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Decreased Tidal Volume May Limit Cardiopulmonary Performance during Exercise in Subacute Stroke

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Abstract

PURPOSE—The aim of this retrospective study was to determine whether pulmonary function was reduced at submaximal and peak exercise in subacute stroke (SG) when compared to sedentary adults (CON).

METHODS—Ten individuals with subacute stroke and 10 sedentary, age- and gender-matched adults performed cardiopulmonary exercise testing (CPET) using a recumbent stepper. We used independent t-tests to determine between-group differences at peak effort. We used repeated measures analysis of variance with Test Minute (minutes 1-6) as the within subject factor and Group (SG, CON) as the between subject factor to assess cardiopulmonary submaximal performance.

RESULTS—SG had significantly lower values ($P < .05$) for oxygen uptake, minute ventilation (VE) and tidal volume (Vt) compared to CON at peak effort of the CPET. During CPET submaximal effort, we report a significant main effect for Test Minute and Group for Vt and respiratory rate (RR) but no main effect of Group for VE. To maintain adequate VE during submaximal effort and decreased Vt, higher RR was observed.

CONCLUSIONS—These results suggest that diminished Vt in subacute stroke patients may limit performance during submaximal and peak effort of CPET. Rehabilitation professionals should consider methods for improving pulmonary function during stroke rehabilitation.

Keywords

exercise test; cerebrovascular accident; pulmonary function

It is well-known that peak oxygen uptake ($\dot{V}O_2$) is diminished after stroke when compared to apparently healthy individuals who are age- and gender-matched.^{1,2} Lower peak $\dot{V}O_2$

values have significant implications for performance of activities of daily living (ADLs).^{3,4} For example, individuals post-stroke tend to work at a higher energy expenditure compared to apparently healthy individuals during normal activities such as dressing, grooming and walking.³ Further, lower peak $\dot{V}O_2$ values result in less “physiologic reserve”, or the physiologic capacity to increase $\dot{V}O_2$ during activities.³ There are several physiologic systems that could potentially contribute to low peak $\dot{V}O_2$ in patients after a stroke including decreased cardiac function,⁵ skeletal muscle atrophy^{1,2,6,7} in the affected limb(s), and/or poor pulmonary mechanics.^{1,8}

Seminal work by Haas and colleagues showed that insufficient pulmonary function in people with hemiplegia stemmed from deficits in respiratory mechanics.⁸ Decreased pulmonary diffusing capacity and decreased diaphragmatic excursion during inspiration was found in people with hemiplegia compared to controls. Therefore, vital capacity, inspiratory capacity and expiratory reserve volume were below normal levels. Further, they reported that with poor breathing mechanics, air may move through the lungs less efficiently, resulting in greater residual volume in both men and women with hemiplegia.⁸ Several studies have demonstrated that pulmonary function is diminished in people with chronic stroke,^{9,10} with inspiratory capacity worsening within 6 months post-stroke.⁹ Tomczak and colleagues reported significant differences in minute ventilation (VE) and tidal volume (Vt) in chronic stroke patients compared to apparently healthy controls at peak exercise⁵, and our previous work has shown that VE was a significant predictor of peak $\dot{V}O_2$ in chronic stroke.¹¹ In a recent study in subacute stroke, we demonstrated that an 8-week aerobic exercise program improved peak $\dot{V}O_2$.¹¹ However, values for VE were almost identical to pre-exercise training. This suggests that pulmonary function may not respond to traditional aerobic exercise training, potentially blunting the training response that can be realized. Therefore, the goal of this study was to characterize pulmonary function in subacute stroke (SG; stroke group) during a cardiopulmonary exercise testing (CPET) and determine whether pulmonary function was impaired when compared to sedentary age- and gender-matched adults (CON; controls). Our secondary goal was to explore ventilatory efficiency between SG and CON using the oxygen uptake efficiency slope (OUES). First, we hypothesized that the SG would have significantly lower values for: (1) VE, (2) Vt, and (3) respiratory rate (RR) at peak exercise compared to CON. Secondary outcomes from the exercise test at peak effort were $\dot{V}O_2$, heart rate (HR) and respiratory exchange ratio (RER). Second, we hypothesized that SG would have lower values in VE and Vt and higher RR during submaximal effort compared to CON. Finally, for our exploratory goal, we hypothesized that the OUES at 50% and peak effort would be lower in SG compared to CON.

METHODS

Study Design

This was a retrospective study design. All study participants were enrolled into an exercise intervention^{11,12} but only baseline exercise testing data was used for the current analysis. The Human Subjects Committee at the University of Kansas (KU) Medical Center approved

the respective study protocols and all individuals previously signed institutionally approved consent prior to their study participation.

Participants

Data from 10 participants in the subacute stage of stroke recovery were used for this data analysis.^{11,13} The CON was 10 community-dwelling, age- (± 5 years) and gender-matched sedentary¹⁴ individuals who were identified from the Alzheimer's Prevention Program at the KU Alzheimer's Disease Center. We also gathered information regarding height, weight and medications since these variables could potentially affect exercise testing performance. Information regarding motor impairment from stroke was assessed using the Fugl-Meyer Assessment.¹⁵ The inclusion and exclusion criteria for each study have been reported previously.^{11,12} All exercise testing for the SG and CON was conducted at the KU Clinical and Translational Science Unit and supervised by a medical monitor. Exercise testing was performed for the SG and CON by the same research study staff. We used the NuStep T5XR recumbent stepper (NuStep, Inc., Ann Arbor, Michigan) and the mTBRS-XT protocol¹⁶ for both the SG and CON. Our methods for exercise testing have been previously published.^{11,16} Briefly, the mTBRS-XT protocol is a 2-minute incremental exercise test that begins at 25 watts and increases by 15 watts per stage until test termination criteria are met. We asked participants to maintain a step rate of approximately 80 steps per minute. $\dot{V}O_2$ was measured and analyzed through collection of ventilatory expired gases using the ParvoMedics metabolic measurement system (Parvomedics Inc., Sandy, UT). Calibration procedures for the metabolic measurement system followed manufacture recommended protocols, using gases with known concentrations and a 3-L syringe. Our primary ventilatory measures of interest during peak effort included $\dot{V}E$ ($L \cdot \min^{-1}$), V_t (L) and RR (breaths $\cdot \min^{-1}$). Secondary measures at peak effort included $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot \min^{-1}$), HR and RER. During submaximal effort of the exercise test, we examined data at each minute (minutes 1-6) for $\dot{V}E$, V_t and RR. We chose minutes 1-6 because all participants completed 6 minutes of the exercise test. We calculated the OUES relative to body weight (OUES/kg) at peak effort and 50% of peak effort. The OUES is derived from the following linear least squares regression formula relating $\dot{V}O_2$ and $\dot{V}E$: $\dot{V}O_2 = a * \log_{10} \dot{V}E + b$, where b is the intercept, and the slope, a , is the OUES.¹⁷ Thus, the OUES represents the rate at which $\dot{V}O_2$ changes in response to each 10-fold increase in $\dot{V}E$.^{17,18}

Data Analysis

Independent t-tests were conducted to assess between group differences in our demographics and outcome measures at peak exercise effort. Submaximal performance during the exercise test was assessed using a repeated measures analysis of variance (ANOVA), with Test Minute (minutes 1-6) as the within subject factor and Group (SG, CON) as the between subject factor. All analyses were conducted using SPSS statistical software (Version 20; SPSS, Inc, Chicago, IL) with the alpha level .05.

RESULTS

Table 1 lists demographic data for the SG and CON. No between group differences were found for age, height, and weight. Data regarding motor impairment for the SG is also listed

in Table 1. One participant in the SG had a severe motor impairment with a score less than 50, while 2 participants were considered to have marked motor impairments (score 50-84).¹⁵ The remaining SG participants (n = 7) had scores greater than 99. Scores in the range of 96-99 are defined as slight motor impairment.¹⁵ Therefore, based on scores higher than 99, we would expect that these individuals may not have had noticeable motor deficits.

Peak Exercise Performance

We report that at peak effort, $\dot{V}E$ and V_t were significantly lower in the SG when compared to CON, but no significant differences were found for RR. Peak $\dot{V}O_2$ was significantly lower for the SG, but HR and RER were not significantly different between groups. The SG had a significantly lower OUES at peak effort than CON, but there were no between group differences for the OUES at 50% peak effort (Table 2).

Submaximal Performance

Minute Ventilation—Figure 1 summarizes $\dot{V}E$ during submaximal exercise. No significant interaction was found between Test Minute and Group ($F_{3,04,54.7} = 0.56$, $P = .65$). There was no main effect of Group ($F_{1,18} = 0.025$, $P = .88$) but there was a main effect of Test Minute ($F_{3,04,54.7} = 93.820$, $P < .001$).

Tidal Volume—As noted in Figure 2, no significant interaction was found between Test Minute and Group ($F_{3,03,54.5} = 0.39$, $P = .76$). However, we report significant main effects for Group ($F_{1,18} = 10.53$, $P = .004$) and Test Minute ($F_{3,03,54.5} = 29.74$, $P < .001$).

Respiratory Rate—RR during submaximal effort is displayed in Figure 3. No significant interaction for Test Minute and Group was found ($F_{5,90} = 1.72$, $P = .14$). There were significant main effects for Group ($F_{1,18} = 6.78$, $P = .02$) and Test Minute ($F_{5,90} = 43.95$, $P < .001$).

DISCUSSION

To our knowledge, this is the first study to: (1) characterize pulmonary performance during a CPET in people during the subacute phase of recovery; and (2) compare pulmonary outcomes to a matched group of apparently healthy older adults. Our primary finding supported our hypothesis that pulmonary function is altered even in the early stages of stroke recovery. We report that V_t was significantly reduced at peak and submaximal work effort in the SG when compared to CON. The SG had a significantly lower OUES at peak effort, as we hypothesized, but not for the OUES at 50% peak effort.

Peak Exercise

We report that people in the subacute stage of recovery demonstrated significantly lower $\dot{V}E$ and V_t when compared to CON. Maintaining adequate V_t is important during increased work effort such as exercise. In Table 2, we report V_t is 37% lower at peak effort when compared to the CON, while no difference was found for RR. We hypothesized that all variables would be lower at peak effort; however, RR was not different at peak effort.

In chronic stroke survivors, Tomczak and colleagues reported similar findings with respect to pulmonary performance at peak effort.⁵ They reported significantly lower values in $\dot{V}\dot{E}$ and V_t but no difference in RR when compared to their control group. The pulmonary values from our SG are very similar to those in the study by Tomczak and colleagues. This suggests that pulmonary function is negatively affected in subacute stroke. Further, at peak effort, our participants in the SG demonstrated $49.6 \text{ L}\cdot\text{min}^{-1}$ for $\dot{V}\dot{E}$, 1.5 L for V_t , and RR was 33.6 breaths per minute. In the study by Tomczak et al, participants with chronic stroke had comparable pulmonary values: $\dot{V}\dot{E}$ of $49.4 \text{ L}\cdot\text{min}^{-1}$; V_t of 1.4 L; and RR of 36 breaths per minute.⁵ Peak $\dot{V}\dot{O}_2$ values were also similar with our participants having a mean peak $\dot{V}\dot{O}_2$ of $16.3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ while those with chronic stroke had a peak $\dot{V}\dot{O}_2$ of $16.0 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$.⁵ We observed that decreased pulmonary function exists in the subacute stage of stroke recovery, and impairments may continue to exist into the chronic stage of recovery. It is important to note that both our SG and CON gave good effort during the CPET (defined by a peak RER ≥ 1.10).¹⁹ We also report that peak HR was similar between the groups with the SG at 131.7 bpm and the CON was 130.7 bpm. This finding differs from the work by Tomczak and colleagues, where peak HR was significantly different between their stroke and control group.⁵ However, 3 people in their stroke group were taking beta blockers, while no participants took beta blockers in the control group. In the current study, we report 2 people in each group were taking a beta blocker. Since beta blockers are known to affect peak HR, it is important to have a similar number of participants taking this medication within both groups. Although peak HR was similar between groups, the current study lacks information regarding cardiac function such as ejection fraction or cardiac output. This information would provide insight to whether the heart's pumping capability was normal or impaired.

Submaximal Exercise

We chose to examine submaximal exercise since these early stages (minutes 1-6) could reflect pulmonary function required during daily activities and walking. Although examining data at peak effort is important for overall fitness, the majority of daily effort will be performing activities at a submaximal effort.³

Minute Ventilation—Although we report no significant interaction between Group and Test Minute, we did observe a main effect of Test Minute. We would expect that $\dot{V}\dot{E}$ would increase over time as the workload increases to meet the demands of exercise. In both groups, we observed increases in $\dot{V}\dot{E}$ during the early stages of exercise. However, we did not see a main effect of Group. The SG and CON had similar values for $\dot{V}\dot{E}$ during submaximal work effort.

This finding is different from the work of Haas and colleagues.⁸ In their study, people with chronic stroke walked on a treadmill at 0.5 mph. Once steady state submaximal exercise was reached, $\dot{V}\dot{O}_2$ was recorded for three minutes. They compared data to control participants and found $\dot{V}\dot{E}$ and $\dot{V}\dot{O}_2$ to be higher in the people with stroke during steady state submaximal exercise. In viewing our $\dot{V}\dot{E}$ results, the data suggest that pulmonary function may not be impaired in the subacute stage of stroke and these participants are similar to their

age-similar, gender-matched peers. However, when further examining the components of $\dot{V}_E$ (V_t and RR), a different story unfolds.

Tidal Volume—Although no significant interaction was found between Test Minute and Group, we report significant main effects for Test Minute and Group. As expected, both the CON and SG groups increased V_t during the submaximal portion of the exercise test. As seen in Figure 2, the SG has lower values for V_t than the CON. These lower values in the SG may be due, in part, to weakness in the diaphragm of the stroke affected side⁸ or limited chest wall excursion.²⁰ One of the limitations of the current study was that we did not directly assess pulmonary capacity through pulmonary function testing. Therefore, we do not know whether inspiratory capacity, expiratory reserve volume or both are limited when compared to the CON.

Respiratory Rate—Respiratory rate increased as the workload increased. We observe that RR in the SG is higher than the CON at each minute (minutes 1-6) and that these differences are statistically significant. At these submaximal workloads, it appears that in order to compensate for the decreased V_t the SG increases RR to maintain $\dot{V}_E$. However, at peak work effort we find that the SG is unable to increase V_t and RR sufficiently, and $\dot{V}_E$ is compromised. This respiratory pattern has implications for functional performance as it may lead to respiratory muscle fatigue and dyspnea and, thus, diminished function.²¹

Haas and colleagues work demonstrated decreased pulmonary mechanics in people with hemiplegia after stroke during submaximal exercise. In their study decreased vital capacity in those people with stroke was attributed to paralysis of the inspiratory muscles on the affected side. Likewise, increased residual volumes in this group were reported to be the result of paralysis of the expiratory muscles on the affected side in combination with decreased motion of the diaphragm.⁸ Furthermore, ultrasonography has confirmed decreased diaphragmatic excursion on the affected side in people with hemiplegia after stroke during volitional breathing.²² Haas and colleagues reported that people with stroke consumed 50% more oxygen than controls and had higher $\dot{V}_E$, V_t and RR than controls during submaximal work.⁸ Our findings suggest that the SG can maintain sufficient $\dot{V}_E$ during submaximal work efforts when compared to controls but that a deficit in V_t exists, which is compensated for by a higher RR . Although results of Haas and colleagues and the current study differ to some degree, an altered respiratory pattern and increased respiratory work is apparent in patients with stroke, both of which have implications for diminished functional capacity.

Ventilatory Efficiency

Our results suggest that ventilatory efficiency is compromised in subacute stroke as we report a 33% difference in OUES at peak exercise. OUES is a measure of cardiopulmonary functional reserve and explains the change in $\dot{V}O_2$ in relation to minute ventilation during incremental exercise.¹⁷ This measure is a composite of cardiopulmonary and musculoskeletal function because it is based upon pulmonary dead space, metabolic acidosis build up, skeletal muscle mass, and oxygen extraction.^{17,18} Work by Baert and colleagues suggest the OUES may be indicative of an impaired cardiopulmonary response to exercise at

3, 6 and 9 months post-stroke. These values were approximately 63-82% lower than healthy men and women.²³

We observed significantly lower OUES values at peak exercise in the SG, but there was no statistically significant difference in the OUES at 50% peak effort. This may be due to our small sample size or VE not differing between groups during submaximal effort; therefore the OUES would reflect those findings. Although the OUES at 50% peak effort is not statistically different, there was a 30% difference between SP and controls at submaximal effort. This may have implications for increased work effort³ and may result in decreased ventilatory efficiency. One study found ventilatory efficiency to be higher in people with hemiplegia compared to controls during submaximal treadmill walking.⁸ Haas and colleagues suggested decreased pulmonary diffusing capacity may coincide with deconditioned respiratory musculature.⁸ This may have the potential to affect recovery of cardiopulmonary reserve during stroke recovery.²³ This has significant implications for performing functional activities such as ADLs, walking and exercise. The results of the current study indicate altered pulmonary function exists in patients with subacute stroke, and altered pulmonary function plays a significant role in diminished functional performance. Previous research indicates an aerobic training program can improve peak $\dot{V}O_2$ in people after stroke.^{11,24-27} Initial evidence also indicates inspiratory muscle training (IMT) can improve ventilatory function in people after stroke, which may positively impact the OUES.²⁸ It is important that future work must consider interventions such as aerobic exercise or IMT to improve pulmonary function in people post-stroke.

CONCLUSION

In conclusion, we report that people in the subacute stage of stroke recovery already demonstrate impaired pulmonary function. This is an area of clinical practice that may require the attention of rehabilitation professionals such as physical therapists. Improving pulmonary function specifically through inspiratory muscle training may facilitate improved work performance at submaximal and higher work efforts. More research in this area is needed to determine best practice for improving pulmonary function following stroke.

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CONDENSED ABSTRACT

We studied individuals with subacute stroke to determine whether pulmonary function was reduced at submaximal and peak exercise compared controls. Our results suggest that deficits in tidal volume may limit submaximal and peak exercise in subacute stroke patients. Therefore, rehabilitation professionals should consider therapies designed to improve pulmonary function during rehabilitation.

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Figure 1. Minute ventilation during submaximal exercise and peak exercise effort in subacute stroke (SG) compared to controls (CON). ^a $P < 0.05$ between groups.

Figure 2. Tidal volume during submaximal exercise and peak exercise effort in subacute stroke (SG) compared to controls ^a $P < 0.05$ between groups.

Figure 3. Respiratory rate during submaximal exercise and peak exercise effort in subacute stroke (SG) compared to controls (CON).

Figure 3.
Respiratory rate during submaximal exercise and peak exercise effort in subacute stroke (SG) compared to controls (CON).

Table 1

Participant Characteristics.

	SG (n = 10)	CON (n = 10)	P value
Age, y	61.3 ± 4.7	65.2 ± 4.4	.09
Sex, M:F	7:3	7:3	
Height, cm	168.0 ± 11.6	174.2 ± 8.7	.19
Weight, kg	79.5 ± 11.0	83.1 ± 15.4	.45
BMI kg·(m ²) ⁻¹	27.4 ± 3.8	27.9 ± 5.9	.82
Days post-stroke	66.7 ± 41.5	N/A	
Total Fugl-Meyer score	100.3 ± 29.3	N/A	
Lower Fugl-Meyer score	27.4 ± 8.8	N/A	
Upper Fugl-Meyer score	51.2 ± 19.6	N/A	
Sensation Fugl-Meyer score	21.7 ± 3.4	N/A	
Race, n			
African American	3	0	
White	6	10	
Native American	1	0	
Ethnicity, n			
Hispanic	1	0	
Non-Hispanic	9	10	
Marital Status, n			
Unknown	0	1	
Married/partnered	9	8	
Single	1	1	
Diabetes, n			
Type I	0	0	
Type II	4	0	
Medications, n			
ACE inhibitor	6	3	
β-blocker	2	2	
Calcium channel blocker	3	1	
Cholesterol-lowering agent	3	5	

Abbreviations: ACE, angiotensin-converting enzyme; CON, control; N/A, not applicable; SG, stroke group.

Data presented as mean ± SD unless otherwise noted.

Table 2

Cardiopulmonary Outcomes at Peak Exercise Effort.

	SG (n = 10)	CON (n = 10)	% Difference	P value
VE, L·min ⁻¹	49.6 ± 15.0	69.4 ± 25.8	-33.3	.05
Vt, L	1.5 ± 0.3	2.2 ± 0.5	-37.8	.01
RR, breaths·min ⁻¹	33.6 ± 7.9	34.1 ± 9.3	-1.5	.91
OUES·kg ⁻¹	1.5 ± 0.5	2.1 ± 0.7	-33.3	.05
50% OUES·kg ⁻¹	1.5 ± 0.4	1.9 ± 0.8	-30.3	.12
VQ ₂ , ml·kg ⁻¹ ·min ⁻¹	16.3 ± 3.9	22.9 ± 5.6	-34.0	.01
RER	1.1 ± 0.1	1.1 ± 0.1	0.0	.99
HR, bpm	131.7 ± 13.9	130.7 ± 25.6	0.7	.99

Abbreviations: CON = control; HR = heart rate; OUES = oxygen uptake efficiency slope; RER = respiratory exchange ratio; RR = respiratory rate; SG = stroke group; VE = minute ventilation; VQ₂ = oxygen consumption; Vt = tidal volume; 50% OUES = oxygen uptake efficiency slope at 50% peak effort.

All data are presented as mean ± SD; *P* .05 is statistically significant.