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RESEARCH ARTICLE

Biomechanical and neurocognitive performance outcomes of walking with transtibial limb loss while challenged by a concurrent task

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Abstract

Individuals who have sustained loss of a lower limb may require adaptations in sensorimotor and control systems to effectively utilize a prosthesis, and the interaction of these systems during walking is not clearly understood for this patient population. The aim of this study was to concurrently evaluate temporospatial gait mechanics and cortical dynamics in a population with and without unilateral transtibial limb loss (TT). Utilizing motion capture and electroencephalography, these outcomes were simultaneously collected while participants with and without TT completed a concurrent task of varying difficulty (low- and high-demand) while seated and walking. All participants demonstrated a wider base of support and more stable gait pattern when walking and completing the high-demand concurrent task. The cortical dynamics were similarly modulated by the task demand for both groups, to include a decrease in the novelty-P3 component and increase in the frontal theta/parietal alpha ratio power when completing the high-demand task, although specific differences were also observed. These findings confirm and extend prior efforts indicating that dual-task walking can negatively affect walking mechanics and/or neurocognitive performance. However, there may be limited additional cognitive and/or biomechanical impact of utilizing a prosthesis in a stable, protected environment in TT who have acclimated to ambulating with a prosthesis. These results highlight the need for future work to evaluate interactions between these cognitive–motor control systems for individuals with more proximal levels of lower limb loss, and in more challenging (ecologically valid) environments.

Keywords Limb loss · Cognitive workload · Biomechanics · Electroencephalogram · Dual-task walking

Abbreviations

ANOVA	Analysis of variance
CAREN	Computer-Assisted Rehabilitation ENvironment
EEG	Electroencephalography
ERPs	Event-related potentials
FT/PA	Frontal theta/parietal alpha ratio
NASA-TLX	National Aeronautics and Space Administration-Task Load Index
TT	Transtibial limb loss

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Introduction

The study of cognitive workload to understand the mechanisms underlying human cognitive–motor performance has largely focused on healthy individuals without considering a rehabilitation perspective (e.g., Deeny et al. 2014; Miller et al. 2014; Shuggi et al. 2017, 2018). For persons with lower limb loss, altered sensorimotor function and control may challenge these individuals when walking with a prosthesis, which may increase cognitive workload and/or adversely impact gait quality. It is, therefore, important to better understand the interaction between cognitive resources and biomechanical performance when walking to identify needs for targeted interventions for this population.

Electroencephalography (EEG) can be employed to assess cognitive workload in various ways (Brouwer et al. 2012). First, task-irrelevant stimuli can be presented while participants engage in a primary task, and the stimuli-elicited event-related potentials (ERPs) can be examined (Dyke et al. 2015; Gentili et al. 2014; Miller et al. 2011; SanMiguel et al. 2008; Shaw et al. 2018). The ERP waveform's novelty-P3 component amplitude reflects stimulus-driven attentional orienting, which depends on attentional resources not being consumed by the primary task (i.e., attentional reserve) (Alderman et al. 2015; Murray and Janelle 2007; Olson et al. 2016). Since attentional reserve is inversely related to cognitive workload, novelty-P3 amplitude elicited by task-irrelevant stimuli indexes the cognitive workload imposed by the primary task. Second, cognitive workload can be examined via the power in different frequency bands in the EEG spectrum. Specifically, alpha (~8–13 Hz) power decreases when cognitive–motor neural resources are recruited to meet the challenge imposed by a task, and thus alpha power is inversely related to cognitive workload (Gentili et al. 2018; Jaquess et al. 2017; Rietschel et al. 2012; Shaw et al. 2018). Conversely, neuronal oscillations in the theta frequency band (~4–7 Hz) are synchronized when neural resources for attentional processes, such as working memory and action monitoring, are recruited to meet task demands (Cheng et al. 2015; Coombes et al. 2005; Gevins and Smith 2003; Jaiswal et al. 2010; Slobounov et al. 2013, 2015). Thus, theta power is positively associated with cognitive workload. Investigations have examined cognitive workload via cortical dynamics during dual-task walking by employing EEG (Beurskens et al. 2016; De Sanctis et al. 2014); however, relatively few have examined cognitive workload while operating assistive systems (Deeny et al. 2014; Shuggi et al. 2017, 2018; Zhang et al. 2016). This prior work has generally: not focused on prosthesis performance and/or limb loss; assessed cognitive workload via surveys without combining brain dynamics and biomechanical analyses; focused on reaching/grasping, but not walking.

Table 1 Mean (SD) demographic characteristics for individuals with and without unilateral transtibial limb loss (TT)

Group	Without TT ($n=12$)	With TT ($n=12$)
Gender (M/F)	11/1	11/1
Age (years)*	27.4 (3.9)	33.7 (7.6)
Height (cm)	179.0 (7.7)	178.7 (7.1)
Weight (kg)	83.8 (14.3)	88.9 (8.1)
SSWV (m/s)	1.21 (0.16)	1.16 (0.16)

*$p \leq 0.05$

M male, *F* female, *SSWV* self-selected walking velocity

Dual-task walking among uninjured individuals suggests that the execution of a concurrent task can adversely affect walking mechanics (e.g., Beauchet et al. 2005; Beurskens et al. 2016; Dubost et al. 2006; Hollman et al. 2007). Both increases and decreases in the temporospatial variability have been observed under dual-task conditions (Brach et al. 2005; Maki 1997). Few studies have examined biomechanical outcomes with dual-task walking in individuals with lower limb loss (Hof et al. 2007; Lamoth et al. 2010; Morgan et al. 2016, 2017). Although the results are relatively mixed, it appears that dual-task walking in a complex environment may require individuals with lower limb loss to further recruit cognitive resources to control their gait (Morgan et al. 2017). However, these dual-task walking studies have mainly focused on behavior (biomechanics, cognitive performance) without examining the underlying cortical dynamics.

This study aimed to concurrently evaluate gait mechanics and cortical dynamics in a population with and without unilateral transtibial limb loss (TT). We hypothesized that dual-task walking induces larger cognitive workload (reduced novelty-P3 amplitude to task-irrelevant probes, lower alpha power, and higher theta power) in individuals with TT due to the use of the prosthesis. Additionally, we hypothesized that these larger workloads would result in a degradation of walking mechanics (increased stride time, stride width, and double limb support time mean and variability) among individuals with vs. without TT. Such differences between individuals with and without TT should not be observed during the performance of the concurrent task when not walking (i.e., while seated), and concurrent task performance should change consistently between task difficulties whether seated or walking.

Methods

Participants

Thirty participants, 15 with and 15 without TT, enrolled in this study, however, the final sample consisted of 24 individuals ($n = 12$ within each group; Table 1) due to equipment malfunctions and/or excessive noise within the EEG data. All participants were able to ambulate for 15 min in a controlled setting (i.e., level treadmill) without the use of any assistive device other than a prosthesis. Self-reported pain was less than 4/10 on a visual analog scale at the time of data collection for all enrolled participants. Participants in both groups were also free from vestibular, auditory, or visual conditions that may have influenced their performance walking within the environment. In addition, participants in both groups were screened to ensure there was no known diagnosis of a brain injury resulting in functional impairment or decreased learning capabilities and that all participants were free from any drug or alcohol use at the time of the study (assessed by employing a urine screen test and breathalyzer, respectively). All participants with TT wore passive energy storage and return prosthetic feet with suction suspension, and demonstrated normal strength and sagittal range of motion for the contralateral (uninjured) limb. Participants with TT were acclimated to their prostheses, demonstrating a median (range) of 1.75 (0.33–25) years since their initial prosthetic fitting. This present study was limited to TT who had completed formal gait training rehabilitation to minimize any practice effects that could impact mental workload and performance and interpretation of the findings (Gentili et al. 2011; Rietschel et al. 2014; Shuggi et al. 2017). In addition, there was a concern that novice ambulators would be unable to complete the testing battery due to possible fatigue with repeated walking conditions. While it is difficult to properly grade each participant's proficiency ambulating with a prosthesis, all participants were reasonably steady/stabilized in their walking abilities and prosthetic fit such that this study could focus on the inherent effects of dual-task walking with a prosthesis on attentional resources, as opposed to a separate and distinct question focusing on examining novices who learn over time how to use their prosthesis under the proposed conditions of challenge. The study was carried out in accordance with the procedures approved by the Institutional Review Board at Walter Reed National Military Medical Center, and all subjects provided written informed consent.

Task

Participants completed a concurrent task with two levels of difficulty (low- and high-demand), while seated and walking at a self-selected speed (motor task) on a dual-belt treadmill within a virtual environment (Computer-Assisted Rehabilitation ENvironment (CAREN); Motekforce Link, Amsterdam, The Netherlands), resulting in four 8-min experimental conditions (i.e., seated with low-demand task; seated with high-demand task; walking with low-demand task; walking with high-demand task). Participants also performed an additional 8-min condition of walking without performing the concurrent task to provide a biomechanical baseline without any further constraints (i.e., no interference with the concurrent task). The presentation order of the five conditions was counterbalanced across participants to minimize order effects (Fig. 1). To determine the treadmill speed employed during all walking conditions, participants first completed a 4-min acclimation period walking utilizing a self-paced mode within the CAREN, which resulted in the treadmill speeding up or slowing down as the participant neared the front or back of the treadmill, respectively (Sloot et al. 2014); the mean speed during the last 30 s of this period was used to set the treadmill speed for all walking conditions for each participant (Table 1). Of note, during seated conditions, one treadmill belt was set to move at the participant's self-selected speed to standardize noise generated by the treadmill across all experimental conditions.

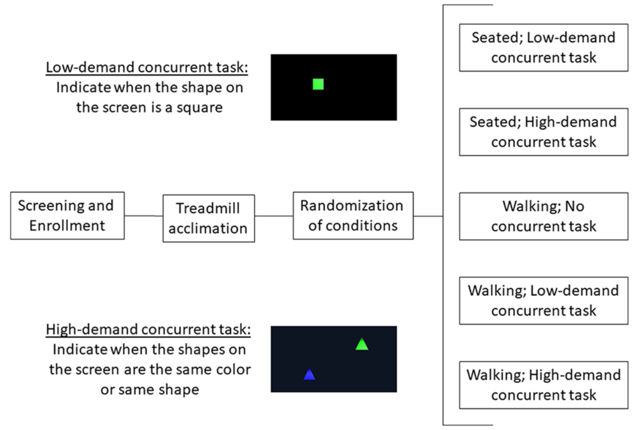

Fig. 1 Overall experimental workflow with inset illustrations for both the low- (top) and high- (bottom) demand concurrent tasks

In the concurrent task, participants were required to detect objects (i.e., stimuli) of various shapes and colors displayed (500 ms; random inter-stimulus interval of 100–1000 ms) on a large 180-degree projection screen in front of the treadmill (at a distance of ~3 m). To vary the demand of the concurrent task, these objects could be displayed in three shapes (squares, circles, and triangles) and three colors (red, green, and blue). All stimuli were centrally presented on the screen to minimize head movements and saccades. During the low-demand level, only one stimulus was displayed and participants had to press a button as quickly and accurately as possible on a wireless hand-held controller every time a square (regardless of color) appeared on the screen. During the high-demand task, two stimuli were simultaneously displayed and participants had to press a button on the hand-held controller as quickly and accurately as possible every time the two stimuli were of the same shape or same color (e.g., a red circle and a red square, or a green triangle and a blue triangle).

Throughout each experimental condition, a previously developed probing technique was employed to assess attentional reserve as participants completed the concurrent task described above (Dyke et al. 2015; Gentili et al. 2018; Jaquess et al. 2017; Miller et al. 2011, 2014; Shaw et al. 2018).[1] Namely, individuals were intermittently probed by employing a set of 30 task-irrelevant novel auditory stimuli (i.e., woman coughing, baby crying) obtained from a larger database developed by the New York State Psychiatric Institute (Fabiani et al. 1996). Wall-mounted speakers located in the room with the CAREN system randomly delivered the auditory probes at a comfortable volume (less than 95 decibels) during each 8-min cognitive–motor performance condition (for further details see Miller et al. 2011). To assess the self-reported mental demand, physical demand, and more generally, the perceived effort resulting from task performance, participants were required to complete the National Aeronautics and Space Administration-Task Load Index (NASA-TLX) at the end of each condition. Individuals were permitted to take a 2-min break between conditions to minimize effects due to the fatigue. Data collection for all participants was completed in a single session.

Electrophysiological data collection

While participants performed the concurrent task, EEG was recorded (1000 Hz) from 64 scalp sites (extended 10–20 system) using an actiCAP EEG system (Brain Products GmbH, Germany) and wirelessly transmitted through the MOVE system (Brain Products GmbH, Germany). The EEG data were referenced online to the left earlobe and a common ground was employed at the FPz site on the scalp. All electrode impedances were maintained below 10 kΩ and band pass filters were set at 0.01–100 Hz throughout the study. The EEG signal was amplified and digitized using a BrainAmp DC Amplifier (Brain Products GmbH, Germany) linked to Brain Vision Recorder software version 2.1 (Brain Products GmbH, Germany).

Biomechanical data collection

During all walking conditions, full-body kinematics were continuously recorded by tracking (120 Hz) reflective markers (diameter = 8 mm) using a 12-camera optical motion capture system (T40 series, Vicon, Oxford, UK). Markers were placed at the following anatomical landmarks: mid-sagittal plane over the sacrum (S1), T10, and C7 spinous processes, sternal notch, and xiphoid; and bilaterally over the acromion, anterior/posterior superior iliac spines, and the upper and lower extremities (Helen Hayes marker set).

Data processing

Concurrent task performance and perceived demand

For each level of task difficulty and experimental condition (seated and walking), performance on the concurrent task was indexed by the response time (i.e., time elapsed between the target stimuli appearance on the screen and the response of the individuals) for correct responses only and Dprime (i.e., account for correct and incorrect hits while indicating the capacity to detect information). Furthermore, for each level of challenge, the NASA-TLX was employed to subjectively assess overall perceived workload by measuring various contributing sources via six dimensions including cognitive, physical, and temporal task demands, as well as, effort, frustration, and perception of performance. As such, the score for each dimension of the NASA-TLX was computed (Hart and Staveland 1988; Hart 2006).

Biomechanical processing and analysis

Raw marker trajectories were low-pass filtered using a bidirectional, second-order Butterworth filter (cutoff frequency = 6 Hz). Biomechanical measures describing the temporospatial features of gait were subsequently computed in Visual3D software (C-Motion, Germantown, MD, USA). Specifically, these included the mean and variability in stride time, step width, and double limb support time, which were selected based on sensitivity to dual-task walking demonstrated in prior work and their representation of gait "rhythmicity" and stability (Lord et al. 2011; Yogev-Seligmann et al. 2010). Gait events (e.g., foot contact and toe off) were identified using a 20N ascending and descending threshold in the vertical ground reaction force and visually inspected for accuracy to facilitate the computation of each biomechanical measure as a function of gait cycle. Stride time was defined as the time between consecutive heel strikes

[1] Auditory and not visual probes were employed since with the latter it is difficult to ascertain whether attenuations in probe-evoked brain responses are due to reductions in attentional reserve or simply failures of participants to be looking at the probes. The various shapes/colors displayed on the screen and auditory probes were simultaneously presented during the whole dual task. The frequency of presentation of the visual stimuli and auditory probes differed (objects appeared for 500 ms at a time with a random 100–1000 ms inter-stimulus interval; auditory probes were played randomly with an inter-stimulus interval of 6–30 s).

of the same foot, step width as the distance between heel markers (at heel strike) in two successive steps, and double limb support time as the period of time when both feet are in contact with the ground (Plummer-D'Amato et al. 2010). Variability in these measures across gait cycles within each trial was computed using the coefficient of variation [(standard deviation/mean) × 100].

EEG ERPs processing and analysis

Signal processing of the EEG data was conducted using BrainVision Analyzer software version 2.0 (Brain Products GmbH, Munich, Germany). Continuous data collected during the entire experiment were re-referenced to an averaged ears montage offline before further processing for both the ERPs and spectral analysis (for the latter see "Spectral power processing and analysis" below).

EEG data were low-pass filtered (zero-phase Butterworth filter at 20 Hz with a 48-dB rolloff), and visually inspected such that all non-stereotyped artifacts were excluded from further analysis by employing a pruning method (Onton et al. 2006). Then, an ICA-based approach was employed for examining the impact of artifact produced by excessive muscle, eye or body movement. In particular, eye movement artifact was reduced using an ICA-based ocular artifact rejection function using the Brain Vision Analyzer software. Electrode FP2 served as the VEOG channel and electrodes AF7 and AF8 served as the bipolar HEOG channel. The VEOG and HEOG algorithms found ICA-derived components that accounted for 70% and 30% of the amount of variance in the entire signal from the FP2 and AF7/AF8 channels, respectively. These components were removed from the raw EEG signal which was then reconstructed for further processing. Once this preprocessing stage was completed, the data were segmented into 1-s epochs surrounding the presentation of the auditory stimuli (100 ms before and 900 ms after auditory stimulus presentation) and baseline corrected by employing the average of the pre-stimulus interval. All epochs were then visually inspected for any remaining artifact. The remaining epochs were averaged for each subject and experimental condition. All averages contained at least 20 epochs ($M = 23.19$, $SD = 2.68$), to have an adequate signal-to-noise ratio (Cohen and Polich 1997). The grand-average waveform collapsed across all participants and experimental conditions was used to determine novelty-P3 peak amplitude. Peak amplitude was identified as maximal at electrode Fz. A 40 ms time window (292–332 ms) centered on novelty-P3 peak amplitude was identified and mean amplitudes within this window were extracted for each participant and experimental condition. Also, to ensure that the observed topographic distribution for the identified window was consistent with that reported in the literature, current source densities were computed and projected onto the scalp. The mean amplitudes of the novelty-P3 component were then subjected to statistical analysis.

Spectral power processing and analysis

To minimize any transient effects at the beginning or end of the task (e.g., task adjustment, fatigue), EEG data collected between 3 and 6 min during each experimental condition were subjected to spectral power analysis. Once the data were low-pass filtered (at 50 Hz with a 48-dB rolloff and notch filtered at 60 Hz using a zero-phase shift Butterworth filter offline), the same pruning and eye movement artifact denoising techniques as previously mentioned in the ERP section were employed. Then, the 3-min block of data was epoched into 1-s sweeps and baseline corrected using the mean of the pre-sweep interval. A visual inspection of these epochs was conducted to remove any remaining artifact. Spectral power was computed across 1-Hz bins and summed across the frequency bandwidths theta (4–7 Hz), low-alpha (8–10 Hz), and high-alpha (11–13 Hz). To account for possible differences between brain dynamics of both groups, the spectral power for each of these frequency bandwidths was divided by the spectral power of the entire spectrum considered here. The frontal theta/parietal alpha (FT/PA) ratio power was computed since it was shown that it can robustly index changes in cognitive workload (Gentili et al. 2014, 2018; Gevins and Smith 2000, 2003; Holm et al. 2009; Jaquess et al. 2017). Then, spectral power was natural log transformed prior to statistical analysis to approximate a normal distribution.

Experimental design and statistical analysis

Concurrent task performance and NASA-TLX scores

The response time, Dprime, and NASA-TLX scores were subjected to a 2 × 2 × 2 [Group (Uninjured vs. Injured) × Condition (Seated vs. Walking) × Difficulty (Low vs. High demand)] mixed-factorial analysis of variation (ANOVA) where Condition and Difficulty are within-subjects factors and Group is a between-subjects factor. Post hoc analyses were computed using the Tukey's HSD test, when needed. When the sphericity assumption was not met, the Greenhouse–Geisser correction was applied and the corrected p values and degrees of freedom are reported. Partial eta squared (η^2_p) and Cohen's d effect sizes are also reported when appropriate. All criterion alpha significance levels were set to $p < 0.05$. The same corrective approach and significance level were employed for all the biomechanics and EEG metrics presented below.

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Biomechanical measures

Stride time, step width, and double limb support time mean and variability were subjected to a 2 × 3 [Group (Uninjured vs. Injured) × Difficulty (No vs. Low vs. High demand)] repeated measures ANOVA where Difficulty is a within-subjects factor and Group is a between-subjects factor. Post hoc analyses were computed using the Tukey's HSD test, when necessary.

ERPs

The ERP analysis was conducted on the amplitude of the novelty-P3 component at the cortical site Cz, which has been demonstrated to be maximal for the specific manipulation considered in this study (i.e., seated vs. walk; low vs. high demand; Shaw et al. 2018). Thus, mean amplitudes of the novelty-P3 component at Cz were subjected to a 2 × 2 × 2 [Group (Uninjured vs. Injured) × Condition (Seated vs. Walking) × Difficulty (Low vs. High demand)] mixed-factorial ANOVA where Difficulty and Condition are within-subject factors and Group is a between-subjects factor. Post hoc analyses were computed using the Tukey's HSD test, when needed.

Spectral power

The changes in theta power were examined at site Fz, since midline frontal theta reflects attentional processes and working memory, which are critical to cognitive workload assessment (Cavanagh et al. 2009; Onton et al. 2005). In addition, the spectral power within the low-alpha and high-alpha bandwidth was averaged at the sites C3 and C4 to assess the activity in the central motor regions in light of the involvement in locomotor regulation. Thus theta, low-alpha and high-alpha power as well as the FT/PA ratio were subjected to a 2 × 2 × 2 [Group (Uninjured vs. Injured) × Condition (Seated vs. Walking) × Difficulty (Low vs. High demand)] mixed-factorial ANOVA where Difficulty and Condition are within-subject factors and Group is a between-subjects factor. Post hoc analyses were computed by employing the Tukey's HSD test.

Results

Concurrent task performance

Across all tasks, performance (e.g., response time and Dprime) on the concurrent task was comparable for both groups (no main/interaction effect for the factor Group, $p > 0.05$), and task performance data were not recorded due to technical issues for one participant with and one

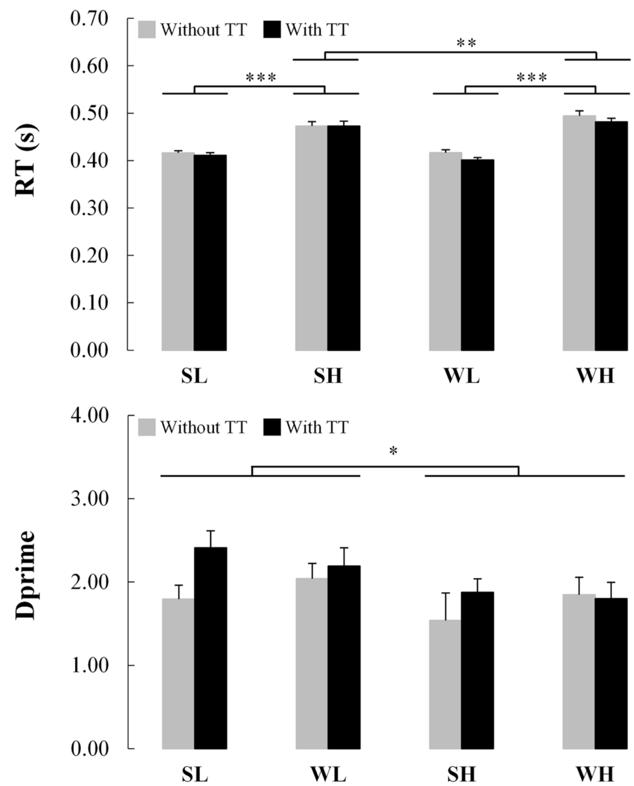


Fig. 2 Concurrent task performance for individuals with and without unilateral transtibial limb loss completing a low- or high-demand concurrent task while seated and walking. *SL* seated, low-demand task, *SH* seated, high-demand task, *WL* walking, low-demand task, *WH* walking, high-demand task. *$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$

without TT. However, a Difficulty × Condition interaction was revealed (F (1, 20) = 15.441, $p < 0.001$, $\eta^2_p = 0.436$); response times were greater for the high- compared to the low-demand task while performing the concurrent task in the seated ($p < 0.001$, $d = 2.257$) and walking ($p < 0.001$, $d = 2.933$) conditions. Furthermore, response times were greater during the walking compared to the seated conditions while performing the high-demand concurrent task ($p = 0.002$, $d = 0.428$), whereas no difference was observed for the low-demand task ($p > 0.551$). A main Difficulty effect was observed for Dprime (F (1, 19) = 4.907, $p = 0.039$, $\eta^2_p = 0.205$) which revealed that both groups had a smaller Dprime for the high- compared to the low-demand task (Fig. 2). No other significant effects were identified ($p > 0.05$; see Supplementary online material for details regarding non-significant results).

NASA-TLX

The NASA-TLX scores revealed a main effect of Difficulty as participants reported significantly higher levels of mental demand (F (1, 21) = 47.805, $p < 0.001$, $\eta^2_p = 0.695$), temporal demand (F (1, 21) = 25.136, $p < 0.001$, $\eta^2_p = 0.545$),

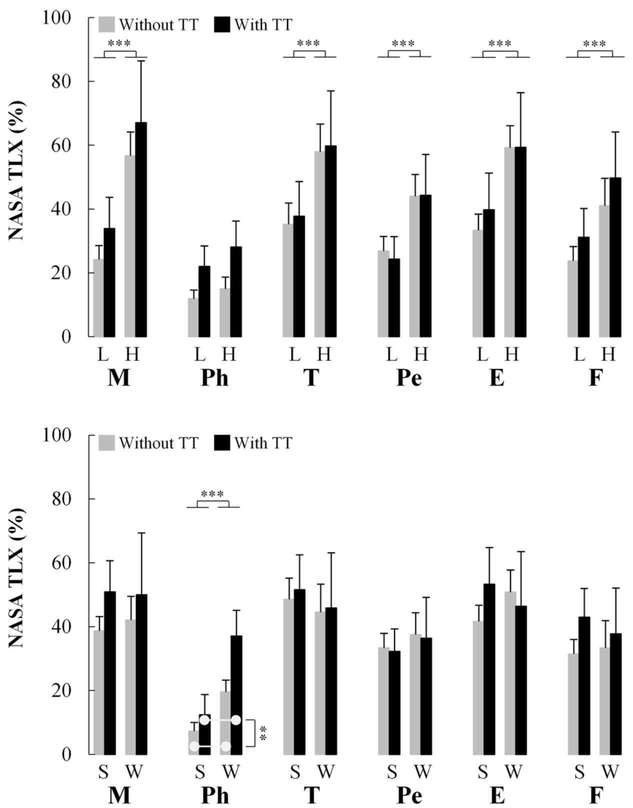


Fig. 3 NASA-TLX scale scores for individuals with and without unilateral transtibial limb loss (TT) completing a low- or high-demand concurrent task (top row) and seated or walking (bottom row). *L* low-demand task, *H* high-demand task, *S* seated, *W* walking, *M* mental demand, *Ph* physical demand, *T* temporal demand, *Pe* performance, *E* effort, *F* frustration. $^{*}p \leq 0.05$; $^{**}p \leq 0.01$; $^{***}p \leq 0.001$

performance (F (1, 21) = 34.275, $p < 0.001$, $\eta^2_p = 0.620$), effort (F (1, 21) = 36.755, $p < 0.001$, $\eta^2_p = 0.648$), and frustration (F (1, 21) = 15.343, $p < 0.001$, $\eta^2_p = 0.447$) for the high-demand task compared to the low-demand task. Also, for the effort dimension, there was a Group x Condition interaction (F (1, 20) = 6.933, $p = 0.015$, $\eta^2_p = 0.257$). However, the post hoc analysis did not reveal any significant differences ($p > 0.117$; all comparisons considered). For the physical dimension, a significant main effect of Group was observed as injured participants reported higher levels of physical demand (F (1, 20) = 12.086, $p = 0.002$, $\eta^2_p = 0.377$) compared to the uninjured individuals. For the same dimension, a significant main effect of Condition was observed as participants reported higher levels of physical demand (F (1, 20) = 29.530, $p < 0.001$, $\eta^2_p = 0.596$) for the walking compared to the seated conditions (Fig. 3). No other significant effects were detected ($p > 0.05$; see Supplementary online material for details regarding non-significant results).

Biomechanical measures

There was a main effect of Difficulty for mean stride width (F (2, 44) = 6.206, $p = 0.004$, $\eta^2_p = 0.220$) and stride width variability (F (2, 44) = 4.626, $p = 0.015$, $\eta^2_p = 0.174$). Post hoc analysis indicated that participants demonstrated a wider base ($p = 0.003$) and decreased variability ($p = 0.016$) in their stride width when completing the high-demand task compared to the no-demand task (Fig. 4). In addition, a Group × Difficulty interaction effect (F (1.544, 30.971) = 3.858, $p = 0.041$, $\eta^2_p = 0.149$, $\varepsilon = 0.772$) was observed for stride time variability, revealing that stride time variability decreased for injured individuals when executing the low-demand task ($p = 0.016$) compared to the no-demand task. A significant difference was not observed when comparing the no-demand and high-demand tasks in this group, and the same comparisons for the uninjured individuals were also not significant. No other effects reached significance ($p > 0.05$; see Supplementary online material for details regarding non-significant results) (Fig. 4).

ERPs—novelty-P3

For the novelty-P3 component, a Group × Difficulty interaction effect (F (1, 22) = 6.008, $p = 0.023$, $\eta^2_p = 0.215$) was observed, however, the post hoc analysis did not reveal any significant differences ($p \geq 0.080$; all comparisons considered) (Fig. 5a). A main effect of Condition (F (1, 22) = 6.199, $p = 0.021$, $\eta^2_p = 0.220$) was also observed reflecting that the novelty-P3 amplitude was smaller for the walking compared to the seated condition (see Fig. 5b). No other effects were identified ($p > 0.05$; see Supplementary online material for details regarding non-significant results).

EEG spectral power

Theta

A main effect of Difficulty (F (1, 22) = 11.121, $p = 0.003$, $\eta^2_p = 0.336$) was revealed such that frontal midline theta power was elevated under the high compared to the low cognitve task demand (see Fig. 6a). Moreover, a main effect of Condition (F (1, 22) = 30.263, $p < 0.001$, $\eta^2_p = 0.579$) was also observed, revealing an increase in theta power during walking, relative to the seated condition, in the frontal midline region (see Fig. 6b). No other significant effects were detected ($p > 0.05$; see Supplementary online material for details regarding non-significant results).

Alpha

For the low-alpha band, a main effect of Difficulty (F (1, 22) = 11.286, $p = 0.003$, $\eta^2_p = 0.339$) revealed a reduction of

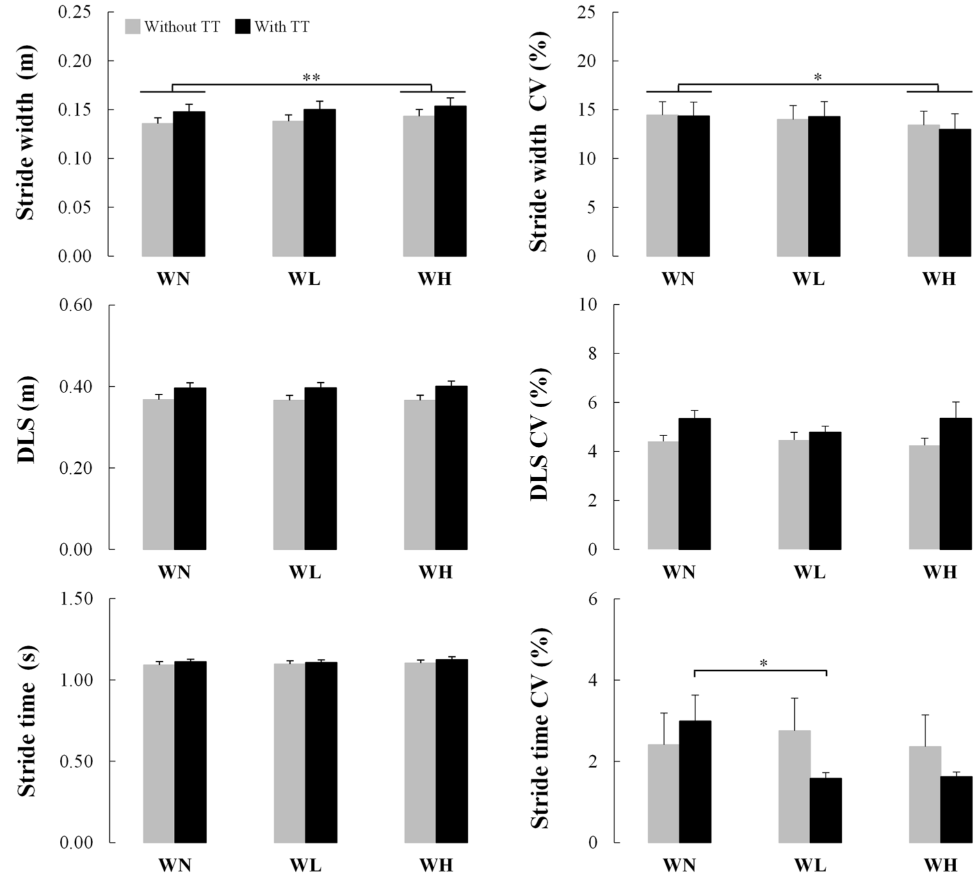


Fig. 4 Changes in biomechanical performance during walking for individuals with and without unilateral transtibial limb loss (TT) completing a low- or high-demand concurrent task. *WN* walking, no-demand task, *WL* walking, low-demand task, *WH* walking, high-demand task, *DLS* double limb support, *CV* coefficient of variation. $^{*}p \leq 0.05$; $^{**}p \leq 0.01$; $^{***}p \leq 0.001$

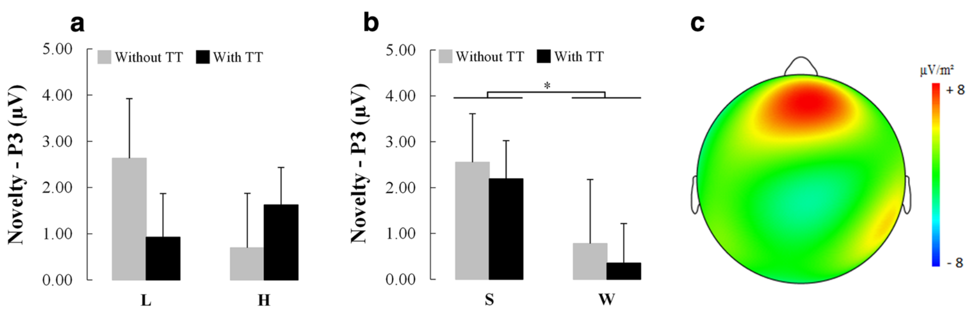


Fig. 5 Changes in the novelty-P3 component at Cz for individuals with and without unilateral transtibial limb loss (TT) completing a low- or high-demand concurrent task (**a**) and seated or walking (**b**). **c** Topographic distribution for the novelty-P3 component (time window 292–332 ms) to assess that our ERP results were in agreement with those observed in prior work. *L* low-demand task, *H* high-demand task, *S* seated, *W* walking. $^{*}p \leq 0.05$; $^{**}p \leq 0.01$; $^{***}p \leq 0.001$

low-alpha power for both groups during the performance of the high- compared to the low-demand (see Fig. 6c). For the high-alpha band, a main effect for Difficulty (F (1, 22) = 21.739, $p < 0.001$, $\eta^2_p = 0.497$) was identified for high-alpha power such that for both the injured and uninjured groups exhibited lower power in the central region under the high- compared to the low-demand condition (see Fig. 6e). In addition, an effect of Condition (F (1, 22) = 8.351, $p = 0.009$, $\eta^2_p = 0.275$) indicated that the high-alpha power was attenuated in the central motor regions for both the injured and uninjured groups while performing the secondary task during the walking relative to the seated condition (see Fig. 6f). No other effects for low-alpha or high-alpha reached significance ($p > 0.05$; see Supplementary online material for further details regarding non-significant results).

The relationship between the changes in high-alpha power in the central cortical region and the biomechanical variables were considered because of its involvement in locomotion regulation. Thus, for descriptive purposes, bivariate Pearson correlations were conducted between EEG high-alpha

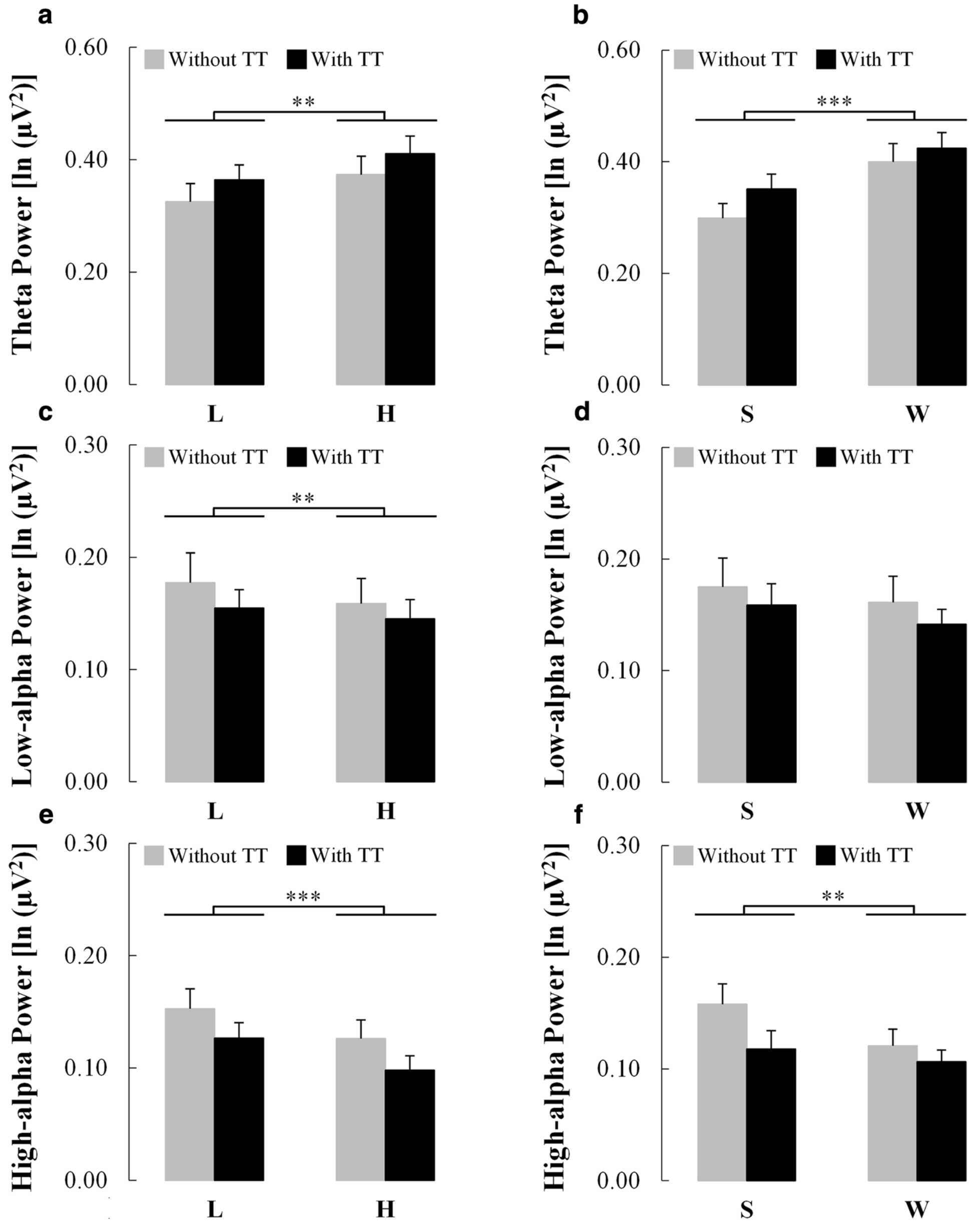
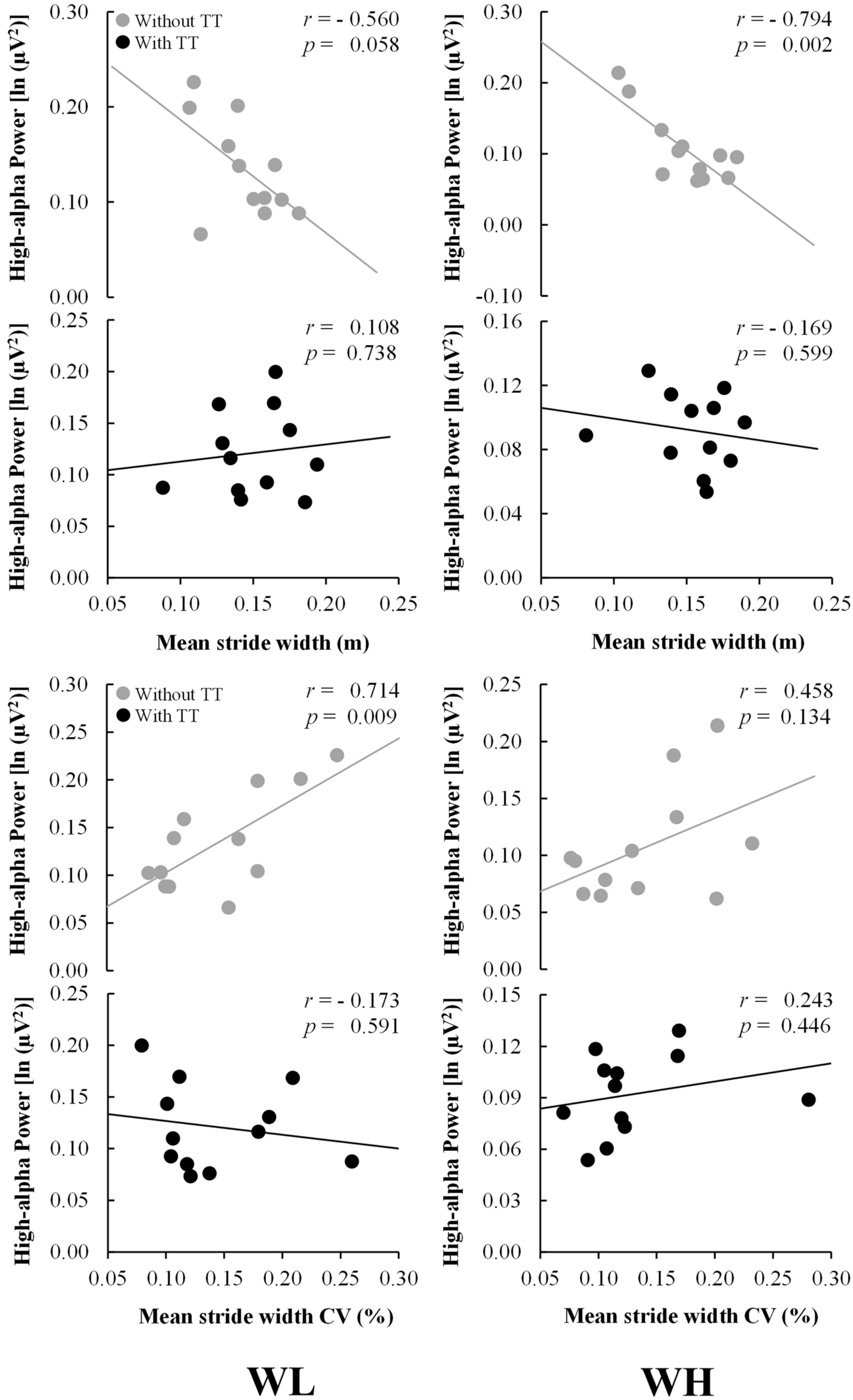


Fig. 6 Changes in frontal midline theta (first row), central low-alpha (second row) and central high-alpha (third row) power for individuals with and without unilateral transtibial limb loss (TT) completing a low- or high-demand concurrent task (left column) while seated or walking (right column). *L* low-demand task, *H* high-demand task, *S* seated, *W* walking. $*p \leq 0.05$; $**p \leq 0.01$; $***p \leq 0.001$

power in the central region and mean stride width as well as stride width coefficient of variation variables. The results revealed that for the uninjured individuals, high-alpha power was negatively correlated during the high-demand condition with the mean stride width ($r_{low} = -0.560$, $p = 0.058$; $r_{high} = -0.794$, $p = 0.002$) but was positively correlated during the low-demand condition with the stride width coefficient of variation ($r_{low} = 0.714$, $p = 0.009$; $r_{high} = 0.458$, $p = 0.134$). The same correlations were not observed for the injured participants (mean stride width: $r_{low} = 0.108$, $p = 0.738$; $r_{high} = -0.169$, $p = 0.599$) and stride width coefficient of variation ($r_{low} = -0.173$, $p = 0.591$ and $r_{high} = 0.243$, $p = 0.446$). Those findings are illustrated along with their linear fit in Fig. 7.

Frontal theta/parietal alpha

For the FT/PA ratio power, a main effect of Difficulty (F $(1, 22) = 20.023$, $p < 0.001$, $\eta^2_p = 0.476$) was observed such that both groups exhibited elevated ratio power for the high-demand compared to the low-demand concurrent task. In addition, a main effect of Condition was detected, which indicated that for both groups the ratio power was significantly larger for the walking compared to the seated



Without TT
With TT
r = - 0.560
p = 0.058
r = - 0.794
p = 0.002
r = 0.108
p = 0.738
r = - 0.169
p = 0.599
High-alpha Power [ln (μV²)]
Mean stride width (m)
Without TT
With TT
r = 0.714
p = 0.009
r = 0.458
p = 0.134
r = - 0.173
p = 0.591
r = 0.243
p = 0.446
Mean stride width CV (%)
WL
WH

◂**Fig. 7** Correlations between high-alpha power in the central cortical region and the mean stride width (top four panels) as well as the stride width CV (bottom four panels) for individuals without (filled gray circle) and with (filled black circle) unilateral transtibial limb loss (TT) during the performance of a low- (left column) and high- (right column) demand concurrent task. *WL* walking, low-demand task, *WH* walking, high-demand task, *CV* coefficient of variation

conditions (F (1, 22) = 24.666, $p < 0.001$, $\eta^2_p = 0.529$) (Fig. 8). No other significant effects were identified ($p > 0.05$; see Supplementary online material for details regarding non-significant results).

Discussion

This study concurrently evaluated temporospatial gait mechanics and cortical dynamics in a population with and without TT while completing concurrent tasks of varying difficulty, seated and walking. It was hypothesized that while a difference would not be noted in the seated conditions, use of the prosthesis would require additional cognitive resources, noted by changes in cortical dynamic variables, which would result in a decline in walking mechanics during dual-task walking. Contrary to expectations, the results revealed similar walking mechanics for both participants with and without TT under various task demands, with the exception of stride time variability, and both groups generally revealed similar cortical dynamics, save for a few subtle specific differences when facing an elevation of the level of challenge (due to the concurrent task difficulty and/or task conditions). Performance on the concurrent task and the perceived task difficulty was not different between groups, which was expected specifically in the seated condition. This overall suggests that both populations had a similar cognitive workload as indicated by a comparable engagement of their cognitive–motor resources (save for a few specific alterations), which translated into similar cognitive performance and walking mechanics, indicating that participants with TT may not need to recruit more cognitive–motor resources compared to individuals without TT during dual-task walking, at least in the experimental settings considered here.

Overall, individuals with and without TT exhibited similar changes in gait mechanics when walking and performing a concurrent task at varying levels of difficulty. Stride width mean and variability differed between tasks, across both groups, demonstrating that an increased base of support and a more stable gait pattern was chosen by all participants in response to the increased cognitive effort. Stride width has been demonstrated to be similar between young healthy individuals with TT and those without limb loss (Jarvis et al. 2017), and increases when performing a concurrent task, likely as a method to improve walking stability (Hak et al. 2013; Morgan et al. 2016). The current study partially supports these previous results, noting a similar pattern in stride width for both groups, with all participants adapting a wider base of support when completing the high-demand, relative to the low-demand, concurrent task. The potential cause of this difference in findings may be the more proximal level of limb loss investigated by Morgan et al., whom have been reported to walk with a wider base of support than those without limb loss, even amongst young, healthy adults with and without transfemoral limb loss (Jarvis et al. 2017).

Increased variability in gait parameters has historically been considered a sign of decreased stability (Hausdorff 2005), though recent literature has proposed that both high and low variability may be an indication of gait stability (Beauchet et al. 2009). Here, stride width variability decreased in both populations and stride time variability decreased in the injured population when walking and completing more complex concurrent tasks. While this result is contrary to what was hypothesized, a similar pattern of increased gait stability has been observed in healthy young adults while walking and completing a concurrent task, potentially as the body's strategy to prevent falls (Grabiner and Troy 2005). The increase in stability (reduced stride width and time variability) demonstrated in this study, despite a decline in the performance on the cognitive task (increased response time), suggests a prioritization that may be slightly more pronounced for injured relative to uninjured individuals, to maintain posture over performance of the task (Yogev-Seligmann et al. 2010). Such prioritization of gait mechanics may support previous work which suggests that challenging gait tasks and/or environments (e.g., walking on a treadmill in a virtual environment) result in individual prioritization of gait parameters and postural stability over cognitive performance (Kelly et al. 2013).

Individuals with and without TT generally exhibited comparable cortical dynamics as indicted by similar theta synchrony, high-alpha desynchrony and reductions of the ERP-P3 amplitude as a function of task condition (i.e., seated vs. walking), and elevations in theta/alpha ratio as concurrent task difficulty increased. Therefore, as condition/task demand increased, both populations exhibited comparable modulations of theta, alpha and their ratios across the scalp. Such modulations in frontal regions suggest both groups similarly recruited attentional control, working memory, and action monitoring resources critical to maintain performance under elevated demands (e.g., Beurskens et al. 2016; Coombes et al. 2005; Gevins and Smith 2003; Jaiswal et al. 2010; Mirelman et al. 2014; Slobounov et al. 2013, 2015). Similarly, both groups exhibited reduced attentional reserve when performing the walking condition, suggesting additional recruitment of attentional resources in this condition (Alderman et al. 2015; Dyke et al. 2015; Gentili et al. 2018; Miller et al. 2011; Murray and Janelle 2007; Olson et al.

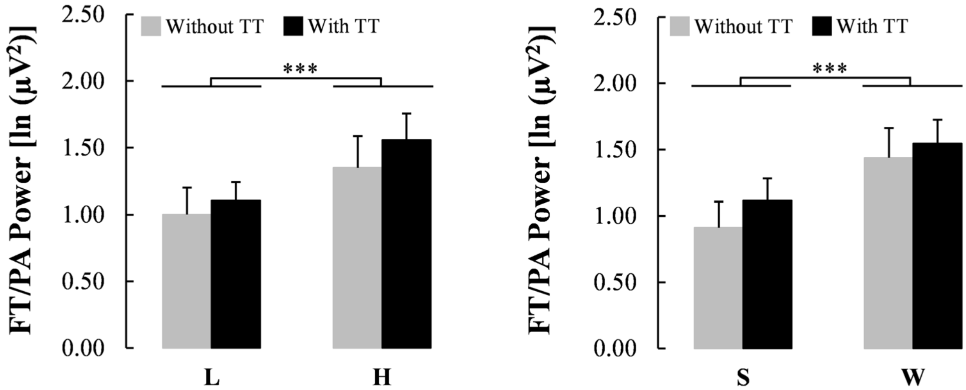


Fig. 8 Changes in frontal theta/parietal alpha ratio (FT/PA) power for individuals with and without unilateral transtibial limb loss (TT) completing a low- or high- demand concurrent task (left panel) and seated or walking (right panel). *L* low-demand task, *H* high-demand task, *S* seated, *W* walking. $^{*}p \leq 0.05$; $^{**}p \leq 0.01$; $^{***}p \leq 0.001$

2016; Shaw et al. 2018). Notably, both groups exhibited similar cognitive–motor performance, possibly because the TT individuals have achieved automaticity while walking (across a flat surface without obstacles) with their prosthesis due to extensive practice. This result aligns with previous work that revealed individuals with and without limb loss exhibit similar walking patterns across standard terrain (Morgan et al. 2016) and that practice promotes automaticity and a refinement of cortical dynamics (Gentili et al. 2011; Rietschel et al. 2014; Smith et al. 1999).

Despite these similarities, subtle group differences suggest their cortical dynamics have distinct features. The directionality of the correlation for uninjured individuals between high-alpha power and stride width (mean or coefficient of variation) for both levels of cognitive task demand suggests that an increase of cortical activity (i.e., reduction of high-alpha power in the central cortical region) translates into increased stability (wider base of support; reduced variability) possibly engaging more cortically mediated locomotion regulation, while such a pattern is less clear for TT individuals.

As a whole, both populations revealed similar recruitment of cognitive–motor resources, resulting in comparable neurocognitive and biomechanical performance under various task demands. Possibly, the fact that individuals with TT considered here may have reached a certain level of skill and automaticity when walking with their prosthesis and that these dual-task walking conditions were executed on a stable terrain may have limited the overall environmental challenge leading to similar cognitive–motor performance for both groups.

Limitations related to the virtual environment, as well as the size and characteristics of the sample likely influenced the study results. While the environment/system facilitated control of the testing conditions and measurement of the outcome variables, the forced pace induced by use of a treadmill may have impacted the biomechanical outcomes measures, specifically reducing variability in temporospatial features of gait (Riley et al. 2007). Also, while not an objective of this study, the research team was not able to accurately determine which task (motor or cognitive) the participant may have prioritized (i.e., "primary" versus "secondary"), potentially influenced by the instructions provided to the participant, the experimental set-up, and/or the implicit consequence with compromised performance in one area vs. the other (e.g., falling vs. not performing well on concurrent task). In particular, in this study it was not possible to attribute if the changes in EEG dynamics represented a modulation of the engagement of cognitive resources due to locomotor regulation or the performance of the secondary cognitive task during dual-task walking. Given that prioritization can influence dual-task outcomes (Yogev-Seligmann et al. 2010), future research efforts should aim to address these concerns by experimentally controlling/manipulating the instructions provided as well as evaluating participant perception of prioritization. In addition, while sitting and walking conditions were considered here to examine the cognitive–motor processes underlying cognitive workload during dual-task walking with TT individuals, part of the observed changes in cortical dynamics may have been related to upright standing postural control and balance mechanisms which are critical for locomotive functions (Fraizer and Mitra 2008; Howard et al. 2017; Huang et al. 2014; Little and Woollacott 2015). Future studies could further examine this issue by employing a similar approach to examine specific changes in mental workload related to dual-task standing and/or walking in non-injured and injured individuals.

Generalization of these results may also be limited to individuals with TT limb loss who are young, active, and fully acclimated to utilizing their prosthesis. It remains unknown whether the neurocognitive pattern in trained, acclimated prosthesis users would differ from individuals participating in gait training rehabilitation and/or if there are differing levels of familiarization with the device that display different patterns, warranting future research in these areas. The sample size in each group may have impacted the ability to identify group differences in the outcome measures, as the group differences in some measures greatly exceeded the difficulty differences despite lack of statistical significance. This finding is likely a result of differences between within- vs. between-subject variables, and future research may allow for confirmation of this study's findings. In addition, although the CAREN system allows for simultaneous collection of biomechanical and cognitive information in a safe, immersive setting that likely minimizes distractions and may enable future work with more complex and realistic tasks, the CAREN system integrates visual flow with treadmill walking, which may not be fully translatable to overground walking. As such, the present results may slightly differ in real-world situations where individuals walk on the ground (Gates et al. 2012; Ochoa et al. 2017; Oliveira et al. 2016; Yang and King 2016).

In summary, these results confirm and extend previous work demonstrating that dual-task walking can adversely affect walking mechanics and/or neurocognitive performance but importantly, also suggest that there may be limited cognitive and/or biomechanical impact of utilizing a prosthesis when walking and completing a concurrent task for individuals with TT who are fully trained in utilizing a prosthesis. These results need to be confirmed for individuals with more acute and/or proximal levels of lower limb loss, and in more challenging environments to better understand the interaction between cognitive resources and gait mechanics for this broader population in ecologically valid scenarios.

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Compliance with ethical standards

Conflict of interest The authors declare no competing financial interests. The views expressed in this article are those of the authors and do not reflect the official policy of the Department of Army/Navy/Air Force, Department of Defense, or U.S. Government. The identification of specific products or instrumentation is considered an integral part of the scientific endeavor and does not constitute endorsement or implied endorsement on the part of the authors, Department of Defense, or any component agency.

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