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Short communication

User-driven treadmill walking promotes healthy step width after stroke

Margo C. Donlin [a,*], Nicole T. Ray [b,1], Jill S. Higginson [a,b]

[a] Department of Biomedical Engineering, University of Delaware, Newark, DE, USA
[b] Department of Mechanical Engineering, University of Delaware, Newark, DE, USA

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ABSTRACT

Background: Walking with user-driven treadmill control is believed to be more like overground walking than fixed-speed treadmill walking. Walking speed and ground reaction forces differ between overground and fixed-speed treadmill walking, but not between overground and user-driven treadmill walking in healthy and post-stroke subjects. However, studies assessing spatiotemporal gait parameters during user-driven treadmill walking are limited. This information may help confirm that user-driven treadmill walking is more like overground walking than fixed-speed treadmill walking, as well as inform the development of post-stroke gait rehabilitation programs.

Research question: How do spatiotemporal gait parameters for individuals post-stroke differ between fixed-speed and user-driven treadmill walking?

Methods: Eighteen subjects (10 M, 8 F; 62 ± 12 years; 1.73 ± 0.12 m; 84.9 ± 12.9 kg; 40 ± 30 months post-stroke) with chronic post-stroke hemiparesis participated in this study. Participants walked on an instrumented treadmill in its fixed-speed and user-driven modes at their self-selected and fastest comfortable walking speeds. Subjects wore retroreflective markers for motion capture. Shapiro-Wilk tests were used to assess for normality and one-way repeated measures ANOVAs were used to compare between conditions with $\alpha = 0.05$. Bonferroni corrections were used for multiple comparisons.

Results: Step width was significantly smaller with user-driven control (13.7 cm, 95 % CI: [0.131, 0.145]) than fixed-speed control (16.8 cm, 95 % CI:[0.160, 0.174]), while step length and step time did not differ across treadmill conditions. Step length and step time differed between self-selected and fast walking speeds, but not treadmill control conditions.

Significance: The results of this study show that user-driven treadmill control encourages healthy gait biomechanics and a greater sense of stability in post-stroke subjects. Individuals post-stroke walked with smaller step width with user-driven treadmill control, which has been associated with increased balance. Post-stroke gait rehabilitation may benefit from programs with user-driven treadmill training paradigms to improve mobility following stroke.

1. Introduction

Each year, 795,000 people experience a stroke, which often impairs gait and balance [1–4]. Spatiotemporal parameters differ between healthy and post-stroke subjects, and step width is adjusted to modulate stability [3]. Post-stroke gait rehabilitation typically uses a fixed-speed treadmill (FSTM) because it is spatially and financially efficient [5]. However, walking speed [6,7] is slower with FSTMs than overground, limiting training because slower speeds increase the risk of falls and mortality [8].

Custom user-driven treadmill (UDTM) control changes the treadmill speed in real time by responding to the user's step length, propulsion, and center-of-mass position, leading to faster self-selected (SS) walking speeds in healthy [6] and post-stroke [7] subjects compared to FSTM speeds. Kinematic gait variability that is inherent to healthy walking is reduced during FSTM walking in unimpaired individuals, but restored with UDTM walking, suggesting that UDTM conditions may provide an overground-like environment [9–11].

* Corresponding author at: University of Delaware, 540 S College Ave, STAR Health Sciences Complex, Rm 201, Newark, DE 19713, USA.
E-mail address: donlinm@udel.edu (M.C. Donlin).

[1] Present affiliations: (1) Naval Aerospace Medical Research Lab (NAMRL), Naval Medical Research Unit Dayton (NAMRUD), Dayton, OH. (2) Oak Ridge Institute for Science and Education (ORISE), Oak Ridge, TN.

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The purpose of this study was to examine the effects of UDTM control on spatiotemporal gait measures in post-stroke subjects compared to FSTM control at matched speeds. We hypothesized that step length would increase and step time would decrease with the increased speeds associated with UDTM control. Step width was expected to be similar between UDTM and FSTM conditions because the UDTM controller does not account for step width.

2. Methods

2.1. Participants

Twenty individuals with chronic post-stroke hemiparesis were recruited through the University of Delaware's Stroke Registry database. Two were excluded from analysis for failure to complete all trials due to time constraints. Power analysis determined that 18 participants were sufficient for distinguishing a mean step width difference of 5 ± 4 cm [3] with a power of 0.8. Participant characteristics are shown in Table 1, and all were independent ambulators [7]. Inclusion and exclusion criteria were the same as Ray et al. [7]. The study was approved by the University of Delaware's Institutional Review Board and participants signed an informed consent.

2.2. Experimental protocol

Subjects were outfitted with 42 retroreflective markers for motion capture with an 8-camera system (Motion Analysis Corp., Santa Rosa, CA, USA) [6,7]. For this analysis, only the heel markers were required. Kinematic data was sampled at 100 Hz.

Subjects performed a series of walking trials on an instrumented split-belt treadmill (Bertec Corp., Worthington, OH, USA) with fixed-speed and user-driven control [6]. Kinetic data was sampled at 2000 Hz from the treadmill and handrails, which the subjects could use with a "light touch." Participants wore a harness to prevent falls.

After a maximum of five minutes of familiarization with FSTM and UDTM conditions, subjects performed six trials, each for one minute, at their steady-state (± 0.2 m/s) SS and fastest comfortable (Fast) walking speeds [7]. The first four trials were randomized:

1. FSTM at SS Speed
2. FSTM at Fast Speed
3. UDTM at SS Speed
4. UDTM at Fast Speed

Then, two speed-matching conditions were performed in a random order, where the UDTM speed was imposed upon the FSTM [7]:

5. FSTM at UDTM SS
6. FSTM at UDTM Fast

2.3. Analysis

Kinetic and kinematic data were filtered with a fourth order low-pass Butterworth filter at 30 Hz and 6 Hz, respectively. Calculations were performed using Visual 3D (C-Motion Inc., Germantown, MD, USA) and MATLAB (MathWorks, Natick, MA, USA). Step width and paretic and non-paretic step length and step time were averaged over the trial for each condition. Step width was the medial-lateral distance between the heel markers at subsequent heel strikes. Step length was the anterior-posterior distance between the heel markers at subsequent heel strikes. Step time was the time between contralateral and ipsilateral heel strikes, determined by the kinetic data. Step length and step time asymmetry were calculated (Eq. 1) [3].

$$Asymmetry\ (\%) = \frac{100\ (paretic—non\text{-}paretic)}{max\ (paretic, non\text{-}paretic)} \quad (1)$$

The Shapiro-Wilk test assessed normality. One-way repeated measures ANOVAs compared between conditions, with Tukey post-hoc analysis performed as needed ($\alpha = 0.05$) [7]. Bonferroni corrections compensated for multiple comparisons.

Table 1
Participant characteristics. Data are presented as mean ± standard deviation.

Characteristic	Value
Sex	10 M | 8 F
Age	62 ± 12 years
Time since stroke	40 ± 30 months
Height	1.73 ± 0.12 m
Mass	84.90 ± 12.92 kg

3. Results

Step width was significantly narrower on the UDTM (13.7 cm) than the FSTM (16.8 cm), even at matched speeds ($p < 0.0001$, Fig. 1A). There were no significant differences in step width between FSTM conditions.

Both paretic and non-paretic step length differed between SS and Fast speeds but not between FSTM or UDTM conditions ($p < 0.05$, Fig. 1B). Paretic and non-paretic step length did not differ from each other across any conditions ($p > 0.6$). Step length asymmetry differed in 4 of 15 comparisons (Table 2).

Paretic and non-paretic step time differed with walking speed, but not treadmill control ($p < 0.001$, Fig. 1C). Paretic and non-paretic step time differed from each other for all conditions ($p < 0.05$). Step time asymmetry did not differ across any conditions ($p > 0.5$, Table 2).

4. Discussion

Step width was consistent across FSTM trials, suggesting that walking speed did not influence step width. However, step width was significantly smaller in UDTM conditions than FSTM conditions, indicating that the control algorithm impacted step width. The FSTM step width (16.8 cm) was similar to post-stroke FSTM values (17.3 cm) in the literature [3], while unimpaired step width was narrower overground (12 cm) [12] and with FSTM control (11.5 cm) [3]. Post-stroke step width in all conditions was larger than reported unimpaired step width, likely due to a decreased sense of stability. Post-stroke UDTM step width (13.7 cm) showed trends toward unimpaired overground and FSTM step width, suggesting that the UDTM encouraged post-stroke participants to walk with narrower steps. Narrower steps may show an increased sense of stability with UDTM control, which is vital after stroke [1,3,13]. By promoting narrower step width in post-stroke participants that is like unimpaired values, UDTM control may improve the gait rehabilitation environment, which could improve rehabilitation outcomes and increase mobility.

Step length differed between walking speeds, but not between treadmill conditions. Step length was not expected to differ for the speed-matched conditions because step length is related to walking speed. However, the controller showed no effect on step length regardless of walking speed. Subject-specific effects of treadmill control on walking speed have been seen [7] and may exist with step length. Step length asymmetry differed in a few comparisons, potentially an effect of walking speed, but those comparisons spanned differing treadmill conditions and walking speeds so a conclusion cannot be drawn from these results.

Step time also differed with walking speed but not treadmill control, indicating no effect of UDTM control. Step time was not expected to differ for the speed-matched conditions, as step time is related to walking speed. Although temporal asymmetry is often targeted by rehabilitation programs [14,15], UDTM control may not show any benefits over FSTM control for addressing temporal asymmetry.

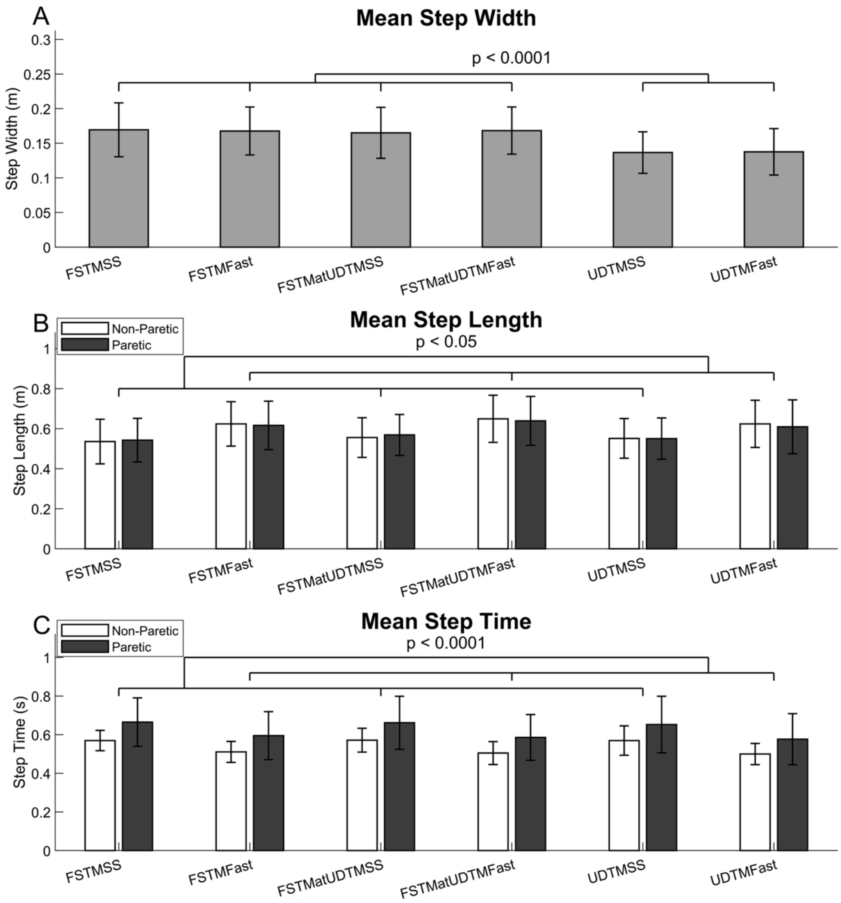

Fig. 1. Mean ± standard deviation for variables of interest. (A) Mean step width was significantly narrower in both UDTM control conditions than in all four FSTM control conditions. The four FSTM conditions did not differ from each other, and the two UDTM conditions did not differ from each other. (B) Mean step length did not differ with treadmill control, only with walking speed. The three SS conditions had shorter step lengths than the three Fast conditions. Paretic and non-paretic step length did not differ from each other for all conditions. (C) Mean step time did not differ between UDTM control and FSTM control but did between SS and Fast speeds. Both paretic and non-paretic step time were shorter in the three Fast conditions than the three SS conditions. Paretic and non-paretic step time differed from each other for all conditions.

Table 2
Step length asymmetry and step time asymmetry data presented as group mean ± standard deviation. Step length asymmetry differed in 4 of 15 comparisons: FSTM at UDTMSS vs. UDTMFast ($p = 0.001$); FSTMSS vs. UDTMFast ($p = 0.007$); FSTM at UDTMSS vs FSTM at UDTMFast ($p = 0.025$); and FSTM at UDTMSS vs FSTMFast ($p = 0.036$). Step time asymmetry did not differ in any comparisons.

Condition	Step Length Asymmetry (%)	Step Time Asymmetry (%)
FSTMSS	1.385 ± 4.184	12.291 ± 2.761
UDTMSS	−0.257 ± 2.244	10.715 ± 2.870
FSTMFast	−1.540 ± 2.009	11.694 ± 3.122
UDTMFast	−2.899 ± 4.413	10.710 ± 2.645
FSTM at UDTMSS	2.088 ± 2.612	11.574 ± 1.857
FSTM at UDTMFast	−1.698 ± 3.335	11.735 ± 2.393

4.1. Limitations

The primary limitation of this study is the heterogeneity of stroke survivors. A more severe stroke may increase balance impairments, requiring larger step width and reducing the likelihood of decreasing step width in UDTM conditions. The participants were high-functioning to ensure they could complete all trials, but individuals with more severe hemiparesis may have more potential for improvement and could benefit from UDTM-based training.

4.2. Conclusion

This research demonstrates the potential benefits of UDTM-based gait training. UDTM conditions maintain the increased repetitions and controlled environment of FSTMs [5] while encouraging narrower step width to promote stability for more efficient training. Rehabilitation paradigms may consider adopting UDTM control to improve post-stroke gait rehabilitation.

Author contributions

Margo C. Donlin: Formal Analysis, Writing- original draft, Writing-review and editing, Visualization. **Nicole T. Ray:** Conceptualization, Methodology, Investigation, Data curation. **Jill S. Higginson:** Conceptualization, Methodology, Supervision, Project Administration, Funding Acquisition

Declaration of Competing Interest

The authors have no conflicts of interest to report.

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