Within-Session Responses to High-Intensity Interval Training in Chronic Stroke

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ABSTRACT

BOYNE, P., K. DUNNING, D. CARL, M. GERSON, J. KHOURY, and B. KISSELA. Within-Session Responses to High-Intensity Interval Training in Chronic Stroke. *Med. Sci. Sports Exerc.*, Vol. 47, No. 3, pp. 476–484, 2015. Poststroke hemiparesis often leads to a vicious cycle of limited activity, deconditioning, and poor cardiovascular health. Accumulating evidence suggests that exercise intensity is a critical factor determining gains in aerobic capacity, cardiovascular protection, and functional recovery after stroke. High-intensity interval training (HIT) is a strategy that augments exercise intensity using bursts of concentrated effort alternated with recovery periods. However, there was previously no stroke-specific evidence to guide HIT protocol selection. **Purpose**: This study aimed to compare within-session exercise responses among three different HIT protocols for persons with chronic (>6 months after) stroke. **Methods**: Nineteen ambulatory persons with chronic stroke performed three different 1-d HIT sessions in a randomized order, approximately 1 wk apart. HIT involved repeated 30-s bursts of treadmill walking at maximum tolerated speed, alternated with rest periods. The three HIT protocols were different on the basis of the length of the rest periods, as follows: 30 s (P30), 60 s (P60), or 120 s (P120). Exercise tolerance, oxygen uptake ($\dot{V}O_2$), HR, peak treadmill speed, and step count were measured. **Results**: P30 achieved the highest mean $\dot{V}O_2$, HR, and step count but with reduced exercise tolerance and lower treadmill speed than P60 or P120 (P30: 70.9% $\dot{V}O_{2peak}$, 76.1% HR reserve (HRR), 1619 steps, 1.03 m·s^{-1}; P60: 63.3% $\dot{V}O_{2peak}$, 63.1% HRR, 1370 steps, 1.13 m·s^{-1}; P120: 47.5% $\dot{V}O_{2peak}$, 46.3% HRR, 1091 steps, 1.10 m·s^{-1}). P60 achieved treadmill speed and exercise tolerance similar to those in P120, with higher mean $\dot{V}O_2$, HR, and step count. **Conclusions**: For treadmill HIT in chronic stroke, a combination of P30 and P60 may optimize aerobic intensity, treadmill speed, and stepping repetition, potentially leading to greater improvements in aerobic capacity and gait outcomes in future studies.

Key Words: AEROBIC EXERCISE, LOCOMOTION, REHABILITATION, DECONDITIONING

After stroke, persons with hemiparesis often enter a vicious cycle of limited activity and aerobic deconditioning (6). This vicious cycle stymies motor recovery (28) and contributes to a high long-term risk for cardiac events (1) and recurrent stroke (18). Exercise guidelines recommend moderate-intensity continuous aerobic exercise as an evidence-based intervention for addressing activity limitations, aerobic deconditioning, and cardiovascular health after stroke (23). However, accumulating evidence suggests that higher-intensity exercise may be significantly more effective than moderate-intensity exercise (7,27).

High-intensity interval training (HIT) is a strategy that maximizes exercise intensity using bursts of concentrated effort alternated with recovery periods (19). Several randomized controlled trials have shown that HIT is superior to moderate-intensity continuous aerobic exercise for improving aerobic capacity and other outcomes (e.g., ventilatory threshold, gait economy, endothelial function) among healthy adults and persons with heart disease (7). For persons with stroke, two randomized controlled trials conducted during inpatient rehabilitation have shown that treadmill HIT produced significantly ($P < 0.05$) greater improvements in gait speed (31,36), spatiotemporal parameters (31,36), and functional ambulation category (36) compared with conventional therapy (36) or other forms of treadmill training (31,36). Furthermore, two single groups, pre–post test design studies in subacute (4) (mean, 5.8 months after) and chronic (21) (mean, 7.2 yr after) stroke demonstrated that treadmill HIT was associated with significant improvements in gait speed (21), the Timed Up and Go (21), gait endurance (4,21), gait economy (21), and aerobic capacity (21).

Despite these promising findings, the optimal HIT protocol for targeting motor recovery and aerobic deconditioning after stroke remains unknown. Parameters like burst and recovery duration have varied widely between studies, from 30-s bursts with recovery periods 2 min or longer (31,36) to 4-min bursts with 3-min recovery periods

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(4,21). No previous studies have compared different HIT protocols among persons with stroke.

One efficient strategy for optimizing an HIT protocol for a specific population is to examine within-session exercise responses that are known to predict outcomes. This methodology has successfully identified optimized HIT protocols among healthy adults (5,13–15) and persons with heart disease (24,34). For poststroke treadmill HIT, aerobic capacity and gait function are the outcomes of interest and several predictive within-session exercise responses have been identified, as follows: 1) higher aerobic training intensity (oxygen consumption or HR) has been consistently shown to yield greater improvement in aerobic capacity, including after stroke (7,22,30), 2) faster treadmill speed during training has consistently been shown to produce greater improvements in gait among persons with stroke (31,35,36,38), and 3) repetition of practice (e.g., number of steps taken during a session) is a key determinant of neuroplasticity and motor learning, including after stroke (27,29).

To maximize treadmill speed, it is important to keep burst duration short to mitigate the effects of fatigue (24,25,34). Because 30 s seems to be the minimum time needed for some persons with stroke to ramp up and stabilize at peak speed (31), this may be the optimal burst duration for maximizing gait outcomes. Although the use of 30-s bursts has some justification, no stroke-specific data were previously available to guide selection of recovery duration. This HIT parameter has the potential to increase both aerobic intensity and stepping repetition during training. However, insufficient recovery duration could limit treadmill speed or exercise tolerance because of fatigue. Therefore, the purpose of this study was to compare within-session exercise responses between three HIT protocols, which differed by recovery duration (30, 60, and 120 s). We hypothesized that the 120-s recovery protocol would achieve significantly higher treadmill speed than the other protocols and that the 30-s recovery protocol would achieve significantly higher aerobic intensity and stepping repetition.

METHODS

Setting and participants. This study was approved by local institutional review boards and was performed in a cardiovascular stress laboratory within a university hospital from January to July 2013. Subjects were recruited from the community and signed an informed consent before participation.

The *inclusion criteria* were as follows: 1) age, 40–85 yr; 2) unilateral stroke experienced >6 months before enrollment; 3) gait speed $\leq$1.0 $m \cdot s^{-1}$, measured by the 10-m walk test (40); 4) able to walk 10 m overground with assistive devices as needed and no physical assistance; 5) able to walk for 3 min on the treadmill at $\geq$0.13 $m \cdot s^{-1}$ (0.3 mph) with no aerobic exercise contraindications (2,33); 6) stable cardiovascular condition (American Heart Association class B (2), allowing for aerobic capacity <6 METs); 7) not currently participating in formal rehabilitation.

The *exclusion criteria* were as follows: 1) significant resting ECG abnormalities (2), 2) evidence of myocardial ischemia or significant arrhythmia on treadmill ECG stress test (2), 3) hospitalization for cardiac or pulmonary disease within 3 months, 4) pacemaker or implanted defibrillator, 5) lower extremity (LE) claudication, 6) Mini-Mental State Examination result <23/30 (39), 7) severe LE spasticity (Ashworth, $\geq$3) (3), and 8) LE weight-bearing pain >4/10 on a visual analog scale.

Design overview. A within-subject repeated-measures design was used. Each subject underwent a clinical examination and maximal effort, graded treadmill exercise testing (GXT) with ECG (stress testing) to determine eligibility (33). This was followed by a repeated GXT with gas exchange analysis to determine peak oxygen consumption ($\dot{V}O_{2peak}$) and HR_{peak} (33). Single sessions of three different treadmill HIT protocols were then performed with an approximate 1 wk washout period between sessions. The order of the three HIT protocols was randomized and counterbalanced across subjects.

Clinical examination. A detailed medical history was taken, medical records were reviewed, and a clinical examination was performed to assess LE hypertonia (Ashworth scale) (3), light touch sensation (37), proprioception (37), neglect (8), LE motor function (Fugl-Meyer assessment) (17), functional ambulation category (26), and comfortable walking speed (10-m walk test) (40). After a resting ECG, subjects performed a 5- to 10-min treadmill screening test to acclimate to treadmill walking and to determine the fastest comfortable treadmill speed for the GXT (33).

GXT. The GXT protocol of Macko et al. (33) was implemented for both stress testing and the GXT with gas exchange analysis. Treadmill speed was held constant while incline was increased 2%–4% every 2 min until volitional fatigue, severe gait instability, or a cardiovascular safety limit (2,16).The GXT with gas exchange analysis was performed on a separate day from the stress test using the same protocol but with open-circuit spirometry.

Intervention. Subjects wore a harness secured to an overhead support system (Biodex Offset Unweighting System; Biodex Medical Systems, Inc., Shirley, NY) for fall protection (not body weight support) during all treadmill walking. No physical assistance was provided during the sessions. Subjects used a handrail hold for balance and wore their habitual orthotic devices during every session.

Starting HIT speed was determined before the first session by a steep ramp test. This test began at the fastest comfortable speed from the GXT (0% incline) and increased by 0.1 mph every 5 s until reaching the limit where the subject exhibited a mechanical fault (e.g., drifted backward or exhibited marked gait instability) or requested to stop. Each HIT protocol for a subject was started at 0.1 mph below this limit.

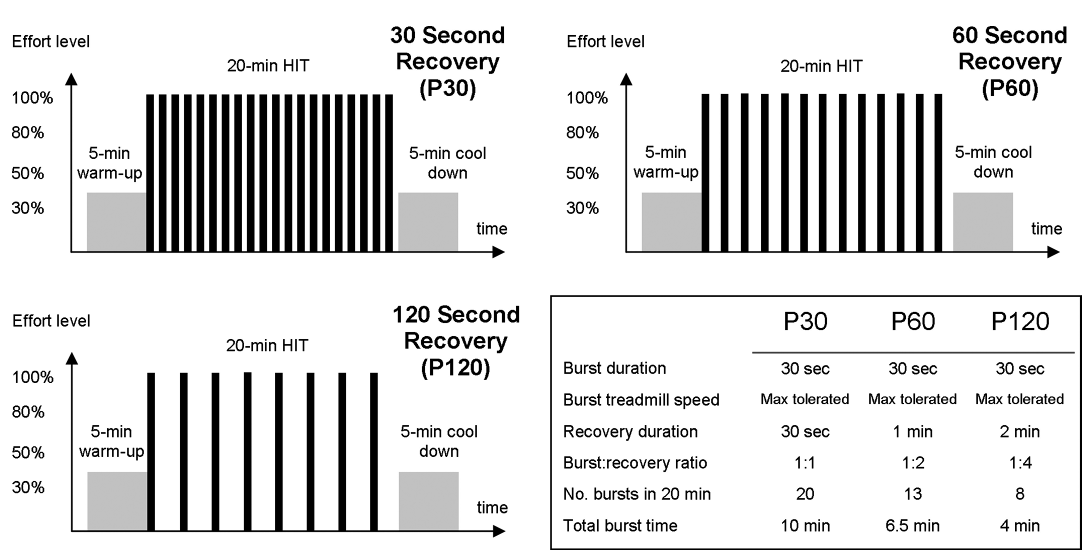
HIT protocols included a 5-min warm-up (30%–50% $\dot{V}O_{2peak}$) up to 20 min of HIT and a 5-min cooldown

(30%–50% $\dot{V}O_{2peak}$). HIT involved repeated 30-s bursts at maximum tolerated speed (0% incline), alternated with prespecified recovery periods according to protocol, where the treadmill was stopped. Similar to previous studies (31,36), each time the subject completed a burst successfully, treadmill speed was increased by 0.1 mph for the next burst. Likewise, each time the subject exhibited a mechanical fault, speed was decreased by 0.1 mph for the next burst. The three HIT protocols (Fig. 1) were different on the basis of the length of the recovery periods, as follows: 30 s (P30), 60 s (P60), or 120 s (P120). During recovery, subjects were given the option to stand still, march in place, or sit, similar to previous studies (9,20). The HIT portion of the session lasted 20 min or until exhaustion, whichever came first. ECG activity, blood pressure, and other signs or symptoms of cardiorespiratory insufficiency, worsening neurologic impairments, or orthopedic injury were monitored for safety using accepted stopping criteria (2,16). The number of times the harness system was engaged during each session was also recorded.

Outcome variables. The following outcome variables were measured during each protocol:

- *Exercise tolerance* was measured by the number of subjects who were able to complete a full 20 min of HIT and by the actual amount of HIT time tolerated (time to exhaustion) for each protocol.
- *Aerobic intensity* was measured by oxygen consumption ($\dot{V}O_2$) and HR.
  - *Oxygen consumption* ($\dot{V}O_2$) was recorded as the number of subjects who achieved different threshold percentages of $\dot{V}O_{2peak}$, as the amount of time (min) each subject spent at or above different threshold percentages of $\dot{V}O_{2peak}$, and as the mean $\dot{V}O_2$ during HIT for each subject. Threshold percentages were selected to represent the lower limits of moderate intensity (40% $\dot{V}O_{2peak}$), vigorous intensity (60% $\dot{V}O_{2peak}$), and very hard intensity (85% $\dot{V}O_{2peak}$) (2,23). Unlike mean values, time spent at or above different thresholds additionally reflects exercise tolerance. For example, a person who only tolerated 5 min of exercise could have a very high mean $\dot{V}O_2$ but could have spent no more than 5 min at any $\dot{V}O_{2peak}$ threshold. $\dot{V}O_2$ testing during exercise has been previously shown to be reliable among persons with stroke (11,12). It was measured with the TrueOne 2400 metabolic system (TrueOne 2400; Parvo Medics, Sandy, UT) using a facemask interface.
  - *HR* was recorded as the number of subjects who achieved different threshold percentages of HR reserve (HRR), as the amount of time (min) each subject spent at or above different threshold percentages of HRR, and as the mean HR during HIT for each subject. HRR thresholds were calculated using the formula HR (bpm) = HRR threshold % × ($HR_{peak} - HR_{resting}$) + $HR_{resting}$(2). Threshold percentages were the same as $\dot{V}O_2$ (40%, 60%, and 85% HRR) (2,23).
- *Treadmill speed* was recorded as the peak speed attained during each HIT protocol.
- *Repetition of practice* was measured by *step count* (7,27), which was recorded as the number of subjects achieving at least 1000 steps during each HIT protocol (10) and as the actual number of steps taken. Step count was measured by a StepWatch Activity Monitor (Orthocare Innovations, LLC, Oklahoma City, OK) placed around the nonparetic ankle. The StepWatch has been previously shown to be reliable and valid among persons with stroke (32).

Statistical analysis. Histograms of the continuous variables and their residuals were visually inspected for normality, and skewness and kurtosis were examined. For each continuous variable, a general linear mixed effects model was used to test for an overall difference between protocols. The



	P30	P60	P120
Burst duration	30 sec	30 sec	30 sec
Burst treadmill speed	Max tolerated	Max tolerated	Max tolerated
Recovery duration	30 sec	1 min	2 min
Burst:recovery ratio	1:1	1:2	1:4
No. bursts in 20 min	20	13	8
Total burst time	10 min	6.5 min	4 min

FIGURE 1—HIT protocol schematics.

repeated nature of the data was accounted for by including subject ID as a random effect in the model. When protocol was a significant factor in the model, paired *t*-tests between individual protocols were obtained and Tukey–Kramer adjustment was used to account for multiple comparisons. For dichotomous variables, Cochran *Q* was used to test for an overall difference between protocols. When this test was significant, McNemar tests between individual protocols were obtained and Bonferroni adjustment was used to account for multiple comparisons. SAS version 9.3 (SAS Institute, Inc., Cary, NC) and SPSS version 22 (IBM Corporation, Armonk, NY) were used for analysis. The significance level was set at 0.05.

We estimated *a priori* that a sample size of 17 would result in 85% power to detect significant differences between our protocols. This estimate was based on the effect size from a previous study, which compared $\dot{V}O_2$ between different HIT protocols among healthy adults (15). To account for a potential 20% loss to follow up, we recruited 22 subjects.

RESULTS

Of the 22 subjects who consented, three were excluded for not meeting the eligibility criteria. One subject had 1.5 mm of asymptomatic ST depression on the ECG during the stress test, one subject had resting ECG abnormalities that would have made an ECG stress test noninterpretable, and one subject had excessive LE pain. The 19 remaining subjects were enrolled, completed $\dot{V}O_{2peak}$ testing, and began HIT protocol testing. Demographics and clinical characteristics are summarized in Table 1. One subject was lost to follow up, leaving 18 subjects with complete data for analysis. Further intention-to-treat analysis was also performed using all available data. A restricted maximum likelihood approach was used, making the assumption of missing at random.

Safety. No serious adverse events occurred, and no HIT sessions had to be stopped for safety reasons. The primary self-selected recovery activity was marching in place for one subject, standing still for 14 subjects, and sitting for three subjects. However, some subjects who primarily stood still occasionally marched and the subject who primarily marched occasionally stood still. All subjects chose the same primary recovery activity for all three protocols. However, the three subjects who chose to sit had to stand during P30 recovery because there was inadequate time to unclip the harness rope, place a chair on the treadmill, sit, rest, stand, clip the harness rope, and remove the chair. One subject reported mild transient lightheadedness during one HIT session when questioned at the end of the session. No other abnormal signs or symptoms were found. Four subjects engaged the safety harness during HIT sessions. Three of these subjects engaged the harness one time each, and one subject engaged the harness 14 times across the three sessions. No falls occurred, no subjects had increased pain or orthopedic injury, and no subjects requested to discontinue a session for any reason other than fatigue.

TABLE 1. Subject characteristics (n = 18).

Male, *n* (%)	10 (56)
Age, yr	61.9 (8.3) (48.9–82.2)
Race, *n* (%)	
Caucasian	13 (72)
African-American	5 (28)
Body mass index, kg·m^{-2}	28.5 (6.1) (21.4–42.9)
Stroke type, *n* (%)	
Ischemic	16 (89)
Hemorrhagic	2 (11)
Left affected hemisphere, *n* (%)	8 (44)
Years after stroke	5.8 (4.2) (0.5–13.9)
Cardiac history, *n* (%)	
CAD	3 (17)
Myocardial infarction	2 (11)
Coronary artery bypass grafting	1 (6)
Valve surgery	2 (11)
Cardiovascular risk factors, *n* (%)	
Hypertension	9 (50)
Hypercholesterolemia	14 (78)
Current smoker	3 (17)
Diabetes mellitus	2 (11)
Taking a beta blocker, *n* (%)	5 (28)
Wheelchair use, *n* (%)	5 (28)
Habitual assistive device, *n* (%)	
None	3 (17)
Single-point cane	10 (56)
Small-base quad cane	2 (11)
Large-base quad cane	2 (11)
Rolling walker	1 (6)
Habitual orthotic device, *n* (%)	
None	7 (39)
Ankle foot orthosis	8 (44)
Foot drop stimulator	2 (11)
Ankle inversion splint	1 (6)
Ashworth hypertonia score of 1 or 2, *n* (%)	
Knee flexion	5 (28)
Knee extension	2 (11)
Ankle dorsiflexion	10 (56)
Impaired paretic light touch, *n* (%)	12 (67)
Impaired paretic proprioception, *n* (%)	
<8/10 correct trials at great toe	6 (33)
Extinction/neglect, *n* (%)	
NIHSS item 11 score of 1	5 (28)
LEFM motor score (0–34)	24.2 (5.6) (11–34)
Functional ambulation category, *n* (%)	
Dependent on supervision	5 (28)
Independent on level surfaces	5 (28)
Independent	8 (44)
Comfortable overground gait speed	
Meters per second	0.60 (0.29) (0.19–0.96)
% predicted	45.1 (20.5) (13.5–73.2)
Fastest overground gait speed, m·s^{-1}	0.76 (0.40) (0.19–1.34)
Treadmill speed for GXT, m·s^{-1}	0.62 (0.27) (0.22–1.07)
Maximum grade achieved during GXT, %	8.3 (4.0) (2.0–14.0)
$\dot{V}O_{2peak}$ on GXT	
Milliliters per kilogram per minute	16.2 (3.4) (10.4–23.5)
% predicted	67.6 (16.3) (36.3–93.3)
HR_{peak} on GXT	
Beats per minute	133.7 (16.5) (99–156)
% predicted	87.9 (8.5) (71.0–107.1)
Starting HIT treadmill speed	
Meters per second	0.84 (0.32) (0.22, 1.39)
Miles per hour	1.86 (0.73) (0.50, 3.10)

Data are presented as mean (SD) (range) unless otherwise noted.
LEFM, LE Fugl-Meyer; NIHSS, National Institutes of Health Stroke Scale.

Exercise tolerance. Results for the 18 subjects with complete data are shown in Figures 2 and 3 and Table 2. Significantly fewer subjects were able to complete P30 compared with P120. For the seven subjects who were not able to complete the full 20-min P30 protocol, median time to exhaustion was 14.0 min (range, 2.8–19.2). Among these subjects, three were also unable to complete the full P60

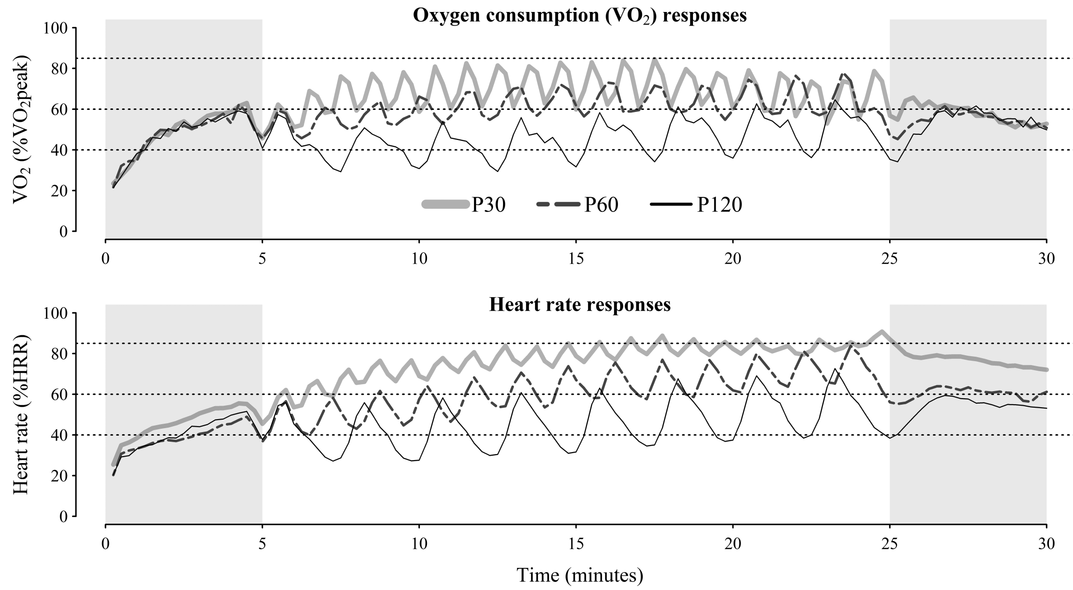


FIGURE 2—Mean time course of exercise responses by protocol (n = 18). *Shaded regions* represent warm-up and cooldown. *Dotted lines* represent 40%, 60%, and 85% aerobic intensity thresholds.

protocol, with a median time to exhaustion of 11.9 min (range, 11.1–13.4). After performing the planned analysis on the complete data set (n = 18) (Table 2), an exploratory subgroup analysis was performed on subjects who were able to tolerate the full session of P30 (n = 11) (Table 3).

Aerobic intensity. In the complete data set, time spent at or above moderate and vigorous aerobic intensity (≥40% and ≥60% of $\dot{V}O_{2peak}$ or HRR) was significantly greater for P30 and P60 compared with that for P120, but P30 and P60 were not statistically different. Time spent at or above very hard aerobic intensity (≥85% of $\dot{V}O_{2peak}$ or HRR) was significantly greater for P30 compared with that for P60 or P120, and significantly more subjects reached very hard aerobic intensity with P60 compared with P120. When looking only at subjects who completed the P30 protocol, time spent at or above vigorous aerobic intensity was also significantly greater for P30 compared with that for P60 and P120. In the complete data set, mean aerobic intensity ($\dot{V}O_{2peak}$ and HRR) was significantly different across all of the protocols, with P30 > P60 > P120.

Treadmill speed and stepping repetition. Peak treadmill speed during the fastest HIT protocol (P60) was 178% ± 84% of fastest overground walking speed, 140% ± 20% of starting HIT treadmill speed, and 193% ± 48% of the GXT speed used to elicit $\dot{V}O_{2peak}$. Peak treadmill speed during the slowest HIT protocol (P30) was 157% ± 74% of fastest overground walking speed, 124% ± 14% of starting HIT treadmill speed, and 173% ± 46% of the GXT speed used to elicit $\dot{V}O_{2peak}$. Treadmill speed was significantly higher for P60 and P120 compared with that for P30, but P60 and P120 were not statistically different from each other. When looking only at subjects who completed P30, treadmill speed was still significantly higher for P60 compared with that for P30. In both the complete data set and the subset who completed P30, step counts were significantly different across all of the protocols, with P30 > P60 > P120.

None of these overall results were altered in the intention-to-treat analysis (n = 19) by including the subject who was lost to follow up.

DISCUSSION

This study sought to identify the optimal HIT recovery period duration (30, 60, or 120 s) for persons with chronic stroke to maximize aerobic intensity ($\dot{V}O_2$ and HR), treadmill speed, and step count during training. The major findings were that 1) all three protocols elicited high relative treadmill speeds and step counts with at least moderate aerobic intensity, 2) P60 elicited higher aerobic intensity and step count than P120 without sacrificing treadmill speed or exercise tolerance, 3) when tolerated for the full session, P30 elicited even higher aerobic intensity and step count than P60 but had lower treadmill speed likely because of fatigue.

On the basis of these findings, it seems that a combination of P30 and P60 may be optimal for treadmill HIT in chronic stroke. We suggest using P60 for the first few sessions to maximize treadmill speed, then integrating P30 to further increase aerobic intensity and stepping repetition. Because persons with stroke often exhibit continual improvement in treadmill speed over the course of an HIT training regimen (31,36), we also suggest that each P30 session should still begin with P60 to ensure continued opportunity for speed increases. Although it could be argued that 45-s recovery or some other intermediate duration might be just as good, it benefits clinical utility to use recovery durations that are multiples of burst duration. For P30 and P60, a simple timer can signal every 30 s to mark the start of bursts and recoveries. The clinician can use 60-s recovery by just waiting for

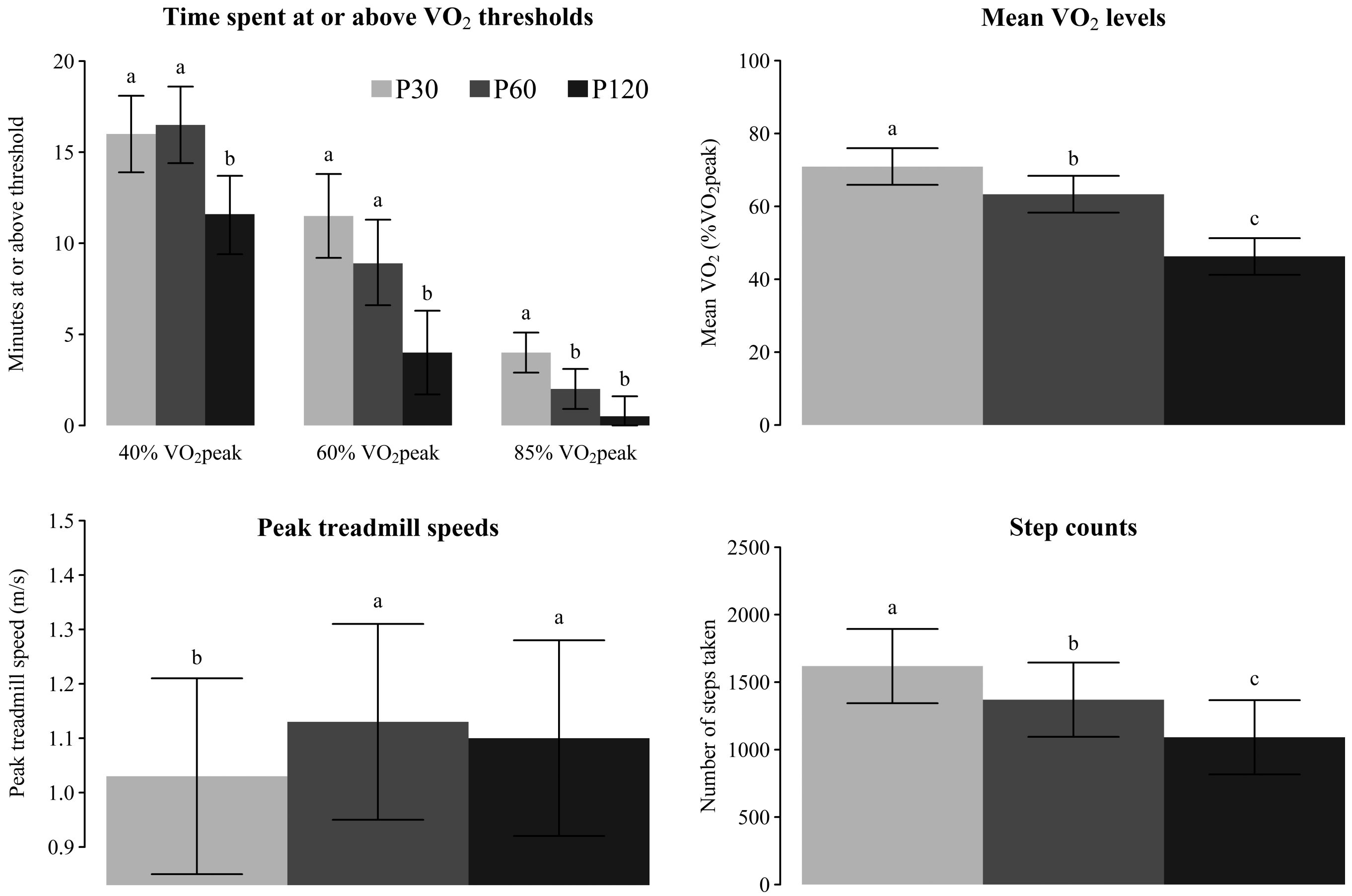


FIGURE 3—Differences in mean oxygen consumption ($\dot{V}O_2$), treadmill speed, and step count between protocols (n = 18). ***Error bars*** **represent 95% confidence intervals for the least square means.** ***Nonmatching letters*** **(*a*, *b*, *c*) indicate a significant (P < 0.05) difference between protocols after Tukey–Kramer adjustment for multiple comparisons. In the bottom left, treadmill speed graph, the mean starting speed for each protocol (0.84 $m \cdot s^{-1}$) was used as the base of the *y*-axis.**

two signals rather than using a more complex timer that allows for different burst and recovery duration. This method also allows clinicians to transition between longer and shorter recovery without having to reprogram the timer during a session.

Interestingly, peak treadmill speed during the fastest HIT protocol (P60) averaged 193% of the GXT speed used to elicit $\dot{V}O_{2peak}$. Even with no treadmill incline, these HIT speeds likely elicited workloads higher than those associated with $\dot{V}O_{2peak}$. Such workloads are only sustainable for short periods because they rely primarily on anaerobic metabolism, resulting in acid–base balance disturbances. Therefore, it is likely that poststroke HIT protocols with longer burst duration would not be able to elicit the same treadmill speeds (7).

Comparison with previous studies. To our knowledge, this was the first HIT study among persons with stroke to describe within-session exercise responses, to compare different HIT protocols, or to include recovery duration shorter than 120 s. P60 elicited either similar or superior exercise responses to P120 for all variables tested, and P30 elicited superior exercise responses to P120 for all variables except exercise tolerance and treadmill speed. This suggests that HIT protocols used in previous studies (31,36) may have been suboptimal. The fact that these potentially suboptimal HIT protocols were still highly effective for improving gait (31,36) shows the strong potential of this approach.

Previous studies using similar designs have identified optimized HIT protocols in other populations. Guiraud et al. (24) compared within-session exercise responses to four different HIT protocols among persons with CAD. Protocols differed by recovery type (passive or active) and interval duration (15-s bursts and recovery or 60-s bursts and recovery). The protocol with 15-s intervals and passive recovery was found to provide the best combination of aerobic intensity and exercise tolerance. In a similar study among persons with heart failure, Meyer et al. (34) compared 30-s intervals with 90-s intervals under both active and passive recovery conditions. The protocol with 30-s intervals and passive recovery (similar to our P30) was found to provide the best combination of aerobic intensity and exercise tolerance. Compared with these optimized heart disease protocols, the optimized poststroke HIT protocol suggested by our data differs by including longer recovery at the beginning of each session and for the entirety of early sessions.

TABLE 2. HIT protocol comparisons (n = 18).

	P30	P60	P120	*P* value
No. of those completing 20 min, n (%)	11 (61)[b]	15 (83)	18 (100)[a]	0.005
Oxygen uptake				
No. of those achieving ≥40% $\dot{V}O_{2peak}$, n (%)	18 (100)	18 (100)	18 (100)	N/A
No. of those achieving ≥60% $\dot{V}O_{2peak}$, n (%)	18 (100)	17 (94)	16 (89)	0.22
No. of those achieving ≥85% $\dot{V}O_{2peak}$, n (%)	16 (89)[a]	16 (89)[a]	10 (56)[b]	0.002
Minutes at ≥40% $\dot{V}O_{2peak}$	16.0 (13.9–18.1)[a]	16.5 (14.4–18.6)[a]	11.6 (9.4–13.7)[b]	<0.001
Minutes at ≥60%$\dot{V}O_{2peak}$	11.5 (9.2–13.8)[a]	8.9 (6.6–11.3)[a]	4.0 (1.7–6.3)[b]	<0.001
Minutes at ≥85% $\dot{V}O_{2peak}$	4.0 (2.9–5.1)[a]	2.0 (0.9–3.1)[b]	0.5 (0.0–1.6)[b]	<0.001
Mean, % VO_{2peak}	70.9 (65.9–76.0)[a]	63.3 (58.3–68.4)[b]	46.3 (41.2–51.3)[c]	<0.001
HR				
No. of those achieving ≥40% HRR, n (%)	18 (100)	18 (100)	18 (100)	N/A
No. of those achieving ≥60% HRR, n (%)	18 (100)[a]	16 (89)	14 (78)[b]	0.05
No. of those achieving ≥85% HRR, n (%)	11 (61)	12 (67)	8 (44)	0.20
Minutes at ≥40% HRR	16.6 (13.9–19.3)[a]	15.2 (12.5–17.9)	11.7 (9.0–14.4)[b]	0.02
Minutes at ≥60% HRR	12.9 (9.9–15.9)[a]	9.5 (6.5–12.5)[a]	5.2 (2.2–8.2)[b]	<0.001
Minutes at ≥85% HRR	5.7 (3.6–7.9)[a]	2.7 (0.5–4.8)	0.5 (0.0–2.6)[b]	0.002
Mean, % HRR	76.1 (68.4–83.7)[a]	63.1 (55.5–70.7)[b]	47.5 (39.9–55.1)[c]	<0.001
Peak treadmill speed, $m \cdot s^{-1}$	1.03 (0.85–1.21)[b]	1.13 (0.95–1.31)[a]	1.10 (0.92–1.28)[a]	0.002
No. of those achieving ≥1000 steps, n (%)	15 (83)	15 (83)	14 (78)	0.37
Total number of steps taken	1619 (1344–1894)[a]	1370 (1095–1645)[b]	1091 (816–1366)[c]	<0.001

Data are presented as n (%) or least square mean (95% confidence interval). Subjects who did not reach a particular $\dot{V}O_{2peak}$ or HRR threshold for any protocol were analyzed as having spent 0 min at or above that threshold.
P values indicate significance of the overall mixed effects model (continuous variables) or Cochran *Q* (dichotomous variables).
[a,b,c]Nonmatching letters indicate a significant ($P < 0.05$) difference in pairwise comparisons. Adjustment for multiple comparisons was made with the Tukey–Kramer (continuous variables) or Bonferroni (dichotomous variables) methods.
N/A, not applicable.

These differences reflect the limited exercise tolerance to P30 in our sample and the greater focus on high treadmill speed for improving gait function in stroke rehabilitation.

Safety considerations. Combining our data with four previous studies (4,21,31,36), 75 subjects with stroke have now performed a combined 457 recorded hours of treadmill HIT. Previous studies that reported training HR reached 85%–95% of HR_{peak} during bursts (4,21), and no serious adverse events have been found to date. Therefore, this strategy seems to be reasonably safe for future studies with appropriate screening, monitoring, and precautions. However, given the high rate of silent myocardial ischemia in this population (1), further study is needed before widespread clinical implementation can be recommended because this was the first poststroke HIT study to report ECG results.

Another important safety consideration with HIT is the potential risk of blood pooling-induced hypotension during recovery periods. Active recovery (e.g., marching in place) may help reduce this risk but may also cause more rapid fatigue (13,14,24,34). Similar to previous studies among healthy adults (9,20), we allowed subjects to self-select recovery activity (sitting, standing still, or marching in place) as an individualized approach to mitigating hypotensive responses and fatigue. Such an individualized approach seems especially important after stroke, given the wide variation in cardiovascular exercise responses and exercise tolerance in the study sample. The majority of our subjects chose to stand still during recovery, and symptoms of hypotension were found only in one subject during questioning after one HIT session (mild, transient lightheadedness). Despite these initial promising findings, future study is needed to fully evaluate the potential risk of hypotensive responses during poststroke HIT. We suggest that forced active recovery or forced sitting recovery should be considered for subjects who are symptomatic.

Generalizability. We believe that the findings of this study are applicable to many patients typically seen in outpatient stroke rehabilitation, given the range of age, stroke

TABLE 3. Protocol comparisons among subjects who completed P30 (n = 11).

	P30	P60	P120	*P* value
Oxygen uptake				
Minutes at ≥40% $\dot{V}O_{2peak}$	19.0 (17.2–20.0)[a]	18.2 (16.4–20.0)[a]	12.3 (10.5–14.1)[b]	<0.001
Minutes at ≥60% $\dot{V}O_{2peak}$	13.8 (10.7–16.8)[a]	9.1 (6.1–12.2)[b]	3.9 (0.8–6.9)[b]	<0.001
Minutes at ≥85% $\dot{V}O_{2peak}$	4.9 (3.3–6.4)[a]	1.6 (0.0–3.2)[b]	0.4 (0.0–2.2)[b]	<0.001
Mean, % VO_{2peak}	71.5 (64.8–78.1)[a]	60.8 (54.2–67.5)[b]	46.9 (40.3–53.5)[c]	<0.001
HR				
Minutes at ≥40% HRR	19.5 (16.5–20.0)[a]	15.5 (12.5–18.5)	12.3 (9.3–15.3)[b]	0.001
Minutes at ≥60% HRR	15.5 (11.3–19.6)[a]	8.2 (4.0–12.3)[b]	5.7 (1.6–9.8)[b]	<0.001
Minutes at ≥85% HRR	8.6 (5.6–11.7)[a]	2.4 (0.0–5.4)[b]	0.7 (0.0–3.7)[b]	<0.001
Mean, % HRR	80.9 (70.4–91.4)[a]	58.1 (47.6–68.6)[b]	48.9 (38.4–59.4)[b]	<0.001
Peak treadmill speed, $m \cdot s^{-1}$	1.23 (1.09–1.37)[b]	1.33 (1.19–1.47)[a]	1.28 (1.14–1.42)	0.03
Total number of steps taken	2027 (1836–2218)[a]	1600 (1409–1792)[b]	1268 (1007–1460)[c]	<0.001

Data are presented as least square mean (95% confidence interval). Subjects who did not reach a particular $\dot{V}O_{2peak}$ or HRR threshold for any protocol were analyzed as having spent 0 min at or above that threshold.
P values indicate significance of the overall mixed effects model.
[a,b,c]Nonmatching letters indicate a significant ($P < 0.05$) difference in pairwise comparisons. Adjustment for multiple comparisons.

characteristics, comorbidities, and function of the study sample (Table 1). However, longitudinal randomized controlled trials with a larger sample size are needed to confirm these findings and extend to other subpopulations (e.g., subacute stroke) and exercise modes (e.g., recumbent stepper).

Study limitations. The main limitation of this study is that it did not measure the longitudinal effects of each training protocol. Previous research has established that higher aerobic training intensity yields greater longitudinal changes in aerobic capacity (7,22,30) whereas higher treadmill speed (27,31,35,36,38) and stepping repetition (10,27,29,35) during training yield greater longitudinal changes in gait outcomes. This study found significant differences in these intensity and repetition variables between HIT protocols, suggesting that effectiveness for improving aerobic capacity and gait outcomes may also differ between protocols. However, the effect size that the observed differences would have on longitudinal outcomes remains unknown.

When interpreting our results, it is also important to note that each protocol was only tested for one session. For example, exercise tolerance and treadmill speed would likely improve over the course of a training regimen, which would permit higher stepping repetition and aerobic intensity. Therefore, our data likely underestimate longitudinal exercise responses.

CONCLUSIONS

HIT with 30-s bursts at maximal tolerated speed elicited high relative treadmill speeds and step counts with at least moderate aerobic intensity among persons with chronic stroke. We suggest that a protocol combining 30- and 60-s recovery periods may optimize aerobic intensity, treadmill speed, and stepping repetition, potentially leading to greater improvements in aerobic capacity and gait outcomes in future studies.

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