE rating. The healthy control also demonstrated an increase in oxygen consumption. Relative to the healthy control the individuals post stroke had lower oxygen consumption both at pre and post-test.

Table 1. *Results of Metabolic Testing Before (Pre) and After (Post) VR training*

Participant	Time (min)		Workload (watts)		HR (bpm)		VO_2		RPE	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
HC1	15	16.4	171	196	149	152	34.6	36.5	13	12
S1	12	14	98	123	167	167	18.3	21.5	14	9
S2	9	9	98	98	119	112	24.1	25.8	15	15
S3	7	11.5	98	123	110	117	19.5	25.8	13	13
S4	12	12	147	118	119	118	17.3	18.5	15	15

HC: Healthy control, S: Stroke, HR heart rate; VO_2: oxygen consumption; RPE: rate of perceived exertion.

5. DISCUSSION

The objectives of the study were met. The VRACK reliable read the user's heart rate as an input into the virtual environment, participants achieved training durations between 40 and 70 minutes per sessions and there was an improvement in aerobic capacity after training. Although not the focus of this paper, there were also kinetic changes of cycling indicative that the stroke affected lower extremity was recruited during the cycling pattern.

Rehabilitation of mobility for individuals post-stroke requires a multi-factorial approach. These factors are sensori-motor, cognitive, perceptual as well as physiological. The ability to incorporate physiologic variables to drive training intensity can expand the functionality of virtual reality applications for post-stroke rehabilitation. Given the complexity of training in VR it may be difficult to isolate the active ingredient; although this would be a relevant line of inquiry for future studies.

6. CONCLUSIONS

To our knowledge this is the first report to describe improvements in cardiovascular and pulmonary fitness after individuals post-stroke trained in a virtual reality augmented cycling environment. While the early finding is encouraging, it requires replication and extension to rehabilitation of relevant motor behaviors for people post-stroke.

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