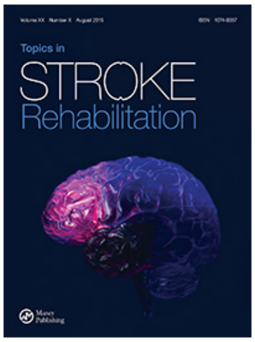


Taylor & Francis
Taylor & Francis Group

Topics in Stroke Rehabilitation

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ytsr20

# Targeted verbal cues can immediately alter gait following stroke

Chelsea J Parker, Hailey Guerin, Ben Buchanan & Michael D Lewek

**To cite this article:** Chelsea J Parker, Hailey Guerin, Ben Buchanan & Michael D Lewek (2021): Targeted verbal cues can immediately alter gait following stroke, Topics in Stroke Rehabilitation, DOI: 10.1080/10749357.2021.1928840

**To link to this article:** https://doi.org/10.1080/10749357.2021.1928840

Published online: 22 May 2021.

Submit your article to this journal

View related articles

View Crossmark data

Full Terms & Conditions of access and use can be found at
https://www.tandfonline.com/action/journalInformation?journalCode=ytsr20

TOPICS IN STROKE REHABILITATION
https://doi.org/10.1080/10749357.2021.1928840

Taylor & Francis
Taylor & Francis Group

Check for updates

# Targeted verbal cues can immediately alter gait following stroke

Chelsea J Parker[a], Hailey Guerin[b], Ben Buchanan[b], and Michael D Lewek[a,b]

[a]Human Movement Science Curriculum, University of North Carolina at Chapel Hill, Chapel Hill, United States; [b]Division of Physical Therapy, Department of Allied Health Sciences, University of North Carolina at Chapel Hill, Chapel Hill, United States

**ABSTRACT**

**Background**: Physical therapists use verbal cueing extensively during gait rehabilitation. Nevertheless, little is known about the ability of individuals post-stroke to make immediate changes to targeted spatiotemporal gait parameters from verbal commands. Additionally, adequate muscle strength may be necessary to promote positive alterations in gait.

**Objectives:** To determine the influence of targeted verbal cues on spatiotemporal gait parameters for individuals with chronic stroke. Further, we assessed the potential of a relationship between cue-induced gait modifications and paretic lower limb strength.

**Methods:** Using a within-subjects design, twenty-seven adults with chronic stroke walked over a pressure mat with verbal cues to walk at (1) comfortable and (2) fast speeds, with increased (3) arm swing, (4) foot height, (5) step length, (6) push off, and (7) cadence. We also assessed lower extremity strength using a hand-held dynamometer. We measured gait speed, step length, stance time, and cadence for comparisons between conditions and performed correlational analyses to assess the influence of strength on gait alterations.

**Results:** Specific cues elicited increased walking speed, cadence, step lengths and paretic limb stance time. Only greater paretic hip and knee flexion strength was related to the ability to increase cadence when cued to do so ($r > 0.41$).

**Conclusion:** With targeted verbal cueing, clinicians can improve step length, gait speed, stance time and cadence for individuals with chronic stroke. Lower extremity strength does not appear to be related to the ability to alter gait with verbal cueing in individuals with chronic stroke.

**ARTICLE HISTORY**
Received 15 February 2021
Accepted 7 May 2021

**KEYWORDS**
Gait; stroke; verbal cues; instruction; gait recovery

## Introduction

Although verbal cueing is ubiquitous in gait rehabilitation, we know relatively little about the ability of individuals post-stroke to make immediate changes to spatiotemporal parameters from simple verbal commands.[1,2] Of potential concern is the possibility that verbal cues may require greater cognitive resources, contributing to a delayed or inadequate response.[3] Nevertheless, verbal cues can immediately elicit select changes in muscle activity and kinematics for individuals post-stroke.[3] In particular, verbal cues provided before walking, during walking, and when provided as knowledge of results can contribute to improvements in gait speed, step length, trailing limb angle, and paretic push off.[4–6] Unfortunately, prior work has used inconsistent verbal cues across subjects, such that we are unable to determine the ability of specific verbal cues to change gait parameters.[7]

Additionally, adequate muscle strength may be necessary, but not sufficient, to promote positive alterations in gait. Given the perceived importance of lower extremity muscle weakness on gait function,[8] it appears that modifying gait would only be possible if adequate muscle strength was available. In fact, strength deficits are considered more responsible for limitations in gait kinematics than deficits in range of motion.[9] Specifically, deficits in hip abduction, knee extension, ankle dorsiflexion, hip flexion, and knee flexion may be particularly influential[10–12] for weight-bearing, stability, propulsion, and swing generation during gait.[13,14] In addition, the strength of the knee extensors, ankle plantarflexors, and hip flexors may influence fast walking speed post-stroke.[10,15]

Given the ability of individuals following stroke to change spatiotemporal aspects of gait, it is

**CONTACT** Michael D Lewek mlewek@med.unc.edu Division of Physical Therapy, Department of Allied Health Sciences, Human Movement Science Curriculum, University of North Carolina at Chapel Hill, Chapel Hill, United States

© 2021 Taylor & Francis Group, LLC

critical to determine the effects of specific verbal cues on gait to allow therapists to create appropriate treatments for specific gait deficits. Therefore, the purpose of this study was to determine the immediate effect of specific verbal cues on overground spatiotemporal gait parameters of the paretic and non-paretic limbs. Additionally, we sought to determine the role of muscle strength on the ability to alter spatiotemporal parameters in response to specific verbal cues. We hypothesized that individuals post-stroke would alter their gait in response to specific verbal instructions intended to elicit longer step lengths, greater cadence, increased paretic stance times, and faster speeds than 'typical' walking. Furthermore, we hypothesized that individuals with greater muscle strength would be capable of producing greater changes in gait parameters (i.e. velocity, step length, cadence, symmetry) in response to these verbal cues. We expect that the outcomes of this study will help guide clinical practice by elucidating the role of verbal cues in altering gait for individuals following stroke.

## Methods

### Participants

We recruited individuals with chronic stroke to participate in a single testing session consisting of two quasi-randomized components (overground gait analysis and strength testing). Participants were recruited from local physical therapy clinics and various local stroke support groups. Potential participants were included if they experienced a stroke at least 6 months prior to testing and could walk ~10 m without therapist support. Potential participants were excluded due to additional neurologic or orthopedic disorders that could affect the ability to walk, a history of balance deficits or unexplained falls not related to the stroke, or the presence of receptive aphasia or an inability to understand and follow directions. Participants used their usual shoes, assistive devices, and orthoses during testing, but were excluded if they required anything greater than standby-assist from a physical therapist. All participants signed an informed consent form approved by the IRB of the University of North Carolina at Chapel Hill before participating. This study conforms to the STROBE guidelines.

### Gait analysis

Participants completed eight conditions of walking across a 4.27 m (14 ft) GAITRite mat (CIR systems, Franklin, NJ). For each condition, participants completed two passes and had several feet of space at each end of the mat to accelerate and decelerate. The first condition always consisted of participants walking at their comfortable gait speed (CGS). This was intended to capture the baseline, typical walking of our participants. Here, participants were instructed to "walk at your self-selected comfortable pace". The next six conditions were randomized to minimize the influence of a verbal command on subsequent conditions. Verbal commands were provided by a physical therapist prior to each condition.

Fast: "Please walk as fast as you can, while being safe", which was intended to determine how well participants changed their speed.[16]

Arm Swing: "Please walk while swinging your arms as much as you can", which was intended to generate longer steps given the propriospinal connections between arms and legs.[17] For participants who required use of an assistive device in the non-paretic arm, they attempted to increase paretic arm swing only.

High Steps: "Please walk while lifting your feet as high as you can", which was intended to encourage weight shift to the stance leg for greater stance times.

Long Steps: "Please walk while stepping as far as you can", which was intended to provide an internal focus of attention to encourage longer steps.

Push-off: "Please push off of the ground as hard as you can with each step", which was intended to provide an external focus of attention to produce longer step lengths.[18]

Quick Steps: "Please step as quickly as you can", which was intended to determine how participants increased their cadence by quickly loading/unloading each limb.

After the preceding six randomized test conditions, all participants completed another CGS condition that was identical to the initial condition. This final CGS condition was intended to determine any residual influence of the verbal commands. We provided participants with rest breaks between conditions, if needed. If participants were unable to understand the verbal cue, we repeated the command, but no further explanation, coaching, or demonstration was given to clarify the command.

### *Muscle strength*

Isometric muscle strength was assessed using a MicroFET 2 hand-held dynamometer (Hoggan Scientific, Salt Lake City, UT). Manual muscle testing was performed in seated positions (see Table 1) for the following movements: hip flexion, hip abduction, knee flexion, knee extension, ankle dorsiflexion, and ankle plantarflexion. Despite the potential importance of the hip extensors we were unable to test this muscle group in sitting and thus do not have those data. We measured the distance from the tested joint to the applied force in centimeters using a standard tape measure, and the applied force from the dynamometer was measured in pounds and converted to Newtons. This allowed us to calculate joint torque in N·m.

### *Data management and analysis*

We used the GAITRite software to eliminate assistive devices, toe-drags, or partial steps at the beginning or end of each pass. We then calculated gait speed, step length, step width, cadence, and stance times for each condition.[19] We computed asymmetry ratios as:

step length asymmetry ratio = max(paretic, non-paretic)/(paretic + non-paretic)

stance time asymmetry ratio = paretic/(paretic + non-paretic)

Normalized strength data were compared between limbs using paired-samples t-tests. The strength of each muscle group was assessed relative to the non-paretic limb, such that:

muscle strength = paretic/(paretic + non-paretic)

We used SPSS (ver 26, IBM, Chicago, IL) to perform all statistical analyses. We first compared the baseline CGS condition to the final CGS condition to ensure that the verbal commands did not extend to subsequent conditions. We observed comparable parameters between the two CGS conditions with the exception of gait speed, which was slightly faster for the final test (+0.05 m/s, consistent with previous reports).[19] Consequently, each outcome measure was compared between the remaining seven conditions (baseline CGS and six verbal commands) using a one-way repeated measures ANOVA, repeated for verbal instruction. When significant main effects were found, we performed planned paired samples t-tests between the CGS condition and each of the verbal instructions. Multiple comparisons were accounted for with Bonferroni corrections. We report effect sizes as Cohen's d values.

Strength data was first normalized to body mass. The relative change of each gait parameter (e.g. cadence, step length, etc) was computed as follows: (parameter with verbal cue – parameter at CGS)/parameter with verbal cue. This provided the ratio of change for gait parameters associated with each verbal cue. Next, we performed Pearson correlations to determine the presence of a linear relationship between the normalized strength of each muscle group and the relative spatiotemporal changes induced with the differing verbal cues, using an alpha level of 0.05. Given our specific interest in certain aspects of gait with each cue (fast = increased gait speed, quick steps = increased cadence, etc), we only examined the relationship between strength

**Table 1.** Manual muscle testing details.

| Muscle Group | Dynamometer Placement | Testing Position | Paretic Strength (N·m) | Non-Paretic Strength (N·m) |
|---|---|---|---|---|
| Hip flexion | Distal anterior femur | 90° hip and knee | 42.1 ± 16.0 | 56.5 ± 17.9 |
| Hip abduction | Distal lateral femur | 90° hip and knee | 43.2 ± 18.5 | 52.9 ± 15.2 |
| Knee flexion | Distal posterior tibia | 90° knee | 35.01 ± 19.9 | 50.1 ± 16.7 |
| Knee extension | Distal anterior tibia | 90° knee | 40.4 ± 15.8 | 51.6 ± 16.0 |
| Ankle plantarflexion | Plantar surface of metatarsal head | 90° knee and ankle | 23.8 ± 14.8 | 30.8 ± 13.1 |
| Ankle dorsiflexion | Dorsal surface of metatarsal heads | 90° knee and ankle | 14.5 ± 17.2 | 20.5 ± 8.0 |

N = 27 for all measures. Strength represents mean ± SD.

and change in the gait parameter targeted by each verbal cue.

## Results

We recruited a total of 27 individuals (11 M; 16 F; age: 64.7 ± 12.2 years old; height: 1.70 ± 0.09 m; mass: 83.0 ± 19.4 kg; stroke chronicity: 75.4 ± 89.1 months) for testing. Within our participants (13 left paretic/14 right paretic), we had 11 individuals use an assistive device (single point cane (N = 9), quad cane (N = 1) or rolling walker (N = 1)), with four of these 11 also using an ankle foot orthosis.

### Effect of verbal cues on gait speed

In response to verbal cueing, individuals altered their gait speed ($p < .001$; $\eta_p^2 = 0.558$, Figure 1). In particular, participants slowed their gait when asked to walk with high knees ($p = .014$; d = 0.74), and walked quicker when asked to walk with quick steps ($p = .011$; d = 0.76) and at their fastest speed ($p < .001$; d = 1.72).

### Temporal measures

Cadence was influenced by verbal cues ($p < .001$; $\eta_p^2 = 0.621$, see Figure 2), with a slower cadence used for the high knees ($p < .001$; d = 1.04), long steps ($p = .002$; d = 0.88), and large push-off cues ($p = .005$; d = 0.81). Participants increased their cadence when asked to walk with quick steps ($p < .001$; d = 1.10), and as fast as possible ($p < .001$; d = 1.93).

Relatedly, the stance times for both the paretic and non-paretic limbs (paretic: $p < .001$; $\eta_p^2 = 0.507$; non-paretic: $p < .001$; $\eta_p^2 = 0.480$; Figure 3) were altered with various cues. In particular, participants spent longer in stance phase when instructed to walk with high knees (paretic: $p = .001$; d = 0.91; non-paretic: $p = .033$; d = 0.68),

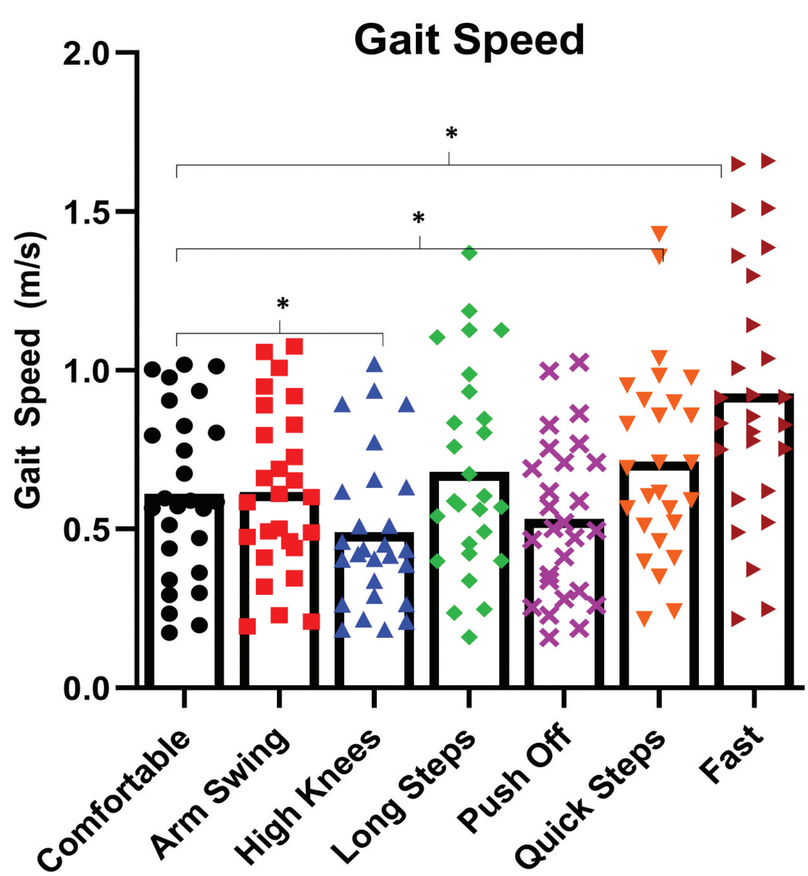


Figure 1. Gait speed for each participant in response to the 7 cues/conditions. Individual data points represent each subject's gait speed in response to the specific cue. The bar graph represents the mean across all subjects. Significant increases in gait speed were found for 'quick steps' and 'fast' cues, with a significant decrease in gait speed in response to 'high knees' cue.

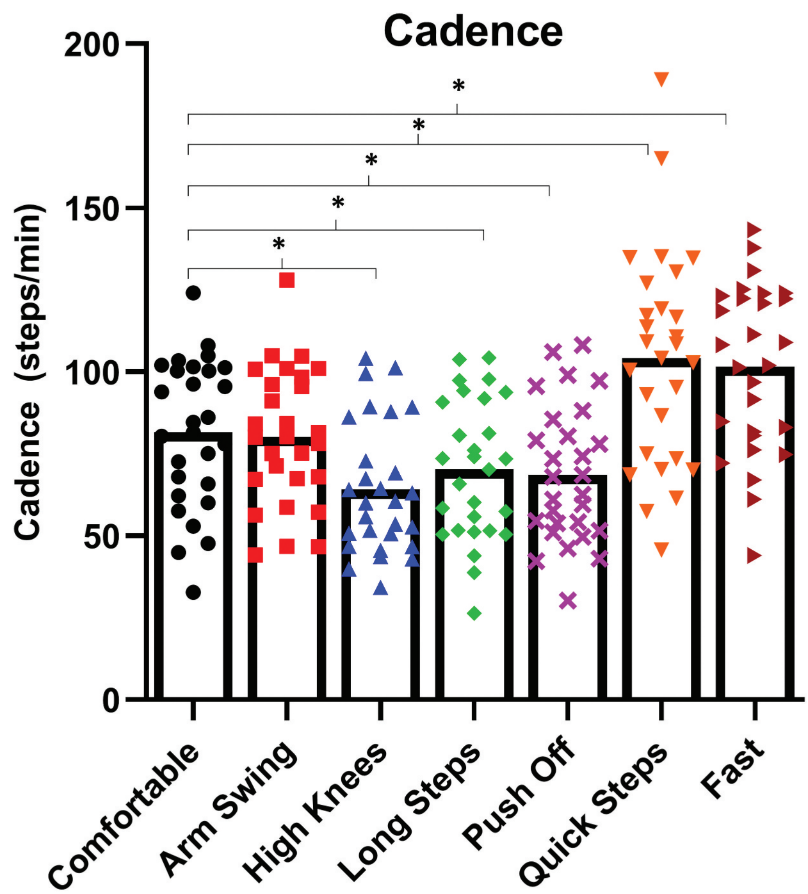


**Figure 2.** Cadence for each participant in reaction to the 7 cues/conditions. Individual data points represent each subject's gait cadence in response to cueing. The bar graph represents the mean across all subjects. Significant increases in cadence found for 'quick steps' and 'fast' cues, with a significant decrease in cadence with cues for 'high knees', 'long steps', and 'push off' cues.

take longer steps (paretic: $p = .019$; d = 0.72; non-paretic: $p = .044$; d = 0.67), and push harder off the ground (paretic: $p = .026$; d = 0.70). In contrast, participants spent less time on the stance limb when instructed to use a quick cadence (paretic: $p < .001$; d = 1.08; non-paretic: $p < .001$; d = 1.09) and to walk as fast as they could (paretic: $p < .001$; d = 1.13; non-paretic: $p < .001$; d = 1.14). Because the changes to stance time appeared to occur on both limbs, participant's stance time asymmetry did not change in response to the verbal instructions ($p = .496$; $\eta_p^2 = 0.030$).

### Spatial measures

Both the limb taking the shorter step ($p < .001$; $\eta_p^2 = 0.432$) and the limb taking the longer step ($p < .001$; $\eta_p^2 = 0.419$) showed altered step lengths based on the verbal cue provided (Figure 4). Specifically, both limbs increased step length when prompted to take long steps (shorter stepping limb: $p < .001$; d = 1.67; longer stepping limb: $p < .001$; d = 1.56) and when asked to walk at the fastest speed (shorter stepping limb: $p < .001$; d = 1.33; longer stepping limb: $p < .001$; d = 1.24). Because changes in step length occurred on both limbs, we did not observe any effect of verbal cue on participant's step length asymmetry ($p = .465$; $\eta_p^2 = 0.034$).

### Role of muscle strength on changes in spatiotemporal gait parameters

Across all participants, we observed weakness on the paretic side compared to the non-paretic side for hip flexion, hip abduction, knee flexion, knee extension, ankle plantarflexion, and ankle dorsiflexion moments (all $p < .026$; see Table 1). When instructed to walk with a quick cadence, we observed a weak positive correlation between the change in cadence

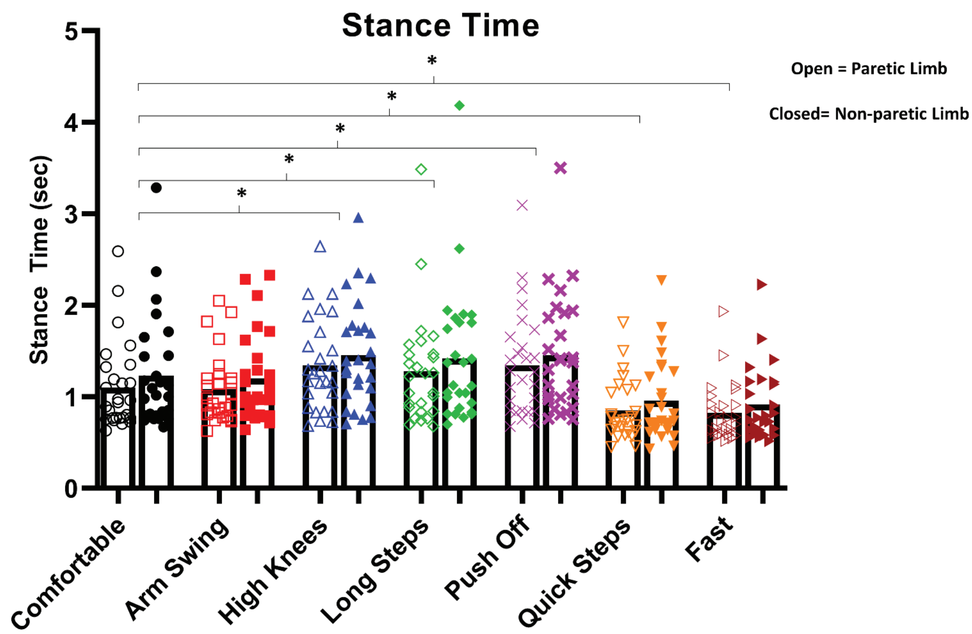


Figure 3. Stance time on paretic and non-paretic limb for each participant following the 7 cues/conditions. Individuals data points represent each subject's measurement. Paretic limb is represented by an open symbol and non-paretic limb data points are closed symbols. An increase in stance time was found for 'high knees', 'long steps' and 'push off' cues with a decrease in stance time with 'quick steps' and 'fast' cues. increases and decreases in stance time were seen for both the paretic and non-paretic limb, therefore there was no change in stance time symmetry.

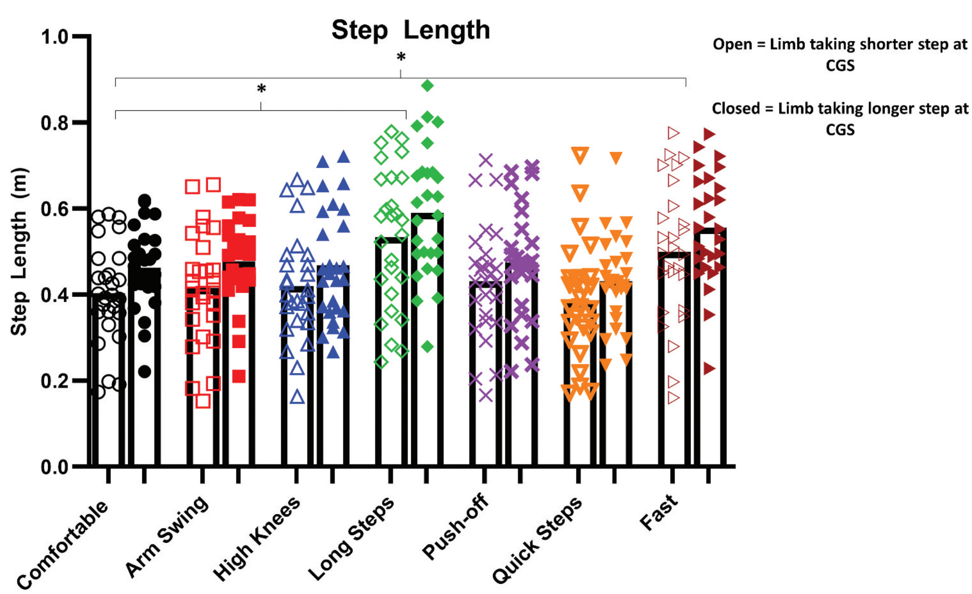


Figure 4. Step length for both the limb taking the longer step at baseline and the limb taking the shorter step at baseline for each of the 7 cues/conditions. Individual data points represent each participant's step length. The paretic limb is represented by an open symbol, non-paretic limb is closed symbol. Significant increase in step length noted with cues for 'long steps' and 'fast'. increases in step length were found for both the paretic and non-paretic extremity, therefore there was no change in step length symmetry.

and paretic hip ($r = 0.43$ $p = .02$, Figure 5a) and knee ($r = 0.41$ $p = .03$, Figure 5b) flexion strength. When instructed to walk as fast as they could, there was a weak negative correlation between the strength of the paretic limb hip abductors ($r = -0.43$, $p = .03$), knee flexors ($r = -0.41$, $p = .03$), and ankle dorsiflexors ($r = -0.43$, $p = .03$) with step width. We did not observe any relationship between the strength of the paretic limb and targeted changes to speed, stance time, or step length.

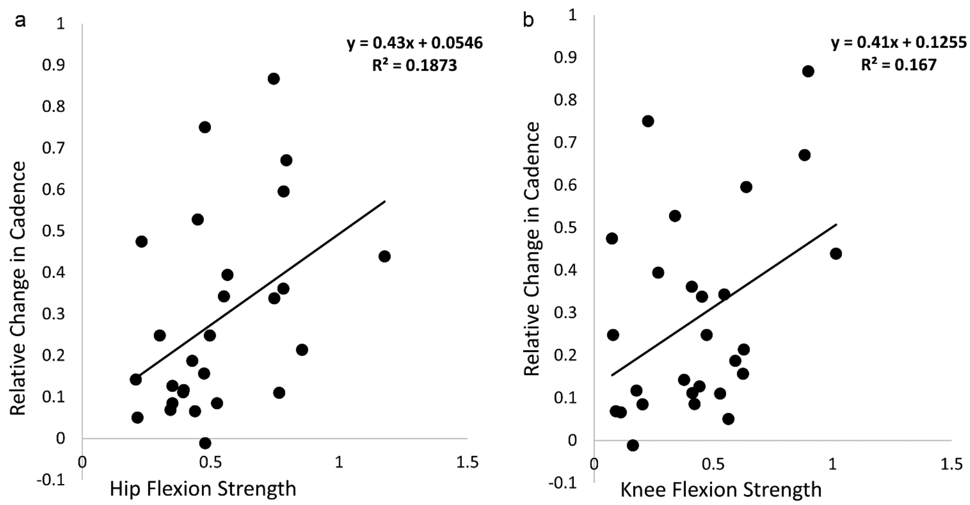


**Figure 5.** **(a & b)**: Relationship between hip and knee flexion strength and change in cadence. There was a significant relationship between increased strength of the hip and knee flexors and ability to increase cadence during 'quick steps' condition.

## Discussion

Our hypothesis that specific verbal cues can be used to alter spatiotemporal aspects of gait for individuals with chronic stroke was supported by the data; however, the finding that paretic leg strength had little relationship to these gait changes did not support our second hypothesis. Results of this study suggest that individuals with chronic stroke can use specific verbal cues to alter gait speed, cadence, paretic stance time, and step length. Regarding the importance of paretic limb strength, however, there was only a weak relationship between the ability to alter cadence and the available hip and knee flexion strength. Though there were no cues specifically for step width, we also noted a negative relationship between step width change and the strength of paretic hip abductors, knee flexors, and ankle dorsiflexors. There were no other relationships observed between paretic limb strength and the ability to alter gait with verbal cues. These data provide important information regarding the use of verbal cues during gait training for individuals with chronic stroke.

These findings may assist therapists and caregivers with the selection of verbal cues to elicit desired gait changes. For example, with a goal to increase cadence and gait speed, a cue for quick steps or to walk as fast as possible may be beneficial. When attempting to improve step length, cues to walk fast or with long steps were favorable. Despite ample research on the effects of propulsion on step length,[20,21] the cue to increase push off did not result in an observable increase in step length. Given the relative importance of the ankle plantarflexors in generating push-off forces,[22] it is possible that the observed deficits in ankle plantarflexion strength impeded the participants ability to respond appropriately to the 'push-off' cue. Cues for high knees, long steps, and to push-off harder were all successful at improving stance time on the paretic extremity. Previously, an increase in dynamic weight shift and stance time of the paretic extremity was linked to improved balance, sit to stand ability, and general walking ability.[23,24] Therefore, though it may not be reasonable to expect "high knees" performed in standing to translate to ambulation (i.e. 'pre-gait' activities for already ambulator individuals), it may be more relevant to incorporate this cue into intensive stepping practice.

Although not measured, we were particularly concerned that the use of verbal cues may detrimentally impact gait through cognitive-motor (dual-task) interference. Such interference in individuals with stroke can contribute to reduced gait speed, cadence, and stride length.[25] We can speculate that requiring multiple cues to address various components of gait might actually reduce the overall effect of the cues themselves. Our results, however, suggest that cueing patients with chronic stroke to "walk as fast as you can, while being safe" can improve gait speed, cadence, and step length. Therefore, the use of a single cue may reduce the dual-task cost associated with external cueing, as a single cue can improve three gait parameters.[26] Furthermore, it is important that the 'fast' walking cue was able to enhance multiple gait parameters. Faster walking has been advocated as a form of increasing the intensity of practice in a set of recent clinical practice guidelines for individuals with chronic stroke.[27] Therefore, there may be numerous benefits associated with cueing people with chronic stroke to walk faster during practice.

Spatiotemporal gait parameters improve more during gait retraining with cueing compared to gait training alone,[6] indicating that cueing is an important aspect of gait retraining post-stroke. Our work extends this evidence to provide specific cues that impact targeted spatiotemporal aspects of gait. Though previous studies have shown that verbal cues can alter gait characteristics and muscle activation[3] no prior study has investigated the specific gait changes associated with cues that intend to increase gait speed, cadence, step length, and stance time. By using consistent language for each participant across conditions, we were able to accurately report on the effects of therapist cueing during gait.

Our second hypothesis was that individuals with greater muscle strength in the paretic limb would produce greater changes in gait parameters. This hypothesis was only partially supported by our data. In fact, the only instance in which strength was related to a verbal cue-induced change, was during cueing to walk with quick steps. There was no relationship between relative muscle strength of participants and the change in velocity (cue to walk as fast as possible), stance time (with cues to step high), or step length (with changes to step long, push off hard, or walk fast). Despite evidence that lower extremity strength post-stroke can influence gait speed,[28] our results suggest that other factors (e.g. motor coordination and control) may play a larger role in influencing gait parameters in response to verbal cues.

Despite not including cues specific to step width, we observed a relationship between the relative strength of the paretic hip abductors, knee flexors, and ankle dorsiflexors and step width following cueing to walk as fast as possible. The greater strength of the hip abductors may be particularly relevant, as the hip abductors are important for guiding mediolateral foot placement during walking for individuals post-stroke.[29] Our data provides further evidence on the importance of hip abductor muscle strength for maintaining frontal plane stability during potential balance challenges. Nevertheless, the relatively weak relationship suggests that factors other than muscle force generating capacity are also important.

### Limitations

The lack of hip extension strength measurements represents a limitation in our testing. As participants were assessed in the seated position, we were unable to acquire hip extension strength. We recognize the relative importance of the strength of this muscle group as a contributing factor in gait parameters.[30] In addition, our study design does not allow for insight into long-term retention of changes in gait parameters from verbal cueing. Finally, our relatively small sample size potentially limits generalizability to other individuals with stroke.

In summary, this study demonstrated the malleable nature of gait post-stroke. With simple targeted verbal cues, we were able to immediately alter gait post-stroke. Therapists and caregivers now have specific verbal cues at their disposal that can be used to alter targeted spatiotemporal aspects of gait for this population.

## Acknowledgments

he authors acknowledge Katie Stephens, PT and her staff for assistance with subject recruitment.

## ORCID

Chelsea J Parker http://orcid.org/0000-0001-8181-779X
Michael D Lewek http://orcid.org/0000-0002-1917-5594

## Declarations of interest

The authors report no conflicts of interest.

## References


1. Nascimento LR, De Oliveira CQ, Ada L, et al. Walking training with cueing of cadence improves walking speed and stride length after stroke more than walking training alone: a systematic review. *J Physiother*. 2015; 61 (1):10–15. 2014/ 12/23. doi:10.1016/j.jphys.2014.11.015.
2. Johnson L, Burridge JH, Demain SH. Internal and external focus of attention during gait re-education: an observational study of physical therapist practice in stroke rehabilitation. *Phys Ther*. 2013;93(7):957–966. 2013/ April/06. doi:10.2522/ptj.20120300.
3. Ploughman M, Shears J, Quinton S, et al. Therapists' cues influence lower limb muscle activation and kinematics during gait training in subacute stroke. *Disabil Rehabil*. 2018; 40(26):3156–3163. 2017/ October/19. doi:10.1080/09638288.2017.1380720.
4. Suzuki M, Miyai I, Ono T, et al. Activities in the frontal cortex and gait performance are modulated by preparation. An fNIRS study. *Neuroimage*. 2008; 39 (2):600–607. 2007/ October/24. doi:10.1016/j.neuroimage.2007.08.044.
5. Dobkin BH, Plummer-D'Amato P, Elashoff R, et al. International randomized clinical trial, stroke inpatient rehabilitation with reinforcement of walking speed (SIRROWS), improves outcomes. *Neurorehabil Neural Repair*. 2010; 24(3):235–242. 2010/ February/19. doi:10.1177/1545968309357558.
6. Rendos NK, Zajac-Cox L, Thomas R, et al. Verbal feedback enhances motor learning during post-stroke gait retraining. *Top Stroke Rehabil*. 2020;1–16. 2020/ September/19. doi:10.1080/10749357.2020.1818480.
7. Harrison SL, Laver KE, Ninnis K, et al. Effectiveness of external cues to facilitate task performance in people with neurological disorders: a systematic review and meta-analysis. *Disabil Rehabil*. 2019; 41 (16):1874–1881. 2018/ March/11. doi:10.1080/09638288.2018.1448465.
8. Pak S, Patten C. Strengthening to promote functional recovery poststroke: an evidence-based review. *Top Stroke Rehabil*. 2008;15(3):177–199. 2008/ July/24. doi:10.1310/tsr1503-177.
9. Schindler-Ivens S, Desimone D, Grubich S, et al. Lower extremity passive range of motion in community-ambulating stroke survivors. *J Neurol Phys Ther*. 2008;32(1):21–31. 2008/May/09. doi:10.1097/NPT.0b013e31816594ea.
10. Hsu AL. Tang PF and Jan MH. Analysis of impairments influencing gait velocity and asymmetry of hemiplegic patients after mild to moderate stroke. *Arch Phys Med Rehabil*. 2003;84(8):1185–1193. doi:10.1016/S0003-9993(03)00030-3.
11. Nadeau S, Gravel D, Arsenault AB, et al. Plantarflexor weakness as a limiting factor of gait speed in stroke subjects and the compensating role of hip flexors. *Clin Biomech (Bristol, Avon)*. 1999;14(2):125–135. doi:10.1016/S0268-0033(98)00062-X.
12. Mentiplay BF, Adair B, Bower KJ, et al. Associations between lower limb strength and gait velocity following stroke: a systematic review. *Brain Inj*. 2015; 29 (4):409–422. 2014/ December/31. doi:10.3109/02699052.2014.995231.
13. Holleran CL, Straube DD, Kinnaird CR, et al. Feasibility and potential efficacy of high-intensity stepping training in variable contexts in subacute and chronic stroke. *Neurorehabil Neural Repair*. 2014; 28(7):643–651. 2014/February/12. doi:10.1177/1545968314521001.
14. Williams G, Hassett L, Clark R, et al. Improving walking ability in people with neurologic conditions: a theoretical framework for biomechanics-driven exercise prescription. *Arch Phys Med Rehabil*. 2019; 100 (6):1184–1190. 2019/ January/29. doi:10.1016/j.apmr.2019.01.003.
15. Lin PY, Yang YR, Cheng SJ, et al. The relation between ankle impairments and gait velocity and symmetry in people with stroke. *Arch Phys Med Rehabil*. 2006;87 (4):562–568. doi:10.1016/j.apmr.2005.12.042.
16. Middleton A, Braun CH, Lewek MD, et al. Balance impairment limits ability to increase walking speed in individuals with chronic stroke. *Disabil Rehabil*. 2017; 39(5):497–502. 2016/ March/15. doi:10.3109/09638288.2016.1152603.
17. Zehr EP, Hundza SR, Vasudevan EV. The quadrupedal nature of human bipedal locomotion. *Exerc Sport Sci Rev*. 2009;37(2):102–108. 2009/March/24. doi:10.1097/JES.0b013e31819c2ed6.
18. Balasubramanian CK, Bowden MG, Neptune RR, et al. Relationship between step length asymmetry and walking performance in subjects with chronic hemiparesis. *Arch Phys Med Rehabil*. 2007;88(1):43–49. doi:10.1016/j.apmr.2006.10.004.
19. Lewek MD, Randall EP. Reliability of spatiotemporal asymmetry during overground walking for individuals following chronic stroke. *J Neurol Phys Ther*. 2011;35 (3):116–121. Research Support, Non-U.S. Gov't 2011/ September/22. doi:10.1097/NPT.0b013e318227fe70.
20. Fickey SN, Browne MG, Franz JR. Biomechanical effects of augmented ankle power output during human walking. *J Exp Biol*. 2018;221(22): 2018/September/30. doi:10.1242/jeb.182113.
21. Roelker SA, Bowden MG, Kautz SA, et al. Paretic propulsion as a measure of walking performance and functional motor recovery post-stroke: a review. *Gait Posture*. 2019;68:6–14. 2018/ November/09. doi:10.1016/j.gaitpost.2018.10.027.
22. Hsiao H, Knarr BA, Higginson JS, et al. The relative contribution of ankle moment and trailing limb angle to propulsive force during gait. *Hum Mov Sci*. 2015;39:212–221. Research Support, N.I.H.,

Extramural 2014/ December/17. doi:10.1016/j.humov.2014.11.008.

23. Goldie PA, Matyas TA, Evans OM, et al. Maximum voluntary weight-bearing by the affected and unaffected legs in standing following stroke. *Clin Biomech (Bristol, Avon)*. 1996; 11(6):333–342. 1996/ September/01. doi:10.1016/0268-0033(96)00014-9.
24. Cheng PT, Liaw MY, Wong MK, et al. The sit-to-stand movement in stroke patients and its correlation with falling. *Arch Phys Med Rehabil*. 1998;79(9):1043–1046. doi:10.1016/S0003-9993(98)90168-X.
25. Yang YR, Chen YC, Lee CS, et al. Dual-task-related gait changes in individuals with stroke. *Gait Posture*. 2007; 25(2):185–190. 2006/ May/03. doi:10.1016/j.gaitpost.2006.03.007.
26. Baetens T, De Kegel A, Palmans T, et al. Gait analysis with cognitive-motor dual tasks to distinguish fallers from nonfallers among rehabilitating stroke patients. *Arch Phys Med Rehabil*. 2013; 94(4):680–686. 2012/ November/29. doi:10.1016/j.apmr.2012.11.023.
27. Hornby TG, Reisman DS, Ward IG, et al. Clinical practice guideline to improve locomotor function following chronic stroke, incomplete spinal cord injury, and brain injury. *J Neurol Phys Ther*. 2020; 44(1):49–100. 2019/ December/14. doi:10.1097/NPT.0000000000000303.
28. Lee SM, Cynn HS, Yoon TL, et al. Effects of different heel-raise-lower exercise interventions on the strength of plantarflexion, balance, and gait parameters in stroke survivors. *Physiother Theory Pract*. 2017; 33(9):706–715. 2017/July/18. doi:10.1080/09593985.2017.1346024.
29. Roelker SA, Kautz SA, Neptune RR. Muscle contributions to mediolateral and anteroposterior foot placement during walking. *J Biomech*. 2019;95:109310. doi:10.1016/j.jbiomech.2019.08.004.
30. Cruz TH, Lewek MD, Dhaher YY. Biomechanical impairments and gait adaptations post-stroke: multi-factorial associations. *J Biomech*. 2009;42 (11):1673–1677. 2009/ May/22. Research Support, Non-U.S. Gov't Research Support, U.S. Gov't, Non-P.H.S. doi:10.1016/j.jbiomech.2009.04.015.