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Step Length Symmetry Adaptation to Split-Belt Treadmill Walking after Acquired Non-traumatic Transtibial Amputation

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Abstract

Background: Between-limb step length asymmetry is common following transtibial amputation (TTA) and contributes to negative health consequences. There are limited evidence-based interventions targeting reduced gait asymmetry for people with TTA. Split-belt treadmill walking with asymmetrical belt speeds has successfully reduced gait asymmetry in other patient populations. However, individuals with non-traumatic TTA have critical health-related impairments that may influence the ability to respond to split-belt treadmill walking.

Research Question: Do people with acquired, non-traumatic TTA adapt and retain a more symmetrical gait pattern in response to split-belt treadmill walking?

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CRediT Author Statement
All authors have made substantial contributions to the study. The study was conceptualized by PWK, AMM, MJM, TF, CLC). Data were acquired and curated by PK, AMM, and CLC, analyzed and interpreted by PK, AMM, MJM, TF, CLC. PK drafted the initial manuscript with other authors each providing critical review for subsequent versions. Lastly, all authors have approved this version of the manuscript to be submitted. The CRediT roles are outlined below.
PWK: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Software, Supervision, Validation, Visualization, Writing (Original Draft Preparation), Writing (Review and Editing).
AMM: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Software, Validation, Visualization, Writing (Review and Editing).
MJM: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Software, Validation, Visualization, Writing (Review and Editing).
NS: Methodology, Supervision, Visualization, Writing (Review and Editing).
TF: Conceptualization, Formal Analysis, Methodology, Supervision, Visualization, Writing (Review and Editing).
CLC: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing (Review and Editing).

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Methods: Step length asymmetry was measured during split-belt treadmill walking. Eight participants walked under two alternating belt speed conditions: symmetrical (3 sets; Baseline, TIED1, TIED2) and asymmetrical belt speeds (5 sets; SPLIT1–5). One-way repeated-measures ANOVA with post-hoc Tukey's HSD tests were used to assess adaptation and short-term retention of step length symmetry. Adaptation was assessed as the level of asymmetry during TIED walking following repeated exposure to SPLIT walking. Retention was measured as the change in level of asymmetry during each set of SPLIT walking.

Results: Significant adaptation to split-belt walking was observed from late Baseline to early TIED1 and early TIED2. Between-limb step length asymmetry decreased from late Baseline (5.3±3.4) to early TIED1 (−9.4±3.6) and this change was sustained between early TIED1 and early TIED2 (−11.2±3.1) (ANOVA F=73.043, p<.001). Adaptations were retained as step length asymmetry decreased from early SPLIT1 (48.5±5.3) to early SPLIT3 (31.4±3.5) to early SPLIT5 (23.9±5.1) (ANOVA F=35.284, p<.001).

Significance: Individuals with non-traumatic TTA are capable of gait adaptation to split-belt walking and short-term retention of adaptations after removal of the asymmetrical belt speeds. Adaptability of step length symmetry is possible without modification to the prosthetic limb. Split-belt walking should be tested as a potential intervention to help people with acquired, non-traumatic TTA increase between-limb step symmetry.

Keywords

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

Introduction

Approximately 1.6 million people currently live with lower-limb amputation in the United States, with this number expected to grow to 2.3 million by 2050 [1]. Over 80% of lower-limb amputations result from non-traumatic etiologies, such as diabetes mellitus (DM) and peripheral artery disease (PAD), with transtibial amputation (TTA) accounting for 25% [1]. After TTA, individuals commonly adopt movement compensations to account for loss of ankle function [2, 3]. Post-TTA compensations typically manifest as asymmetrical movement patterns and are characterized by preferential use of the intact limb [2]. For example, despite optimizing prosthetic fit and function, individuals with TTA often exhibit asymmetrical step length during gait [3, 4]. Asymmetrical stepping characteristics contribute to reduced gait speed and metabolic efficiency during walking after TTA [5]. Furthermore, severe gait asymmetry may contribute to excessive joint loading, leading to chronic low back pain, osteoarthritis, and increased residual limb wound incidence [6, 7]. Persistent gait asymmetry may be due, in part, to limited evidence-based interventions targeting symmetry for persons with non-traumatic TTA. To date, three case series studies provide preliminary evidence for improved gait symmetry using spatiotemporal feedback in single [4, 8] and repeated-session training [9].

One potential approach for improving gait symmetry is with an error-augmentation gait training (EGT) paradigm, which typically uses a split-belt treadmill to exaggerate stepping asymmetries and induce motor adaptation of a new gait pattern by the nervous system [10, 11]. The motor learning principles of adaptation and retention are central to EGT [10]. Adaptation is the process of modifying well-learned movements and occurs with practice in response to novel task demands, such as split-belt treadmill walking [12]. Retention is the degree to which learned adaptations can be repeated after de-adaptation [10]. Evaluating gait adaptation and retention allows for the determination of an individual's capacity for gait pattern modification. If desired spatiotemporal gait adaptations are achieved and retained, repeated adaptation training may result in learning a more permanent symmetrical gait pattern [13].

EGT has been successfully implemented in patient populations with similar spatiotemporal asymmetries to non-traumatic TTA, including stroke and traumatic TTA [10, 14–17]. People with traumatic TTA demonstrate similar adaptations as those without amputation in response to split-belt walking [15, 17]. However, individuals with non-traumatic TTA are typically older, more medically complex, have greater limb sensation deficits, and experience greater disability than individuals with traumatic TTA, which may limit the ability to participate in, adapt to, and retain adaptations to an EGT intervention [18]. Thus, the purpose of this study was to evaluate step length asymmetry adaptation and short-term retention with an EGT protocol in persons with non-traumatic TTA.

Methods

Participants

Persons with acquired, non-traumatic, unilateral TTA were recruited for this single-session quasi-experimental study. Inclusion criteria were: 1) diagnosis of DM and/or PAD; 2) age >50 years; 3) able to walk four minutes without rest or assistive device; and 4) 1–5 years post-amputation. Exclusion criteria were: 1) traumatic, congenital, or cancer-related amputation; 2) contralateral limb amputation (above ankle-level); 3) unstable heart condition; 4) uncontrolled hypertension; 5) acute systemic infection; 6) active cancer treatment; 7) cerebrovascular accident within the previous two years; and 8) ambulation-limiting lower extremity wound. All participants provided written informed consent prior to participation as approved by the Institutional Review Board.

Procedures

Participant Descriptive Measures and Prosthetic Assessment—Age, body height, body mass, sex, and time since TTA were recorded for each participant. Participants were tested for neuropathy in the non-amputated foot using the Michigan Neuropathy Screen Instrument (MNSI). The MNSI is a 15-item questionnaire and a lower extremity examination (vibratory sensation, ankle reflexes, protective sensation). Both components are scored by summing abnormal findings. A questionnaire score ≥7 or physical exam score ≥2 indicates possible presence of neuropathy [19]. Comorbidities were documented using the Functional Comorbidity Index (FCI) [20]. Participants wore their personal prosthetic devices for all procedures with foot type, socket type, and suspension method recorded. A certified prosthetist confirmed appropriate prosthesis fit and function. Prosthesis usage habits and functional ability were documented using the Houghton Scale and the Prosthesis Evaluation Questionnaire - Mobility Scale (PEQ-MS) [21, 22]. Participants's preferred self-selected gait speed and baseline direction of step length asymmetry were determined using a 5.7 m GAITRite Electronic Walkway System (CIR Systems, Inc., Franklin, NJ, USA), which has excellent validity and reliability for determining gait spatiotemporal measures [23, 24]. As participants walked along the walkway, electronic sensors were activated by foot contact pressure. Step length was measured as the distance between the positions of the most posterior activated sensors of consecutive steps and labeled according to the leading limb (e.g. prosthetic step length = leading with the prosthetic limb). Gait speed was calculated by dividing the distance traveled (first activated sensor and final activated sensor) by time.

Error-augmentation Gait Training Protocol—Participants completed the EGT protocol on an instrumented split-belt treadmill (Fig. 1) (Bertec Corp, Columbus, OH). The protocol involved two conditions: symmetrical belt speeds (TIED), and asymmetrical belt speeds (SPLIT). During TIED, the belts were set to 75% of each participant's self-selected over-ground walking speed. During SPLIT, the faster belt remained at 75% of self-selected over-ground walking speed while the slower belt was set to 50% the speed of the faster belt (2:1 ratio). The limb with the shorter step length during over-ground walking was assigned to the faster belt during SPLIT.

The protocol began with participants walking for two, two-minute accommodation periods under the TIED condition. The two accommodation periods, separated by a 1–2 minute rest period, allowed for participants to acclimate to treadmill walking and testers to confirm participant safety. Following accommodation, the two walking conditions were tested as follows: 2-minutes TIED (Baseline), 3-minutes SPLIT for 2 sets (SPLIT1 & 2), 1-minute TIED (TIED1), 3-minutes SPLIT for 2 sets (SPLIT3 & 4), 1-minute TIED (TIED2), and 3-minutes SPLIT (SPLIT5) (Fig. 1). Between conditions and following each SPLIT walking period, participants were allowed a seated rest break of 1–3 minutes. Participants wore a safety harness, which did not provide body-weight support, to prevent falls and were allowed minimal handrail use throughout the protocol when required to maintain balance.

Step-length Asymmetry Index—Throughout the protocol, reflective markers placed on the heel, 5th metatarsal head, and great toe of each foot were used to track each foot segment using a 12-camera motion analysis system at 100 Hz and synchronized with two force platforms embedded under each treadmill belt (2000 Hz) (Oxford Metrics, Oxfordshire, UK). Spatiotemporal data were calculated using gait events (e.g. heel strike, toe off) determined from vertical ground reaction data (20N threshold) and foot segment position. Step length during treadmill walking was calculated as the distance between the proximal end position of the foot segments for the previous contralateral toe off and the ipsilateral heel strike. A custom data processing program (Visual 3D, C-Motion, Bethesda, MD) was used to calculate step length. Prior use of a similar protocol resulted in accurate capture of marker position and spatiotemporal measures [25].

Step length asymmetry index (AI) was calculated as: AI = 2*(Long−Short)/(Long +Short)*100, with "Long" and "Short" representing the longer and shorter step lengths during the initial over-ground walking assessment [26]. Using this formula, a value moving toward zero (absence of asymmetry), compared to baseline, would indicate improved symmetry. Increasing magnitude in the positive or negative direction would indicate worse symmetry towards either the “Long” (positive) or “Short” (negative) limb.

Data Reduction & Statistical Analysis—Average step length AI was calculated for the final 10 strides of Baseline, first 10 strides of TIED1, and first 10 strides of TIED2 for each participant to evaluate adaptation in response to the EGT protocol (Fig. 2). To assess short-term retention of the adapted walking patterns, step length AI of the initial 10 strides of SPLIT1, SPLIT3, and SPLIT5 periods were averaged. SPLIT3 and SPLIT5 followed a one-minute period of TIED walking, providing a potential opportunity for de-adaptation of the new gait pattern achieved during the SPLIT periods. Step length AI was also calculated for the final 10 strides of SPLIT2 and SPLIT4 to evaluate adaptation across early and late periods of each SPLIT exposure.

A repeated-measures ANOVA was used to evaluate adaptation of step length AI across Baseline, TIED1, and TIED2. A second ANOVA was used to assess short-term retention from SPLIT1, SPLIT3, and SPLIT5. If significant differences were observed in the ANOVA model ($p<.05$), post-hoc Tukey HSD tests were subsequently used. To further evaluate change in gait symmetry magnitude, Cohen’s *d* effect sizes were calculated for each post-hoc comparison with values 0.2–0.5, 0.5–0.8, and >0.8 considered to be small, medium, and large effect sizes, respectively [27]. Paired sample t-tests were used to evaluate adaptation across early and late periods of each SPLIT exposure by comparing the first 10 strides of SPLIT1 and SPLIT3 to the last 10 strides of SPLIT2 and SPLIT4, respectively. Exploratory subgroup analyses of potential confounding factors (e.g. direction of step length asymmetry, DM or PAD status) were performed using independent samples t-tests ($p<.05$).

Sample Size Calculation—We conservatively estimated an effect size of 0.5 for change in step length asymmetry. Assuming an alpha of 0.05, 7 participants were required to detect changes across 6 time points for the single group with a power of 0.90. A total of 8 participants were recruited to account for possible lost data during acquisition. This sample size is consistent with prior work in split-belt treadmill walking in people with traumatic TTA [16].

Results

Eight male participants completed the split-belt treadmill walking protocol (Table 1). One participant did not have complete MNSI data. Otherwise, no data were missing. All used total surface bearing sockets with two having additional patellar tendon loading areas. Five participants used a pin-lock liner suspension and three used a sleeve suspension. All participants used a dynamic response foot. Six (75%) participants used handrails throughout the treadmill protocol. Two (25%) were able to walk without handrail use during the TIED conditions, but required handrail use during the SPLIT conditions. Four (50%) participants walked overground with a longer prosthetic limb step. Four (50%) had a diagnoses of DM while the remaining 50% had a diagnoses of PAD. The MNSI scores indicated six of seven (85%) participants likely had peripheral neuropathy.

Significant adaptation of step length AI in response to SPLIT walking was observed from Baseline, TIED1, and TIED2 (Fig. 3). Between-limb step length became more symmetrical from Baseline (5.3±3.4; mean±Standard Deviation) to TIED1 (−9.4±3.6) and this change was sustained between TIED1 and TIED2 (−11.2±3.1) (ANOVA F=73.043, p<.001). Post-hoc testing indicated significantly decreased step length asymmetry at TIED1 (p<.001, *d*=4.21) and TIED2 (p<.001, *d*=5.11) compared to Baseline. No significant changes in step length AI were observed from TIED1 to TIED2 (p=.453, *d*=0.54).

Step-length AI decreased from SPLIT1 (48.5±5.3) to SPLIT3 (31.4±3.5) to SPLIT5 (23.9±5.1) (ANOVA F=35.284, p<.001) indicating short-term retention of the adapted gait pattern following each TIED condition (Fig. 3). Post-hoc testing demonstrated significant reductions in step-length AI at SPLIT3 (p<.001, *d*=3.78) and SPLIT5 (p<.001, *d*=4.69) compared to SPLIT1. No significant changes in step-length AI were observed from SPLIT3 to SPLIT5 (p=.070, *d*=1.68).

Significant adaptation was observed from early to late periods of each SPLIT exposure. Step length AI decreased during the final 10 strides of SPLIT2 (20.7±1.9, p<.001) and SPLIT4 (17.2±2.9, p=.004) compared to the first 10 strides of SPLIT1 (48.5±5.3) and SPLIT3 (31.4±3.5), respectively. The additional analyses revealed no significant differences between participant subgroups. Those with a longer prosthetic limb step responded comparably to those with a longer intact limb step across all periods (Prosthetic vs Intact. Baseline: 3.2±11.3 vs 7.3±8.8, p=.593; TIED1: −10.5±10.9 vs −14.3±9.9, p=.624; TIED2: −8.3±18.0 vs −15.7±7.4, p=.473; SPLIT1: 61.7±37.5 vs 35.4±16.9, p=.249; SPLIT2: 14.5±14.5 vs 26.8±13.9, p=.266; SPLIT3: 24.7±6.9 vs 38.1±11.3, p=.088; SPLIT4: 12.5±19.7 vs 21.9±14.6, p=.472; SPLIT5: 21.5±8.8 vs 26.4±27.9, p=.744) (Fig. 4). Participants with DM demonstrated similar baseline asymmetry and response to split-belt treadmill walking as those with PAD (DM vs PAD. Baseline: 6.5±6.3 vs 4.0±13.2, p=.748; TIED1: −7.4±26.9 vs −12.3±8.8, p=.742; TIED2: −10.4±18.6 vs −11.4±7.1, p=.926; SPLIT1: 49.5±45.8 vs 34.3±13.4, p=.548; SPLIT2: 24.3±13.9 vs 16.9±16.6, p=.523; SPLIT3: 23.9±16.7 vs 44.6±13.7, p=.105; SPLIT4: 19.0±14.7 vs 15.4±20.9, p=.784; SPLIT5: 15.3±10.9 vs 32.7±23.6, p=.230) (Fig. 5).

Discussion

The results of this study suggest that persons with non-traumatic TTA are 1) capable of gait adaptation in response to EGT, 2) retain short-term motor adaptations after removal of the SPLIT condition, and 3) EGT has potential to improve step length symmetry for persons with non-traumatic TTA.

Prior studies have assessed gait adaptability to split-belt walking in persons with TTA [15–17]. This study is the first to assess adaptability to split-belt walking in persons with non-traumatic TTA. The underlying cause of non-traumatic amputation is typically related to DM and/or PAD, which can compound sensory impairment beyond the limb loss. In the current sample, ~85% of the assessed participants likely had peripheral neuropathy based on MNSI scores. Split-belt treadmill walking adaptation is thought to, in part, utilize sensorimotor input [28]. Despite the additional sensory impairment observed in this cohort of persons with non-traumatic TTA, step length symmetry adaptation patterns were similar to those observed in people with traumatic TTA. No significant differences were observed when comparing underlying dysvascular etiology of TTA (Fig 5). However, the current study is underpowered to detect the EGT response differences between people with DM and PAD etiologies.

In addition, persons with non-traumatic TTA retain adapted gait patterns following de-adaptation during TIED walking, resulting in reduced step length asymmetry during the initial period of SPLIT3 and SPLIT5 compared to SPLIT1. Demonstrating a smaller initial increase in step length asymmetry with subsequent exposure to SPLIT walking after one-minute TIED walking bouts indicates a retained motor pattern [10, 29]. Such short-term retention of a gait pattern with increased step length symmetry suggests that additional peripheral sensory impairments associated with underlying amputation etiology do not preclude storage of the novel walking pattern. Instead, sensory feedback from proximal joints or upregulation of other sensory systems may facilitate adaptation in the absence of lower limb sensation. As such, intact joints of the amputated limb in combination with the non-amputated limb may provide sufficient sensory information on leg speed for both adaptation and retention after non-traumatic amputation.

This study protocol determined belt assignment for each limb based upon the direction of baseline step-length asymmetry during over-ground walking. In doing so, predicted adaptations were leveraged to target improvement in step-length symmetry. The results demonstrate proof-of-concept for EGT as an intervention to restore movement symmetry after non-traumatic TTA. Through improved understanding of the magnitude and duration of adaptation and retention, EGT could facilitate symmetrical gait pattern learning during rehabilitation. One possible model for gait symmetry intervention development has been used for persons following stroke [10, 11, 13]. In this model, split-belt treadmill walking is repeated to develop, refine, and store the novel movement pattern. It is important to note that the mechanism for adaptation in persons with TTA may differ from those post-stroke. Unlike persons following stroke, participants in the present study were without diagnosed central nervous system impairment, which may influence the mechanisms by which the novel movement pattern is achieved and stored.

Gait pattern adaptation occurred independent of whether the amputated limb was assigned to the fast or slow belt. Based upon the directionality of overground walking gait asymmetry, four participants had the prosthetic limb assigned to the fast belt and four were assigned to the slow belt. Despite varying directions of step length asymmetry no significant differences were observed between groups when separated by direction of asymmetry (Fig 4). However, the limited sample size precludes definitive conclusions about the relative importance of asymmetry direction with EGT. Although the specific mechanisms of gait adaptation to EGT are unclear, a prior study identified that persons with TTA used a center-of-mass displacement strategy in which the center-of-mass traveled posteriorly on the fast belt to create symmetrical step length [16]. It remains unknown if and how strategies for adaptation differ by direction of step length asymmetry. It is also important to note that symmetrical gait was achieved momentarily without modification to the participant’s prosthesis. Each participant in the current study utilized a dynamic response foot with a non-mobile ankle joint, indicating that a more symmetrical gait pattern can be achieved without advanced ankle componentry. As such, split-belt walking and gait retraining may have a role as a rehabilitative intervention to further improve walking patterns following non-traumatic TTA.

Limitations of this study should be considered. As a proof-of-concept study, absence of a comparison group limits the ability to understand the mechanism of effect. Future work should examine EGT efficacy in people with non-traumatic TTA compared to either those with traumatic TTA or persons without amputation. Secondly, the study sample size is small and was not powered to allow for additional subgroup comparisons or identification of other factors that may influence adaptation and retention with EGT. Also, the current study evaluated retention after a one-minute tied-belt walking period. De-adaptation times in existing literature vary, with some reports using periods of 5–10 minutes [11, 15, 16]. Fast and slow learning processes decay at different rates with fast learning de-adapting more rapidly than slow learning [30]. The one-minute de-adaptation period of the current study was likely too short to washout the slow motor learning processes, thus potentially contributing to the observed retention levels. Future studies are needed to determine the effects of multi-day, repeated sessions of split-belt walking and identify the duration of retention in step-length symmetry. In addition, evaluation of the necessary dosage to retain longer-term improvement in gait symmetry is needed. Lastly, the mechanism used to achieve improved symmetry during the tied belt conditions is unclear and requires further investigation as certain mechanisms used to improve symmetry may reduce energy efficiency or negatively influence joint loading.

Conclusions

Individuals with acquired, non-traumatic TTA are capable of gait adaptation to split-belt walking and short-term retention of motor adaptations after removal of the asymmetrical belt speeds. Adaptability of step length symmetry is possible despite reduced sensation from limb loss and without modification to the prosthetic limb. Split-belt walking may serve as a potential intervention to improve gait symmetry in persons with acquired non-traumatic TTA.

Declaration of Interest Statement/Acknowledgements

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Highlights

- Step length asymmetry is common after non-traumatic transtibial amputation.
- Split-belt treadmill walking improves gait asymmetry in other patient populations.
- Gait adaptation in people with non-traumatic transtibial amputation is unclear.
- Participants are capable of gait adaptation during split-belt treadmill walking.
- Step length asymmetry is reduced with the split-belt treadmill protocol.

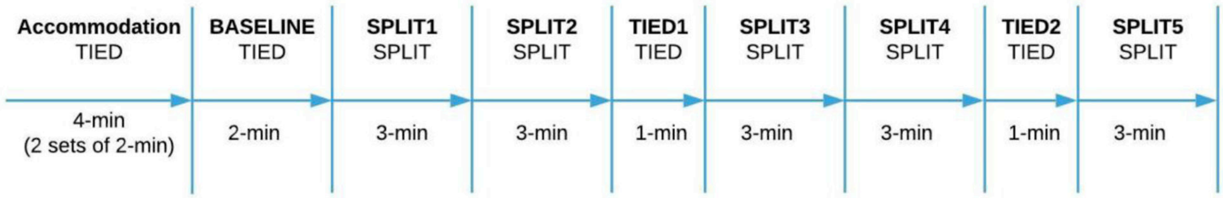

Figure 1.

Error-augmentation Gait Training protocol including duration of each TIED and SPLIT condition. TIED condition involves belts moving together at the same speed (75% of self-selected overground gait speed). SPLIT condition involves belts moving at asymmetrical speeds (2:1 ratio; fast belt: 75% of self-selected overground gait speed; slow belt: 37.5% of self-selected overground gait speed).

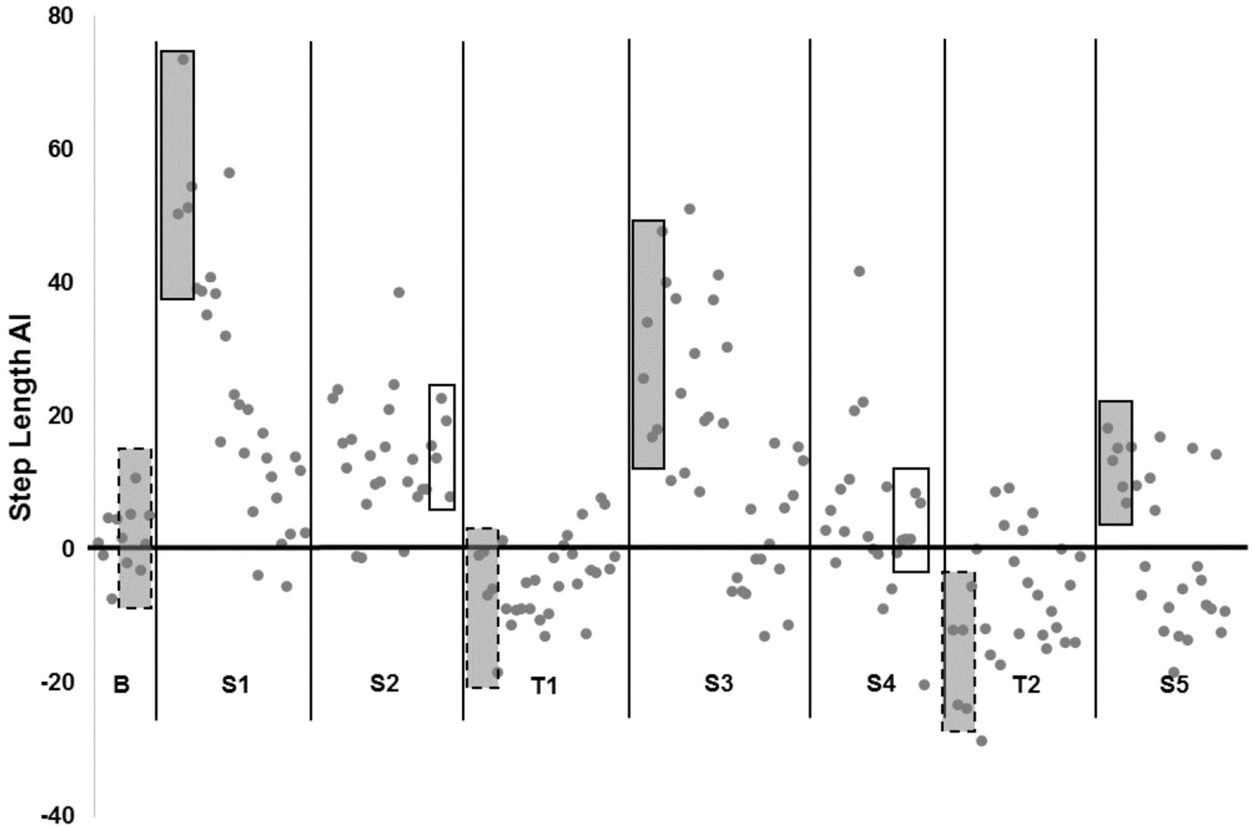

Figure 2.

Step Length Asymmetry Index (AI) from a representative participant at Baseline (B), SPLIT (S) and TIED (T) conditions demonstrating gait adaptation and retained responses following exposure to the SPLIT conditions. Each dot represents the AI of two consecutive steps. Data from the shaded boxes with dashed borders were used for comparison of adaptation across B, TIED1 (T1), and TIED2 (T2). Data from the shaded boxes with the solid borders were used for comparison of short-term retention from SPLIT1 (S1), SPLIT2 (S2), to SPLIT3 (S3). Data from the unshaded boxes with solid borders were used for comparison of early (S1, S3) and late (SPLIT2 [S2], SPLIT4 [S4]) adaptation.

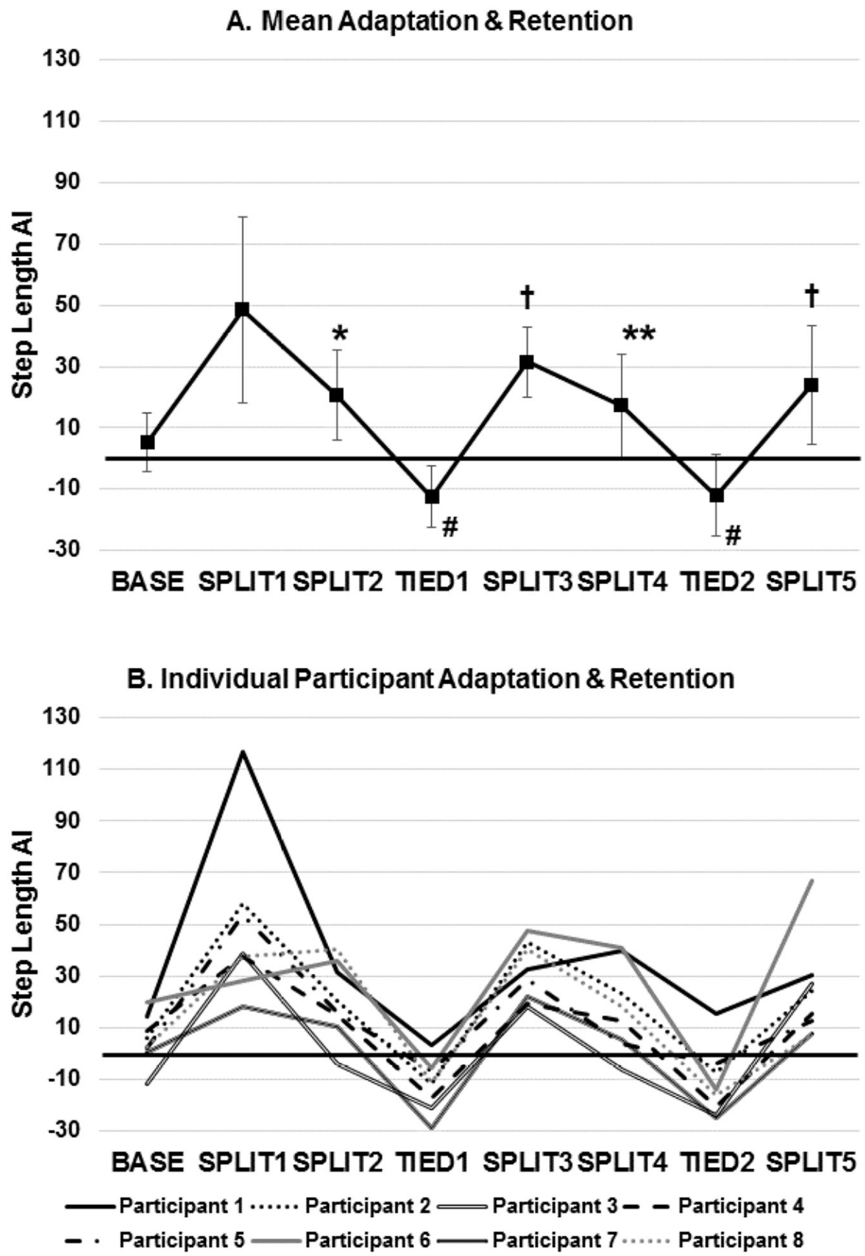

Figure 3.

Step Length Asymmetry Index (AI) of (A) mean adaptation and retention and (B) individual participants at Baseline (BASE), SPLIT and TIED conditions. Data represent the mean step length AI of 10 strides during each condition. # and † indicate significant change in step length AI compared to BASE (p<.001) and SPLIT1 (p<.001), respectively. * and ** indicate significant changes in step length AI compare to SPLIT1 (p<.001) and SPLIT4 (p=.004), respectively.

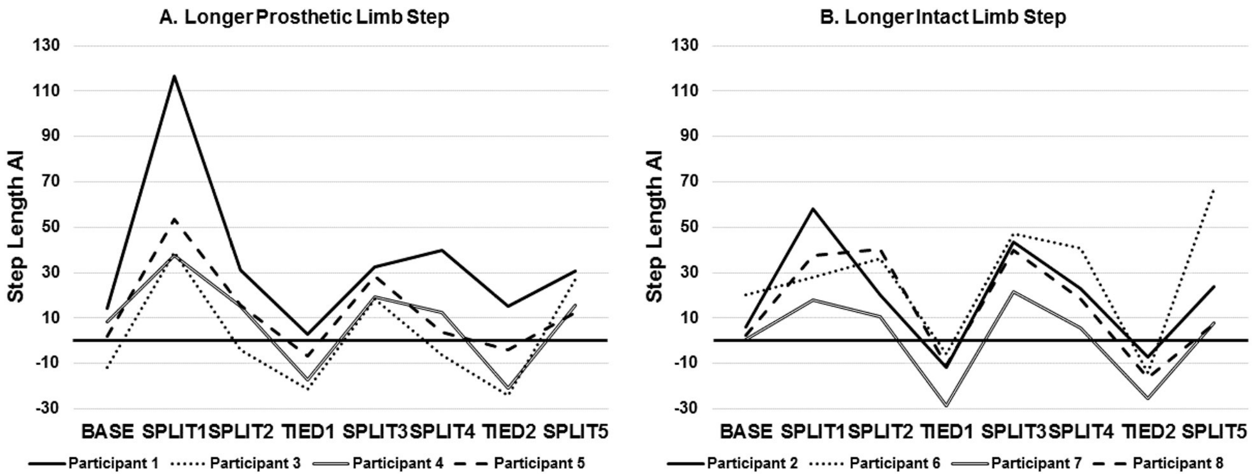

Figure 4.

Step Length Asymmetry Index (AI) of (A) participants with longer prosthetic limb step length and (B) participants with longer intact limb step lengths. Data represent the mean step length AI of 10 strides during Baseline (BASE), TIED, and SPLIT condition.

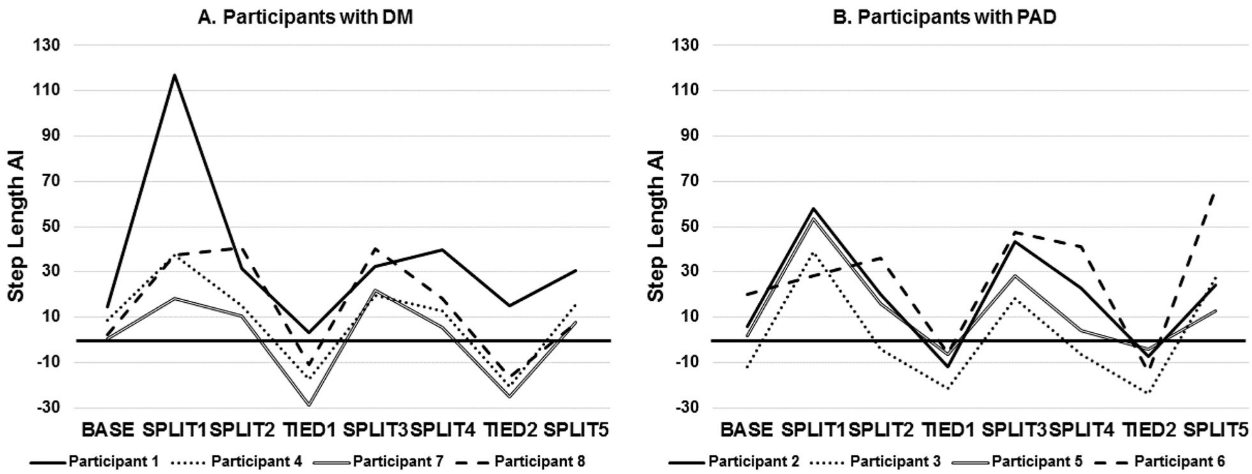

Figure 5.
Step Length Asymmetry Index (AI) of (A) participants with diabetes mellitus (DM) and (B) participants with peripheral artery disease (PAD). Data represent the mean step length AI of 10 strides during Baseline (BASE), TIED, and SPLIT condition.

Table 1:

Participant Demographics and Descriptive Measures

Descriptive Measures	Mean ± Standard Deviation, Range
Age, years	69 ± 5, 58–76
Body Mass Index, kg/m^2	29.5 ± 5.8, 21.5–38.1
FCI	6 ± 2, 3–9
Overground Walking Speed, m/s	1.1 ± 0.1, 0.9–1.2
Houghton	9.5 ± 1.3, 8–12
PEQ-MS	36.4 ± 9.1, 25–48
Prosthesis type	6 total surface bearing 2 total surface bearing with additional patellar tendon loading
Suspension type	5 pin-lock liner 3 sleeve
Time since amputation, months	33 ± 18, 17–60
MNSI Questionnaire	4.71 ± 3.25, 0–10
MNSI Physical Exam	2.57 ± 1.31, 0–4
Long Step Length, cm	50.5 ± 7.6, 38.9–63.2
Short Step Length, cm	48.1 ± 7.6, 37.9–58.0

FCI: Functional Comorbidity Index

PEQ-MS: Prosthesis Evaluation Questionnaire Mobility Scale

MNSI: Michigan Neuropathy Screening Instrument