Feasibility of Virtual Reality Augmented Cycling for Health Promotion of People Post-Stroke

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Abstract

Manuscript

Drs. Deutsch, Ranky, Sivak, Mavriodis and Mr. Lewis are inventors of the VRACK.

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ABSTRACT

A virtual reality (VR) augmented cycling system was developed to address motor control and fitness deficits of individuals post-stroke. 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 peak VO_2 with a range of 6-24.5 %. For these individuals, VR augmented cycling, using their heart rate to set the avatar's speed, fostered training of sufficient duration and intensity to promote fitness.

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 when compared to standard of care found that upper extremity VR applications were favored when compared to an active control condition.[1] 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. This is important both for health promotion and the possible transfer of training from virtual environments to real world mobility.

It is well established that individuals post-stroke experience fitness deficits and are sedentary. Aerobic capacity post-stroke is reduced.[2,3] 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.[2] Similar decreases in cardiorespiratory fitness were found in individuals who are chronic post-stroke. Further, reduced aerobic capacity is associated with walking limitations.[4,5] Finally, individuals post-stroke have a sedentary life style, and rarely meet recommendations for physical activity. [6,7]

Training to reverse fitness deficits post-stroke has been approached in a variety of ways. These include an 8 week water-based exercise program,[8] 10 and 14 week cycling ergometer programs,[9-11] walking programs ranging from three to six months,[12,13] which have used BWSTT for acute[2,14] as well as chronic post-stroke individuals,[15,16,17] progressive adaptive physical activity[18] and 19 weeks of community based mobility training.[19] Most recently research in which cardiovascular health training using total body recumbent stepping for 8 weeks for people with sub-acute stroke demonstrated improved fitness as well as transfer of training to walking. [20] The consistent finding is that cardiovascular fitness measured with peak VO_2 can be improved with training.

While it is recognized that fitness training and health promotion are important, challenges to engaging in such training include adherence, motivation and access to equipment. For people post-stroke a specific challenge with mobility training in standing stems from low self-efficacy, fear of falling [21-23]and actual falls [24,25]. Thus they are less likely to exercise at home where they might not have the equipment or supervision to exercise safely. Additionally, adherence to long-term exercise may be compromised once individuals are discharged from a structured rehabilitation setting, where motivation may be provided through socialization with others and goals set in their rehabilitation program, (ref).

Virtual environments and active video games have been proposed as a method to engage individuals in long-term physical activity. It is proposed that game-based activities will promote motivation and therefore adherence.

We have developed a virtual reality augmented cycling system (VRACK) 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 it was safe, feasible and efficacious to use the VRACK. Specifically we wanted to know if it was feasible to be immersed and train for a long duration (up to an hour) without adverse events. Was training in the cycling virtual environment (VE) efficacious at the body-function structure level of cardiovascular fitness, and would there be transfer to the activity level of walking endurance. We hypothesized that coupling of the VR assets with sound exercise physiology principles [26] would result in fitness benefits and based on previous work [27]speculated that there would be a transfer to mobility.

VIRTUAL REALITY AUGMENTED CYCLING

The virtual reality augmented cycling kit (VRACK) was designed to concurrently promote mobility and fitness training (see Figure 1). The kit is modular with sensorized pedals, handlebars and heart rate (HR) monitor (Polar Electro Inc., Lake Success, NY) that control the behavior of the rider in the park-like virtual environment (VE). The kit was designed to convert any bicycle into a virtually augmented cycle. The system is described in more detail elsewhere.[28,29] There are multiple inputs into the VE including the force generated at the pedals and the HR from the polar monitor. In this paper we focus on the HR 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.

INSERT FIGURE 1 here

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's cycling speed is based on a target heart rate (THR) that is set by the therapist, The rider is instructed to catch the pacer by working at an intensity that matches their THR. The rider's HR is displayed in the environment inside a heart . If the rider exceeds their THR 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 recumbent bicycle (Biodex Medical Systems, Shiley, NY): in which the workloard, rate and resistance modes were adjustable. The bike parameters were changed along with the VE features to increase the rider's heart rate.

INSERT FIGURE 2 here

METHODS

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 household 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.

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 (FM) and gait speed. The FM is valid and reliable [30,31] [32] and related to gait pattern and speed. [33] Walking speed was collected using three walking trials at self-selected speed over the Gait Rite mat. Validity, reliability and MCID are well established. [34-37] Feasibility was measured using attendance, adverse events, total exercise time and presence using the Witmer-Singer Presence Questionnaire.[38] Presence is a subjective measure[39] used in VR studies to characterize involvement ("attention and energy are coherent with the VE." Witmer page 227) and immersion (the psychological state of being included and interacting in a VE, Witmer page 227). The complete version of the instrument has 32 items scored with a 1 for low immersion and a 7 for high immersion. The tool was selected as a surrogate measure of engagement. The six-minute walk test was administered as walking an activity measure of endurance. 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 fatigue.

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. This dose was selected based on the 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 [40]. As this was a feasibility trial it was important to determine the duration of training that could be achieved.

Training intensity was set to between 20 and 30 beats per minute above their resting HR. This HR was used to set the pacers' rate in the virtual environment. Cycling included a warm and cool down period as well as time in the THR zone. Intervals of cycling with attention to force generation , by increasing the workload on the bike, were interleaved during the THR training period. Exercise progression was based on HR response, reports of neuromuscular fatigue and perceived rate of exertion. The workload on the bike was increased as the HR response and neuromuscular fatigue tolerated it.

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 perception of the rider's pedaling rate. When a rider rode slower than the pacer, the gain was set to give the impression that they were riding even slower. This precipitated an increase in riding speed. Parameters on the bicycle, as well as in the VE, 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 HR, which was displayed on the practitioner interface. . Concurrent with heart rate and blood pressure (BP) measurements subjects rated their perceived exertion.

To ensure safety during training HR was monitored continuously and BP every ten minutes using a sphygmomanometer. American Congress of Sports Medicine guidelines were followed for exercise responses: a) HR did not exceed THR; b) BP did not exceed 200/100 during exercise.

Data Analysis

Training time data were summarized and binned by week and as totals. Involvement was measuring by summing items 5, 6, 10, 18, 23 and 32 of the Presence Questionnaire, scores each week. The totals were averaged for the four subjects and compared across the eight weeks of training. Metabolic testing data were summarized descriptively. A non-parametric paired t-test with an alpha level of .05 was used 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. Pre and post-data for only two subjects were obtained for the six-minute walk and are presented descriptively.

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. None of the readers had their foot slip out of the pedals. Using the and independent polar monitor to check the readings of the VE. The virtual reality augmented cycling system accurately read the HR throughout the training. Participants reported involvement in VR with a mean score of 39 (SD 3.3) (out of a possible 42) at week one and 38 (SD 3) at week 8. 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 over the total training period.

INSERT FIGURE 3 here

Figure 3 Average Training Time per week

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 %). (Figure 4) 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 are presented in Table 1. 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). Three out of the four stroke 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.

Both participants post-stroke who had their walking distance on the six-minute walk measured improved (S3 increased from 179 to 229 meters; and S4 increased from 331-to 355 meters).

DISCUSSION

The modest objectives of this research project were met. It was feasible and safe to use the VRACK system by four individuals in the chronic phase post-stroke who ranged from household to limited community ambulators. There was 100% adherence and no adverse events. The participants reported involvement with the VE, which did not decrease after eight weeks of training. Participants achieved training durations between 40 and 70 minutes per session and there was an improvement in aerobic capacity after training and for selected participants increases in walking distance.

While there is not an exact study to compare the outcomes of training on a virtually augmented cycle, there is a similar study in which individuals post-stroke trained under several conditions that involved cycling coupled with strengthening (Lee, JAGS 2008). These investigators found the coupling cycling and strengthening yielded better results than cycling alone and strengthening alone. Their oxygen consumption changes as a measure of cardiovascular improvements were comparable to those reported by us (see Figure 6). However, it took almost double the training time 960 minutes in our study and 1,800 minutes in theirs to achieve them. Importantly the total training duration in our study was eight weeks compared to 12 in Lee's study.

The dosing of the study fell within the guidelines for exercise for individuals with low fitness for which, a duration of thirty minutes of continuous exercise is recommended [41]. Further we increased the intensity and duration of exercise as tolerated. This is similar to training studies with sub-acute [42]and chronic [43]stroke patients who trained on a cycle ergometer. Our training intensity was conservative for heart rate but on the stronger side for duration.

While only measured in two subjects, we report improvements in walking endurance that exceed the MCD. The participant who was training walking on treadmill three times a week (S4) had a lower improvement than the participant who swam (S3). Interestingly both stroke patients also decreased their gait asymmetry (calculated from the mean value of the left and right swing times), at self-selected walking speed with and without using a cane. Suggesting that the pedals used to promote symmetry of cycling may have transferred to symmetry of walking. S3 had a dramatic decrease when walking without a cane from an asymmetry of 160% to one of 30%.

This is a preliminary study with a small number of participants that should be interpreted with caution. Participants were tested using a sub-maximal exercise test, which may introduce some error into the measurement. Further, the Witmer-Singer Presence Questionnaire has not been validated in a stroke population.

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. Certainly it opens a line of inquiry for the application of VR to rehabilitation post-stroke. However, given the complexity of training in VR it may be difficult to isolate the active ingredient. This model of VR based cycling may used to parse the relative contributions of cognition and exercise to improvements and maintenance of health. As cycling equipment is ubiquitous in community and health centers the possibility of stroke patients benefitting from their use might be increased they are outfitted with virtual reality augmented cycling kit. The translation of this technology from a lab-based to a community based setting remains to be tested.

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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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.

Figure 1

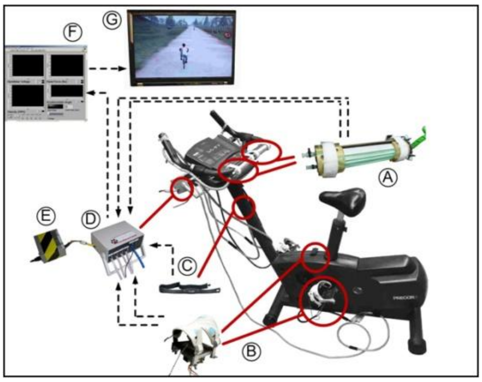

Figure 1. *Virtual Reality Augmented Cycling Kit (VRACK): A: Sensorized handle bars, B: Sensorized pedals, C: Heart Rate sensor and monitor D: Controller E: Power source F: Practitioner interface (where the target heart rate is set) G: Virtual Environment.*

Figure 2

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.*

Figure 3

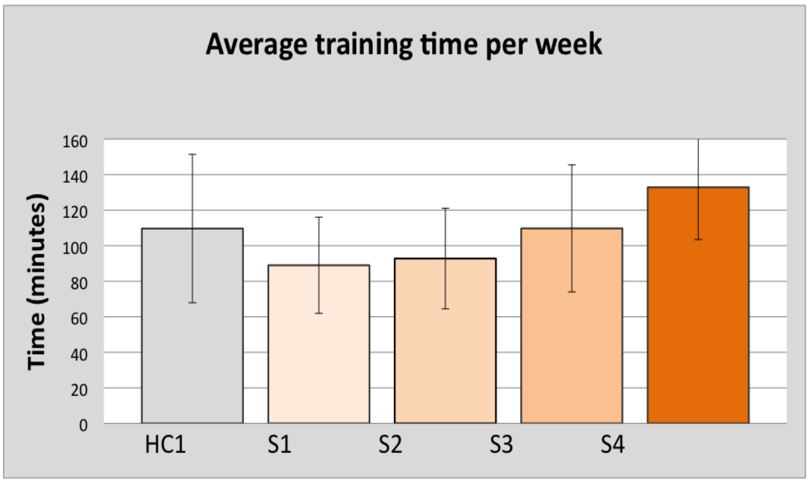

Figure 4 (I know this is redundant with the table so we could omit it).

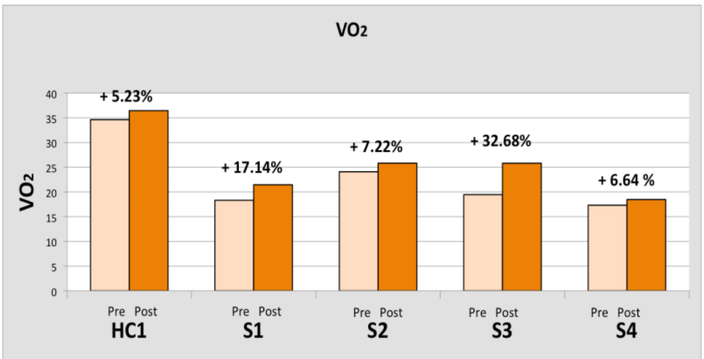

Figure 5

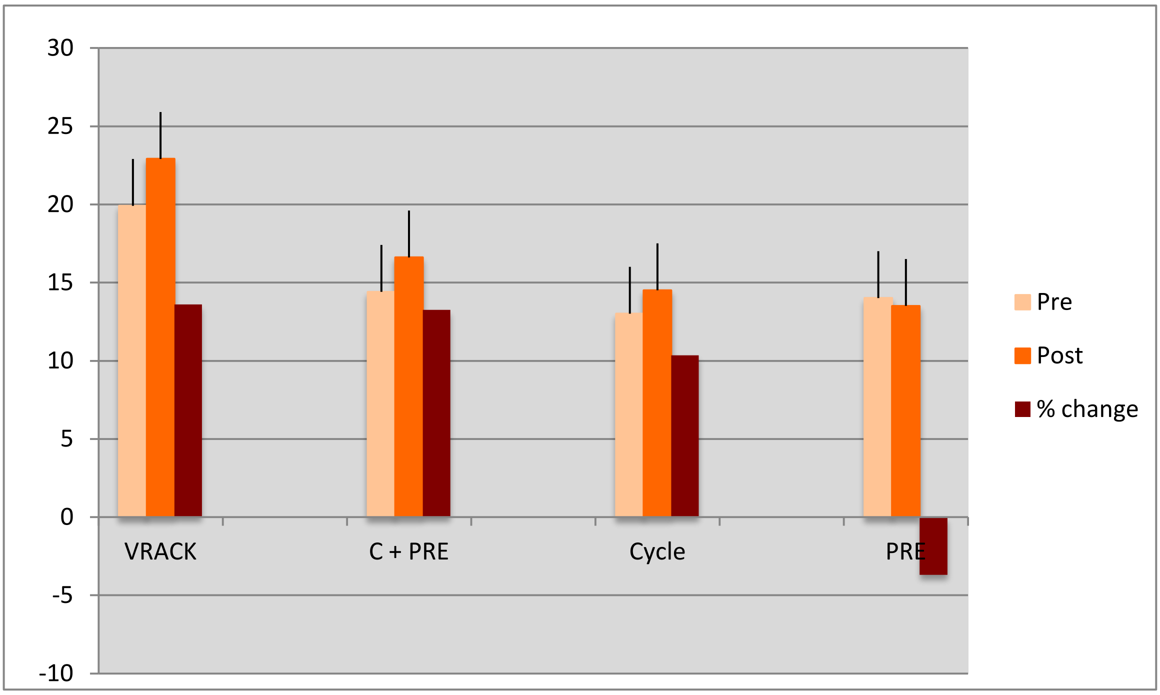

Figure 6 Improvements in oxygen consumption using the VRACK, to the three groups in Lee (2008) who cycled and did progressive resistive exercise (PRE) or cycling and PREs only.