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A Comparison of Mental Workload in Individuals with Transtibial and Transfemoral Lower Limb Loss during Dual-Task Walking under Varying Demand

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Abstract

Objectives: This study aimed to evaluate the influence of lower limb loss (LL) on mental workload by assessing neurocognitive measures in individuals with unilateral transtibial (TT) *versus* those with transfemoral (TF) LL while dual-task walking under varying cognitive demand. **Methods**: Electroencephalography (EEG) was recorded as participants performed a task of varying cognitive demand while being seated or walking (i.e., varying physical demand). **Results**: The findings revealed both groups of participants (TT LL *vs*. TF LL) exhibited a similar EEG theta synchrony response as either the cognitive or the physical demand increased. Also, while individuals with TT LL maintained similar performance on the cognitive task during seated and walking conditions, those with TF LL exhibited performance decrements (slower response times) on the cognitive task during the walking in comparison to the seated conditions. Furthermore, those with TF LL neither exhibited regional differences in EEG low-alpha power while walking, nor EEG high-alpha desynchrony as a function of cognitive task difficulty while walking. This lack of alpha modulation coincided with no elevation of theta/alpha ratio power as a function of cognitive task difficulty in the TF LL group. **Conclusions**: This work suggests that both groups share some common but also different neurocognitive features during dual-task walking. Although all participants were able to recruit neural mechanisms critical for the maintenance of cognitive-motor performance under elevated cognitive or physical demands, the observed differences indicate that walking with a prosthesis, while concurrently performing a cognitive task, imposes additional cognitive demand in individuals with more proximal levels of amputation.

Keywords: Mental load, EEG dynamics, Spectral power, Amputation levels, Alpha and theta bands, Prosthesis, Concurrent secondary task, Locomotion

INTRODUCTION

The maintenance of cognitive-motor performance under elevated task demands depends on the ability to efficiently regulate attentional resource allocation (Alderman et al., 2015; Murray & Janelle, 2007). This fundamental component of adaptive behavior, however, is compromised in individuals who face additional burdens that require increased mental effort. Specifically, altered sensorimotor function attributed to lower limb loss (LL) increases dependence on cognitive-motor resources for the performance of everyday tasks, including dual-task walking (Miller et al., 2001; Morgan et al., 2017). Amplified mental workload within this population may lead to a diminished capacity to attend and respond to secondary task demands, subsequently increasing the risk for additional injury or falls (Lockhart & Liu, 2008;

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Morgenroth et al., 2010). Therefore, it is critical to examine the cognitive-motor demand imposed on individuals with lower LL while walking during attentional challenges in ecologically valid situations to better inform us of the neural mechanisms underlying complex human cognitive-motor performance, such as rehabilitative ambulation in users of assistive devices.

A few mental workload studies in individuals with lower LL suggest that walking within a complex environment requires increased mental effort and adversely impacts gait mechanics. However, these studies were mainly behavioral in their approach without directly evaluating the underlying brain dynamics (Howard et al., 2017; Morgan et al., 2015; 2017). The assessment of brain dynamics can inform us of the mental cost of cognitive-motor performance by objectively revealing the effort associated with a given task. Specifically, behavioral proficiency during cognitive-motor challenges may be accomplished with varying degrees of effort. Thus, the behavioral outcome may not always be indicative of the level of mental workload required to maintain performance under varying levels of challenge (Alderman et al., 2015; Murray & Janelle, 2007). The only study published to date to examine mental workload via electroencephalography (EEG) during dual-task walking in individuals with lower LL compared uninjured individuals to those with transtibial (TT) LL (Pruziner et al., 2019). Generally, the research conducted on the mental workload of walking with a prosthetic device has compared individuals with lower LL to uninjured individuals, but has not directly compared individuals with varying levels of amputation. The comparison of different levels of LL is critical since proximal amputations (TF), compared to more distal amputations (TT), likely result in elevated deficits in neuromuscular and sensorimotor processes, thereby increasing mental workload and compromising attentional capacity during dual-task walking. Therefore, there is a need to empirically evaluate individuals with varying amputation levels (TT *vs*. TF) to determine if there is a relationship between the proximity of amputation and the recruitment of neurocognitive resources while dual-task walking.

EEG has been successfully employed for mental workload assessment during cognitive-motor performance, including dual-task walking (Gevins & Smith, 2003; Marcar et al., 2014; Murray & Janelle, 2007; Pruziner et al., 2019; Shaw et al., 2018). While EEG theta power is positively related to mental workload, and likely reflects the recruitment of attentional-related processes (e.g., working memory and action monitoring), EEG alpha power is inversely related to cortical activation, which reflects the level of inhibition of nonessential neural processes. Together, these measures can reveal the nature of the brain processes during cognitive-motor performance (Babu Henry Samuel et al., 2018; Chuang et al., 2013; Gentili et al., 2018; Gevins & Smith, 2003; Kao et al., 2013; Rietschel et al., 2012; Wang et al., 2016). The ratio of theta to alpha power at the frontal and parietal midline sites can also serve as a robust index of cognitive-motor effort during both upper- and lower-extremity performance (Hockey et al., 2009; Holm et al., 2009). Collectively, several derivatives of the EEG reflect critical cortical processes associated with mental workload impacted by the varying demands of diverse tasks (Beurskens et al., 2016; De Sanctis et al., 2014; Malcolm et al., 2015). Namely, an increase in cognitive-motor demand under varying motor performance conditions (i.e., seated *vs*. walking) has been associated with increased theta and decreased alpha power, indicative of an elevation of mental effort recruited to maintain cognitive-motor performance (Pruziner et al., 2019; Shaw et al., 2018). Although changes in theta and alpha power have typically been employed as primary metrics to assess the modulation of mental workload, gamma spectral power was also evaluated in the present investigation as an exploratory analysis due to its association with sensory processing, selective attention, and working memory (Basar-Eroglu et al. 1996; Howard et al., 2003; Michels et al., 2010; Pascalis and Ray, 1998).

This study was conducted to examine the neural correlates of mental workload in individuals with unilateral TT LL and TF LL through the assessment of cerebral cortical dynamics during the performance of a cognitive task executed while seated and walking. Changes in workload were examined, separately, during both seated and walking conditions while simultaneously performing a cognitive (secondary) task under varying difficulty (low and high demand). Due to the increased impairment of sensorimotor function for individuals with TF LL (i.e., decreased sensory input and motor output from the affected limb), individuals with TF LL, compared to TT LL, were expected to show elevated mental effort (i.e., greater increase in theta power, theta/alpha ratio power and reduction of low- and high-alpha power) during dual-task walking. However, no such difference between the two groups was expected during the performance of the seated conditions when the use of the prosthetic device was not relevant for successful task completion. Finally, both groups were expected to exhibit elevated levels of mental workload as cognitive task difficulty increased.

METHODS

Participants

Twelve individuals with TT LL and eight individuals with TF LL participated in the study and were provided written informed consent, approved by the institutional review board at Walter Reed National Military Medical Center prior to participation (see Supplementary Material for details about participant information and screening). The current experimental analyses did not include a control group of uninjured participants for two reasons. First, prior work revealed similar responses to cognitive-motor challenge in both individuals with and without TT LL, which justifies a parsimonious approach to compare individuals with TT LL and TF LL without the inclusion of uninjured individuals as a control (Pruziner et al., 2019). Second, the inclusion of uninjured participants introduces a potential confound that could bias

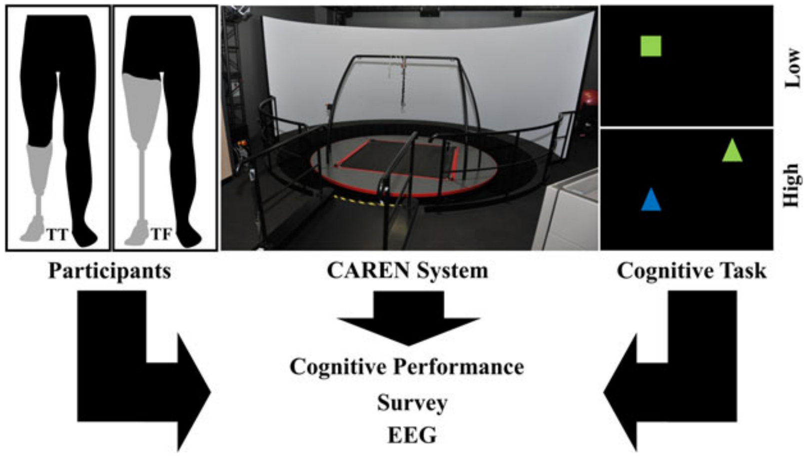

Fig. 1. Experimental platform where individuals with TT LL and TF LL had to execute a cognitive task under two levels of demand (low and high) while being seated or walking on a treadmill within the CAREN system. While participants performed the task, their behavioral performance was recorded, along with EEG in order to assess brain dynamics.

interpretation of the cortical dynamics underlying mental workload in relation to the level of amputation. A group of uninjured individuals provides for a normative contrast, but such an approach does not control for attendant injury and combat-related mental effects associated with LL (e.g., traumatic mental stress). These factors can influence brain dynamics detected by EEG (Bhatnagar et al., 2015; Bhuvaneswar et al., 2007; Lobo et al., 2015). This problem was mitigated by restriction of the consideration of brain dynamics to participants with LL without an uninjured group[1].

Experimental Procedures

Participants completed four 8 min counterbalanced experimental conditions consisting of a cognitive task of varying difficulty (low and high demand) while being seated and while walking. All walking conditions were performed on a dual-belt treadmill within a Computer Assisted Rehabilitation Environment (CAREN; Motekforce Link, Amsterdam, The Netherlands) at the same self-selected speed previously determined for each individual participant in a 4 min acclimation period prior to completing the experimental conditions (TT LL: $1.158 \pm .164\ \text{ms}^{-1}$; TF LL: $1.019 \pm .203\ \text{ms}^{-1}$). No significant difference in self-selected walking speeds between the two groups was detected ($p > .050$).

The cognitive task was composed of different shapes (squares, circles, and triangles) and colors (blue, green, and red), centrally presented (500 ms, random interstimulus interval of 100–1000 ms) in front of the treadmill on a large 180° projection screen approximately 3 m away. The cognitive task difficulty was determined by altering the combination in which the shapes and colors appeared. One and two shape(s) were displayed at a time for the low and high levels of cognitive demand, respectively. Participants had to make a response by pressing a button on a handheld wireless game controller, as quickly and accurately as possible, when a square of any color appeared on the screen for the low demand task and when the two stimuli were of the same shape or of the same color (e.g., a red square and a red circle) for the high demand task. Performance was indexed by response time (RT)[2] for correct responses only and *d*' (accounts for correct hits and false alarms indicating the capacity to detect information)[3]. After each condition, the NASA-Task Load Index (NASA-TLX)[4] was administered to assess perceived workload (Hart & Staveland, 1988) and a 2 min break to avoid fatigue was provided (Figure 1).

Electrophysiological Data Collection and Signal Processing

Continuous EEG data were wirelessly recorded[5] from 64 scalp sites (extended 10-20 system; sampling rate, 1000 Hz; electrode impedances, <10 kΩ; band-pass filters set at .01–100 Hz) and then rereferenced to an averaged ears montage offline before further processing[6]. To minimize any transient effects that were present at the beginning or end of the task (e.g., task adjustment and fatigue), EEG data collected between 3 and 6 min during each experimental condition were extracted for the analysis of EEG spectral power. Under the assumption that the EEG was relatively stable from segment to segment, the data were processed, segmented within a given experimental condition (e.g., seated performing the low demand cognitive task) and averaged across the segments (Borghini et al., 2017; Holm et al., 2009; Pruziner et al., 2019; Shaw et al., 2018). Specifically, the 3 min blocks of data were low-pass filtered at 50 Hz with a

[1]Information about the EEG dynamics for uninjured individuals as well as individuals with *versus* without TT LL performing the same experimental procedures presented here can be found in Shaw et al. (2018) and Pruziner et al. (2019).

[2]Time elapsed between the appearance of the target stimuli and the response of the individual.

[3]$d' = Z(H) - Z(F)$, where $Z(H)$ and $Z(F)$ are the Z transform of hit rate and false alarm rate, respectively.

[4]Due to large data loss, the NASA-TLX analysis and results are reported in the Supplementary Material.

[5]ActiCAP and wireless MOVE systems (Brain Products GmbH, Munich, Germany).

[6]BrainVision 2.0 Analyzer software (Brain Products GmbH, Munich, Germany).

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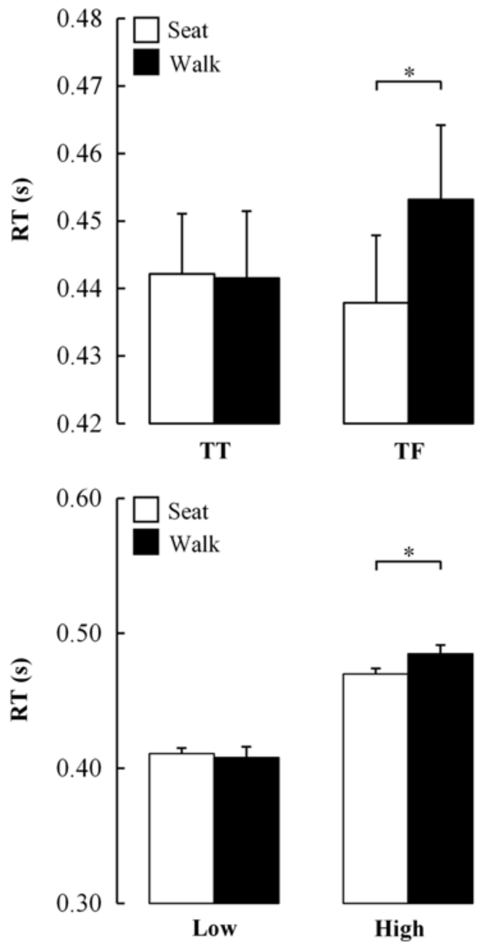

Fig. 2. Behavioral performance on the cognitive task for individuals with TT LL and TF LL (top panel) and under low and high cognitive demands (bottom panel) during the seated (white bars) and the walking (black bars) conditions. RT: Response time. $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

48-dB roll-off and notch filtered at 60 Hz using a zero-phase shift Butterworth filter. A manual visual inspection known as pruning (Onton et al., 2006) was conducted to manually remove nonstereotypical artifact, which included major motion artifact. In addition, an independent component analysis (ICA) approach was employed. Although most artifact removed using this approach were ocular related, there were some motion and muscular-related artifact removed using ICA. Following the removal of artifact, each 3 min block of data was epoched into 1 s sweeps and baseline corrected using the mean potential (0–1000 ms). Subsequently, a final visual inspection of the epochs was conducted to remove any remaining artifact (trial rejection rate post-ICA: 12.70%). Spectral power was computed across 1-Hz bins and summed across the frequency bandwidths to estimate theta (4–7 Hz), low-alpha (8–10 Hz), high-alpha (11–13 Hz), and gamma (36–44 Hz) power (Pizzagalli, 2007). To account for possible differences in brain dynamics between both groups, spectral power for each frequency bandwidth was normalized by the spectral power of the entire spectrum considered. The frontal theta/parietal alpha (FT/PA) and frontal theta/frontal alpha (FT/FA) ratio power were also computed to provide robust indices of mental workload (Gevins & Smith, 2003; Holm et al., 2009).

Statistics

Task Performance

RT and d' were subjected to a $2 \times 2 \times 2$ [Group (TT *vs.* TF) × Condition (Seated *vs.* Walking) × Difficulty (Low *vs.* High)] mixed-factorial analysis of variance (ANOVA) with Condition and Difficulty as within-subjects factors and Group as a between-subjects factor[7]. Conventional degrees of freedom are provided throughout. When the sphericity assumption was violated, the Greenhouse–Geisser correction was employed. Partial eta squared ($\eta_p{}^2$) and Cohen's *d* effect sizes were provided when appropriate. *Post hoc* analyses were conducted using the Tukey's honestly significant difference (HSD) test and all criterion alpha levels were set to .050. The same corrective approach, *post hoc* procedure, and significance level were employed for the EEG metrics.

EEG Spectral Power

Theta, low-alpha, high-alpha, and gamma power were subjected to a $2 \times 2 \times 2 \times 2 \times 5$ [Group (TT *vs.* TF) × Condition (Seated *vs.* Walking) × Difficulty (Low *vs.* High) × Hemisphere (Left *vs.* Right) × Region (Frontal, Central, Parietal, Temporal, and Occipital)] mixed-factorial ANOVA with Condition, Difficulty, Hemisphere, and Region as within-subjects factors and Group as a between-subjects factor[7]. FT/PA and FT/FA ratio power were subjected to a $2 \times 2 \times 2$ [Group (TT *vs.* TF) × Condition (Seated *vs.* Walking) × Difficulty (Low *vs.* High)] mixed-factorial ANOVA with Condition and Difficulty as within-subjects factors and Group as a between-subjects factor.

RESULTS

Task Performance

Accuracy for the cognitive task was similar between both groups ($p > .107$). A significant Condition × Difficulty interaction (F (1, 17) = 8.467, $p = .010$, $\eta_p{}^2 = .332$) was revealed for RT. *Post hoc* analyses revealed that both groups took longer to correctly respond to target stimuli during only the high demand cognitive task when walking relative to being seated ($p = .013$, $d = .482$). The analysis of RT also revealed a Group × Condition interaction (F (1, 17) = 5.253, $p = .035$, $\eta_p{}^2 = .236$), as individuals with TF LL responded slower to target stimuli while walking relative to being seated ($p = .045$, $d = .342$; Figure 2).

[7]The Kolmogorov–Smirnov test and *Q*–*Q* plots revealed that the data did not significantly depart from normality and as such no data transformation prior to conducting the statistical analyses was considered.

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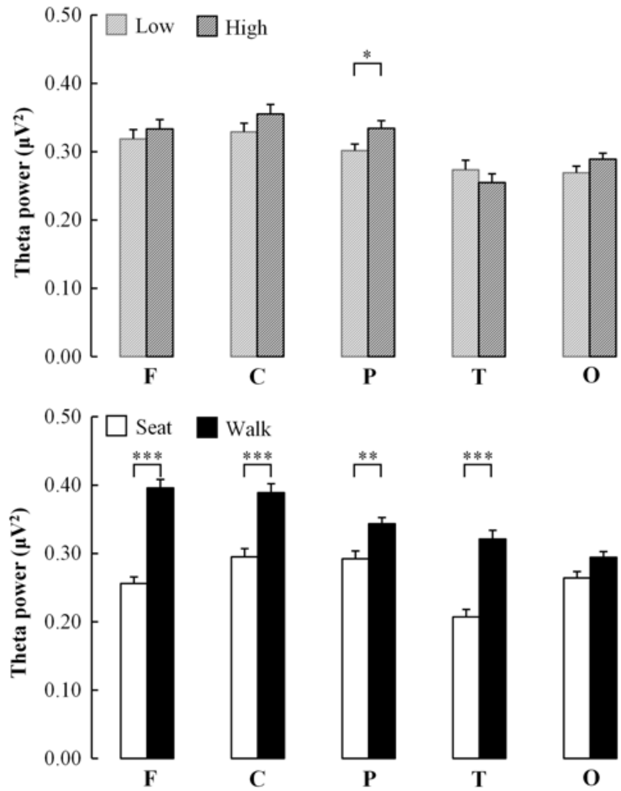

Fig. 3. Spectral power for the theta (4–7 Hz) frequency bandwidth recorded in the frontal, central, parietal, temporal, and occipital regions while individuals with TT LL and TF LL performed the low or high cognitive task demand (top panel) while being seated and walking (bottom panel). Theta power for the low and high cognitive task demands are depicted as stripped gray and black bars, respectively. Theta power for the seated and walking conditions are illustrated with white and black bars, respectively. $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

Theta Power

A significant Condition × Region interaction was detected (F (2.643, 47.576) = 12.923, $p < .001$, $\eta_p^2 = .418$, $\varepsilon = .660$). *Post hoc* analyses revealed theta power was significantly greater for both groups during the walking relative to the seated conditions in the frontal ($p < .001$, $d = 1.413$), central ($p < .001$, $d = .839$), parietal ($p = .002$, $d = .564$), and temporal ($p < .001$, $d = 1.083$) cortical regions. A significant Difficulty × Region interaction was also observed (F (2.028, 36.496) = 4.482, $p = .018$, $\eta_p^2 = .199$, $\varepsilon = .506$). *Post hoc* analyses revealed a significant increase of parietal theta power for both groups during the high relative to the low demand cognitive task ($p = .011$, $d = .352$; Figure 3).

Low-Alpha Power

A significant Group × Condition × Hemisphere × Region interaction (F (4, 72) = 3.514, $p = .011$, $\eta_p^2 = .163$) was revealed. To further investigate this four-way interaction, separate Condition × Hemisphere × Region ANOVAs were conducted for each group. For individuals with TT LL, a significant Condition × Hemisphere × Region interaction was observed (F (4, 44) = 3.504, $p = .014$, $\eta_p^2 = .242$). To examine this three-way interaction, separate Condition × Region ANOVAs were conducted for each hemisphere. This analysis revealed a significant Condition × Region interaction for both the right (F (2.550, 28.048) = 7.534, $p < .001$, $\eta_p^2 = .406$, $\varepsilon = .637$) and left (F (4, 44) = 3.740, $p = .011$, $\eta_p^2 = .254$) hemispheres. *Post hoc* analyses revealed a reduction in low-alpha power during the walking relative to the seated conditions for the right ($p < .001$, $d = .540$), left ($p = .009$, $d = .383$) parietal regions and the right ($p < .001$, $d = .701$), left ($p < .001$, $d = .569$) occipital regions (Figure 4A,B). For individuals with TF LL, a significant Condition × Region interaction was detected (F (1.947, 13.631) = 8.290, $p = .005$, $\eta_p^2 = .542$, $\varepsilon = .487$). *Post hoc* analyses revealed low-alpha power was lower during the walking conditions in the parietal ($p = .042$, $d = .616$) and occipital ($p = .024$, $d = .827$) regions (Figure 4C).

Although the pattern of low-alpha power between the seated and walking conditions was similar for both groups, there was a notable difference in the pattern between cortical regions. For individuals with TT LL, low-alpha activity exhibited regional differences during both seated and walking conditions in the right (Figure 4A) and left (Figure 4B) hemispheres. For individuals with TF LL, regional differences were observed for the seated conditions, but contrary to those with TT LL, low-alpha activity did not exhibit regional differences during the walking conditions (compare left and right panels, Figure 4C). Overall, while both groups exhibited regional differences in low-alpha activity during the seated conditions, such differences were only observed in the walking conditions for individuals with TT LL which appeared to be the primary basis of the significant Group × Condition × Hemisphere × Region interaction (see Table 1).

High-Alpha Power

A significant Group × Difficulty × Hemisphere interaction (F (1, 18) = 4.573, $p = .046$, $\eta_p^2 = .203$) was detected. To investigate this three-way interaction, separate Difficulty × Hemisphere ANOVAs were conducted for each group. While the locus of this interaction could not be identified, a main effect of Difficulty for individuals with TT LL (F (1, 11) = 11.877, $p = .005$, $\eta_p^2 = .519$) and TF LL (F (1, 11) = 11.756, $p = .011$, $\eta_p^2 = .627$) was revealed. Specifically, there was a significant reduction of high-alpha power for the high relative to the low cognitive demand across both hemispheres (Figure 5A, TT LL group). Furthermore, a significant Group × Condition × Difficulty × Region interaction (F (2.202, 39.629) = 5.047, $p = .009$, $\eta_p^2 = .219$, $\varepsilon = .550$) was observed. Separate Condition × Difficulty × Region ANOVAs were conducted for each group to investigate the four-way interaction. For individuals with TT LL, a significant Condition × Region

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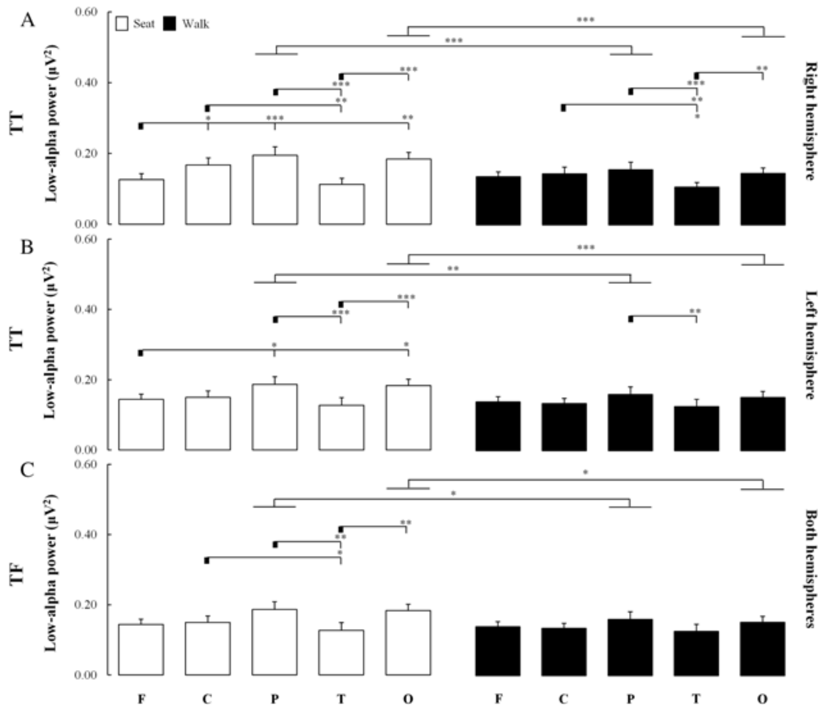

Fig. 4. Spectral power for the low-alpha (8–10 Hz) frequency bandwidth recorded in the frontal, central, parietal, temporal, and occipital regions while individuals with TT LL (two first rows) and TF LL (third row) performed the cognitive task under various demands while being seated (white bars) and walking (black bars). Low-alpha power obtained for individuals with TT LL in the right and left hemispheres is depicted in the first and second row, respectively. The last row represents the changes in low-alpha power in both hemispheres for individuals with TF LL. The thick portion of the fork illustrates the reference value which is compared to other values (thin tick) (e.g., in the first row for the seated conditions, comparison between the frontal and central, parietal, and occipital regions). *$p < .05$; **$p < .01$; ***$p < .001$.

interaction was observed (F (2.448, 26.925) = 5.205, $p = .009$, $\eta_p^2 = .321$, $\varepsilon = .612$). *Post hoc* analyses revealed lower parietal ($p = .009$, $d = .378$) and occipital ($p < .001$, $d = .604$) high-alpha power for the walking compared to the seated conditions. Additionally, for this group, the same main effect of Difficulty observed above was revealed (F (1, 11) = 11.877, $p = .005$, $\eta_p^2 = .519$) (Figure 5A). For individuals with TF LL, a significant Condition × Difficulty × Region interaction was observed (F (1.717, 12.017) = 4.664, $p = .036$, $\eta_p^2 = .400$, $\varepsilon = .429$). To examine this three-way interaction for individuals with TF LL, Difficulty × Region ANOVAs were conducted, separately, for the seated and the walking conditions. This analysis revealed a significant Difficulty × Region interaction for the seated conditions (F (1.408, 9.856) = 6.669, $p = .021$, $\eta_p^2 = .488$, $\varepsilon = .352$). The post hoc analyses for the seated conditions revealed a reduction of parietal ($p < .001$, $d = .662$) and occipital ($p < .001$, $d = .761$) high-alpha power for the high relative to the low cognitive task demand. No other effect involving the factor Difficulty was detected for the walking conditions ($p > .578$) in this group, suggesting that the main difficulty effect identified for the TF LL group in both hemispheres was exclusive to the parietal and occipital regions and only present during the seated conditions (Figure 5B).

Gamma Power

A significant Group × Condition × Hemisphere × Region interaction (F (3.312, 59.618) = 3.610, $p = .015$, $\eta_p^2 = .167$, $\epsilon = .828$) was observed. To investigate this four-way interaction, separate Condition × Hemisphere × Region ANOVAs were conducted for each group. For individuals with TT LL, a significant Condition × Region interaction was observed (F (1.939, 21.331) = 8.567, $p < .001$, $\eta_p^2 = .438$, $\varepsilon = .485$). The *post hoc* analyses revealed a significant reduction of gamma power for the frontal ($p = .012$, $d = .525$) and a tendency for the temporal ($p = .065$, $d = .547$) regions during the walking compared to the seated conditions (Figure 6A). For individuals with TF LL, a significant Condition × Region interaction was also observed (F (4, 28) = 8.712, $p < .001$, $\eta_p^2 = .554$). *Post hoc* analyses revealed a significant reduction of gamma power for the temporal ($p < .001$, $d = 1.13$) region during the walking compared to the seated conditions (Figure 6B). Additionally, a significant Condition × Difficulty × Hemisphere × Region interaction (F (2.681, 48.251) = 3.344, $p = .031$, $\eta_p^2 = .157$, $\epsilon = .670$) was observed. To investigate this four-way interaction, separate Difficulty × Hemisphere × Region ANOVAs were conducted separately for the seated and walking

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Table 1. Summary of the *post hoc* statistics for low-alpha interregional modulation

Group	Hemisphere	Condition	Region Contrasts	*p* Value (Cohen's *d*)
TT	R	S	F < C	.044 (.618)
TT	R	S	F < P	< .001 (.938)
TT	R	S	F < O	.002 (.897)
TT	R	S	C > T	.003 (.802)
TT	R	S	P > T	< .001 (1.098)
TT	R	S	T < O	< .001 (1.08)
TT	R	W	F > T	.031 (.698)
TT	R	W	C > T	.003 (.785)
TT	R	W	P > T	< .001 (.936)
TT	R	W	T < O	.002 (.899)
TT	L	S	F < P	.024 (.609)
TT	L	S	F < O	.042 (.635)
TT	L	S	P > T	< .001 (1.058)
TT	L	S	T < O	< .001 (.779)
TT	L	W	P > T	.007 (.565)
TF	R + L	S	C > T	.013 (.902)
TF	R + L	S	P > T	.001 (1.111)
TF	R + L	S	T < O	.009 (.982)

Note. The *p* values and Cohen's *d* effect sizes associated with the interregional modulation depicted in Figure 4 for the low-alpha (8–10 Hz) frequency bandwidth were collected in the frontal (F), central (C), parietal (P), temporal (T), and occipital (O) cortical regions in the right (R) and left (L) hemispheres for individuals with transtibial (TT) LL and across both hemispheres (R + L) for individuals with transfemoral (TF) LL who performed the cognitive task under various demands while being seated (S) and walking (W).

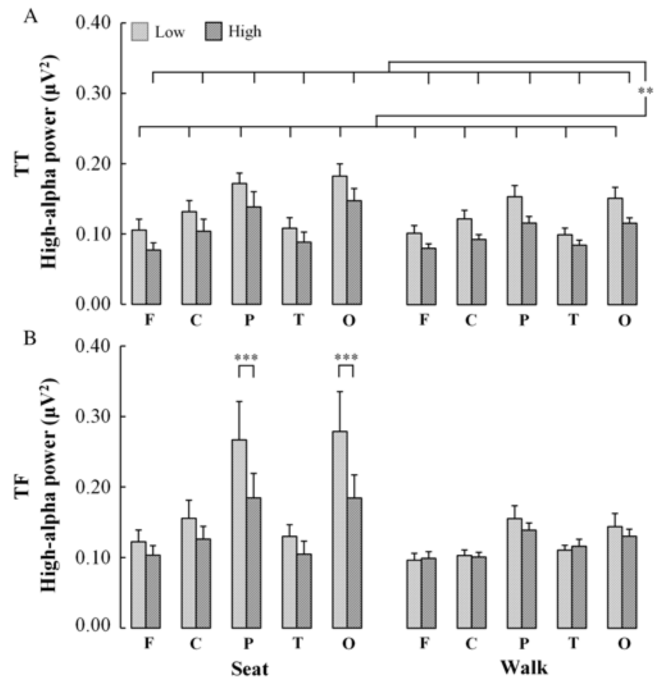

Fig. 5. Spectral power for the high-alpha (11–13 Hz) frequency bandwidth recorded in the frontal, central, parietal, temporal, and occipital regions while individuals with TT LL (first row) and TF LL (second row) performed the cognitive task under low (stripped gray bars) and high (stripped black bars) demands while being seated (left column) and walking (right column). *$p < .05$; **$p < .01$; ***$p < .001$.

conditions. For the seated conditions, there was a main effect of Difficulty (F (1, 19) = 5.997, p = .024, η_p^2 = .240), with greater gamma power for the cognitive task of high relative to the low demand. No significant differences were revealed for the walking conditions (p > .050) (Figure 6C).

Theta/Alpha Ratio Power

A main effect of Condition (F (1, 18) = 39.646, p < .001, η_p^2 = .688) revealed that for both groups the FT/PA ratio power increased during the walking relative to the seated conditions. There was a significant Group × Difficulty interaction (F (1, 18) = 5.906, p = .026, η_p^2 = .247). *Post hoc* analyses revealed elevated FT/PA ratio power for the high relative to the low cognitive demand for individuals with TT LL (p = .001, d = .784) only (left column, Figure 7).

A main effect of Condition (F (1, 18) = 18.387, p < .001, η_p^2 = .505) suggested that both groups increased their FT/FA ratio power for the walking relative to the seated conditions. A significant Group × Difficulty interaction was apparent (F (1, 18) = 5.815, p = .027, η_p^2 = .244). Namely, the FT/FA ratio power increased for the high relative to the low cognitive demand for individuals with TT LL (p = .018, d = .671) only (right column, Figure 7).

DISCUSSION

This study evaluated mental workload through the assessment of neurocognitive measures in individuals with unilateral TT LL and TF LL while dual-task walking under varying cognitive demand. The findings revealed that individuals with TT LL and TF LL share some similar behavioral (i.e., cognitive task performance) and neurocognitive responses under elevated cognitive-motor demands. Additionally, several between-group differences were apparent, suggesting there is an additional impact on neurocognitive processes to utilize a prosthesis in individuals with TF LL compared to TT LL while dual-task walking.

Recruitment of Neurocognitive Mechanisms Irrespective of Lower Limb Loss Level

Both groups exhibited theta synchrony as cognitive-motor demands increased due to an elevation in cognitive task difficulty or the condition performed. Specifically, frontal theta synchrony observed during the walking compared to the seated conditions suggests that both groups were able to similarly recruit neural mechanisms, such as attentional control, working memory, and action monitoring, which are all critical for the maintenance of cognitive-motor performance under elevated demands (Chuang et al., 2013; Jaiswal

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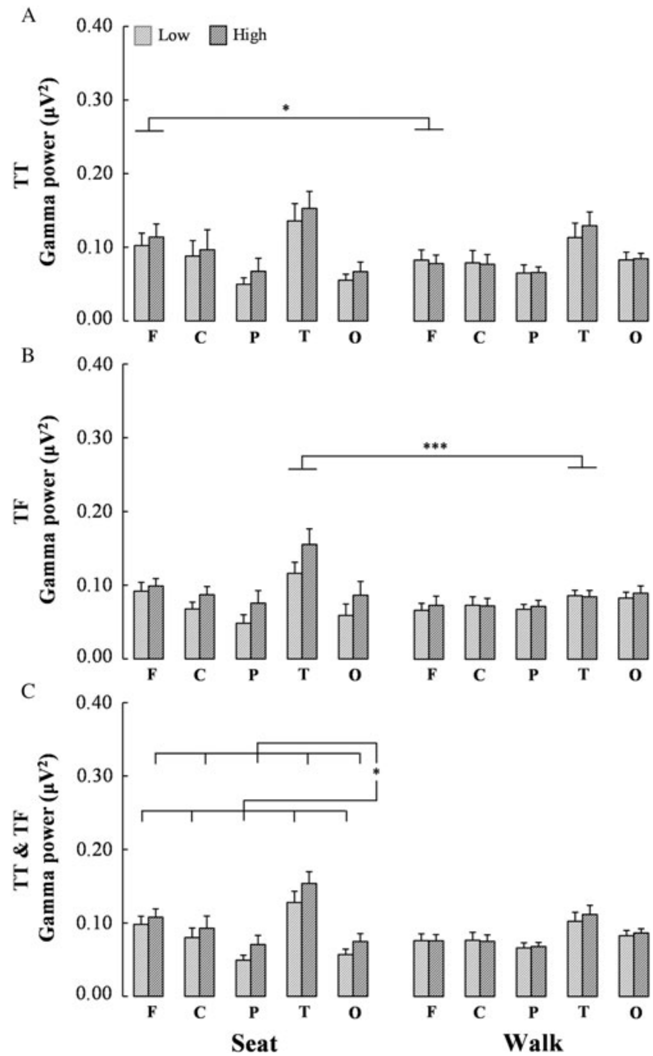

Fig. 6. Spectral power for the gamma (36–44 Hz) frequency bandwidth recorded in the frontal, central, parietal, temporal, and occipital regions while individuals with TT LL (first row) and TF LL (second row) as well as both groups of individuals (third row) performed the cognitive task under low (stripped gray bars) and high (stripped black bars) demands while being seated (left column) and walking (right column). *$p < .05$; **$p < .01$; ***$p < .001$.

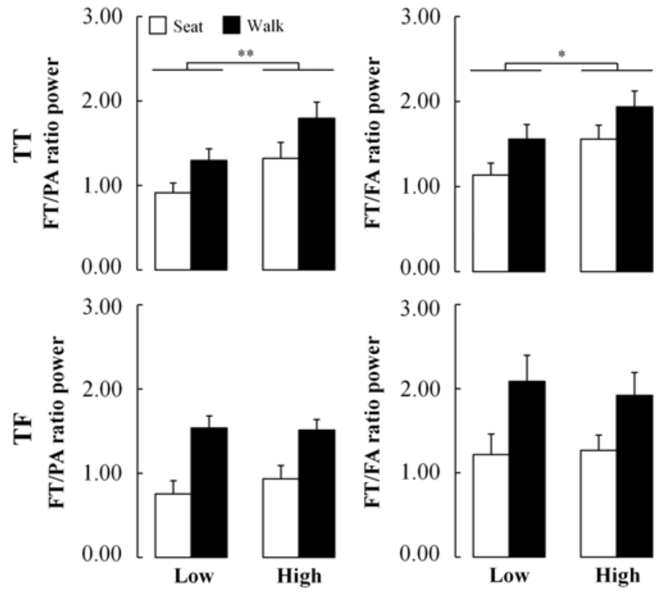

Fig. 7. Spectral power ratios for the frontal and parietal regions obtained in individuals with TT LL (top row) and TF LL (bottom row) while they performed under low and high cognitive task demands in the seated (white bars) and walking (black bars) conditions. The left and right columns represent the frontal theta/parietal alpha ratio spectral power and the frontal theta/frontal alpha ratio spectral power, respectively. *$p < .05$; **$p < .01$; ***$p < .001$.

et al., 2010; Kao et al., 2013; Slobounov et al., 2013, 2015). It must be noted that the observed theta power for individuals with lower LL during dual-task walking may be somewhat altered, compared to those without LL. Previous work revealed theta synchrony across the entire scalp within an uninjured population, whereas the results of the present study revealed specificity of cortical regions for individuals with LL (Shaw et al., 2018). Additionally, as cognitive-motor task demands increased (due to cognitive task difficulty and/or task condition), similar patterns of low-alpha (parietal, occipital regions) and high-alpha (parietal, occipital regions while seated) desynchrony were observed. This pattern possibly reflects changes in both general (low-alpha desynchrony) and task-specific arousal (high-alpha desynchrony). Particularly, the high-alpha desynchrony observed in both groups suggests there was an increased recruitment of high-level multisensory integration and visual mechanisms while performing the cognitive task during walking compared to being seated (Babu Henry Samuel et al., 2018; Brooks & Kerick, 2015; Cheng et al., 2015; Gentili et al., 2011; Jaiswal et al., 2010; Kerick et al., 2007; Slobounov et al., 2013; Wang et al., 2016). Lastly, both groups exhibited increased gamma synchrony under elevated demands on the secondary cognitive task during the seated conditions. Such a finding is consistent with prior work that has linked gamma synchronization with increased attentional and working memory demands during the performance of a purely cognitive task (Basar-Eroglu et al., 1996; Howard et al., 2003; Michels et al., 2010; Pascalis and Ray, 1998). It is possible that no such change was detected during the walking conditions since a reduction of gamma power may reflect cortical recruitment for more challenging locomotion (i.e., here from seated to walking) (Bradford et al., 2016; Sipp et al., 2013; Wagner et al., 2014).

Therefore, the recruitment of relevant neural mechanisms (attentional control, working memory, action monitoring, high-level multisensory integration) represents the engagement of specific neurocognitive processes in individuals with lower LL, irrespective of the level of amputation, to maintain performance under elevated demands due to variations in the difficulty of the concurrent cognitive task or condition performed (i.e., seated *vs.* walking).

Neurocognitive Dynamics as a Function of Amputation Level

Although there were similarities in the neurocognitive dynamics, discrepancies between the groups were also apparent. While individuals with TT LL maintained similar performance on the cognitive task in both seated and walking conditions, those with TF LL exhibited deteriorated performance during walking compared to being seated. The cortical dynamics mirrored the differences between the groups. Specifically, individuals with TT LL maintained cognitive task performance in both the seated and walking conditions, consistent with a comparable modulation of their low- and high-alpha cortical dynamics in both conditions. Individuals with TT LL revealed regional differences in low-alpha power in the seated and walking conditions for both cerebral hemispheres (refer to the left and right columns of the two first rows, Figure 4). Although individuals with TF LL revealed regional differences in low-alpha power in the seated conditions, regional differences in low-alpha power were not apparent during the walking conditions (refer to the left and right columns of the last row, Figure 4). The findings suggest that individuals with more proximal levels of amputation do not exhibit interregional cortical activation differences, possibly due to general arousal, while walking and performing a cognitive task (Cheng et al., 2015; Jaiswal et al., 2010; Klimesch, 1999; Slobounov et al., 2013).

Furthermore, individuals with TT LL exhibited a reduction of high-alpha power, suggesting increased recruitment of cognitive resources, as the cognitive task difficulty increased during both seated and walking conditions (refer to the left and right columns in the top row, Figure 5). When individuals with TF LL faced the same increased difficulty on the cognitive task, however, high-alpha desynchrony was observed only for the seated conditions (refer to the left and right columns in the bottom row, Figure 5). Thus, individuals with TF LL did not recruit cognitive resources in the same manner as those with TT LL during the walking conditions to maintain performance when the cognitive task difficulty increased (Babu Henry Samuel et al., 2018; Cheng et al., 2015; Chuang et al., 2013; Kao et al., 2013; Murray & Jannelle, 2007; Slobounov et al., 2013; Wang et al., 2016). Such lack of engagement of cognitive resources during walking in the TF LL group may be the cause of degraded (increased RT) performance during the cognitive task. This pattern of cortical activation in response to variations in cognitive-motor demands may reflect changes in task-specific arousal. These findings are consistent with the observation that only the TT LL group exhibited increased FT/PA and FT/FA ratio power under elevated cognitive task demands.

When considering the findings for the theta and alpha bandwidths, a lack of modulation for FT/PA and FT/FA ratio power in individuals with TF LL may be driven by the absence of adaptive cortical dynamics within the alpha band. Overall, compared to individuals with TT LL, those with a higher locus of amputation exhibited a lack of: (i) regional differences in activation related to general arousal while walking and (ii) recruitment of additional task-specific cortical mechanisms possibly needed to successfully perform the high cognitive task demand while walking. In addition to low- and high-alpha power, as well as the FT/PA and FT/FA ratio power, differences in gamma power between the two groups were observed. In particular, individuals with TT LL exhibited gamma desynchrony in the frontal region, along with a tendency for temporal desynchrony during the walking compared to the seated conditions. This finding likely reflects the engagement of local motor processing and is consistent with prior work, which revealed frontal and temporal gamma desynchrony in uninjured individuals during dual-task walking (Shaw et al., 2018). More generally, this finding is also in agreement with previous studies, which suggested that a reduction of gamma power in various cortical regions is indicative of enhanced cortical engagement when facing more challenging walking (i.e., here from seated to walking; Bradford et al., 2016; Sipp et al., 2013; Wagner et al., 2014). For individuals with TF LL, gamma desynchrony was also observed during the walking compared to the seated conditions, but was localized to the temporal cortical region only. Overall, the differences in the observed pattern of regional gamma modulation suggest those with more distal *versus* proximal levels of LL may to some extent function similarly to uninjured individuals. These differences in cortical dynamics between the two groups across the FT/PA and FT/FA ratio power, low-alpha, high-alpha, and gamma bandwidths may be due to a larger neuromechanical loss in individuals with TF LL and a need to further recruit neurocognitive resources to ensure safe walking. This in turn may have translated in a reduction of engagement and ultimately a degradation of cognitive performance during walking.

CONCLUSIONS AND FUTURE WORK

In order to control for potential confounding factors (i.e., learning effects), the individuals recruited for this study were young, active, and proficient at walking with their prosthetic device. Although the dual-task employed here was ecologically valid, this task is likely more complex in real-world settings without the CAREN providing a safe environment with few-to-no consequences of making an error (e.g., falling). Additionally, self-selected walking speeds were predetermined prior to completing the experimental conditions and were maintained during the entirety of the experiment. Although walking speeds between the two groups did not significantly differ and thus limited walking speed as a confounding factor, future work could evaluate how participants adjust their motor performance (e.g., walking speed) under varying cognitive-motor demands. Future studies could examine brain and behavioral dynamics in more diverse lower LL populations (elderly, less experienced prosthesis users) in real-world settings under varying cognitive-motor demands. The sample size considered here was a limitation of the current work. However, the study lasted approximately 3 hr (mainly due to EEG setup) and required individuals to walk continuously without breaks or the use of assistive devices (e.g., handrails) for extended periods of time (10 min intervals). In addition to these constraints, a stringent criteria selection along with the limited availability of such a special population (particularly individuals with TF LL) made its recruitment very challenging.

As with any dual-task walking study, it is difficult to disambiguate cognitive and motor mechanisms which likely engage cognitive-motor resources somewhat differently. Although this is a limitation of using a dual-task paradigm, the current investigation was not intended to disentangle cognitive and motor mechanisms, but instead aimed to assess mental workload under varying cognitive-motor demands. In addition, the data processing employed here aimed to minimize any transient EEG effects and has been commonly employed in many EEG studies (i.e., data segmented, processed/averaged for each experimental condition; e.g., Borghini et al., 2017; Holm et al., 2009; Shaw et al., 2018), but alternative approaches such as event-related based methods should also be considered in the future since it can provide additional information related to specific events.

Furthermore, participants may have disengaged from the task demands and began to "mind-wander" during the completion of the experimental tasks, subsequently biasing the results and interpretation of the cortical dynamics (Baldwin et al., 2017; Braboszcz & Delorme, 2011). While a possibility, there are several arguments to suggest that the observed brain dynamics were reflective of underlying cognitive-motor processes. First, although high-alpha modulation as a function of cognitive task difficulty for both groups was detected (i.e., greater cortical activation for the cognitive task of high compared to low demand), performance on the cognitive task (as indicated by d') across all experimental conditions did not significantly differ ($p > .107$) and thus did not mirror the brain dynamics. This finding suggests participants: (i) were engaged across all conditions, and (ii) could perform the cognitive task equally well under varying cognitive-motor demands, but required the recruitment of additional neural resources in order to do so as the demand increased. Second, the results for the theta band did not present complex interactions, no effect of group was observed, and they were consistent with those from previous relevant mental workload investigations. Namely, the increase in theta power for both groups (when the cognitive and motor difficulty increased) is consistent with prior research and suggests there was an increased recruitment of attentional control and working memory. Third, it is possible participants may have been fatigued towards the end of data collection. All experimental conditions, however, were counterbalanced across participants to avoid potential order effects.

Additionally, there is some debate regarding the influence of motion artifact in EEG collected during walking and raises the question to what extent they alter the cortical dynamics underlying mental workload assessment (Castermans et al., 2014; Gwin et al., 2010; Nathan & Contreras-Vidal, 2016; Wagner et al., 2012). While it is difficult to completely eliminate motion artifact, there are several arguments suggesting that the cortical dynamics observed here were not determined by motion-related artifact, but reflected the underlying cognitive-motor mechanisms. First, contrary to prior EEG work, which focused on the cortical control of specific locomotor elements (e.g., heel strike), the current effort investigated the underlying cognitive-motor processes of mental workload during dual-task walking. Since the gait cycle was not synchronized to the cognitive task, the probability of motion-related artifact biasing data processing and subsequent interpretation was relatively limited (Kline et al., 2015). Second, this investigation employed a system with pre-amplified EEG signals and secured shielded cables limiting the influence of motion-related artifact (Kline et al., 2015; Nathan & Contreras-Vidal, 2016; Reis et al., 2014). Third, this study employed similar signal processing methods and obtained similar findings as those from previous work which successfully assessed mental workload via EEG spectral analyses during dual-task walking (Beurskens et al., 2016; De Sanctis et al., 2014; Marcar et al., 2014; Pruziner et al., 2019; Shaw et al., 2018) as well as upper-extremity tasks executed while seated (Dyke et al., 2015; Gentili et al., 2018; Jaquess et al., 2018; Rietschel et al., 2012).

Overall, this work suggests that both groups share common, but also different neurocognitive features under increased task demands. The findings suggest that both groups similarly engage specific cortical resources (attentional control, working memory, action monitoring, high-level multisensory integration) in response to elevated demands due to changes in the cognitive task difficulty or performance condition, independent of the level of amputation. Nevertheless, contrary to individuals with TT LL, those with TF LL lacked an adaptive cortical response related to general arousal and task-specific processes when challenged with increased cognitive task demands during walking. The lack of cortical engagement under increased demands during walking coincided with a decrease in cognitive task performance (slower RT to target stimuli). Although both groups further engaged cognitive-motor resources during dual-task walking, likely to ensure stability, it is possible that individuals with higher levels of amputation recruited additional cognitive-motor resources to ensure safe walking patterns while performing the secondary cognitive task due to a larger neuromechanical loss. Consequently, individuals with TF LL have fewer neurocognitive resources left to face the cognitive task demand and exhibit limited adaptive cortical dynamics, resulting in reduced engagement and a degradation of cognitive performance during walking[8]. When considering this effort along with prior EEG studies that examined mental workload during dual-task walking, it appears the cortical dynamics become increasingly altered from uninjured to

[8]This lack of cortical resource recruitment to overcome increased cognitive demands is consistent with the TF LL participant's NASA-TLX scores. Specifically, as the cognitive task demand increased in the seated position, there was a general pattern of elevated NASA-TLX scores observed for both the TF LL (albeit non-significant) and TT LL groups, whereas this pattern was only maintained for the TT LL group during walking. However, it is important to note that this difference may be due to the limited number of NASA-TLX scores recorded for the TF LL group (see Supplementary Material section for details about the results of the NASA-TLX).

individuals with LL, with a more pronounced alteration from distal (TT) to proximal (TF) LL (Pruziner et al., 2019; Shaw et al., 2018). This work can inform the development and assessment of rehabilitative interventions for individuals with lower extremity assistive devices such as prostheses and more generally populations whose control of posture or locomotion is compromised.

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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, scientific instrumentation, or organizations is considered an integral part of the scientific endeavor and does not constitute endorsement or implied endorsement on the part of the author, DoD, or any component agency.

SUPPLEMENTARY MATERIALS

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