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Single Limb Exercise: Pilot Study of Physiological and Functional Responses to Forced Use of the Hemiparetic Lower Extremity

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Abstract

Purpose—Stroke-related deficits can impede both functional performance and walking tolerance. Individuals with hemiparesis rely on the stronger limb during exercise and functional tasks. The single limb exercise (SLE) intervention was a unique training protocol that focused only on the hemiparetic limb. Our objective was to determine the effect of the SLE intervention on cardiorespiratory fitness parameters.

Methods—Twelve participants (5 male) with a mean age of 60.6 ± 14.5 years and 69.1 ± 82.2 months post stroke participated in the training intervention. All participants performed SLE using the hemiparetic leg three times a week for 4 weeks. The nonhemiparetic limb served as the control limb and did not engage in SLE. Peak oxygen uptake (VO_2 peak) and oxygen uptake (VO_2) were measured at baseline and post intervention in all 12 participants. At pre and post intervention, gait velocity was assessed in a subset of participants ($n = 7$) using the 10-m fast-walk test.

Results—After the 4-week SLE training intervention, significant improvements were found for VO_2 during submaximal work effort ($P = .009$) and gait velocity ($n = 7$) ($P = .001$). Peak oxygen uptake did not increase ($P = .41$) after the training intervention.

Conclusion—These data suggest that SLE training was an effective method for improving oxygen uptake and reducing energy expenditure during submaximal effort. Unilateral exercise focused on the hemiparetic leg may be an effective intervention strategy to consider for stroke rehabilitation.

Keywords

exercise; hemiparesis; oxygen consumption; stroke

Stroke-related deficits can impede both functional performance (ie, walking) and exercise tolerance.^{1–4} Musculoskeletal and cardiorespiratory impairments are often present early post stroke. A sedentary lifestyle and various secondary effects, such as an overexpression of fatigable type II muscle fibers,^{5,6} lean tissue atrophy,^{7,8} and higher energy expenditure during activities,^{3,9} increase the risk for decline in cardiorespiratory fitness. According to Shephard,¹⁰ a minimum fitness capacity of $15 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ is needed to perform functional activities for independent living. His work illustrates an important relationship between cardiorespiratory fitness and the energy requirements needed for daily activities. For people post stroke, compromised cardiorespiratory fitness^{3,9,11–14} may diminish recovery of functional activities^{15–17} and affect quality of life.^{18,19}

In response to the wide range of neuromotor dysfunction after stroke, rehabilitation research has attempted to identify exercise strategies to improve motor control,^{20–22} functional performance,^{20–23} and cardiorespiratory fitness.^{3,9,20,23} Aerobic exercise training is one method that has been used in an attempt to maximize stroke recovery. In people post stroke, many studies have reported benefits related to aerobic exercise and cardiorespiratory health.^{3,9,20,23} Recently, improvements in cardiorespiratory fitness have been reported after a short duration (4 weeks) of aerobic exercise training.²⁴

However, several challenges exist for individuals post stroke with the traditional modes of exercise (ie, walking or upright cycling^{25,26}). Studies have reported that exercise using bilateral lower extremity movement may impede both functional^{5,26,27} and physiological performance⁵ of the hemiparetic limb after stroke. Specifically, in a study by Landin and colleagues, individuals with chronic stroke cycled at a submaximal workload for 40 minutes.⁵ During the exercise session, 65% more work was generated with the non-hemiparetic limb. This reduces the amount of work performed by the hemiparetic limb and increases fatigability in the stronger limb.^{25,28} Not only do individuals post stroke prefer to use the non-hemiparetic limb during exercise but also during functional activities such as ambulation and transfers.^{29–32}

With such a strong tendency to use the non-hemiparetic limb, the feasibility and effectiveness of training interventions that encourage use of the hemiparetic leg should be explored.²⁶ Currently, research provides evidence that task-specific unilateral activities improve motor function in the hemiparetic upper extremity.^{33–38} For example, constraint-induced movement therapy (CIMT) or modified CIMT has been utilized to “force” individuals to use their affected limb to improve motor function. Forced-use therapeutic interventions such as CIMT for the lower extremity are cumbersome for functional activities.²⁶ However, exercise training focused on encouraged use of the hemiparetic lower extremity may be an advantageous therapeutic intervention for increasing cardiorespiratory fitness and functional outcomes.

One lower extremity intervention that could simulate the forced-use concept in the hemiparetic leg is single limb exercise (SLE). In healthy adults, SLE has been one method for assessing cardiorespiratory performance and peripheral cardiovascular function using a knee extension/ flexion protocol^{39,40} or a cycle ergometer.^{41–49} For healthy adults participating in the SLE training intervention, improvements in cardiorespiratory fitness and

peripheral physiological parameters such as oxygen uptake, muscle blood flow, and citrate synthase activity were reported in the trained leg.^{40,42,44,46,47,50} Based on the evidence in healthy adults that 5 to 6 weeks of SLE would elicit significant improvements in VO_2 peak^{41,42,46} and the potential for decreased work performed by the hemiparetic leg during bilateral cycle training,^{5,26} we decided to explore the feasibility of using a 4-week SLE training intervention to improve cardiorespiratory fitness after stroke.

The purpose of this pilot study was to determine the effect of SLE on central and peripheral cardiorespiratory fitness outcome measures. It was hypothesized that after 4 weeks of SLE training (a) a significant increase in VO_2 peak values during the graded maximal exercise test and (b) a significant decrease in oxygen uptake (VO_2) during SLE would be observed when compared to baseline values.

The initial five participants self-reported improved walking after the SLE intervention. Therefore, we added a secondary purpose to determine whether the SLE training could affect a functional task such as walking speed. In a subset of participants, the 10-m fast-walk test^{22,23} was chosen as the outcome measure. It was hypothesized that significant improvements in walking time would be observed after the training intervention.

Methods

Participants

Twelve participants with chronic stroke (5 male) 69.1 ± 82.2 months post stroke completed this within-subject design study (see Table 1 for baseline demographics). A subset of these participants ($n = 7$) performed a 10-m fast-walk test.

Inclusion criteria included (a) a diagnosis of hemiparesis from a stroke at least 6 months previously confirmed by clinical assessment⁵¹; (b) the ability to transfer from a sitting to standing position with minimal assist; (c) the ability to walk 10 m independently with or without an orthotic or assistive device; (d) mild to moderate stroke deficits defined by a lower extremity Fugl-Meyer score (LEFM) score from 20 to 33/34⁵²; (e) ability to extend and flex the knee joint a minimum of 35° with movement against gravity (Shoemaker and colleagues used 35° of active knee extension/flexion, which was shown to be sufficient during SLE to elicit an increase in blood flow^{40,53} and oxygen uptake kinetics.⁴⁰); and (f) medical clearance from the primary care physician for exercise testing. Exclusion criteria consisted of the following: (a) recent hospitalization with new diagnosis or severe cardiopulmonary conditions, (b) currently smoking, (c) type 1 or 2 diabetes, (d) current participation in SLE or physical therapy, (e) peripheral vascular disease ($\text{ABI} < 0.40$) or known stenosis of the lower extremity vessels, (f) prescribed alpha-adrenergic vasodilators that improve peripheral vasodilation, and (g) a difference $\geq 2\%$ for baseline Doppler ultrasound measures regarding femoral artery diameter and blood flow velocity between the hemiparetic and non-hemiparetic limbs. Results for vascular outcome measures are reported elsewhere.⁵³

A power analysis was not performed *a priori*. Our sample size was based on previous work that reported a sample size of 9 was needed to determine a moderate effect of functional

electrical stimulation (FES) and cycle ergometry on limb blood flow in individuals with spinal cord injury.⁵⁴ Because limb blood flow was the primary outcome measure for the overall project,⁵³ we chose to recruit 15 individuals to allow for attrition. Institutionally approved informed consent was obtained in writing prior to participation in the study.

Intervention

SLE using the Biodex System 3 (Biodex Medical Systems, Inc., Shirley, New York) involved only the hemiparetic limb (Figure 1). The knee attachment unit was used for the isokinetic extension/flexion protocol. During the initial training session, adjustments were made for leg length, chair height, and trunk support. These values were recorded and used for consistency with positioning during exercise sessions. Once this was completed, the trunk support straps, hip stabilization strap, and leg strap were properly placed to limit any compensatory movements from the hip or trunk in an effort to assist the hemiparetic leg.⁵⁵

No studies are available to suggest a valid protocol as an exercise intervention using SLE to improve aerobic performance in individuals post stroke. Several studies^{4,55,56} have suggested that $60^{\circ} \cdot s^{-1}$ is most appropriate for assessing knee extension/flexion strength in people post stroke. We were not interested in a strength-training protocol, so we believed that participants in our study would not maintain the $60^{\circ} \cdot s^{-1}$ pace intensity for an extended length of time. Initial testing in our lab revealed $120^{\circ} \cdot s^{-1}$ was still too difficult to maintain. However, pilot data suggested that the SLE protocol using $150^{\circ} \cdot s^{-1}$ was well-tolerated by participants with stroke. In addition it was a feasible training intervention, which provided less resistance and avoided significant gains in muscle strength. Therefore, an isokinetic extension/flexion protocol at $150^{\circ} \cdot s^{-1}$ for 40 repetitions per set with 30-second rest breaks in between each set was used. The participants were instructed to self-progress their exercise training with the goal of reaching 40 sets. Participants exercised at an intensity of 60% to 70% of maximal heart rate (determined by maximal effort exercise test) for the duration the exercise intervention period, which was three times per week for 4 weeks. Ten seconds prior to the end of each exercise interval, heart rate was assessed at the radial pulse. In addition, at the end of each exercise interval, the participant was asked whether “he/ she felt the exercise was too easy, moderately hard but tolerable and could continue or too hard and needed to stop.” To our knowledge, the SLE protocol has not been used in people post stroke, so we chose to use a simple method to guide exercise progression through the protocol. Each exercise session lasted 60 to 90 minutes. This allowed for pre- and postexercise stretching, patient set-up, and the exercise session. As a safety precaution, participants were educated for breathing techniques and to avoid a valsava maneuver during the exercise sessions.

Baseline and Postintervention Assessments

Maximal exercise test—Participants performed a maximal effort graded exercise test at baseline and after the exercise intervention to assess cardiorespiratory fitness (VO_2 peak). Participants were instructed not to consume food, caffeine, or alcohol for 3 hours prior to exercise testing⁵⁷ but were allowed to hydrate with water ad libitum. Height, weight, and resting heart rate and blood pressure were obtained prior to exercise testing. Participants were familiarized to the testing protocol prior to the exercise test. The maximal effort exercise test used a total body recumbent stepper (TBRS; NuStep, Inc, Ann Arbor,

Michigan) and the modified TBRS exercise test (mTBRS-XT) as described previously.²⁵ A metabolic cart (Parvomedics, Sandy, Utah) was used to continuously collect and analyze expired gases through a two-way rebreather valve (Hans Rudolph, Inc, Kansas City, Missouri). The metabolic cart was set to a 30-second averaging of the data collected for the sampling technique. Before exercise testing, all equipment was calibrated according to the manufacturer's recommendations.

During the exercise test, an exercise physiologist and physician continuously monitored heart rate and rhythm with a 12-lead electrocardiogram (ECG). Every 2 minutes during the test, heart rate (HR), blood pressure (BP), and rating of perceived exertion (RPE) using Borg's 6–20 scale were recorded. Test termination criteria for VO_2 peak were identical to those used previously²⁵: (a) participant reached volitional fatigue and requested to end the test, (b) the participant's VO_2 peak plateaued or decreased despite continuation of exercise, (c) the participant was unable to maintain the stepping rate, or (d) a respiratory exchange ratio (RER) > 1.10. If an adverse cardiovascular event or response to the exercise test was observed, the test would be terminated.

Submaximal exercise—Oxygen uptake (VO_2) was assessed during submaximal effort on Day 1 and Day 12 (final training session) of SLE training. The session was conducted using the SLE training protocol and the metabolic cart with open circuit spirometry to analyze gas exchange. VO_2 and HR were the variables of interest for submaximal performance. To assess oxygen uptake during a steady state performance, HR needed to be within 5 beats $\cdot \text{min}^{-1}$ of each other at 3 and 5 minutes of exercise during the isokinetic SLE protocol. Values for oxygen uptake at the 3- and 5-minute time point were averaged and recorded at baseline and post intervention. Visual feedback from the Biodex was used to gauge force production during SLE. Because the protocol was isokinetic, muscle force generated by the hemiparetic leg was variable with each contraction. Mean values for force production (ft-lbs) from baseline submaximal performance were calculated. Individuals were then instructed to exert the same force during posttest exercise.

10-Meter Fast Walk Test—The 10-m fast-walk test was chosen to assess gait velocity.^{21,22} Participants were instructed to perform a fast walk with their usual walking device.²² The participant's time was recorded for the middle 10 m of the 12-m walkway. A brief rest was given in between trials. Three trials were performed, and the average was recorded for data analysis.

Secondary Outcome Measures

Body composition, lower extremity force production, and motor performance

—Lean tissue mass and knee extensor strength was assessed pre and post intervention to ensure that the SLE protocol was an aerobic training intervention not resistive in nature to induce significant strength gains and that increased oxygen consumption was not the result of increased lean tissue in the leg. In addition, pre and post intervention, the LEFM was used to assess motor performance. This ensured that the training protocol did not elicit deleterious effects in the hemiparetic lower extremity.

Total body scans were performed using the DEXA (GE Lunar, Madison, Wisconsin) with participants in the supine position. Participants avoided food or water consumption 3 hours prior to the scan. An overnight fast was not performed; the DEXA and maximal effort exercise test were completed at the same session. Lean tissue and fat mass values of the lower extremities were obtained from both limbs. Tissue composition in grams was calculated from the region of the greater trochanter to the foot.

Bilateral knee extension muscle strength was measured prior to the start of the exercise intervention. Using the Biodex, an isokinetic knee extension protocol at $60^\circ \cdot \text{s}^{-1}$ was chosen based on the available literature for stroke.^{4,56} The system was calibrated and participant set-up was completed according to the manufacturer's recommendations. Testing was performed within the participants' available active range of motion. Participants were familiarized with the movement without resistance and to the strength test protocol prior to the test. The less affected leg was tested first and then the hemiparetic limb. Participants were asked to give a maximal effort for three consecutive knee extension movements to assess quadriceps strength. The mean peak torque (from the three trials) was generated by the Biodex system analysis. Strength data were collected at baseline and post training.

Statistical Analysis

Two-tailed paired *t* tests were used to detect whether significant differences existed after the intervention when compared to baseline values. Our secondary outcome measures of interest were muscle strength, body composition, and LEFM scores. An effect size (ES) was calculated to assess a real and meaningful difference between pre and post measures for VO_2 , 10-m fast-walk test, and the LEFM.⁵⁸ All statistical analyses were conducted using SPSS 16.0 (SPSS, Inc, Chicago, Illinois). Alpha was set at 0.05 to detect significance.

Results

Twelve individuals completed the SLE training intervention without adverse events. Seven of the 12 participants completed all training sessions. Five individuals completed 92% (11 out of 12) of the SLE training sessions. (see Table 3).

Cardiorespiratory Fitness

SLE training did not elicit significant improvements in VO_2 peak during a maximal effort graded exercise test (baseline: $19.3 \pm 2.0 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ vs post-intervention: $19.0 \pm 2.2 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$; $P = .41$). No significant changes were found for peak HR, respiratory exchange ratio (RER), and RPE. Eight of 12 participants reached 90% of age-predicted maximal HR during the baseline exercise test and 9 of 12 met the criteria at post exercise test, which suggest maximal effort was given by the majority of participants. No significant group differences were found between age-predicted maximal HR ($220 - \text{age}$) and peak HR from the exercise test at baseline ($P = .36$) or at post test ($P = .59$). Physiological responses during steady state submaximal exercise improved after the SLE intervention. VO_2 during SLE significantly decreased post training when compared to baseline values ($5.5 \pm 1.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ vs $4.1 \pm 1.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$; $P = .02$); representing a 24.3% decrease in energy expenditure during the exercise session. A large effect size (ES) of 0.84 suggests a

meaningful difference between the amount of change from baseline to post training⁵⁸ (Table 2).

10-Meter Fast Walk Test

The results of the 10-m fast-walk test indicated that after the 4-week SLE training, individuals ($n = 7$) were able decrease their walk time from 1.18 ± 0.6 to $1.35 \pm 0.6 \text{ m} \cdot \text{s}^{-1}$ ($P = .001$), a 13.8% increase in gait velocity. A small to moderate ES of 0.386 was found, which indicates that there was a meaningful difference between pre- and posttraining gait velocity.

Body Composition, Lower Extremity Force Production, and Motor Performance

No significant changes were observed in either limb for knee extensor strength. Knee extensor peak torque generated for the hemiparetic limb was increased but was not significantly different baseline and post training. No significant differences for the non-hemiparetic limb were observed after the training intervention. Knee extensor strength for the hemiparetic limb was significantly lower ($P = .003$) at baseline than the non-hemiparetic limb. A significant difference ($P = .018$) between the two limbs remained post intervention (see Table 2 for results).

At baseline, no significant differences were found between the less affected and hemiparetic leg for fat mass ($P = .11$). A significant difference ($P = .05$) in lean tissue mass was found between the two limbs. After the training period, no significant changes ($P > .12$) in lean muscle tissue or fat mass were reported for either limb (see Table 2). However, post SLE training, no significant difference ($P = .058$) in lean tissue between the limbs was found.

LEFM scores significantly improved after the training intervention (baseline: 27.2 ± 3.5 to post-training: 28.7 ± 4.8 ; $P = .007$). A moderate ES of 0.461 indicates a meaningful difference⁵⁸ between the amount of change that was associated with SLE from pre- to postintervention LEFM scores.

Discussion

A study on the effects of a 4-week SLE training intervention that focused on the hemiparetic leg was conducted to determine whether improvements would be observed in (a) VO_2 peak at maximal effort of a graded exercise test, (b) VO_2 at submaximal effort during SLE, and (c) the 10-m fast-walk test in a subset ($n = 7$) of individuals. After 4 weeks of SLE training, VO_2 peak during a maximal effort exercise test did not improve after the training intervention. Oxygen uptake (VO_2) during SLE at submaximal effort was significantly lower than baseline. In our previous work, we reported that SLE training improved resting blood flow and arterial diameter in people with stroke.⁵⁹ The increased blood flow to the limb may enhance oxygen uptake in the hemiparetic limb. This may be attributed to peripheral mechanisms such as efficiency of oxygen extraction, greater oxygen delivery via increased blood flow, or vascular dilation⁶⁰ rather than central cardiovascular changes (ie, larger cardiac output). At the end of the intervention, we found that participants ($n = 7$) decreased their time to complete the 10-m fast-walk test.

The American College of Sports Medicine (ACSM)⁵⁷ states that improvements in aerobic fitness can occur as a result of exercise training when the heart rate response is lower at fixed workload over a period of time. Previous research conducted in healthy individuals demonstrates that “repeated bouts of exercise”⁶¹ such as SLE can produce a training effect such as decreased VO_2 ⁵⁰ or heart rate^{44,50} while improving cardiac output⁴⁴ (via increased stroke volume) at submaximal workloads. It is known from previous work^{3,9} that people with stroke can improve energy expenditure after a treadmill training intervention. Our findings support previous work^{3,9} for a reduction in VO_2 and HR during submaximal effort, but the mechanisms for these cardiorespiratory changes warrant further research. Our work adds to the current stroke rehabilitation literature to include a forced-use exercise training intervention (ie, SLE) focused on the hemiparetic limb. Our study is unique because VO_2 was measured during SLE involving the hemiparetic limb pre and post intervention. This pilot work suggests that steady state HR can be reached even when submaximal work is focused on the hemiparetic limb. We suggest that economy of movement⁶² improved during a specific motor activity such as SLE as demonstrated by the decreased oxygen uptake at specific time points. However, these results should be interpreted with caution because our SLE protocol did have 30-second rest breaks in between each set. Although HR was within ± 5 beats⁵⁷ at the two designated time points as recommended, the rest breaks may have influenced heart rate. We found that individuals post stroke with mild to moderate lower extremity hemiparesis can tolerate an intensive, forced-use exercise protocol. Future work that assesses steady state VO_2 during unilateral activity should choose a continuous protocol.

The 10-m walk test is used to assess gait velocity because of its simplicity and recognition as a useful tool in research and rehabilitation.⁶³ In our participants, the improvements in gait velocity could be attributed to decreased energy demand by the hemiparetic limb during walking. Assessment of VO_2 during SLE showed decreased energy expenditure at submaximal workloads. Similarly, the improved peripheral mechanisms of oxygen exchange could result in greater intensity (walking more quickly) while participants perceived less exertion. Certainly, the concept of forced use of the hemiparetic limb during an intense training intervention could result in improved walking speed. Although, it should be noted that the training strategy used in the present study is not task specific such as a walking activity.²² However, for the seven participants who performed the 10-m walk test, increases in gait speed were observed only after 12 training sessions. Anecdotally, participants in the current study reported that the affected limb did not “feel as tired.” The available literature suggests that lower extremity muscle strength can play an important role in walking speed.^{22,64,65} However, the results of the current study demonstrate that improvements in gait speed can be obtained from a training intervention that performs high repetition of knee extension/flexion of the hemiparetic limb without task specificity and significant improvements in lower extremity strength or muscle mass. Further work needs to be completed to determine how this type of training influences gait speed. In addition, a more complete assessment of walking performance such as the 6-minute walk test would provide information for endurance-related activities.

Another potential explanation for increased gait velocity during the 10-m fast-walk test could be related to motor performance. LEFM scores increased from baseline, which may be

the result of repetitive exercise using knee extension/flexion. Recent studies suggest that task-repetitive training such as walking with or without body weight support elicits positive outcomes in cardiorespiratory fitness²³ and functional mobility.^{22,23,64,65} Our study included a repetitive task (knee extension/flexion), but the training protocol focused on encouraged use of the hemiparetic limb. As mentioned by Lang and colleagues, the difference between the animal and human model for stroke recovery may be related to the amount of practice or repetition of an activity.⁶⁶ In our study, the lowest number of knee extension/flexion repetitions by an individual was 120 per session and the highest was 1,600. The mean number of repetitions performed during the 4-week training protocol was 899.4. It has been reported that a high number of repetitions can induce neuroplastic changes.^{67,68} Although we did not use a task-specific activity, a moderate ES of 0.46 and a statistically significant increase in LEFM scores were found post SLE. However, it is unclear if a 2-point change in LEFM has clinical relevance. Therefore, we are uncertain whether the improvements in walking speed occurred as a result of improved economy of movement after the intervention or from repetitive nature of the SLE protocol. We believe this topic warrants further investigation to examine the physiological mechanisms behind the cardiovascular and functional changes in the hemiparetic limb.

Previous literature suggests that improvements in VO_2 peak using bilateral lower extremities can be observed after SLE in healthy adults.^{42,44,50} In the previous studies using healthy adults, the unilateral protocol used a training intensity at 80% of VO_2 max and a duration of 6 to 8 weeks. The data from this study suggest contradictory results, which may be the difference in the training intensity, duration, or participant population used in our study. Despite recent findings that suggest 4 weeks may be sufficient for improving maximal VO_2 ,²⁴ our unilateral training protocol may not have been adequate to detect differences in VO_2 max. Our participants maintained an exercise intensity at 70% of peak HR. Perhaps a higher training intensity such as 75% or 80% of peak HR or the Karvonen method for exercise prescription would have been preferential. Davies and colleagues used SLE as a training intervention to assess central and peripheral cardiovascular responses to one and two leg exercise in healthy adults.⁴² The authors stated that a central component of the cardiovascular system (ie, cardiac output) is sufficient to provide adequate oxygen uptake to the working muscles during SLE, but the peripheral factors such as oxygen utilization limit continued exercise. Bilateral exercise places a greater demand on the cardiovascular system whereby cardiac output will not be able to meet the continued work demands and supply enough blood to exercising muscles. In addition, we used a total body recumbent stepper to assess VO_2 peak, which has implications to our findings. This device used all four extremities during exercise testing, which may not have been sensitive enough to detect cardiorespiratory fitness changes related to the SLE protocol. However, because no data were available for using one-legged maximal exercise testing in people post stroke and the potential safety concerns for overloading the limb at maximal effort were not determined, we chose to use an exercise test that was safe and feasible in this population.²⁵

This pilot study was, to our knowledge, the first study to examine the effects of a forced-use exercise protocol (SLE) on cardiovascular fitness, body composition, and functional performance in people post stroke. In our previous work and in this study, we used the nontrained limb as the control limb for assessing outcome measures. However, we realize

for comparing oxygen uptake during submaximal and maximal effort, a control group would have been preferred to determine the benefit of using an SLE training protocol. Our future work will include a larger sample size, and participants will be randomized into a usual care intervention (control group) and SLE training so that meaningful comparisons can be made between training interventions for outcomes related to functional performance and cardiovascular function. Additional research is needed to examine the physiological mechanisms (ie, oxygen extraction, increased capillary density, or vascular function) at rest and during exercise that can contribute to changes cardiorespiratory fitness.

Conclusion

In physical therapy practice and stroke rehabilitation research, exercise interventions and task-specific training incorporate both lower extremities.^{3,9,13,14,18,22,23,69–71} This study examined the effect of a novel training strategy that encouraged use of the hemiparetic limb in people with stroke. The time course and intensity of the training intervention appear sufficient for improving VO_2 during submaximal work efforts and gait velocity (10-m fast walk). However, VO_2 peak from a maximal effort exercise test did not improve after 4 weeks of training. This pilot study clearly illustrates the need for future research to determine the effect of SLE in a broad spectrum of stroke survivors and in comparison to bilateral exercise interventions.

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Figure 1.
Participant engaging in single limb exercise (SLE).

Table 1

Participant demographics

Characteristics n = 12	Mean $\pm$ SD	Range
Male gender, n	5	
Age, years	60.6 $\pm$ 14.5 43–77	43–77
<i>Race/ethnicity</i>		
African American	2	
Caucasian	8	
Hispanic	1	
Native American	1	
Body Mass Index (DEXA scan)	29.7 $\pm$ 4.0	
<i>Medication</i>		
Beta blockers	4	
<i>Stroke characteristics</i>		
Time poststroke, months	69.1 $\pm$ 82.2	6–276
Right side weakness	5	
Type of stroke:		
Ischemic	9	
Hemorrhage	3	
<i>Stroke severity</i>		
LE Fugl-Meyer score (34 maximum)	26.7 $\pm$ 3.8	20–32

Note: DEXA = dual-energy x-ray absorptiometry; LE = lower extremity.

Table 2

Outcome measures at baseline and post training (after 12 exercise sessions)

	Baseline	Post training	<i>P</i> value
Cardiorespiratory fitness			
<i>Maximal effort</i>			
VO ₂ peak, mL • kg ⁻¹ • min ⁻¹	19.3 ± 6.9	19.0 ± 7.5	.413
Peak HR, bpm	136.5 ± 21.9	139.2 ± 21.8	.720
RER	1.1 ± 0.10	1.1 ± 0.15	.893
RPE	16 ± 2.61	17 ± 2.83	.306
<i>Submaximal effort</i>			
VO ₂ , mL • kg ⁻¹ • min ⁻¹	7.0 ± 1.6	5.4 ± 1.5	.009*
HR, bpm	85.5 ± 16.6	80.6 ± 13.7	.046*
Workload, Watts	39.0 ± 20.5	41.4 ± 14.1	N/A
Strength			
<i>Peak LE extensor torque, ft-lbs</i>			
Hemiparetic leg	53.3 ± 36.4**	59.5 ± 34.1	.060
Less affected leg	82.3 ± 35.0	78.6 ± 37.8	.186
LE tissue composition			
<i>Fat mass, g</i>			
Hemiparetic leg	5433.8 ± 2173.3	5582.2 ± 2246.0	.118
Less affected leg	5582.2 ± 2246.0	5731.1 ± 2441.1	.237
<i>Lean tissue mass, g</i>			
Hemiparetic leg	7380.4 ± 1723.3	7317.5 ± 1587.8	.563
Less affected leg	7584.0 ± 1910.6	7527.4 ± 1691.3	.650
LE motor function			
10-m fast walk, m • s ⁻¹ (n = 7)	1.18 ± 0.6	1.35 ± 0.6	.001*
LE Fugl-Meyer score	26.7 ± 3.8	28.7 ± 4.8	.007*

Note: Values are reported as mean ± SD. VO₂ = oxygen uptake; HR = heart rate; bpm = beats per minute; RER = respiratory exchange ratio; RPE = rate of perceived exertion; LE = lower extremity.

* *P* .05 from baseline to post training.

** *P* .05 between the hemiparetic and less affected limb.