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Error-Augmentation Gait Training to Improve Gait Symmetry in Patients with Non-Traumatic Lower Limb Amputation: A Proof of Concept Study

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Abstract

Background—Asymmetrical stepping patterns are a chronic gait impairment for individuals with non-traumatic lower limb amputation. Persistent gait asymmetries contribute to poor gait efficiency, decreased physical function, and development of secondary orthopedic conditions.

Objectives—Evaluate the feasibility and preliminary responsiveness of a treadmill-based, error-augmentation gait training (EGT) protocol to improve gait symmetry in patients with non-traumatic transtibial amputation.

Study Design—Single group, pre- and post-test

Methods—The EGT protocol involved walking on a split-belt treadmill with asymmetrical belt speeds for five, 3-minute sets. Spatiotemporal gait characteristics during overground walking at self-selected and fast walking speeds were assessed prior to, immediately after, and 20 minutes following the EGT protocol. Outcomes included practicality, implementation feasibility, safety, participant acceptability, and change in gait asymmetry.

Results—All four participants completed the EGT protocol as prescribed, without adverse events, and found the intervention to be acceptable. Step length and stance time asymmetry during overground walking changed immediately following the EGT protocol with inconsistent changes retained after a 20-minute washout period.

Conclusions—A single-session of EGT is a feasible and safe intervention to modify gait asymmetry in patients with non-traumatic transtibial amputation. Additional study with larger sample sizes and repeated EGT dosing are warranted.

Keywords

non-traumatic amputation; transtibial; gait training; gait symmetry

BACKGROUND

Over one million individuals live with a lower limb amputation (LLA) in the United States,¹ of which 80% are from non-traumatic etiologies.² By 2050, this number is expected to be greater than two million due to increases in vascular conditions like diabetes mellitus and peripheral vascular disease.¹ Following LLA, gait compensations are often adopted to accommodate for the loss of limb function.³ Specifically, individuals with LLA demonstrate asymmetrical spatiotemporal gait parameters (e.g., step length, stance time), which may adversely influence gait efficiency and functional performance and contribute to the development of pain conditions such as low back pain and osteoarthritis.^{4–7}

Post-amputation rehabilitation and prescription of a prosthetic limb are intended to improve mobility following LLA; however, there is limited evidence for interventions to optimize gait symmetry after LLA. As a result, asymmetrical gait patterns often persist after accommodating to the prosthesis.³ A possible intervention to correct asymmetrical gait patterns after non-traumatic LLA is error-augmentation gait training (EGT), which involves exaggerating movement errors to induce neuromotor adaptation to a new movement pattern.⁸ Using a split-belt treadmill, step length asymmetry can be exaggerated by walking with separate belts under each limb set to different speeds. Initially, walking with the asymmetrical belt speeds will amplify step length asymmetry, but in a short time the neuromotor system will over-correct for the error and adopt a more symmetrical step length pattern.^{9, 10} Similar EGT protocols have improved gait symmetry in patient populations with comparable spatiotemporal gait asymmetries.^{9, 11, 12} For example, in individuals with chronic stroke, a single session of EGT induced short-term improvements in step length asymmetry during treadmill and over-ground walking.^{9, 11} Furthermore, individuals with chronic stroke exhibit long-term improvements in step length symmetry during walking following repeated sessions of EGT.¹² Additionally, EGT was successfully implemented in a small sample of young adults with traumatic LLA.¹³ In this sample, patients with traumatic LLA adapted to EGT similarly to those without suggesting that LLA alone does not prevent gait adaptation.¹³

Despite EGT demonstrating potential for improving spatiotemporal gait asymmetry in other patient populations, individuals with non-traumatic LLA have unique characteristics to consider before exploring EGT as a viable intervention. For instance, patients with non-traumatic LLA demonstrate slower healing times after amputation, greater movement asymmetry, limited walking tolerance, and greater comorbidity than those with traumatic LLA.^{14, 15} Due to the multi-morbidity, limited functional capacity, and unique pathophysiology underlying non-traumatic LLA, evaluating the feasibility of EGT in this population is a critical step in the development of an intervention to improve gait symmetry.

The purpose of this study was to determine the feasibility of using EGT in adults with non-traumatic LLA. We assessed five key dimensions of feasibility,^{16, 17} including whether participants: 1) successfully completed EGT as prescribed (practicality), 2) tolerated the EGT protocol (implementation feasibility), 3) completed EGT safely (safety), 4) found EGT

interesting and enjoyable (acceptability), and 5) responded with improved spatiotemporal gait asymmetry (responsiveness).

METHODS

Participants

Individuals with unilateral, non-traumatic, transtibial amputation identified through the local Veterans Affairs Hospital were recruited between August – December 2017 to participate in a single day intervention. Inclusion criteria were: 1) diagnosis of diabetes mellitus and/or peripheral artery disease, 2) age >50 years, 3) able to walk four minutes without rest or assistive device, and 4) one to five years post-amputation. Exclusion criteria were: 1) traumatic or cancer-related amputation, 2) contralateral limb ankle-level or above amputation, 3) unstable heart condition, 4) uncontrolled hypertension, 5) acute systemic infection, 6) active cancer treatment, 7) stroke within two years, and 8) lower extremity wound or ulcer that limits ambulation. All participants provided written informed consent prior to participation as approved by the Institutional Review Board.

Procedures

Participant Descriptive Measures and Prosthetic Assessment—Sex, age, anthropometrics, smoking status, and date of amputation were collected for each participant. Additionally, participants were tested for neuropathy in the intact foot using the Michigan Neuropathy Screen in which a score seven indicates possible presence of diabetic neuropathy.^{18, 19} Presence of additional comorbidities was documented using the Functional Comorbidity Index.²⁰ Participants wore their personal prosthetic device for all procedures. Foot and socket type and suspension method were recorded and prosthesis usage habits documented using the Houghton Scale and the Prosthesis Evaluation Questionnaire – Mobility subscale.^{21, 22}

Overground Walking Assessment—Overground spatiotemporal gait parameters were assessed using the GAITRite Electronic Walkway system (CIR Systems, Inc., Franklin, NJ, USA). As participants walk along the 5.76m walkway, sensors every 1.27 cm are activated with pressure from each foot contact. GAITRite software determines the geometric borders of each foot strike using the most posterior, lateral, medial, and anterior activated sensors. Step length is measured in centimeters along the length of the walkway using the position of the posterior activated sensors of consecutive steps. Stance time is determined as the time elapsed between first and last contact of a foot strike with first contact occurring when the first sensor is activated and last contact when the last sensor is deactivated. Data are sampled at 120 Hz, with a resolution of 1.27cm and 0.008 sec for spatial and temporal measures, respectively. Each GAITRite trial includes 3–4 strides per limb, depending on gait speed, with parameters for each stride averaged within each trial. Participants performed 10 overground walking trials, five at their self-selected speed and five at their fastest speed. Mean step length and stance time for each limb and gait speed were recorded for each trial. The GAITRite has demonstrated good to excellent validity and within-subject reliability for step length and stance time.^{23–25} GAITRite assessments were performed at three instances:

1) prior to EGT (PRE), 2) immediately following EGT (POST), and 3) after a 20-minute washout period following EGT (WO) to assess retention of gait adaptation (Fig 1).

Error-Augmentation Gait Training Protocol—The EGT protocol was completed on a split-belt treadmill (Bertec Corporation, Columbus, OH, USA). Participants walked for two two-minute accommodation periods on the treadmill with both belts set to matching speeds (“tied” condition). The first accommodation period involved walking at ½ of self-selected overground gait speed while the second accommodation period was set to ¾ of self-selected speed. Following the accommodation period, participants underwent five three-minute sets of EGT in the “split speed” condition. During the EGT periods, the faster belt (¾ of self-selected speed) was assigned to the limb with shorter step length and the slower belt (½ of the faster belt speed) was assigned to the limb with the longer step length (2:1 ratio). Following the second and fourth sets of EGT, a one-minute trial was performed with the belts in the “tied” condition and speed set to ¾ of self-selected speed to expose participants to the sensation of switching between “tied” and “split speed” conditions.²⁶ Between conditions and following each EGT set, participants had a seated rest break for up to five minutes. Each participant wore a safety harness during the treadmill protocol to prevent falls but not provide body weight support. Use of handrails was permitted throughout the EGT protocol, but participants were encouraged to only use handrails when necessary to maintain balance.

Feasibility Outcomes—Intervention practicality was assessed by completion rate, calculated as a percentage of participants who completed the protocol as prescribed. Implementation feasibility was determined as the attainment and maintenance of the EGT dosage for intensity (belt speed) and duration (treadmill time), reported as percentages. Safety was tracked as the incidence of adverse events. Adverse events were defined as falls, musculoskeletal injury, residual limb skin breakdown, and/or excessive exertion (>85% of age-adjusted heart rate maximum).²⁷ Heart rate and pain level, including residual limb pain, were recorded throughout the session. Following completion of the protocol, the residual limb was inspected for skin breakdown. Participant acceptability of the EGT intervention was assessed using the Intrinsic Motivation – Interest/Enjoyment subscale, with a score greater than five out of seven indicating good acceptability. Lastly, responsiveness to EGT was assessed by calculating the asymmetry index (AI) of overground step length and stance time at PRE, POST, and WO. To calculate AI, the following equation was used:

$$AI = 2 * (Long - Short) / (Long + Short) * 100$$
 with “Long” and “Short” representing the longer and shorter step lengths of PRE overground walking trials, respectively.^{28, 29} An AI value of zero would indicate perfect symmetry. Individual responses were classified into four categories 1) improvement in asymmetry (decreased AI towards zero), 2) exaggeration of baseline asymmetry (increased AI value), 3) overcorrection of asymmetry (negative AI value, indicating a switch in “Long” and “Short” step length limb assignment), and 4) no change.

Data Analysis

Frequencies and percentages were calculated for practicality, implementation feasibility, and safety outcomes. Means and standard deviations were calculated for acceptability and responsiveness in AI of spatiotemporal gait parameters. Additionally, change values, percent change, and 95% confidence intervals from PRE-POST and PRE-WO were calculated for step length and stance time AI. Lastly, effect sizes (Cohen's *d*) of change in AI from PRE at each assessment, regardless of direction, were calculated to inform sample size estimates for future trials and aid in interpretation of the effect of EGT.³⁰ Due to the proof of concept design, *a priori* sample size calculations and formal statistical significance testing were not performed.

RESULTS

Four participants were enrolled in the treadmill training protocol (Table 1). All participants (100%) completed the EGT protocol at the prescribed intensity and duration (practicality) and attained the target belt speeds and walking duration (implementation feasibility). No falls occurred, no musculoskeletal injuries were reported, heart rate remained <85% of age-adjusted heart rate maximum, and no increases in pain were reported during the session. No signs of residual limb skin breakdown were observed following EGT. The participants found EGT acceptable based on scores from the Intrinsic Motivation – Interest/Enjoyment subscale (6.5 ± 0.3) (mean $\pm$ SD) (Table 2).

Overground step length asymmetry changed immediately following EGT for both self-selected (79%) and fast gait speeds (163%) (Table 3). Following a 20-minute washout period, asymmetry further changed for self-selected gait speed (128%) but regressed for the fast gait speed (110%) (Table 3). Step length AI demonstrated change values (mean $\pm$ SD) from PRE to POST of -3.2 ± 4.5 and -6.2 ± 1.7 and from PRE to WO of -5.3 ± 4.2 and -4.2 ± 3.0 during self-selected and fast gait speed, respectively. Changes in stance time AI were similar to those observed with step length AI (Table 3). Stance time AI improved for both self-selected (66%) and fast gait speeds (51%) with continued improvement for self-selected speed (68%) but regression with fast gait speed (24%) following a 20-minute washout. No meaningful changes in self-selected (PRE: 1.05 ± 0.12 , POST: 1.10 ± 0.15 , WO: 1.11 ± 0.13 m/s) or fast gait speed (PRE: 1.40 ± 0.36 , POST: 1.37 ± 0.41 , WO: 1.37 ± 0.42 m/s) were observed.

Individual participant responses of step length asymmetry to EGT varied and were dependent on gait speed. For self-selected gait speed, Participants B and C demonstrated improvement toward symmetry at POST, with further improvement at WO (Fig 2A). Participant A demonstrated a small increase in step length asymmetry from baseline to POST test, which changed at WO to an “overcorrected” asymmetry (opposite step length difference than baseline). Participant D presented with an overcorrection of asymmetry at POST, with further overcorrection at WO. In fast overground walking, Participant A had improved symmetry at POST, which continued to improve at WO. Participants B, C, and D each presented with overcorrection at POST. Participant B and C ultimately presented with improved symmetry at WO while Participant D continued with overcorrection of asymmetry (Fig 2B).

DISCUSSION

Recovery of symmetrical gait following non-traumatic LLA remains a challenge for many as asymmetries persist long after accommodation to a prosthetic limb and contribute to poor gait efficiency, additional orthopedic conditions, and limited community function.^{6, 7} While a prosthetic limb often improves mobility, few interventions target improved gait symmetry. The purpose of this study was to assess the feasibility and describe the effects of a treadmill-based, EGT protocol on asymmetry of spatiotemporal gait measures in patients with unilateral, non-traumatic transtibial LLA. The results of this proof of concept study indicate that a single session of EGT is feasible for people with non-traumatic LLA, although no consistent sustained improvement was observed in this sample.

It is important to note that no large studies assessing gait training protocols targeting gait asymmetry following LLA have been reported. Three previous case series demonstrated improvement in asymmetry using spatiotemporal feedback with single^{31, 32} and repeated-session training.³³ Although the asymmetry metrics vary, the participants in the current study demonstrated greater percentage change in step length asymmetry (79%) than those in a prior single-session treadmill protocol (26%).³¹ Similarly, we observed greater change in stance time asymmetry (51%) than previous case series of single-session (23%)³² and repeated-session training (9.9%).³³ The effect sizes observed in this sample represent medium (>0.5) to large (>0.8) effects for change in step length asymmetry, medium effects for change in stance time asymmetry during self-selected walking speed, and small (>0.2) effects for change in stance time asymmetry during fast walking speed.³⁰ Despite the observed changes in gait asymmetry, critical methodological differences are present between prior studies and the current study. Primarily, each of the three prior studies utilized visual, tactile, or auditory feedback to minimize gait asymmetry while EGT exaggerates asymmetry to facilitate sensorimotor adaptation. Recent evidence suggests that exaggerating movement errors may be superior in promoting motor learning than strategies to minimize movement errors.³⁴ Furthermore, two of three studies provided feedback (visual plus vibrotactile or auditory) for stance time symmetry, observed improvement in stance time symmetry but did not report step length symmetry.^{32, 33} Notably, despite targeting step length symmetry, we observed changes in both step length and stance time symmetry. Although stance time and step length have a predictable association, Dingwell et al. note an inconsistent relationship between changes in spatiotemporal variables in response to real-time feedback to improve symmetry.³¹ Based upon this preliminary evidence and the initial change in gait asymmetry observed, EGT may have potential to improve gait symmetry for individuals with non-traumatic LLA.

The medical complexity, older age, and relatively low cardiovascular fitness of patients with non-traumatic LLA warrant specific assessment of safety and patient acceptability.⁶ Each participant successfully completed EGT at the prescribed belt speeds and completed the desired dosage of walking and rest. Additionally, there were no falls, no injuries, no increased pain, no residual limb skin breakdown, and all participants were able to complete the protocol without excessive exertion. Additionally, the EGT intervention was acceptable to the participants according to the Intrinsic Motivation items indicating the intervention was enjoyable (6.5 ± 1), fun (6.25 ± 1), and interesting (6.75 ± 0.5) (Table 2). It is important to

consider the physiological demands of any exercise-based intervention for medically complex patient populations and these data indicate that EGT is feasible, safe, and acceptable in this small sample of patients with non-traumatic LLA.

Furthermore, potential insights for future implementation can be drawn from the individual variations in response to EGT. Individuals with the largest asymmetry at baseline demonstrated the greatest change, perhaps due to having more room for improvement. Additionally, baseline asymmetry varied depending on gait speed with some participants demonstrating similar asymmetry at both speeds, while Participant A exhibited increased asymmetry with fast speed walking. In general, the EGT intervention resulted in step length AI change in the direction of improved symmetry. However, the magnitude of response varied among the participants. The large overcorrections resulted in an increased magnitude of step length asymmetry despite a reversal in the direction of asymmetry. In addition to variation in magnitude of change at POST, there was a variable response in retention of the EGT effect at WO. Three of four participants at self-selected gait speed and two of four at fast gait speed demonstrated further changes in gait symmetry in the expected direction. Given the variability in retention of step length and stance time symmetry at WO, no consistent response or sustained effect of EGT was noted. In patients with chronic stroke, repeated session EGT training resulted in long-term improvement in gait symmetry.¹² In patients with non-traumatic LLA, repeated EGT may increase the opportunity for prolonged adaptation and the development of a new learned gait pattern.^{8, 35} Additionally, future trials with larger sample sizes should explore potential contributors to variation in response to EGT and the duration of effects including, among others, baseline asymmetry, habitual walking activity, walking speed, and prosthesis characteristics.

There are limitations that should be considered when interpreting our findings. First, we are unable to determine whether change in symmetry was a direct result of EGT or due to additional walking volume. Habitual walking activity was not objectively monitored and the potential increase in walking during the session may have influenced gait asymmetry. Second, this proof of concept design involves only four participants, which limits extrapolation of efficacy to larger populations. Nevertheless, EGT appears to have promise to modify gait symmetry and may provide clinicians with an intervention to address this common impairment in individuals with non-traumatic LLA. Additionally, the EGT protocol and assessments were completed in a single day with varying levels of retention in gait symmetry following a 20-minute washout, leaving unknown the long-term effects of this intervention.

This proof-of-concept study establishes a foundation for future study of the efficacy of EGT to improve gait symmetry in individuals with non-traumatic LLA. The next step would be a randomized controlled trial comparing EGT to treadmill walking alone. Based on the smallest observed effect size for change in step length AI ($d = 0.72$), a total sample of 18 participants would have 80% power to detect improvement in step length asymmetry. Additionally, future work will evaluate the effect duration with varying doses of EGT.

CONCLUSIONS

This proof of concept study describes the use and feasibility of EGT following non-traumatic LLA. A single-session of EGT was acceptable and safe in individuals with non-traumatic LLA and resulted in modified step length and stance time symmetry at both self-selected and fast overground walking speeds. Additional studies are needed to determine the appropriate dosing and response duration for an EGT intervention.

Acknowledgements/Conflict of Interest

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CLINICAL RELEVANCE

Gait training using error-augmentation on a split-belt treadmill may modify step length and stance time asymmetry for patients with non-traumatic transtibial amputation, but additional research is needed regarding short- and long-term efficacy. Additional training sessions may be needed to sustain initial changes achieved from a single session.

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Figure 1.

Timeline for testing session including overground walking assessments before (PRE), immediately after (POST) the error-augmentation gait training (EGT) protocol, and after a 20-minute washout period.

Figure 2. Effects of error-augmentation gait training (EGT) on step length. Mean step length asymmetry index for self-selected (SSGS) and fast (FGS) overground walking at pre-EGT (PRE), post-EGT (POST), and following 20-min washout (WO). (a) Individual participant step length asymmetry index for SSGS and (b) individual participant step length asymmetry index for FGS.

Table 1.

Participant Demographic and Prosthetic Descriptors

Sex	Age (yrs)	Height (m)	Mass (kg)	Time Since Amputation (mo)	Socket Type	Suspension Type	Prosthetic Foot Type	Amputated Limb	Functional Comorbidity Index	Houghton Scale	PEQ-MS	Michigan Neuropathy Screen-Physical Assessment
A	M	68	83.0	18	Total Surface Bearing	Pin-lock	Dynamic Response	Right	7	10	3.25	3
B	M	64	64.4	44	Partial Patellar Tendon Bearing	Suction with sleeve	Dynamic Response	Right	3	12	4.00	0
C	M	62	104.3	22	Total Surface Bearing	Pin-lock	Dynamic Response	Left	8	8	2.08	3.5
D	M	73	93.0	24	Partial Patellar Tendon Bearing	Pin-lock	Dynamic Response	Right	3	10	2.42	2

yrs = years; mo = months; PEQ-MS = Prosthesis Evaluation Questionnaire-Mobility Subscale; M = male

Table 2.

Intrinsic Motivation – Interest/Enjoyment Score.

Item	Participant A	Participant B	Participant C	Participant D
I enjoyed this activity very much.	7	7	7	5
This activity was fun to do.	7	7	6	5
I thought this was a boring activity.	1	1	1	1
This activity did not hold my attention at all.	1	1	1	5
I would describe this activity as very interesting.	7	7	7	6
I thought this activity was quite enjoyable.	7	7	7	6
While I was doing this activity, I was thinking about how much I enjoyed it.	7	7	6	5

Responses range from 1 (“not at all true”) to 7 (“very true”).

Step length and stance time asymmetry index during self-selected and fast overground walking.

Table 3.

		PRE	POST	WO	PRE-POST	PRE-WO	PRE-POST <i>d</i>	PRE-WO <i>d</i>
SSGS	Step Length AI	4.1 ± 2.6 (1.5 – 6.7)	0.9 ± 4.8 (–3.9 – 5.6)	–1.2 ± 5.0 (–6.1 – 3.8)	–3.2 ± 4.5 (–3.9 – 10.5)	–5.3 ± 4.2 (–1.3 – 11.9)	0.72	1.26
	Stance Time AI	2.1 ± 2.9 (–0.8 – 5.0)	0.7 ± 5.0 (–4.2 – 5.6)	0.7 ± 5.6 (–4.8 – 6.1)	–1.4 ± 2.6 (–2.8 – 5.6)	–1.4 ± 3.0 (–3.3 – 6.2)	0.53	0.59
FGS	Step Length AI	3.8 ± 2.0 (1.8 – 5.8)	–2.4 ± 3.0 (–5.3 – 0.5)	–0.4 ± 4.5 (–4.8 – 4.0)	–6.2 ± 1.7 (3.5 – 8.9)	–4.2 ± 3.0 (–0.5 – 8.9)	3.71	1.39
	Stance Time AI	3.2 ± 10.4 (–7.0 – 13.4)	1.6 ± 5.9 (–4.2 – 7.4)	2.5 ± 6.0 (–3.4 – 8.3)	–1.6 ± 5.8 (–7.5 – 10.8)	–0.7 ± 4.6 (–6.6 – 8.1)	0.28	0.17

Data presented as mean ± standard deviation (95% confidence interval). A value of zero indicates perfect symmetry.

SSGS: self-selected gait speed

FGS: fast gait speed

PRE-POST: change from PRE to POST

PRE-WO: change from PRE to WO

d: effect size