Published in final edited form as:

Top Stroke Rehabil. 2020 October ; 27(7): 483–493. doi:10.1080/10749357.2020.1728953.

Locomotor Training Intensity After Stroke: Effects of Interval Type and Mode

Pierce Boyne¹, Victoria Scholl¹, Sarah Doren¹, Daniel Carl¹, Sandra A. Billinger², Darcy S. Reisman³, Myron Gerson⁴, Brett Kissela⁵, Jennifer Vannest^{6,7}, Kari Dunning¹

¹Department of Rehabilitation, Exercise and Nutrition Sciences, College of Allied Health Sciences, University of Cincinnati, Cincinnati, OH

²Department of Physical Therapy and Rehabilitation Science, School of Health Professions, University of Kansas Medical Center, Kansas City, KS

³Department of Physical Therapy, College of Health Sciences, University of Delaware, Newark, DE

⁴Departments of Internal Medicine and Cardiology, College of Medicine, University of Cincinnati

⁵Department of Neurology and Rehabilitation Medicine, College of Medicine, University of Cincinnati

⁶Department of Communication Sciences and Disorders, College of Allied Health Sciences, University of Cincinnati

⁷Pediatric Neuroimaging Research Consortium, Cincinnati Children's Hospital Medical Center, Cincinnati, OH

Abstract

Background and Objectives: High-intensity interval training (HIIT) is a promising strategy for improving gait and fitness after stroke, but optimal parameters remain unknown. We tested the effects of short vs long interval type and over-ground vs treadmill mode on training intensity.

Methods: Using a repeated measures design, 10 participants with chronic hemiparetic gait performed 12 HIIT sessions over 4 weeks, alternating between short and long-interval HIIT sessions. Both protocols included 10 minutes of over-ground HIIT, then 20 minutes of treadmill HIIT and another 10 minutes over-ground. Short-interval HIIT involved 30 second bursts at maximum safe speed and 30–60 second rest periods. Long-interval HIIT involved 4-minute bursts at ~90% of peak heart rate (HR_{peak}) and 3-minute recovery periods at ~70% HR_{peak} .

Results: Compared with long-interval HIIT, short-interval HIIT had significantly faster mean overground speeds (0.75 vs 0.67 m/s) and treadmill speeds (0.90 vs 0.51 m/s), with similar mean treadmill HR (82.9 vs 81.8 % HR_{peak}) and session perceived exertion (16.3 vs 16.3), but lower

Please address correspondence to: Pierce Boyne PT, DPT, PhD, NCS, University of Cincinnati, Department of Rehabilitation, Exercise and Nutrition Sciences, 3225 Eden Avenue, Cincinnati OH 45267-0394, 513-558-7499 (phone); 513-558-7474 (fax), Pierce.Boyne@uc.edu.

Declaration of Interest Statement

The authors report no conflict of interest.

overground HR (78.4 vs 81.1 %HR_{peak}) and session step counts (1481 vs 1672). For short-interval HIIT, training speeds and HR were significantly higher on the treadmill vs. overground. For long-interval HIIT, the treadmill elicited HR similar to overground training at significantly slower speeds.

Conclusions: Both short and long-interval HIIT elicit high intensities but emphasize different dosing parameters. Based on these preliminary findings and previous studies, we hypothesize that overground and treadmill short-interval HIIT could be optimal for improving gait speed and overground long-interval HIIT could be optimal for improving gait endurance.

Keywords

aerobic exercise; high-intensity interval training; locomotion; treadmill; overground

Introduction

Locomotor high-intensity interval training (HIIT) is a promising strategy for stroke rehabilitation, that seeks to maximize exercise intensity by using bursts of fast walking alternated with recovery periods.¹ Compared with other forms of treadmill training, adding treadmill HIIT to conventional inpatient stroke rehabilitation has been shown to provide significantly greater improvements in gait function.^{2,3} In chronic stroke, preliminary studies suggest that treadmill HIIT can improve both gait function and aerobic fitness,⁴⁻⁷ possibly to a greater extent than traditional moderate-intensity continuous exercise.^{6,7}

In previous stroke studies, HIIT protocols have varied widely and fall into one of three types: low-volume HIIT, short-interval HIIT and long-interval HIIT.¹ Low-volume HIIT (aka sprint interval training) generally involves short maximal-speed bursts and long passive recovery (e.g. 30 second max-speed bursts with 2 minute resting recovery³). Short-interval HIIT similarly involves short maximal speed bursts, but uses shorter recovery (e.g. 30 second max-speed bursts with 30–60 second resting recovery⁶). Unlike typical low-volume and short-interval HIIT, long-interval HIIT uses heart rate (HR) response to determine training speed and includes active recovery. Bursts are performed at vigorous aerobic intensity and recovery involves walking at a moderate intensity (e.g. 4 minute bursts with a HR target of 90% HR_{peak} and 3 minute recovery with a 70% HR_{peak} target⁵). The relative efficacy of these different HIIT types for facilitating stroke recovery remains unknown.

One efficient preliminary strategy for determining the potential for between-protocol differences in efficacy is to examine training intensity differences that are known to predict outcomes. For example, faster gait speed and higher aerobic intensity during post-stroke exercise have been shown to yield greater improvement in gait function and aerobic fitness, respectively.^{1,8} In addition, the amount of walking practice during training may also contribute to gait outcomes.⁹

In a previous repeated-measures study, these training intensity variables were compared between three treadmill HIIT protocols in chronic stroke. Each 20-minute protocol used 30 second bursts at maximum safe speed (where the participant can safely complete the burst, but has some backward drift or gait instability with recovery), with the potential to progress

speed each burst based on performance. The protocols ranged from low-volume (2 minute recovery) to short-interval (60 second recovery and 30 second recovery). Compared with low-volume HIIT, the short-interval 60 second recovery protocol enabled similar treadmill speed with significantly higher aerobic intensity and step count.¹⁰ The 30 second recovery protocol had even higher aerobic intensity and step count, but lower treadmill speed.¹⁰ This led to the development of a combined short-interval HIIT protocol that starts with 60 second recovery for the first 3 bursts of each session to maximize training speed, then progresses to 30 second recovery to further increase aerobic intensity and the amount of walking practice.⁶

However, no previous studies have compared the intensity of short and long-interval HIIT after stroke. While shorter intervals may seem likely to enable faster speeds, this has not been previously shown after stroke, and it was plausible that motor impairment could have limited the capacity for sprint-like speed increases. If present, such speed limitations would have also limited aerobic intensity, potentially making long-interval HIIT a better option in this population. However, it was also unclear how well stroke survivors with gait impairment would be able to sustain the 90% HR_{peak} target of long-interval HIIT. This is because previous studies in those with stroke using such a protocol have recruited samples with normal or near-normal walking capacity (e.g. mean baseline 10-m walk test speeds of 0.85–1.61 m/s; 6-minute walk test distances of 317–474 m) and have reported limited information about actual intensity during training.^{4,5,7}

Another issue with treadmill training is the limited translation into the overground environment, when not combined with overground practice.^{6,11,12} It is possible that overground HIIT could facilitate this translation or eliminate the need for it.¹³ However, previous stroke studies have only tested treadmill HIIT. This study aimed to compare training intensity between short vs. long-interval HIIT and between treadmill vs. overground HIIT among stroke survivors with gait impairment. This also included testing the feasibility of achieving vigorous aerobic intensity with overground HIIT in this population. We hypothesized that short-interval HIIT would promote faster training speeds, that long-interval HIIT would promote higher step counts, and that treadmill HIIT would enable higher training speed and aerobic intensity than overground HIIT.

Materials and Methods

This was a secondary data analysis from study NCT0285834 ([ClinicalTrials.gov](https://clinicaltrials.gov) Identifier), which was approved by institutional review boards and was performed in a cardiovascular stress laboratory and rehabilitation research laboratory from July 2016 to December 2017. STROBE guidelines were followed for this report.¹⁴

Participants

Participants were recruited from the community and provided written informed consent. Inclusion criteria were: age 30–90 years; unilateral stroke in middle cerebral artery territory experienced >6 months prior to enrollment; walking speed <1.0 m/s on the 10 meter walk test¹⁵; and able to walk 10m over ground with assistive devices as needed and no physical assistance. Exclusion criteria were: MRI incompatibility; inability to perform mental imagery¹⁶; evidence of significant arrhythmia or myocardial ischemia on treadmill ECG

stress test, or significant baseline ECG abnormalities that would make an exercise ECG uninterpretable¹⁷; recent cardiopulmonary hospitalization; unable to communicate with investigators or correctly answer consent comprehension questions; significant ataxia or neglect (NIHSS item score >1)¹⁸; severe lower extremity (LE) hypertonia (Ashworth >2)¹⁹; recent drug or alcohol abuse or significant mental illness; major post-stroke depression (PHQ-9 10)²⁰ in the absence of management of the depression by a health care provider²¹; participating in physical therapy or another interventional research study; recent paretic LE botulinum toxin injection; concurrent progressive neurologic disorder or other major conditions that would limit capacity for improvement; and pregnancy.

Study design

After screening and baseline testing, each participant performed 12 sessions of HIIT, approximately 3x/week for 4 weeks. Using a repeated measures design, each participant alternated between short and long-interval HIIT sessions, to control for progression effects. The first session was randomized across participants so that each protocol was either performed on even or odd sessions (Fig 1).

Baseline assessments

Medical history review, physical assessment, treadmill acclimation, graded exercise testing (GXT) with electrocardiography and a repeated GXT with gas exchange analysis (on a separate day) were performed as previously described,^{6,10} including measurement of HR_{peak} and peak oxygen consumption rate (VO_{2peak}). For the GXTs, treadmill speed was held constant at a pre-determined individualized value, while incline was increased 2–4% until volitional fatigue, severe gait instability or a cardiovascular safety limit.^{17,22} Fifteen minutes after the second GXT, participants performed another exercise test for verification of peak exercise capacity. This test started at a pre-determined, individualized fastest safe speed and 2–4% grade. Incremental grade then speed decreases were done as little as needed to enable continued walking as fast as possible for 3 minutes, with close guarding from a physical therapist. The highest HR and VO₂ values from either the GXT or 3-minute test were recorded as HR_{peak} and VO_{2peak}. Baseline results were also expressed as a percentage of normative demographic-predicted values for comfortable gait speed,¹⁵ 6-minute walk test,²³ HR_{peak}^{24,25} and VO_{2peak}.²⁶

Training protocols

Common features between protocols—Both HIIT protocols were administered by the same physical therapist and included a 3 minute warm up (overground walking at ~40% HR reserve [HRR]), 10 minutes of overground training, then 20 minutes of treadmill training, followed by another 10 minutes of overground training and a 2-minute cool down (overground walking at ~40% HRR). HRR bpm targets were calculated by: $(HR_{peak} - HR_{resting}) \times \%HRR \text{ target} + HR_{resting}$.¹⁷ Participants wore habitual orthotic devices, an activity monitor near the non-paretic ankle (Fitbit One), a chest strap HR monitor with a Bluetooth 4.0 transmitter (Polar H7) and a fall protection harness. An Apple iPod worn on the therapist's forearm provided interval timing and continuous HR monitoring, using an application (FitDigits iCardio) that was configured with the study protocols and

individualized target HR zones. Physical assistance was only provided if needed to maintain safety (e.g. to prevent a fall) and verbal cues focused on training speed, while avoiding emphasis on gait kinematics.

During treadmill training, a fall protection rope was attached to the harness and participants held a height-adjusted handrail (~25° elbow flexion) positioned to encourage upright posture (i.e. minimally anterior to the pelvis). During overground training, participants walked back and forth in a corridor, using their habitual assistive device and device pattern unless it was possible to achieve faster speeds with a less restrictive device or pattern. To maximize overground training speed, the distance covered during each burst was marked with a cone or beanbag for visual feedback and participants were encouraged to try to beat their previous distance each burst.

Short-interval HIIT—Short-interval HIIT involved 30 second bursts at maximum safe speed alternated with 30–60 second resting recovery periods.⁶ Each overground and treadmill bout started with 60 second recovery for the first 3 bursts, then progressed to 30 second recovery for the rest of the bout (Fig 2). If burst speed substantially decreased or the participant requested a seated rest break, recovery duration was temporarily increased again.

When selecting treadmill speeds during bursts, the goal was to quickly find the participant's maximum safe challenge speed and to progress that limit as able throughout the bout. At the challenge speed, the participant is able to safely complete the burst, but has some backward drift or gait instability with recovery. Treadmill speed started at ~75% of the previous peak speed. During the initial treadmill bursts each session, belt speed was increased in 0.1 mph increments after 15, 20 and 25 seconds until finding the initial challenge speed. Then, speed was maintained, increased or decreased (by 0.1 mph) for each burst based on performance criteria. If challenge speed criteria were met, speed was maintained. If a burst was safely completed with no backward drift or gait instability, speed was increased for the next burst. If the participant did not safely complete a burst, speed was decreased for the next burst.

Long-interval HIIT—For long-interval HIIT, target HR was ~90% HR_{peak} for bursts and ~70% HR_{peak} for recovery periods (Fig 2). Speed was continually adjusted as needed to achieve and maintain the target HR, by changing the treadmill belt speed or verbally cueing the participant to change overground speed. The goal was to reach the target HR zone within 1–2 minutes each burst. Recovery periods started with rest breaks until the HR trajectory was determined. The 20-minute treadmill bout included three 4-minute bursts with recovery durations of 3-minutes, 3-minutes and 2-minutes. Each 10-minute overground bout included two 3-minute bursts with 2-minute recovery periods.

Intensity measures

- *Gait training speeds* (neuromotor intensities) were measured during overground and treadmill bouts each session. Overground burst speeds were captured at the beginning and end of each overground bout (four times total per session), using a stopwatch over a 2–10 meter interval. For treadmill HIIT, the fastest consistently successful speed and peak successful speed were recorded. For short-interval HIIT, successful meant the participant safely completed the 30 second burst. For

long-interval HIIT, successful meant the participant safely walked at least 30 seconds at that speed without exceeding the target HR zone (85–95% HR_{peak}).

- *Training heart rate (HR)* (aerobic intensity) was continuously recorded by the iPod application. Mean HR was calculated for each bout and expressed as a percentage of HR_{peak} from baseline testing. Minutes spent at or above moderate, vigorous and target intensity thresholds (40% HRR, 60% HRR and 85% HR_{peak})¹⁷ were also calculated for the treadmill bout.
- *Session step count* (practice repetition) was recorded from the activity monitor and included all bouts combined.
- *Session rating of perceived exertion (RPE)* (subjective effort) was recorded on the Borg 6–20 scale at the end of the session.

Statistical analysis

The first analysis was designed to compare mean intensity and across-session intensity progression between short and long-interval HIIT. Each intensity variable was tested as the dependent variable in a separate statistical model, which included fixed effects for protocol, session number (modeled as a linear effect) and their interaction, and a random effect for participant to account for the correlation on repeated sessions. For dependent variables that were assessed at multiple time points during a session (e.g. gait speeds), the models included additional fixed effects for time point and its interaction with protocol, and an unconstrained covariance matrix to model the additional correlation on within-session repeated measures.

The second analysis was designed to test for within-session changes in training speed and HR, especially between the treadmill and overground training bouts. Gait speed and average HR were each tested as the dependent variable in separate statistical models, which included fixed effects for measurement time point (modeled as a categorical effect), protocol and their interaction, a random effect for participant and an unconstrained covariance matrix to model the additional correlation on within-session repeated measures. When comparing treadmill and overground gait speeds, fastest consistently successful treadmill speeds were used, rather than peak treadmill speeds.

For each of the above analyses, we also performed a supplemental effect modification analysis to test whether mean intensities, within-session changes and between protocol differences depended on baseline comfortable gait speed subgroup (< 0.4 m/s vs. ≥ 0.4 m/s)^{27,28} (see Supplemental material for details).

Based on other study aims, the target sample size was 10 participants with complete data. Assuming a standard deviation of 0.35 m/s and a repeated measures correlation of 0.85 with a decay rate of 0.2 across 6 sessions of each protocol, this sample size would provide an estimated 88% power to detect a between-protocol training speed difference of 0.2 m/s with only one measurement per session.²⁹ SAS version 9.4 was used for analysis and the significance level was set at 0.05. Missing data were handled with the method of maximum likelihood.

Results

Among the 14 persons with stroke who consented to participate in the study, 4 were not enrolled, due to MRI compatibility (N=2), significant ataxia (N=1) and transportation issues (N=1). The 10 enrolled participants (Table 1) all completed the study with no missing visits and no serious adverse events.

Short vs long-interval HIIT intensity comparisons

Compared with long-interval HIIT, short-interval HIIT had significantly higher means (main effects) for overground and treadmill training speeds, greater treadmill speed progression across sessions, and greater within-session increases in overground training speed (Fig 3; Tables 2 & 3). Compared with short-interval HIIT, long-interval HIIT had significantly higher means for overground training HR and session step count. Both protocols showed: 1) similar means for treadmill training HR, minutes spent at or above each aerobic intensity threshold during treadmill training and session RPE; 2) similar progression across sessions for overground training speeds and session RPE (although RPE progression was not quite significant for long-interval HIIT); and 3) similar lack of progression across sessions for overground and treadmill HR metrics and session step count.

Treadmill vs overground HIIT intensity comparisons

The effects of training mode significantly differed between protocols (Fig 3 & Table 3). For short-interval HIIT, gait training speed and mean HR were significantly higher on the treadmill versus overground. For long-interval HIIT, overground speed was significantly faster than treadmill speed and mean HR was similar between modes.

Baseline gait speed subgroup comparisons

Results and discussion for the effect modification analyses are provided as supplemental material.

Discussion

This is the first study to compare the effects of short versus long-interval HIIT or treadmill versus overground HIIT on locomotor training intensity post-stroke, and the first to attempt overground HIIT in this population. Both short and long-interval HIIT achieved high mean speeds during overground training (129% and 116% of baseline fastest, respectively), vigorous mean aerobic intensity during overground training (78 and 81% HR_{peak}) and treadmill training (83 and 82% HR_{peak}), mean step counts over 1,000 per session (1481 and 1672) and high perceived exertion (16.3 and 16.3). Additionally, short-interval HIIT achieved very high treadmill speeds, which were consistently 155% of baseline fastest overground speed, with peak speeds at 167%. Treadmill speeds during long-interval HIIT were below this benchmark (88–98% baseline fastest overground speed), but were still 124–139% of comfortable overground speed.

Short versus long-interval HIIT

Short and long-interval HIIT each seem to achieve high intensities, but emphasize different dosing parameters relevant to stroke rehabilitation. Compared with long-interval HIIT, short-interval HIIT enabled 12% faster overground training speeds and 70–76% faster treadmill training speeds, greater within-session increases in overground speed (changes for long-interval HIIT were not significantly different from zero) and greater across-session progression of treadmill speed (no significant progression across 6 sessions of long-interval HIIT). Conversely, long-interval HIIT enabled 3% higher mean aerobic intensity during overground training and 13% more total steps per session. Remarkably, despite these between-protocol differences, treadmill aerobic intensities and session RPE were essentially identical for short and long-interval HIIT.

Faster speed and greater stepping repetition during post-stroke locomotor training have each been associated with greater longitudinal improvements in gait function,^{1,8,9} and higher aerobic intensity during training is known to produce greater improvement in aerobic fitness.¹ However, the optimal prioritization of these different intensity parameters remains unknown, and future studies comparing the longitudinal outcomes of short and long-interval HIIT could help fill this knowledge gap. Based on the current results, we hypothesize that short-interval HIIT may optimally improve gait speed, but that the greater step counts for long-interval HIIT could preferentially target endurance, making overall walking capacity improvements similar between protocols. We also hypothesize that aerobic fitness improvement could be similar between short and long-interval HIIT, particularly if treadmill training is included. This is indeed what was observed in a previous study among neurologically healthy adults.³⁰

Treadmill versus overground HIIT

Compared with overground training, treadmill training enabled 20–29% higher training speeds and 6% higher mean aerobic intensity when using short-interval HIIT, but elicited 15–24% *lower* speeds and similar mean aerobic intensity when using long-interval HIIT. These findings suggest that optimal HIIT mode(s) could depend on interval type, and this should be tested in future studies with longitudinal outcomes. For short-interval HIIT, we hypothesize that the combination of overground and treadmill training may be optimal for improving gait function and aerobic fitness, given the higher intensity of treadmill training and the greater task-specificity of overground training.⁹ This combination could help translate the faster treadmill speeds into the real-world walking environment. For long-interval HIIT, we hypothesize that overground training alone could be optimal, given the faster walking speeds and greater task specificity. Overground-only aerobic training has not been well studied after stroke, but at least one study has shown it to be efficacious for improving walking capacity.³¹

It is noteworthy that participants had essentially identical treadmill and overground heart rates during long-interval HIIT, despite substantially lower speeds on the treadmill. This suggests that treadmill walking was less metabolically efficient than overground walking, which has been previously observed post-stroke.^{32,33} Still, this finding is somewhat surprising, since persons with stroke tend to walk more symmetrically on the treadmill

versus overground.^{32,33} One plausible explanation is that the adaptations toward symmetry induced by the step-by-step consistency of the treadmill speed are more energetically costly due to a greater need for contribution from the paretic lower limb.^{32,34} If so, the treadmill training speeds observed in this study could under-estimate the value of longitudinal treadmill intervention for promoting locomotor recovery.

Limitations

As described above, the primary study limitation is that we could not compare longitudinal outcomes between protocols or modes, which precludes any conclusions about relative efficacy. Another limitation is that treadmill training was always performed in the middle of each session, so it is also possible that warm up, cardiovascular drift or fatigue effects may have confounded differences between treadmill and overground HIIT. For example, heart rates were significantly higher during the second versus first overground training bout. This issue was partially mitigated by including the same total duration of overground and treadmill training, with an equal amount of overground training before and after treadmill training. However, it still may have impacted between-mode comparisons. We also acknowledge that the step monitor used in this study (Fitbit One) is known to underestimate step count for persons with slower gait speed after stroke (e.g. <0.58 m/s).^{35,36} Given that the mean baseline fast gait speed was 0.58 m/s, it is likely that some step counts were underestimated, and particularly for long-interval HIIT, since training speeds were lower during this protocol. When comparing training speeds between training modes, we used consistently successful, rather than peak, treadmill speeds to better match the measurement conditions for overground training. However, it is still possible that differences in speed measurement could have affected between-mode speed comparisons. Another issue is that the supplemental subgroup analysis had very low sample sizes in each gait speed subgroup (6 and 4). While the large number of repeated measures provided sufficient statistical power to detect significant effect modification in some cases, the subgroup estimates may be particularly prone to fluctuate in future studies. Thus, we advise against any firm conclusions about subgroup similarities or differences. On the other hand, one strength of the study was the recruitment of a sample with a wide range of gait function (Table 1), which makes the main results more generalizable to patients typically seen for outpatient rehabilitation.

Conclusions

Both short and long-interval HIIT enable high training intensity for persons with stroke, but short-interval HIIT preferentially maximizes training speed while long-interval HIIT preferentially maximizes stepping repetition and overground aerobic intensity. Importantly, the results suggest it is feasible to achieve fast relative training speeds and vigorous aerobic intensity with overground HIIT, even for participants with baseline gait speed < 0.4 m/s, and to at least temporarily increase fastest overground gait speed within a single 10-minute bout of short-interval overground HIIT. For short-interval HIIT, treadmill training enables higher training speed and aerobic intensity than overground training. For long-interval HIIT, overground training enables higher training speed than overground training despite similar aerobic intensity. Based on these preliminary findings and previous studies, we hypothesize that overground and treadmill short-interval HIIT may be optimal if primarily targeting gait

speed, overground long-interval HIIT may be optimal if primarily targeting gait endurance, and any combination except overground short-interval HIIT may be optimal if primarily targeting aerobic fitness.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

We thank the staff of the University of Cincinnati Medical Center Cardiovascular Stress Laboratory for their assistance with participant screening.

Funding: This work was supported by the National Institutes of Health under grants KL2TR001426, UL1TR001425 and R01HD093694; and the American Heart Association under grant 17MCPRP33670446. This content is solely the responsibility of the authors and does not necessarily represent the official views of the funding agencies.

REFERENCES

1. Boyne P, Dunning K, Carl D, Gerson M, Khoury J, Kissela B. High-intensity interval training in stroke rehabilitation. *Top Stroke Rehabil.* 2013;20(4):317–330. [PubMed: 23893831]
2. Pohl M, Mehrholz J, Ritschel C, Ruckriem S. Speed-dependent treadmill training in ambulatory hemiparetic stroke patients: A randomized controlled trial. *Stroke.* 2002;33(2):553–558. [PubMed: 11823669]
3. Lau KW, Mak MK. Speed-dependent treadmill training is effective to improve gait and balance performance in patients with sub-acute stroke. *J Rehabil Med.* 2011;43(8):709–713. [PubMed: 21698340]
4. Askim T, Dahl AE, Aamot IL, Hokstad A, Helbostad J, Indredavik B. High-intensity aerobic interval training for patients 3–9 months after stroke. A feasibility study. *Physiother Res Int.* 2014;19(3):129–39. [PubMed: 24375978]
5. Gjellesvik TI, Brurok B, Hoff J, Torhaug T, Helgerud J. Effect of high aerobic intensity interval treadmill walking in people with chronic stroke: A pilot study with one year follow-up. *Top Stroke Rehabil.* 2012;19(4):353–360. [PubMed: 22750965]
6. Boyne P, Dunning K, Carl D, et al. High-intensity interval training and moderate-intensity continuous training in ambulatory chronic stroke: A feasibility study. *Phys Ther.* 2016;96(10):1533–1544. [PubMed: 27103222]
7. Munari D, Pedrinolla A, Smania N, et al. High-intensity treadmill training improves gait ability, VO₂peak and cost of walking in stroke survivors: Preliminary results of a pilot randomized controlled trial. *Eur J Phys Rehabil Med.* 2018;54(3):408–418. doi: 10.23736/S1973-9087.16.04224-6 [doi]. [PubMed: 27575015]
8. Lee IH. Does the speed of the treadmill influence the training effect in people learning to walk after stroke? A double-blind randomized controlled trial. *Clin Rehabil.* 2015;29(3):269–276. doi: 10.1177/0269215514542637 [doi]. [PubMed: 25027443]
9. Hornby TG, Straube DS, Kinnaird CR, et al. Importance of specificity, amount, and intensity of locomotor training to improve ambulatory function in patients poststroke. *Top Stroke Rehabil.* 2011;18(4):293–307. [PubMed: 21914594]
10. Boyne P, Dunning K, Carl D, Gerson M, Khoury J, Kissela B. Within-session responses to high-intensity interval training in chronic stroke. *Med Sci Sports Exerc.* 2015;47(3):476–84. [PubMed: 24977698]
11. Moore JL, Roth EJ, Killian C, Hornby TG. Locomotor training improves daily stepping activity and gait efficiency in individuals poststroke who have reached a “plateau” in recovery. *Stroke.* 2010;41(1):129–135. [PubMed: 19910547]

12. Alcantara CC, Charalambous CC, Morton SM, Russo TL, Reisman DS. Different error size during locomotor adaptation affects transfer to overground walking poststroke. *Neurorehabil Neural Repair*. 2018;32(12):1020–1030. doi: 10.1177/1545968318809921 [doi]. [PubMed: 30409103]
13. Combs-Miller SA, Kalpathi Parameswaran A, Colburn D, et al. Body weight-supported treadmill training vs. overground walking training for persons with chronic stroke: A pilot randomized controlled trial. *Clin Rehabil*. 2014;28(9):873–884. doi: 10.1177/0269215514520773 [doi]. [PubMed: 24519922]
14. von Elm E, Altman DG, Egger M, et al. The strengthening the reporting of observational studies in epidemiology (STROBE) statement: Guidelines for reporting observational studies. *Epidemiology*. 2007;18(6):800–804. doi: 10.1097/EDE.0b013e3181577654 [doi]. [PubMed: 18049194]
15. Bohannon RW, Williams Andrews A. Normal walking speed: A descriptive meta-analysis. *Physiotherapy*. 2011;97(3):182–189. [PubMed: 21820535]
16. Malouin F, Richards CL, Durand A, Doyon J. Reliability of mental chronometry for assessing motor imagery ability after stroke. *Arch Phys Med Rehabil*. 2008;89(2):311–319. [PubMed: 18226656]
17. American College of Sports Medicine. ACSM's guidelines for exercise testing and prescription. 9th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2014.
18. Brott T, Adams HP Jr, Olinger CP, et al. Measurements of acute cerebral infarction: A clinical examination scale. *Stroke*. 1989;20(7):864–870. [PubMed: 2749846]
19. Ashworth B. Preliminary trial of carisoprodol in multiple sclerosis. *Practitioner*. 1964;192:540–542. [PubMed: 14143329]
20. Williams LS, Brizendine EJ, Plue L, et al. Performance of the PHQ-9 as a screening tool for depression after stroke. *Stroke*. 2005;36(3):635–638. [PubMed: 15677576]
21. Duncan PW, Sullivan KJ, Behrman AL, et al. Protocol for the locomotor experience applied post-stroke (LEAPS) trial: A randomized controlled trial. *BMC Neurol*. 2007;7:39. [PubMed: 17996052]
22. Macko RF, Katzell LI, Yataco A, et al. Low-velocity graded treadmill stress testing in hemiparetic stroke patients. *Stroke*. 1997;28(5):988–992. [PubMed: 9158639]
23. Enright PL, Sherrill DL. Reference equations for the six-minute walk in healthy adults. *Am J Respir Crit Care Med*. 1998;158(5 Pt 1):1384–1387. [PubMed: 9817683]
24. Gellish RL, Goslin BR, Olson RE, McDonald A, Russi GD, Moudgil VK. Longitudinal modeling of the relationship between age and maximal heart rate. *Med Sci Sports Exerc*. 2007;39(5):822–829. [PubMed: 17468581]
25. Brawner CA, Ehrman JK, Schairer JR, Cao JJ, Keteyian SJ. Predicting maximum heart rate among patients with coronary heart disease receiving beta-adrenergic blockade therapy. *Am Heart J*. 2004;148(5):910–914. [PubMed: 15523326]
26. Guazzi M, Adams V, Conraads V, et al. EACPR/AHA scientific statement. clinical recommendations for cardiopulmonary exercise testing data assessment in specific patient populations. *Circulation*. 2012;126(18):2261–2274. [PubMed: 22952317]
27. Dean CM, Ada L, Lindley RI. Treadmill training provides greater benefit to the subgroup of community-dwelling people after stroke who walk faster than 0.4m/s: A randomised trial. *J Physiother*. 2014;60(2):97–101. [PubMed: 24952837]
28. Schmid A, Duncan PW, Studenski S, et al. Improvements in speed-based gait classifications are meaningful. *Stroke*. 2007;38(7):2096–2100. [PubMed: 17510461]
29. Guo Y, Logan HL, Glueck DH, Muller KE. Selecting a sample size for studies with repeated measures. *BMC Med Res Methodol*. 2013;13:100–100. [PubMed: 23902644]
30. Helgerud J, Hoydal K, Wang E, et al. Aerobic high-intensity intervals improve VO₂max more than moderate training. *Med Sci Sports Exerc*. 2007;39(4):665–671. [PubMed: 17414804]
31. Gordon CD, Wilks R, McCaw-Binns A. Effect of aerobic exercise (walking) training on functional status and health-related quality of life in chronic stroke survivors: A randomized controlled trial. *Stroke*. 2013;44(4):1179–1181. [PubMed: 23471273]
32. Brouwer B, Parvataneni K, Olney SJ. A comparison of gait biomechanics and metabolic requirements of overground and treadmill walking in people with stroke. *Clin Biomech (Bristol, Avon)*. 2009;24(9):729–734. doi: 10.1016/j.clinbiomech.2009.07.004 [doi].

33. Ijmker T, Houdijk H, Lamothe CJ, et al. Effect of balance support on the energy cost of walking after stroke. *Arch Phys Med Rehabil*. 2013;94(11):2255–2261. doi: 10.1016/j.apmr.2013.04.022 [doi]. [PubMed: 23702394]
34. Harris-Love ML, Macko RF, Whittall J, Forrester LW. Improved hemiparetic muscle activation in treadmill versus overground walking. *Neurorehabil Neural Repair*. 2004;18(3):154–160. doi: 10.1177/0888439004267678 [doi]. [PubMed: 15375275]
35. Hui J, Heyden R, Bao T, et al. Validity of the fitbit one for measuring activity in community-dwelling stroke survivors. *Physiother Can*. 2018;70(1):81–89. doi: 10.3138/ptc.2016-40.ep [doi]. [PubMed: 29434422]
36. Klassen TD, Semrau JA, Dukelow SP, Bayley MT, Hill MD, Eng JJ. Consumer-based physical activity monitor as a practical way to measure walking intensity during inpatient stroke rehabilitation. *Stroke*. 2017;48(9):2614–2617. doi: 10.1161/STROKEAHA.117.018175 [doi]. [PubMed: 28784922]

Figure 1. Study design.

Each participant performed 12 sessions of high-intensity interval training (HIIT) over approximately 4 weeks, alternating between short-interval HIIT sessions (S) and long-interval HIIT sessions (L). The first session was randomized across participants.

Figure 2. Session structure and training protocols.

Light gray boxes depict target heart rates (long-interval HIIT plus warm up and cool down for short-interval HIIT). Dark gray boxes depict target speeds (short-interval HIIT bursts were performed at maximum safe speed, which was continually progressed as able throughout the session). Black lines depict examples of actual heart rate responses. HR_{peak} , peak heart rate from symptom-limited exercise testing.

Figure 3. Within-session training intensity changes by protocol.

Values are averaged across sessions within the statistical model. Error bars depict standard error. Dashed lines indicate the mean baseline comfortable and fastest gait speed from the 10m walk test. Treadmill speeds are consistent (not peak) training speeds. *Significant ($p < 0.05$) between-protocol difference. †Significant within-protocol change.

Table 1.**Participant characteristics (n=10)**

Age, years		59.8 ± 6.8 [50.4–69.4]
Female, n (%)		4 (40%)
Ischemic stroke type, n (%)		9 (90%)
Years post stroke		2.4 ± 1.7 [0.5–6.1]
Body mass index, kg/m ²		30.2 ± 4.2 [25.9–37.2]
Comfortable gait speed		
	m/s	0.41 ± 0.35 [0.09–1.03]
	% predicted	30.6 ± 25.6 [6.9–72.3]
Fastest gait speed, m/s		0.58 ± 0.58 [0.12–1.87]
6-minute walk test distance		
	m	154 ± 156 [32–491]
	% predicted	27.8 ± 26.4 [6.3–78.4]
β-blocker use, n (%)		3 (30%)
Age-predicted maximal HR, bpm *		147 ± 22 [121–173]
Resting heart rate, bpm		135 ± 19 [108–160]
Exercise testing results		
Peak oxygen consumption rate (VO _{2peak})		
	mL/kg/min	14.5 ± 4.2 [10.5–23.9]
	% predicted	59.4 ± 14.1 [41.1–81.8]
Peak heart rate (HR _{peak})		
	bpm	147 ± 12 [127–164]
	% predicted	100.4 ± 15.9 [81.5–123.4]
Peak respiratory exchange ratio		1.00 ± 0.11 [0.86–1.24]

Values are mean ± SD [range] or N (%)

* Adjusted for β-blocker use

Table 2.

Mean intensity comparisons between protocols and progression across sessions

	Estimated mean across sessions		Estimated change per session	
	Short-interval HIIT	Long-interval HIIT	Short-interval HIIT	Long-interval HIIT
Gait training speeds, m/s				
Overground combined	0.75 [0.30, 1.19] *	0.67 [0.22, 1.11]	0.03 [0.02, 0.04] †	0.03 [0.02, 0.04] †
Overground bout 1	0.72 [0.27, 1.17] *	0.67 [0.22, 1.12]	0.03 [0.02, 0.04] †	0.03 [0.02, 0.04] †
Overground bout 2	0.77 [0.32, 1.21] *	0.67 [0.22, 1.11]	0.03 [0.02, 0.05] †	0.03 [0.01, 0.04] †
Consistent treadmill speed	0.90 [0.49, 1.31] *	0.51 [0.09, 0.92]	0.03 [0.01, 0.05] †*	0.00 [-0.02, 0.02]
Peak treadmill speed	0.97 [0.55, 1.39] *	0.57 [0.15, 1.00]	0.04 [0.02, 0.06] †*	0.00 [-0.02, 0.02]
Average bout heart rates, % HR_{peak}				
Overground combined	78.4 [72.9, 83.9]	81.1 [75.6, 86.5] *	0.0 [-0.7, 0.7]	0.3 [-0.4, 1.0]
Overground bout 1	72.7 [67.6, 77.8]	76.0 [70.9, 81.1] *	-0.1 [-0.9, 0.6]	0.4 [-0.4, 1.2]
Overground bout 2	84.1 [77.6, 90.7]	86.3 [79.8, 92.9] *	0.2 [-0.5, 1.0]	0.2 [-0.6, 1.0]
Treadmill	82.9 [77.5, 88.3]	81.8 [76.4, 87.2]	0.2 [-0.6, 1.0]	0.5 [-0.4, 1.3]
Minutes at or above aerobic intensity thresholds during 20-minute treadmill bout				
40% HRR _{peak}	17.6 [16.1, 19.1]	17.7 [16.2, 19.2]	0.3 [-0.0, 0.6]	0.2 [-0.1, 0.5]
60% HRR _{peak}	11.9 [9.3, 14.6]	12.5 [9.9, 15.1]	0.4 [-0.2, 0.9]	0.2 [-0.4, 0.7]
85% HR _{peak}	8.1 [5.4, 10.7]	8.6 [6.0, 11.2]	0.4 [-0.2, 1.1]	0.4 [-0.3, 1.1]
Additional intensity metrics				
Session step count	1481 [752, 2211]	1672 [943, 2402] *	21 [-38, 81]	45 [-15, 106]
Session RPE (6–20)	16.3 [14.9, 17.6]	16.3 [15.0, 17.7]	0.3 [0.1, 0.6] †	0.1 [-0.1, 0.4]

Values are mean [95% CI]. Each row shows results from a separate statistical model with the dependent variable from the first column, fixed effects for protocol, session (modeled as a linear effect) and their interaction, and a random effect for participant. For dependent variables that were assessed at multiple time points during a session, the model also included additional fixed effects for time point and its interaction with protocol, and an unconstrained covariance matrix to model the additional correlation on within-session repeated measures.

* Significant ($p < 0.05$) between-protocol difference.

† Significant within-protocol change.

HRR, heart rate reserve; RPE, rating of perceived exertion

Table 3.

Within-session intensity changes

	Short Interval HIIT	Long Interval HIIT
Speed changes during and between overground training bouts, m/s		
Change during overground bout 1	0.08 [0.04, 0.13] ^{†*}	-0.00 [-0.05, 0.05]
Change from overground bout 1 to 2	0.05 [0.02, 0.07] ^{†*}	-0.00 [-0.03, 0.03]
Change during overground bout 2	0.03 [-0.00, 0.07] [*]	-0.03 [-0.07, 0.01]
Consistent treadmill speed vs overground training speeds, m/s		
Treadmill – Overground combined	0.16 [0.12, 0.20] ^{†*}	-0.15 [-0.19, -0.12] [†]
Treadmill – Overground 1	0.18 [0.14, 0.22] ^{†*}	-0.16 [-0.20, -0.11] [†]
Treadmill – Overground 2	0.14 [0.10, 0.18] ^{†*}	-0.15 [-0.20, -0.11] [†]
Treadmill vs overground average training heart rate, % HR_{peak}		
Treadmill – Overground combined	4.5 [3.7, 5.4] ^{†*}	0.7 [-0.2, 1.6]
Treadmill – Overground 1	10.3 [8.9, 11.7] ^{†*}	5.8 [4.4, 7.3] [†]
Treadmill – Overground 2	-1.2 [-2.2, -0.2] ^{†*}	-4.4 [-5.4, -3.4] [†]

Values are mean [95% CI] and were averaged across sessions within the statistical model. Each intensity measure (gait speed, average heart rate and max heart rate) was tested with a separate statistical model with the intensity measure as the dependent variable, fixed effects for protocol, time point (modeled as a categorical effect) and their interaction, a random effect for participant and an unconstrained covariance matrix to model the additional correlation on within-session repeated measures.

[†]Significant (p<0.05) within-protocol change.

^{*}Significant between-protocol difference.