Published in final edited form as:

J Neurol Phys Ther. 2013 September ; 37(3): . doi:10.1097/NPT.0b013e3182a0a078.

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

Judith E Deutsch, PT, PhD, FAPTA^{1,3}, Mary Jane Myslinski, PT, EdD¹, Michal Kafri, PT, PhD¹, Richard Ranky, PhD², Mark Sivak, PhD², Constantinos Mavroidis, PhD², and Jeffrey A Lewis³

¹Rivers Lab, Department of Rehabilitation and Movement Sciences: UMDNJ. 65, Bergen Street Newark NJ

²Biomedical Mechatronics Laboratory: Northeastern University

³VRRehab LLC, USA

Abstract

Background and Purpose—A virtual reality (VR) augmented cycling kit (VRACK) was developed to address motor control and fitness deficits of individuals with chronic stroke. In this paper we report on the safety, feasibility and efficacy of using the VRACK to train cardio-respiratory (CR) fitness of individuals in the chronic phase poststroke.

Methods—Four individuals with chronic stroke (47–65 years old and three or more years post-stroke), with residual lower extremity impairments (Fugl Meyer 24–26/34) who were limited community ambulators (gait speed range 0.56 to 1.1 m/s) participated in this study. Safety was defined as the absence of adverse events. Feasibility was measured using attendance, total exercise time, and “involvement” measured with the Presence Questionnaire (PQ). Efficacy of CR fitness was evaluated using a sub-maximal bicycle ergometer test before and after an 8-week training program.

Results—The intervention was safe and feasible with participants having 1 adverse event, 100% adherence, achieving between 90 and 125 minutes of cycling each week and a mean PQ score of 39 (SD 3.3). There was a statistically significant 13% ($p = 0.035$) improvement in peak VO_2 with a range of 6–24.5 %.

Discussion and Conclusion—For these individuals post-stroke, VR augmented cycling, using their heart rate to set their avatar’s speed, fostered training of sufficient duration and intensity to promote CR fitness. In addition, there was a transfer of training from the bicycle to walking endurance. VR augmented cycling may be an addition to the therapist’s tools for concurrent training of mobility and health promotion of individuals post-stroke. Video Abstract available (see Video, Supplemental Digital Content 1) for more insights from the authors.

INTRODUCTION

Virtual reality (VR) environments for rehabilitation of individuals poststroke have focused primarily on improving movement and use of the upper and lower extremities, as well as, mobility and activities of daily living (ADL). The most recent Cochrane review that summarized the state of the evidence on VR for stroke rehabilitation found that outcomes

CA: Judith E Deutsch, 973 972 2373, 972 972 3717, deutsch@umdnj.edu.

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

Parts of this manuscript were presented at the 9th International Conference for Virtual Reality and Associated Technologies (ICDVRAT), Laval, France

with upper extremity VR applications were more favorable compared to an active control condition.¹ Lower extremity and mobility studies indicate that the outcomes were more favorable with VR but the evidence on walking outcomes was not strong enough to reach significance. This may be explained in part by a lack of power, as only 3 studies²⁻⁴ 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 cardiorespiratory (CR) fitness training. Adding this element of training is important both for health promotion and for the possible transfer of training from virtual environments to real world mobility.

It is well established that individuals poststroke are sedentary and their aerobic capacity is reduced.⁵⁻⁶ In a longitudinal study of individuals poststroke it was reported that while mean peak VO₂ (a measure of aerobic capacity) increased from one to six months poststroke it was still only 73% of the capacity measured in sedentary healthy control participants.⁵ Similar decreases in CR fitness were found in individuals with chronic stroke. Further, reduced aerobic capacity has been associated with walking limitations.⁷⁻⁸

Individuals poststroke have a sedentary life style, and rarely meet American Heart Association⁹ recommendations for physical activity.¹⁰⁻¹¹ Training to reverse CR fitness deficits poststroke has been approached in a variety of ways. These include an 8-week water-based exercise program,¹² 10- and 14-week cycling ergometer programs,¹³⁻¹⁵ walking programs ranging from three to six months,¹⁶⁻¹⁷ which have used body weight supported treadmill training for acute^{5, 18} as well as chronic poststroke individuals,^{19,20,21} progressive adaptive physical activity²² and 19 weeks of community-based mobility training.²³ Most recently, researchers reported that cardiovascular training, using total body recumbent stepping during 8 weeks for people with subacute stroke, improved fitness and there was a transfer of training to walking.²⁴ The consistent finding is that CR fitness measured by peak VO₂ can be improved with training.

While it is recognized that cardiovascular health and fitness are important, there are challenges to engagement in exercise programs for health promotion. Three categories of barriers to exercise for individuals poststroke were identified in a qualitative study: stroke-related physical impairments, lack of motivation, and environmental factors.²⁵ To complement these findings, Rimmer and colleagues,²⁶ used the Barriers to Physical Activity and Disability survey, and found that cost, lack of awareness of fitness centers, transportation, and lack of knowledge about how to and where to exercise were the top five barriers. For people poststroke, a specific challenge to mobility training in standing may be overcoming low self-efficacy, fear of falling²⁷⁻²⁹ and actual falls.³⁰⁻³¹ These factors may make it less likely for people poststroke 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.²⁵

To address some of the limitations with CR fitness training of individuals poststroke, we have developed a VR augmented cycling kit (VRACK). The system is intended to promote motor control and CR fitness. The VRACK uses a common, ubiquitous, and relatively low-cost piece of exercise equipment, a stationary bicycle, augmented by a virtual environment (VE). Virtual environments and active video games have been proposed as technologies to engage individuals in long-term physical activity, by promoting adherence through motivation.³² Additionally, video games played by people poststroke have been shown to promote moderate exercise intensity.³³ We propose that exercising in a VE combines motivation and exercise intensity and may promote health through regular exercise.

The objectives of this pilot project were to determine if it was safe, feasible and efficacious to use the VRACK. Specifically we wanted to know if it was safe to exercise on the system without adverse events, feasible to be immersed and exercise for a long duration (up to an hour) with regular attendance over 8 weeks, and efficacious at the body-function level of CR fitness, and at the activity level of walking endurance. We hypothesized that safety and feasibility would be demonstrated. We hypothesized as well, that coupling of the VR assets³⁴ with sound exercise physiology principles would result in CR fitness benefits and based on previous work³ speculated that there would be a transfer to walking endurance.

METHODS

Participants

Four individuals in the chronic phase poststroke (one female and three males; ranging in age from 47 to 65, three years or more poststroke) and one healthy sedentary control participant (male 48 year old) participated in this study. They were a sample of convenience. The individuals poststroke were included because they had residual lower extremity impairments (lower extremity Fugl-Meyer (FM) scores ranged from 24–26/34, were household to limited community ambulators (walking speed ranged from 0.56 to 1.1 m/s), and reported residual walking deficits such as limitations with walking distances. The healthy control participant was included to have a reference for CR improvements to which to compare the individuals poststroke for this specific training intervention. Participants were approved to participate by their primary care physician. One of the participants (S4) was engaged in a regular exercise program walking on a treadmill several times a week and a second participant (S3) was swimming several times a week. The other two participants (S1 and S2) did not have a regular exercise routine. Participants were asked to maintain their regular exercise activities and not modify them during training.

Testing

Participants were enrolled in the study after receiving permission from their primary physician. Prior to beginning the testing informed written consent was obtained by the first author (JED) to participate in the study that had been approved by the Institutional Review Board of the University of Medicine and Dentistry of New Jersey. Participants were then oriented to the research protocol. Characterization of the participants' poststroke sensorimotor status was performed with the lower extremity FM and gait speed. The FM is valid and reliable^{35–36,37} and related to gait pattern and speed.³⁸ Walking speed was collected using three walking trials at self-selected speed over an instrumented mat (GAITrite, CIR Systems, Sparta NJ, USA)). Validity, reliability and minimal clinically important difference are well established.^{39–42}

Safety was defined as the absence of adverse events: which included syncope, exceeding the parameters for safe exercise and reports of cyber sickness (dizziness, nausea or eye-strain resulting from exposure to a VE). The description of adverse events was provided to the interventionist who was directed to manage and then record them in an interventionist's logs. Feasibility was measured using attendance, total exercise time, participants' ability to maintain each foot in the pedal, and "involvement" using the Witmer-Singer Presence Questionnaire (PQ).⁴³ Presence is a subjective measure⁴⁴ used in VR studies to quantify how immersed a user is in a VE. Involvement is a construct of the PQ that measures how well the VE attracts and holds the attention of the user.^{43, 45} The PQ was used in the study as a surrogate measure of engagement. The complete version of the instrument has 32 items scored with a Likert scale with 1 for low and a 7 for high scores. In this study we used only the involvement items (items 5, 6, 10, 18, 23 and 32). During the training period, attendance

and training time were taken daily, and the involvement items of the PQ were collected once a week.

Efficacy was measured at the impairment level as an improvement in peak VO_2 during a sub-maximal ergometry test, and at the activity level with distance walked on the 6-minute walk test. The distance walked was used to explore the transfer of training from cycling in a VE to walking.

An exercise pre-testing session using YMCA Cycle Ergometry sub-maximal VO_2 cycle stress test was performed as per American College of Sports Medicine (ACSM) Guidelines.⁴⁶ Participants were instrumented with a heart rate monitor (Polar Electro, Kempele, Finland) monitor and outfitted with a mouthpiece. Testing was conducted using a metabolic testing system (COSMED K4b², COSMED, Italy). Participants pedaled at 50 revolutions per minute (rpm), and reported their rate of perceived exertion (RPE)⁴⁷ and exercised until they achieved 85% of maximum HR or needed to stop the test because of fatigue. HR, RPE, blood pressure (BP) and VO_2 were collected using the breath by breath measurement technique during the last thirty seconds of each 3-minute stage. Upon completion of the training period, a post-training bi stress test was performed in the same manner as the pre-training test. At the post-test, two participants reached 85% of their maximum HR and two participants stopped the test because of leg fatigue. To measure walking endurance, the 6-minute walk test was administered using standard procedures.⁴⁸ Participants were asked to walk as much distance as they could in six minutes. The distance walked was calculated.

VR augmented cycling—The VRACK was designed to concurrently promote motor control, CR, and neuromuscular fitness training (see Figure 1). The kit is modular with sensorized pedals, handlebars, and HR monitor (Polar Electro Inc., Lake Success, NY) that control the behavior of the rider's avatar in the park-like VE. The kit was designed to convert any stationary bicycle into a VR augmented cycle. In this study the VRACK was attached to a recumbent bicycle (Biodex Medical Systems, Shiley, NY) in which the workload, rate, and resistance modes were adjustable.

The VRACK is described in more detail elsewhere.⁴⁹ Briefly, inputs into the VE include the force generated by each lower extremity at the instrumented pedals and HR from the HR monitor. The pedals have force transducers, which measure each lower extremity separately. If there is a force asymmetry the rider in the VE will tilt to the weaker side. The HR data are transmitted to the VE, and this input drives the speed of the avatar. As the rider in the real world increases their HR, their avatar pedals faster. The data from the pedals and HR monitor are collected by the system and used as a measure of performance. While both the HR and pedals were used in the study, in this article we focus on CR outcomes, so we emphasize the role of the HR. However, the pedal kinetics, promote riding symmetry, which is 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.

The VE used in this study was a riding simulation with two avatars, one for the rider in the real world and the second for the pacer (see Figure 2). The pacer's cycling speed was based on a target HR (THR) that was set by the therapist. The rider was instructed to catch the pacer by working at an intensity that matched their THR. The rider's HR was displayed in the VE inside a shape of a heart with number and a beat-like sound. If the rider exceeded their THR the heart in the environment beat louder and became larger indicating that the rider needed to exert themselves less in order to stay within their safe training range. As the VRACK integrated with the bicycle's functionality, the rider's workload and the resultant

HR could be adjusted by changing settings on the bicycle, such as the work rate (in watts) and the resistance mode (constant or isokinetic). In addition to using the HR input into the VE to drive a specific aerobic effort, VE features such as cycling gain (amplification or reduction of the rider's rpm) path width and path difficulty could be used to modify riders' HR and maintain their engagement.

Intervention—Training on the VRACK took place over eight weeks. Participants attended two times a week and cycled between 20–30 minutes in the first session, and session durations increased until they achieved 60-minute sessions. In some cases because individuals were not fatigued (based on their RPE and observation of their coordination), they exceeded 60 minutes of training. This dose was selected based on the recommendations for CR fitness training for individuals poststroke published by the American Heart Association, which range from 2–5 days a week for 20–60 minutes a session for 2 and 12-weeks.⁹ As this was a feasibility trial, it was important to determine the maximum duration of training that each participant could achieve.

Training intensity was set at the beginning of the session to between 20 and 30 beats per minute above the participants' resting HR. Participants were able to exceed this intensity during training, as long as their RPE was at 14 or below, and the cycling pattern did not exhibit incoordination secondary to fatigue. This decision was based on the study goals of safe exercise and the knowledge that submaximal tests may not be valid for setting exercise prescription in people poststroke. In addition the recently published ACSM guidelines on exercise include a short discussion on exercise prescription for people with cardiovascular accidents but they do not have specific guidelines for heart rate.⁴⁶

Cycling included a warm-up and cool down period as well as time in the THR zone, which was 20–30 bpm above resting. Exercise was continuous with no rest period. Training at the THR was interleaved with cycling that focused on intervals of cycling with attention to force production (where the bicycle resistance was increased). Exercise progression was based on HR response, reports of neuromuscular fatigue and RPE. (See supplemental digital content 2: **S4 cycling in the VE**)

A variety of features were manipulated in the VE: path width, complexity of the riding environment and perturbations to increase immersion. The gain of the riders' pedaling was also manipulated to change the perception of how fast they were moving in the VE. For example a when a rider rode slower than the pacer, the gain was set to give the impression that they were riding even slower. This modulation was intended to encourage the rider to increase the riding speed and catch the pacer. 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 manually changing the bicycle's workload.

Measuring HR, BP and RPE ensured safety. The HR monitor tracked HR, which was displayed on the practitioner interface allowing continuous monitoring. Blood pressure (using a sphygmomanometer) and RPE were recorded at 5-minute intervals for the shorter sessions and 8-minute intervals for the longer sessions. Training was ended based on ACSM guidelines for exercise responses:⁴⁶ a) HR did not exceed THR and b) BP did not exceed 200/100 mmHg during exercise.

Data Analysis

Safety was assessed by review of the interventionist's logs. Feasibility was measured using attendance, summarizing training time, and the involvement items of the PQ. Training time data were summarized and binned by week and as totals. Involvement was measured by summing items 5, 6, 10, 18, 23 and 32 of the PQ, scores each week. The totals were

averaged for the four participants and analyzed descriptively across the eight weeks of training to determine participants' involvement with the training.

Efficacy was assessed by an inferential analysis of the oxygen consumption ($N=4$) and by descriptive results of the 6-minute walk ($n=2$) test. Although the sample size was small, the strong reliability of the oxygen consumption measure, and the interest in comparing our findings to others, informed our selection of the Wilcoxon Signed Ranked Test with an alpha level of 0.05 to test the hypothesis that training in VR improved aerobic capacity. The dependent variable was the peak VO_2 attained during a sub-maximal bi ergometry test. Pre- and post-training data for only two participants were obtained for the 6-minute walk and are presented descriptively. Testing space was not available to test S1 and S2 on the 6-minute walk test.

RESULTS

All of the participants completed the 8-week training program. There was 100% adherence and only 1 adverse event related to the training program. S1 had an episode of dizziness on the curves in the VE path. Decreasing the gain of her riding speed eliminated the dizziness. With the aid of a binding system at the foot, all participants were able to use both lower extremities to bicycle. Participants had their foot slip off of the pedals on only 5 occasions over a total of 80 training sessions. Participants reported involvement in VR with a mean PQ score of 39 (SD 3.3) (out of a possible 42) at week 1 and 38 (SD 3) at week 8. Poststroke 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.

Figure 3 Average Training Time per week

All participants poststroke increased their aerobic capacity as measured by their peak VO_2 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. There was a statistically significant mean improvement of 13% ($p = 0.035$) in sub-maximal VO_2 (with a range of 6–24.5%) (Figure 4). A summary of the pre- and post-training values for exercise test time (ETT), workload achieved, HR, VO_2 and reported RPE are presented in Table 1. Two individuals poststroke (S1 and S3) increased their ETT and workload, while the other two (S2 and S4) had symptom-limited exercise tests. These participants changed their ETT but their workload either did not change (S2) or decreased (S4). Only one participant had change in their RPE rating (S1). The healthy control participant also demonstrated an increase in oxygen consumption. The healthy control participant improved his peak VO_2 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ by 5%. Relative to the healthy control participant, the individuals post stroke had lower oxygen consumption both at the pre-training and post-training tests.

Both participants poststroke who performed the 6-minute walk test 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 safe and feasible to use the VRACK by four individuals in the chronic phase poststroke who ranged from household to limited community ambulators. There was 100% adherence and only 1 adverse event. 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 with only a few instances of having their foot come off the pedal and there was an improvement in aerobic capacity after training and for participants in whom walking was assessed, increases in walking endurance.

The results of the exercise test were presented in detail to highlight the variability of endpoints as well as the RPE and workload changes. For example it is interesting to note that S1 had an increase in peak VO_2 while her HR remained the same. She achieved the increased peak VO_2 by having a higher workload and longer test. By contrast, S4 who trained at the highest intensity (by exceeding the 30 bpm above resting threshold) had a symptom-limited post-training test and only the HR decreased. The variability of exercise test responses highlights the challenge with applying the guidelines for healthy individuals to people post-stroke.

Our results compare favorably with a previous non-VR study in which individuals post-stroke trained under several conditions that involved cycling coupled with strengthening.¹⁴ These investigators found the coupling of cycling and strengthening yielded better results than cycling alone and strengthening alone. The peak VO_2 changes they observed, which were obtained with a maximal effort cycle ergometer test, as a measure of cardiovascular improvement, were comparable to those reported in our study. The VE utilized here may have improved the efficiency of training in that our results were obtained with one-half the amount of training time (960 minutes in our study and 1,800 minutes in Lee et al) and a shorter total training duration (8 weeks in our study compared to 12 weeks in Lee et al).¹⁴

The dosing of our study fell within the guidelines for exercise for individuals with low fitness for which, thirty minutes of continuous exercise is recommended.⁵⁰ Further we increased the intensity and duration of exercise as tolerated. This is similar to training studies with subacute⁵¹ and chronic⁵² stroke patients who trained on a cycle⁵³ ergometer. Our training intensity was conservative for HR training range but more robust for duration of individual training sessions.

While only measured in two participants, we report improvements in walking endurance that exceed the meaningful detectable change for the 6-minute walk test of 34 meters⁵³ for one participant (S3). The participant who, prior to the VE intervention, was training walking on treadmill three times a week (S4: pre- to post-training increase of 24 meters) had a lower improvement than the participant who swam (S3: pre- to post-training increase of 50 meters). The person who was swimming likely experienced greater demands from the bicycle training on his lower extremity and had more room to improve his aerobic capacity. Interestingly, both participants with stroke 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. Such results may suggest that the pedals used to promote symmetry of cycling may have transferred to symmetry of walking. S3 had a dramatic decrease in asymmetry when walking without a cane from an asymmetry of 160% to one of 30%. The transfer of training from exercising in the cycling VE to walking may be explained by changes in both the CR system and recruitment of the affected lower extremity.

Limitations

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 have introduced error into the measurement. Future studies may use a maximal test, which will then form the basis for higher intensity training. It is interesting to note, however, that the low training intensity (20–30 bpm above the resting HR, which was exceeded by 10 bpm on occasion) was of sufficient intensity for the participants in this study. Therefore the precise dose requirements for exercise coupled with VE requires further study. Finally, the Witmer-Singer PQ⁴³ has not been validated in a stroke population.

CONCLUSIONS

Rehabilitation of mobility and promotion of health and wellness for individuals post-stroke requires a multi-factorial approach. Some of the important factors are sensorimotor, cognitive, perceptual as well as physiological as well as social support. The ability to incorporate physiologic variables to drive training intensity can expand the functionality of VR applications for poststroke rehabilitation. Certainly it opens a line of inquiry for the application of VR to rehabilitation poststroke. However, given the complexity of training in VR, it may be difficult to isolate the active ingredient.

This model of VR-based cycling may be used to parse out 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 if they are outfitted with VRACK. The translation of this technology from a lab-based to a community based setting remains to be tested.

To our knowledge this is the first report to describe improvements in cardio-respiratory fitness after individuals poststroke trained in a VR augmented cycling environment. While the early finding is encouraging, it requires replication and extension to rehabilitation of relevant motor behaviors for people poststroke.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Funded by NICHD R41 HD54261-01 Deutsch PI

References

1. Laver KE, George S, Thomas S, Deutsch JE, Crotty M. Virtual reality for stroke rehabilitation. *Cochrane Database Syst Rev.* 2011; 9:CD008349. [PubMed: 21901720]
2. Jaffe DL, Brown DA, Pierson-Carey CD, Buckley EL, Lew HL. Stepping over obstacles to improve walking in individuals with poststroke hemiplegia. *J Rehabil Res Dev.* 2004; 41:283–292. [PubMed: 15543446]
3. Mirelman A, Bonato P, Deutsch JE. Effects of training with a robot-virtual reality system compared with a robot alone on the gait of individuals after stroke. *Stroke.* 2009; 40:169–174. [PubMed: 18988916]
4. Yang YR, Tsai MP, Chuang TY, Sung WH, Wang RY. Virtual reality-based training improves community ambulation in individuals with stroke: a randomized controlled trial. *Gait Posture.* 2008; 28:201–206. [PubMed: 18358724]
5. MacKay-Lyons MJ, Makrides L. Longitudinal changes in exercise capacity after stroke. *Arch Phys Med Rehabil.* 2004; 85:1608–1612. [PubMed: 15468019]
6. Severinsen K, Jakobsen JK, Overgaard K, Andersen H. Normalized muscle strength, aerobic capacity, and walking performance in chronic stroke: a population-based study on the potential for endurance and resistance training. *Arch Phys Med Rehabil.* 2011; 92:1663–1668. [PubMed: 21872846]
7. Courbon A, Calmels P, Roche F, Ramas J, Fayolle-Minon I. Relationship between maximal exercise capacity and walking capacity in adult hemiplegic stroke patients. *Am J Phys Med and Rehabil.* 2006; 85:436–442. [PubMed: 16628151]
8. Patterson SL, Forrester LW, Rodgers MM, et al. Determinants of walking function after stroke: differences by deficit severity. *Arch Phys Med Rehabil.* 2007; 88:115–119. [PubMed: 17207686]

9. Gordon NF, Gulanick M, Costa F, et al. Physical activity and exercise recommendations for stroke survivors: An American Heart Association scientific statement fFrom the Council on Clinical Cardiology, Subcommittee on Exercise, Cardiac Rehabilitation, and Prevention; the Council on Cardiovascular Nursing; the Council on Nutrition, Physical Activity, and Metabolism; and the Stroke Council. *Circulation*. 2004; 109:2031–2041. [PubMed: 15117863]
10. Baert I, Feys H, Daly D, Troosters T, Vanlandewijck Y. Are patients 1 year post-stroke active enough to improve their physical health? *Disabil Rehabil*. 2012; 34:574–580. [PubMed: 21981331]
11. Rand D, Eng JJ, Tang PF, Jeng JS, Hung C. How active are people with stroke?: use of accelerometers to assess physical activity. *Stroke*. 2009; 40:163–168. [PubMed: 18948606]
12. Chu KS, Eng JJ, Dawson AS, Harris JE, Ozkaplan A, Gylfadóttir S. Water-based exercise for cardiovascular fitness in people with chronic stroke: a randomized controlled trial. *Arch Phys Med Rehabil*. 2004; 85:870–874. [PubMed: 15179638]
13. Potempa K, Lopez M, Braun LT, Szidon JP, Fogg L, Tincknell T. Physiological outcomes of aerobic exercise training in hemiparetic stroke patients. *Stroke*. 1995; 26:101–105. [PubMed: 7839377]
14. Lee MJ, Kilbreath SL, Singh MF, et al. Comparison of effect of aerobic cycle training and progressive resistance training on walking ability after stroke: a randomized sham exercise-controlled study. *J Am Geriatr Soc*. 2008; 56:976–985. [PubMed: 18422947]
15. Rimmer JH, Rauworth AE, Wang EC, Nicola TL, Hill B. A preliminary study to examine the effects of aerobic and therapeutic (Non-aerobic) exercise on cardiorespiratory fitness and coronary risk reduction in stroke survivors. *Arch Phys Med Rehabil*. 2009; 90:407–412. [PubMed: 19254604]
16. Macko RF, DeSouza CA, Tretter LD, et al. Treadmill aerobic exercise training reduces the energy expenditure and cardiovascular demands of hemiparetic gait in chronic stroke patients: A preliminary report. *Stroke*. 1997; 28:326–330. [PubMed: 9040684]
17. Macko RF, Smith GV, Dobrovolsky CL, Sorkin JD, Goldberg AP, Silver KH. Treadmill training improves fitness reserve in chronic stroke patients. *Arch Phys Med Rehabil*. 2001; 82:879–884. [PubMed: 11441372]
18. Texeira da Cunha Filho I, Lim PAC, Qureshy H, Henson H, Monga T, Protas EJ. A comparison of regular rehabilitation and regular rehabilitation with supported treadmill ambulation training for acute stroke patients. *J Rehabil Res Dev*. 2001; 38:245–255. [PubMed: 11392657]
19. Macko R, Ivey FM, Forrester LW, et al. Treadmill exercise rehabilitation improves ambulatory function and cardiovascular fitness in patients with chronic stroke: A Randomized, Controlled Trial. *Stroke*. 2005; 36:2206–2211. [PubMed: 16151035]
20. Patterson SL, Rodgers MM, Macko RF, Forrester LW. Effect of treadmill exercise training on spatial and temporal gait parameters in subjects with chronic stroke: a preliminary report. *J Rehabil Res Dev*. 2008; 45:221–228. [PubMed: 18566940]
21. Jorgensen JR, Bech-Pedersen DT, Zeeman P, Sorensen J, Andersen LL, Schonberger M. Effect of intensive outpatient physical training on gait performance and cardiovascular health in people with hemiparesis after stroke. *Physical Therapy*. 2010; 90:527–537. [PubMed: 20203092]
22. Michael K, Goldberg A, Treuth M, Beans J, Normandt P, Macko R. Progressive adaptive physical activity in stroke improves balance, gait, and fitness: preliminary results. *Top Stroke Rehabil*. 2009; 16:133–139. [PubMed: 19581199]
23. Pang MYC, Eng JJ, Dawson AS. Relationship Between Ambulatory Capacity and Cardiorespiratory Fitness in Chronic Stroke. *Chest*. 2005; 127:495–501. [PubMed: 15705987]
24. Billinger SA, Mattlage AE, Ashenden AL, Lentz AA, Harter G, Rippee MA. Aerobic exercise in subacute stroke improves cardiovascular health and physical performance. *J Neurol Phys Ther*. 2012; 36:159–165. [PubMed: 23111686]
25. Damush TM, Plue L, Bakas T, Schmid A, Williams LS. Barriers and facilitators to exercise among stroke survivors. *Rehabil Nurs*. 2007; 32:253–260. [PubMed: 18065147]
26. Rimmer JH, Wang E, Smith D. Barriers associated with exercise and community access for individuals with stroke. *J Rehabil Res Dev*. 2008; 45:315–322. [PubMed: 18566948]

27. Hellstrom K, Lindmark B. Fear of falling in patients with stroke: a reliability study. *Clin Rehabil.* 1999; 13:509–517. [PubMed: 10588538]
28. Hellstrom K, Lindmark B, Wahlberg B, Fugl-Meyer AR. Self-efficacy in relation to impairments and activities of daily living disability in elderly patients with stroke: a prospective investigation. *J Rehabil Med.* 2003; 35:202–207. [PubMed: 14582550]
29. Salbach NM, Mayo NE, Robichaud-Ekstrand S, Hanley JA, Richards CL, Wood-Dauphinee S. The effect of a task-oriented walking intervention on improving balance self-efficacy poststroke: a randomized, controlled trial. *J Am Geriatr Soc.* 2005; 53:576–582. [PubMed: 15817001]
30. Jorgensen L, Engstad T, Jacobsen BK. Higher incidence of falls in long-term stroke survivors than in population controls: depressive symptoms predict falls after stroke. *Stroke.* 2002; 33:542–547. [PubMed: 11823667]
31. Lamb SE, Ferrucci L, Volapto S, Fried LP, Guralnik JM. Risk factors for falling in home-dwelling older women with stroke: the Women's Health and Aging Study. *Stroke.* 2003; 34:494–501. [PubMed: 12574566]
32. Feltz DL, Kerr NL, Irwin BC. Buddy up: the Kohler effect applied to health games. *J Sport Exerc Psychol.* 2011; 33:506–526. [PubMed: 21808077]
33. Hurkmans HL, Ribbers GM, Streur-Kranenburg MF, Stam HJ, van den Berg-Emons RJ. Energy expenditure in chronic stroke patients playing Wii Sports: a pilot study. *J Neuroeng Rehabil.* 2011; 8:38. [PubMed: 21756315]
34. Rizzo AA, Jounghyun Kim G. A SWOT analysis of the field of virtual reality rehabilitation and therapy. *Presence.* 2005; 14:119–146.
35. Duncan PW, Propst M, Nelson SG. Reliability of the Fugl-Meyer assessment of sensorimotor recovery following cerebrovascular accident. *Physical Therapy.* 1983; 63:1606–1610. [PubMed: 6622535]
36. Gladstone DJ, Danells CJ, Black SE. The fugl-meyer assessment of motor recovery after stroke: a critical review of its measurement properties. *Neurorehabil Neural Repair.* 2002; 16:232–240. [PubMed: 12234086]
37. Sullivan KJ, Tilson JK, Cen SY, et al. Fugl-Meyer assessment of sensorimotor function after stroke: standardized training procedure for clinical practice and clinical trials. *Stroke.* 2011; 42:427–432. [PubMed: 21164120]
38. Dettmann MA, Linder MT, Sepic SB. Relationships among walking performance, postural stability, and functional assessments of the hemiplegic patient. *Am J of Phys Med.* 1987; 66:77–90. [PubMed: 3578493]
39. Perry J, Garrett M, Gronley JK, Mulroy SJ. Classification of walking handicap in the stroke population. *Stroke.* 1995; 26:982–989. [PubMed: 7762050]
40. Evans MD, Goldie PA, Hill KD. Systematic and random error in repeated measurements of temporal and distance parameters of gait after stroke. *Arch Phys Med Rehabil.* 1997; 78:725–729. [PubMed: 9228875]
41. Richards CL, Malouin F, Dean C. Gait in stroke: assessment and rehabilitation. *Clin Geriatr Med.* 1999; 15:833–855. [PubMed: 10499938]
42. Fulk GD, Echternach JL. Test-retest reliability and minimal detectable change of gait speed in individuals undergoing rehabilitation after stroke. *J Neurol Phys Ther.* 2008; 32:8–13. [PubMed: 18463550]
43. Witmer BG, Singer MJ. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence-Teleop Virt.* 1998; 7:225–240.
44. Insko, BE. *Being There: Concepts, effects and measurement of user presence in synthetic environments.* Amsterdam: Ios Press; 2003.
45. Witmer BG, Slater CJ, Singer MJ. The factor structure of the presence questionnaire. *Presence-Teleop Virt.* 2005; 14:298–295.
46. American College of Sports Medicine. *ACSM's Guidelines for Exercise Testing and Prescription.* 9. Philadelphia, PA: Lippincott Williams & Wilkins; 2013.
47. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc.* 1982; 14:377–381. [PubMed: 7154893]

48. Butland RJ, Pang J, Gross ER, Woodcock AA, Geddes DM. Two-, six-, and 12-minute walking tests in respiratory disease. *Br Med J (Clin Res Ed)*. 1982; 284:1607–1608.
49. Ranky, R.; Sivak, M.; Lewis, JA.; Deutsch, JE.; Mavriodis, D. IEEE-VR. Waltham, Mass: IEEE; 2010. VRACK-virtual reality augmented cycling kit: design and validation; p. 4
50. Garber CE, Blissmer B, Deschenes MR, et al. American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. *Med Sci Sports Exerc*. 2011; 43:1334–1359. [PubMed: 21694556]
51. Katz-Leurer M, Shochina M, Carmeli E, Friedlander Y. The influence of early aerobic training on the functional capacity in patients with cerebrovascular accident at the subacute stage. *Arch Phys Med Rehabil*. 2003; 84:1609–1614. [PubMed: 14639559]
52. Lennon O, Carey A, Gaffney N, Stephenson J, Blake C. A pilot randomized controlled trial to evaluate the benefit of the cardiac rehabilitation paradigm for the non-acute ischaemic stroke population. *Clin Rehabil*. 2008; 22:125–133. [PubMed: 18212034]
53. Eng JJ, Dawson AS, Chu KS. Submaximal exercise in persons with stroke: test-retest reliability and concurrent validity with maximal oxygen consumption. *Arch Phys Med Rehabil*. 2004; 85:113–118. [PubMed: 14970978]

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

Figure 2. Virtual Environment (VE): Rider on the right uses exercise intensity based on his measured heartrate to catch the pacer ahead on the left. The rider's trajectory in the VE is displayed in the right upper corner. Copyright Rivers Lab

Figure 3.
Average Training Time For each subject

Figure 4. Peak VO_2 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ tested prior (pre) to and after (post) the conclusion of 8 weeks of training.

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; VO₂: oxygen consumption; RPE: rate of perceived exertion.