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Restoring plantar sensation reduces cognitive cost of dual-task walking after lower limb loss

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Article

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Abstract

Walking in individuals with lower limb loss demands sustained elevated cognitive effort, partly due to the lack of direct sensory feedback from the foot. This feedback plays a critical role in the automatic control of gait. We tested whether restoring somatosensory feedback from the missing foot reduces the cognitive demand of walking. Three participants with unilateral limb loss used a sensory neuroprosthesis (SNP) that provided real-time plantar sensation through electrical stimulation of the remaining peripheral nerves utilizing implanted nerve cuffs. They and two able-bodied controls walked on a self-paced treadmill while performing the Color–Word Matching Stroop (CWMS) test at three difficulty levels. The task was run with and without a response time limit to vary cognitive demand. Reaction time and accuracy were stable and unaffected by the SNP, whereas gait speed showed dual-task interference. Notably, with SNP active, gait speed shifted toward faster walking under the time-limited task, and step length increased, particularly on the prosthetic side. Participants differed in whether they sped up or slowed with task difficulty, consistent with each having a limited range of speeds at which gait is most automatic. The uniform upward shift with the SNP suggests that restored plantar sensation raises that range and shifts the walking from executive to automatic gait control at faster speeds. This reallocation of cognitive resources could facilitate faster, more automatic walking under cognitive load, resulting in safer mobility in daily life.

INTRODUCTION

Walking is often considered automatic for most people, requiring little conscious thought. After lower limb loss, however, even routine ambulation can demand sustained attention and mental effort. Individuals with lower limb loss rely on prosthetic devices for ambulation, and by extension, for many activities of daily living. Although advancements in prosthesis design[1–4] have greatly improved gait, even the most state-of-the-art commercial devices still lack direct sensory feedback of foot-floor interactions.

Sensory feedback from the lower limb plays a critical role in human movement, affecting postural stability[5,6], response to perturbations [7], and gait biomechanics[8–10]. In intact limbs, mechanoreceptors in the skin, together with sensory elements in muscles and joints inform the nervous system about the limb's position and movement during walking[10–13]. Conventional prostheses convey only limited feedback via the residuum-socket interface. To compensate for this incomplete sensory information, individuals with lower limb loss rely on visual feedback to monitor gait and maintain stability[14–17]. This alternative strategy is less intuitive than utilizing native lower extremity sensory feedback. Consequently, a frequently reported challenge after lower limb loss is the high attention or cognitive load required to ambulate with a prosthesis[18–23].

Even for able-bodied individuals, gait constitutes a cognitive demand. Despite being a well-practiced motor activity, ambulation relies on both automatic and executive control processes[24–26]. Automatic gait control arises from spinal circuits and brainstem and cerebellar mechanisms, whereas executive control

of gait is associated with prefrontal cortex activity and other supraspinal structures[24,27,28]. The relative reliance on these two modes is not fixed and shifts with the demands placed on the walker.

Somatosensory input is a pivotal modulator of this balance[25]. Afferent signals from the lower limbs provide critical inputs to the spinal circuits underlying automatic control[29–31]. When such feedback is compromised, gait shifts toward greater executive control[32], resulting in increased cognitive load of walking[33,34]. This situation occurs after lower-limb loss, where plantar sensation is absent on the prosthetic side and walking draws more heavily on limited executive resources, leaving less capacity for the concurrent demands of real-world environments. The consequences extend beyond mental fatigue. Elevated cognitive load during walking is associated with reduced balance confidence[18], diminished community participation[35,36], increased fear of falling[37], and lower quality of life[38].

Reducing this cognitive burden remains an important unmet need for individuals with lower limb loss, particularly given the compromised somatosensory feedback[18,39]. One approach to address this issue is via sensory substitution. Such systems transduce foot-floor interactions or joint angle into an alternate output stimulus such as auditory, vibrotactile, electrocutaneous, or other form of haptic feedback[40–48]. Some of these methods have shown gait benefits without inducing additional cognitive load[49,50]. However, depending on the implementation of the feedback, other systems have resulted in increased mental burden since users must learn to associate an arbitrary feedback signal with the state of their prosthetic limb[41,51–53]. Additionally, these techniques often depend on precise sensor placement and require additional equipment adding to the donning / doffing process of a prosthesis[40,44,45,54].

Peripheral neural interfaces offer an effective alternative for restoring somatosensation by targeting the residual nerves that innervated the missing limb. Electrical stimulation of these nerves elicits sensations perceived as originating from the missing limb and co-located on its phantom projection[55–57]. We have applied this approach in a sensory neuroprosthesis (SNP)[56]. The SNP monitors the pressure distribution under the prosthetic foot and transduces it into small electrical currents delivered directly to the nerve, eliciting sensations corresponding to the location and intensity of the applied loads. The SNP has demonstrated benefits to balance[58], complex locomotion[59], spinal reflex modulation[60], recovery from stumbles[61,62], and locomotor adaptation and speed perception[63]. Critically, unlike sensory substitution systems, this approach engages the same ascending neural pathways that once carried input from the missing foot, making it uniquely positioned to reduce the cognitive load of walking[19,64,65].

In this study, we investigated the effects of neurally integrated sensory feedback from the SNP on cognitive load during gait in individuals with lower limb loss. To assess cognitive load, we implemented a dual-task paradigm (Fig. 1a), in which participants performed a motor (gait) and cognitive task simultaneously. Because gait already entails a level of cognitive load, adding a secondary cognitive task taxes executive resources and produces measurable performance changes in one or both tasks[24,66]. For the cognitive task, we used a visual cognitive task, the Color–Word Matching Stroop (CWMS)[67], so that

participants could not use vision to monitor their gait which is often relied upon as a compensatory strategy after lower limb loss[68–70]. We hypothesized that restored plantar sensation from the SNP would reduce the cognitive load of gait during dual-tasking. Because somatosensory feedback feeds the spinal and subcortical circuits that support automatic gait control, we reasoned that the SNP could shift the balance of gait control toward automaticity, freeing executive resources for the concurrent cognitive task. This improvement would be in faster response times or higher accuracies in the CWMS or in a mitigation of the slower gait speeds seen in previous dual-task gait studies in this population[33,34]. To test whether this benefit scales with cognitive demand, we implemented the CWMS in two forms: a self-directed version, and a time-limited version that forces prioritization of the cognitive task and thereby imposes greater load. We hypothesized the SNP's benefit to be more pronounced under the higher demand of the time-limited task.

RESULTS

Three participants with unilateral amputations (LL1 and LL2 transtibial, LL3 transfemoral) and two age-matched able-bodied controls (AB1 and AB2) completed the dual-task experiments. Participants walked on an instrumented self-paced treadmill recorded gait speed (Fig. 1a) while performing CWMS which comprised three levels of increasing difficulty: neutral (NC), congruent (CC), and incongruent (IC) (Fig. 1b). The CWMS was administered in two forms: self-directed with unlimited response time and time-limited, with a maximum response time. Participants with limb loss completed both forms with and without the SNP active. We measured reaction time and accuracy on the CWMS, gait speed, and, from motion capture, stance time and step length (see Methods for details). Single-task trials of CWMS and walking alone were recorded to compute a dual-task effect (DTE) for reaction time and gait speed. DTE was defined as the percentage change from single to dual-task performance, such that a higher DTE indicates a faster gait speed, or a longer reaction time, during dual-tasking.

Gait Speed Effects

Limb loss participants demonstrated significant main effects of SNP condition and CWMS stimulus type on gait speed DTE during the self-directed and time-limited experiments as shown in Figure 2.

In the self-directed experiment (Fig. 2a), LL1's DTEs were positive for all conditions and appeared to increase with higher CWMS difficulty (mean values ± standard error - inactive: NC 9.2 ± 1.5%, CC 12.6 ± 1.3%, IC 14.7 ± 1.3%; active: NC 12.2 ± 1.2%, CC 16.0 ± 1.1%, IC 17.7 ± 0.7%). LL1 exhibited a significant effect of SNP on gait speed DTE ($F(1, 66) = 10.39$, $p < 0.01$)) with a higher DTE for SNP active with a difference of 3.1 ± 1.1% ($p < 0.01$).

In the time-limited experiment (Fig. 2b), LL1 and LL3 exhibited significant effects of SNP on DTE with no interaction effects. DTEs for LL1 remained positive throughout (inactive: NC 4.5 ± 0.8%, CC 6.4 ± 0.7%, IC 6.7 ± 1.0%; active: NC 8.0 ± 1.5%, CC 9.9 ± 1.7%, IC 10.4 ± 1.5%). Notably for LL3, DTEs were negative for SNP inactive (NC -2.4 ± 1.1%, CC -2.0 ± 1.1%, and IC -1.4 ± 0.7%), and they became positive for SNP

active (NC 2.8 ± 1.3%, CC 3.5 ± 1.4%, and IC 3.6 ± 1.7%), a shift from slowing down to speeding up while dual-tasking. Both participants exhibited higher DTE for gait speed with SNP active (LL1 $F(1, 30) = 11.86$, $p < 0.01$ and LL3 $F(1, 30) = 26.09$, $p < 0.001$). Post hoc tests indicated DTE was higher during SNP active by 3.6 ± 1.0% for LL1 and 5.2 ± 1.0% for LL3.

Stimulus type also modulated gait speed DTE . In the self-directed experiment, all three participants with limb loss showed a main effect (Fig. 2a). For LL1, stimulus type significantly affected gait speed DTE ($F(2, 66) = 11.12$, $p < 0.001$). Gait speed DTE was higher during the CC compared to NC with a difference of 3.6 ± 1.3% ($p < 0.01$), and during IC compared with NC with a difference of 5.5 ± 1.3% ($p < 0.001$). LL2's gait speed DTE also exhibited a main effect of CWMS stimulus type: $F(1, 126) = 6.32$, $p < 0.01$. DTE was lower during the IC compared to the NC by 3.4 ± 1.0% ($p < 0.01$). Overall, DTEs were near zero with a decreasing trend from NC to IC (inactive: NC 3.0 ± 0.8%, CC 1.0 ± 0.7%, IC -0.5 ± 0.8%; active: NC 2.2 ± 1.2%, CC 1.5 ± 1.1%, IC -1.2 ± 1.1%). Finally, LL3 also exhibited a main effect of CWMS stimulus type on gait speed ($F(1, 102) = 4.54$, $p < 0.05$). DTE in the IC was higher than the NC by 3.1 ± 1.1% ($p < 0.01$). LL3's DTEs were near zero and similar to LL2 showed an increasing trend as CWMS grew in difficulty (inactive: NC 0.0 ± 1.2%, CC 1.3 ± 1.0%, IC 2.5 ± 1.0%; active: NC -0.6 ± 1.3%, CC 1.6 ± 0.7%, IC 3.1 ± 0.8%).

In the time-limited experiment, only LL2 retained a significant effect of CWMS stimulus type on DTE (Fig. 2b) ($F(2, 30) = 4.37$, $p < 0.05$). Tukey post hoc test indicated that the IC was lower than the NC by 4.6 ± 1.6% ($p < 0.05$), continuing the decreasing pattern seen in the self-directed experiment (inactive: NC 1.1 ± 2.2%, CC -1.4 ± 2.1%, IC -4.7 ± 1.3%; active: NC 2.2 ± 1.2%, CC -0.4 ± 1.0%, IC -1.2 ± 1.2%).

Able-bodied participants showed no effect of stimulus type on gait speed in the self-directed experiment (Fig. 2c) (AB1: $F(2, 12) = 1.29$, $p = 0.31$ and AB2: $F(2, 15) = 0.34$, $p = 0.72$). In the time-limited experiment (Fig. 2d) AB2 again showed no effect ($F(2,3) = 1.85$, $p = 0.3$), whereas AB1's DTE was lower during NC than during CC and IC by 7.7 ± 2.0% and 10.7 ± 0.6%, respectively (both $p <0.05$).

Spatiotemporal Metrics

To identify the biomechanical changes underlying the gait speed effects, we computed step lengths (Fig. 3) and stance times (Fig. 4) for the prosthetic and intact limbs.

Step length increased with the SNP active in every participant. During the self-directed experiment (Fig. 3a) LL1 exhibited a significant SNP effect on prosthetic and intact step lengths ($F(1, 72) = 21.44$, $p < 0.001$ and $F(1, 72) = 8.76$, $p < 0.01$). Prosthetic step length was longer with SNP active by 3.0 ± 0.8 cm and intact step length was longer by 1.9 ± 0.7 cm. LL2 only had an SNP effect on the intact side ($F(1, 138) = 7.24$, $p < 0.01$), and his intact steps were longer by 1.0 ± 0.4 cm. Finally, LL3 increased prosthetic step lengths by 1.2 ± 0.6 cm ($F(1, 112) = 4.01$, $p < 0.05$).

Step lengths for the time-limited experiment are shown in Figure 3b. Here, step lengths on the prosthetic side increased for all participants: LL1 $F(1, 32) = 15.22$, $p < 0.001$; LL2 $F(1, 32) = 21.83$, $p < 0.001$; LL3

$F(1, 32) = 5.98$, $p < 0.05$. LL1 prosthetic step length increased by 2.5 ± 0.8 cm, LL2 by 3.3 ± 0.9 cm, and LL3 by 5.3 ± 2.0 cm. For LL2, intact step length also increased by 2.2 ± 0.8 cm, $F(1, 32) = 8.08$, $p < 0.01$. In both experiments, these step length changes did not produce significant differences in the step length symmetry between SNP conditions as shown in the supplementary material Figure S1.

For the self-directed experiment (Fig. 4a), stance time was largely unaffected by SNP . Only LL3 had a significant SNP effect for stance time on the prosthetic and intact side ($F(1, 112) = 9.56$, $p < 0.01$ and $F(1, 112) = 4.86$, $p < 0.05$). With SNP active, the stance time was shorter by 0.01 ± 0.003 s on the prosthetic side and 0.009 ± 0.004 s on the intact side. The same pattern persisted in the time-limited experiment. Stance time did not differ between SNP conditions for LL1 and LL2 (Fig. 4b). LL3 again showed a bilateral decrease with the SNP active by 0.029 ± 0.006 s on the prosthetic side and 0.022 ± 0.005 s on the intact side (prosthetic: $F(1, 32) = 22.93$, $p < 0.001$; intact: $F(1, 32) = 18.28$, $p < 0.001$).

Cognitive Task Performance

Error Rates

All participants demonstrated high accuracy on the self-directed CWMS while dual-tasking (Table 1). There were no significant main or interaction effects for stimulus type or SNP condition for any participant.

Similarly, in the self-directed experiment (Table 2), there were no significant effects of the SNP condition. However, stimulus condition did affect the error rates of participants LL1 and LL2 ($F(2, 6) = 12.95$, $p < 0.01$ and $F(2, 12) = 7.15$, $p < 0.05$). LL1's error rate for the IC was greater than the NC rate by 9.2 ± 2.2% ($p < 0.01$) and the CC rate by 7.3 ± 2.3% ($p < 0.05$). For LL2, the IC error rate was greater than the NC by 19.2 ± 3.5% ($p < 0.05$).

During the self-directed experiment, we found a significant main effect between participants with and without limb loss ($F(1, 87) = 8.12$, $p < 0.01$) with no interaction effect for the stimulus type (Table 1). Able bodied participants responded with a significantly lower average error rate compared to those with limb loss with a difference of 5.8 ± 0.8% ($p < 0.01$). However, all participants achieved low dual-task error rates < 14% on average.

Single-task performance on the CWMS was similar with no significant effects due to SNP or stimulus type, but a significant effect between participant groups ($F(1, 87) = 4.31$, $p < 0.05$). Able bodied participants exhibited an average error rate lower than those with limb loss by 4.6 ± 2.1%. In the time-limited CWMS (Table 2), LL1 had a significant interaction effect of SNP and stimulus type on single-task error rates ($F(2, 6) = 5.79$, $p < 0.05$). The inactive, IC error rate was significantly higher than the inactive NC (difference of 14.3 ± 2.6%) and CC (14.3 ± 2.6%) rates as well as the active, NC (14.4 ± 2.5%) and CC (12.5 ± 4.1%) rates.

Reaction Time

For the limb loss participants, we found no significant main effects of SNP condition or CWMS stimulus type on DTE for reaction times during the self-directed (Fig. 5a) and time-limited experiments (Fig. 5b). However, interaction effects between SNP and CWMS conditions were present.

In the self-directed experiment, LL1 demonstrated an interaction effect between SNP condition and CWMS stimulus type ($F(2, 66) = 4.86$, $p < 0.05$). LL3 also demonstrated a significant interaction effect between SNP condition and CWMS stimulus type ($F(1, 30) = 5.12$, $p < 0.05$) but during the time-limited experiment. However, in both cases Tukey post hoc tests between active and inactive conditions of the same CWMS levels found no significant SNP effects.

Finally, we observed a main effect of stimulus type for able bodied participant AB2 ($F(2, 15) = 5.92$, $p < 0.05$) during the self-directed experiment as seen in Figure 5c. AB2 had a lower DTE for the IC reaction times compared to the NC with a difference of 20.5 ± 6.7% ($p < 0.05$). No significant effects were found for AB participants during the time-limited experiment (Fig. 5d).

DISCUSSION

Our findings demonstrate that restoring plantar sensation via the SNP allowed participants with lower-limb loss to walk faster while performing a demanding cognitive task, at no cost to their task performance. This result could be interpreted as a reduction in the cognitive demand of walking which is a frequently reported unmet need in this population[18–20]. The effect was present in two of the three participants (LL1 and LL3) and emerged most clearly under the time-limited task, when cognitive load was greatest. The faster walking speed was achieved by taking longer steps, especially on the prosthetic side, whereas reaction time and accuracy on the cognitive task were preserved but not improved. We also observed that under the time-limited task, the gait speed varied less with CWMS difficulty than it had under the self-directed task. These results indicate that the SNP acted on the motor rather than the cognitive side of the dual-task walking and suggest that neurally integrated feedback let participants shift some of the control of walking from executive processes toward more automatic control, freeing cognitive resources under dual-task demand.

Specifically, participants modulated gait speed as a strategy to shift gait into a speed range that promotes automatic gait control during dual-task walking. Models of dual-tasking (capacity-sharing, bottleneck, cross-talk) all posit a limitation on cognitive processing or capacity that is exceeded in a dual-task situation and leads to reduced task performance[24,66]. Lowering the demand for one or both tasks would alleviate the competition for cognitive resources. Enhanced gait automaticity achieves this goal by reducing gait control by higher cortical centers. We postulate that automatic gait occurs within a limited range of walking speeds. Within this framework, participants may increase or decrease gait speed from baseline to approach this window and benefit from gait automaticity as we observed this with our participants. We suggest that the increased gait speed associated with the SNP indicates plantar sensation alters the window of speeds that supports automatic gait.

The mechanism behind this strategy is rooted in the split nature of gait control which involves automatic, spinal components as well as executive, cortical control[25]. Executive control is associated with activity in the frontal lobe particularly the prefrontal cortex. Executive control is the foundation of dual-task paradigms which introduce interference by adding tasks to gait that require additional higher cognitive processes. The automatic side of gait centers on neural control outside of the cortex such as central pattern generators in the spinal cord and brainstem circuitries[30,71].

Lower extremity sensory feedback interacts directly with spinal networks to affect motor output during locomotion[30,31]. When this tactile somatosensation is impaired, the balance of gait control shifts away from automatic toward executive centers[25]. This dynamic aligns with our observations that individuals with lower limb loss exhibited more errors than able-bodied participants on the CWMS while dual-tasking. Without detailed sensory feedback on the prosthetic side, walking demanded more mental resources.

Gait speed also affects the balance between gait automaticity and executive gait control. Previous work reported evidence of increased automaticity at higher gait speeds. Bandt *et al*. worked with an individual with a vestibular disorder and found that running featured less medial-lateral deviation than walking when asked to move in a straight line blindfolded[72]. Fatar *et al*. demonstrated a reduction in gait variability in a patient with a cerebellar stroke when walking faster[73]. These studies imply that at higher gait speeds, gait control was more automatic which bypassed the dysfunction in the higher cortical centers.

We suggest this mechanism applies to the elevated gait speeds for all participants with the SNP active. Restored sensory feedback interacts with gait centers in the spinal cord and could contribute to gait automaticity by raising the window of gait speeds for automatic gait. Consequently, speeding up would enable participants to shift their gait toward a more automatic domain and take advantage of this new input. Alternatively, automaticity may be more readily utilized at a certain higher range of gait speeds. With the input of the SNP system, participants were able to reach this “sweet spot” and offload some gait management to automatic control.

Crucially, participants sped up with the SNP active regardless of their increasing or decreasing speed strategy in response to increasing CWMS difficulty. This independent effect suggests the automaticity strategy is in response to dual-tasking generally. Adding CWMS to walking compels participants to conserve cognitive resources and the feedback from the SNP facilitates this goal by enabling more automatic gait that requires less executive control.

Our spatiotemporal analysis of gait further supports the role of automaticity. A study on dual-tasking in patients with Parkinson’s disease found that those with less gait automaticity exhibited shorter step lengths[74]. Our results showed an increased step length with SNP active, which indicates an improvement in automaticity with the electrically elicited sensation. A similar increase in step length has been shown for a sensorized prosthesis built on intraneural electrical stimulation[75]. Interestingly, we found an

increase in both the prosthetic and intact legs. On the prosthetic side, this result suggests that real-time sensory information from the SNP might preferentially affect the swing phase of gait. We interpret this to mean that having reliable feedback about the absence and presence of foot placement enhances confidence in moving the prosthetic leg which translates to greater step lengths during gait.

Increased step lengths on the intact side correspond to the prosthetic limb receiving SNP feedback during stance. This result may indicate that restoring somatosensory feedback to one limb modulates whole-body dynamics leading to an effect on the intact limb. Previous studies have examined the importance of cutaneous reflexes during locomotion. They identified interlimb reflexes where spinal pathways are responsible for afferent information from one leg modulating the contralateral limb[10,76]. Such an interaction may underly the intact step length modifications we observed in this study.

The effect of CWMS stimulus type on gait speed can also be understood with the same automaticity mechanism. As CWMS difficulty increased there was little effect of CWMS stimulus type on cognitive task performance. All limb loss participants maintained low error rates with reaction time DTEs near zero, indicating little change in performance with the addition of the secondary task. This consistent performance was paired with increasing (LL1 and LL3) or decreasing (LL2) gait speeds in both the self-directed and time-limited experiments. Able bodied participants demonstrated similar dual-task strategies with reaction time DTEs that tended to fall around zero. During the time-limited experiment, gait speed DTE for AB1 were increasingly positive with CWMS difficulty, indicating increased speed similar to the trend we observed in LL3. Meanwhile, AB2 maintained a similar pace across stimulus types.

We suggest that participants LL1 and LL3 were able to increase their gait speed within a trial as CWMS difficulty rose with the goal of reaching a speed where gait automaticity was maximized. Conversely, LL2 decreased gait speed from NC to IC. Previous work has shown that the process of increasing gait is cognitively costly with higher prefrontal cortex activation during periods of acceleration[77]. LL2 may have directed their cognitive resources toward the cognitive task instead of increasing gait speed transiently for a long-term payoff as with LL1 and LL3. Alternatively, the range of gait speeds where automaticity is maximized for LL2 may have been slower than their baseline walking speed. Consequently, they would decrease speed to reach it with growing cognitive task demands. Overall, these dynamics reflect the same mechanism of modifying gait speed to attain more automatic gait and relieve cognitive load.

Considering the time-limited experiment, we found LL1 and LL3 walked faster with the SNP active. Similarly, all participants also increased their prosthetic step lengths during this experiment and at greater magnitudes than in the self-directed time dual-task. We interpret this result as an increased reliance on the SNP during the more intense cognitive task. Restored sensation facilitates higher gait speeds under cognitive load, again, to increase gait automaticity.

The time-limited experiment highlighted the diminishing returns of this strategy. We observed reduced speed modulation with task difficulty that seemed to suggest a ceiling effect. Participants were already

under pressure in the self-directed setting and in the time-limited experiment it seems the dual-task demands were high enough to preclude accelerating within a trial to the same extent as during the self-directed time dual-task. Only LL2's gait speed modulation remained since reducing speed did not require the same cognitive cost as accelerating[77].

Interestingly, for LL2 this decrease appears to be less drastic with the SNP active. The added feedback from the SNP may have raised the range of speeds where automaticity is maximized. Consequently, this participant could have benefited from more automatic gait with DTEs that stayed closer to zero instead of becoming more negative.

Overall, achieving faster gait during high cognitive load is a noteworthy result since slow walking speeds have been linked to increased fall risks[78,79]. Countless activities of daily living involve dual-task walking, including grocery shopping, navigating a household, and crossing the street. For individuals with lower limb loss who are already risk for falls[37,80–82], these dual-task demands can draw attention away from walking at critical times and lead to injury. Our results indicate that electrically elicited sensations could enable an automatic gait strategy and higher gait speeds in these situations. Therefore, sensory-enabled lower limb prosthesis users would be more resilient to fall in conditions of dual-task pressures encountered during daily life.

This study utilized the Stroop task[68,83]and treadmill walking to create dual-task interference. Though challenging, these tasks were performed in a laboratory setting and therefore lack some ecological validity. Virtual and augmented reality technologies offer compelling tools to construct more realistic scenarios in a controlled and safe environment[84–88]. Future work on the SNP's cognitive benefits could utilize these tools to enable more complex dual-task setups with uneven terrain or obstacle navigation.

Additionally, although a dual-task paradigm allows us to assess a task's cognitive load via performance measures, it would be insightful to measure direct metrics of executive control via brain imaging[25,27,89] or activity in automatic spinal centers via reflex tests[90]. Similarly, subjective ratings by participants of their cognitive load could reveal potential benefits to perceived levels of effort even if functional metrics remain steady.

Overall, the electrically elicited plantar sensation in this study facilitated a strategy that reduced the cognitive load of walking during dual-tasking. Sensory feedback from the prosthetic foot increased confidence in stepping on the prosthetic side leading to longer step length and ultimately faster gait speeds. By reaching higher gait speeds, participants enhanced their gait automaticity and freed mental resources to focus on a secondary task. Reducing the attentional demand of walking in this way is a frequently reported user need for those with lower limb prosthesis[18,19], and improvements in this area offer immediate benefits during everyday dual-task activities. This study highlights the possible benefit of the SNP system in this area and builds on pervious work demonstrating speed and attention benefits from prostheses utilizing peripheral nerve interfaces[64,65,75]. With neurally integrated somatosensory feedback, participants were able to harness an automaticity strategy for gait to mitigate dual-task

pressure. This effect has the potential to cascade into other areas such as walking confidence and prosthesis acceptance to further enhance quality of life for these individuals[18,37]. Furthermore, we have demonstrated how plantar somatosensory feedback affects gait control by modulating the relationship between gait speed and gait automaticity.

MATERIALS AND METHODS

Research Participants

Two able bodied individuals (AB1 and AB2) volunteered for this study. Three individuals with unilateral limb loss due to trauma (designated LL1–3) volunteered to have 16-contact composite flat interface nerve electrodes (C-FINEs) placed on their sciatic and/or tibial, nerves in the popliteal fossa in their residual limbs. Relevant characteristics for the participants with limb loss are summarized in Table 3 including amputation level (LL1 and LL2 transtibial, LL3 transfemoral). All were regular prosthesis users with no medical histories of peripheral neuropathy, dysvascular disease, frequent episodes of phantom pain, or uncontrolled diabetes. Following the outpatient surgical implantation of the C-FINEs, participants regularly returned to the laboratory for measurements of nerve cuff performance and various other assessments described in previous work [91–94]. The specifics of the surgical procedure are also detailed in prior work[91]. The Louis Stokes Cleveland Veterans Affairs Medical Center Institutional Review Board and Department of the Navy Human Research Protection Program approved all study procedures, which were conducted under an Investigational Device Exemption obtained from the United States Food and Drug Administration. The study was designed in accordance with relevant guidelines and regulations, and all individuals gave their written informed consent to participate.

Sensory Neuroprosthesis

The SNP system consisted of an implanted neural interface, external stimulator, and instrumented prosthesis. Each participant received 16-contact C-FINEs implanted on the sciatic and/or tibial nerves in the popliteal fossa of the residual limb. Implanted connectors linked the C-FINEs to percutaneous leads that exit the skin in the anterior thigh (LL1 and LL2) or abdomen (LL3) as described in detail previously[56].

A custom external controller delivered electrical stimulation to the nerves via specific contacts in the C-FINEs. The stimulation waveforms were asymmetric current-controlled charge-balanced cathodic pulses. Pulse amplitudes (PA) ranged between 0.8 and 2 mA and pulse widths (PW) ranged between 0 and 255 μs. Interpulse interval was constant at 50 ms, consistent with previous reports[58,59]. Electrical stimulation to the C-FINE contacts elicited sensations perceived as originating from the plantar surface of the missing foot. We determined specific contacts and stimulation parameters for each participant following a thresholding and mapping process described previously[56].

We utilized a force-sensing insole (High Dynamic Force Sensing Resistor Insole, IEE, Bissen, Luxembourg) with eight force sensing resistors to coordinate stimulation in real-time with foot-floor

interactions. The insole was attached to the bottom of each participant's prosthetic foot and wirelessly transmitted sensor data to the external stimulator via a custom electronic module. The resulting stimulation from the external controller produced sensations that corresponded to the location and intensity of pressure applied to the heel midfoot, and metatarsal plantar regions of the foot for all three participants. To elicit these sensations, the stimulator modulated the C-FINE contact and PW of the stimulation within safe values.

The elicited sensations from the neural interface of the SNP have been shown to be chronically stable[56,95]. Additionally, all participants had prior experience using the SNP while walking overground and on a treadmill.

Experimental Setup

The dual-task experiment was performed on an instrumented split-belt treadmill (R-Mill, ForceLink, Netherlands) paired with a virtual reality environment (V-Gait, Motek Medical, Netherlands). D-Flow software (version 3.34.3, Motek Medical, Amsterdam, Netherlands) controlled the treadmill and the projector screen for the virtual environment. The treadmill belts were driven together throughout the experiment with a maximum speed of 1.47 m/s for the limb loss participants and 2.07 m/s for the able bodied. The projector screen provided visual flow using a simulated pathway. The task stimuli described below was projected on top of this pathway. Gait speed data was recorded from the treadmill belts with a 300 Hz sampling frequency. Kinematic data were recorded with a full-body marker set (Vicon Plug-In Gait Marker Set) with markers below the shoulders removed to allow for unimpeded tracking of the hip markers (27 total markers). Marker trajectories were tracked with a 16-camera motion capture system (VICON, Oxford, UK) with a 100 Hz sampling frequency and used to drive the self-paced treadmill functionality as described below.

Dual-Task Paradigm

Dual-task experiments are commonly employed to examine the cognitive demand of gait. In this paradigm, participants walk while simultaneously engaging in a secondary or cognitive task intended to stress their cognitive resources[24,66]. Dual-task studies specifically with individuals with lower limb reinforce their higher cognitive demand during walking[33,34]. The experiments in this study utilized the CWMS for the cognitive task paired with self-paced treadmill walking as the motor task.

Color–Word Matching Stroop

We implemented the CWMS as described by Zysset et al[67]. CWMS has demonstrated prefrontal cortex activation which made it suitable for a dual-task with walking since both tasks would draw on the same brain regions creating dual-task interference[24]. Furthermore, the visual delivery of CWMS ensured participants could not rely on their vision for gait[14,15].

As depicted in Fig. 1b, there are three possible conditions: neutral, congruent, and incongruent. For all conditions, the participant responds “yes” or “no” to the following: “Does the color of the upper word match the meaning of the lower word?” In the NC, the upper word, “XXXX,” lacks semantic information. In the CC, the upper word does contain color meaning and is presented in a congruent font color. Finally, the IC upper word utilizes the classic Stroop interference stimulus with a color word presented in an incongruent font color[96].

In all conditions, the possible color options are red, blue, green, and yellow. During the experiment, the stimuli was projected on a screen in front of the participant on a white background. As implemented in previous work [67], the upper word was displayed 200 ms before the lower word. This delay prevents the participant from bypassing the Stroop effect by focusing only on the lower word and perceiving the upper word as a block of color in their peripheral vision without parsing its meaning.

Self-Paced Treadmill Walking

The treadmill operated in a self-paced mode using an algorithm in the D-Flow software. The algorithm’s input was an anterior-posterior marker trajectory calculated from an average of four markers from full body Vicon Plug-In Gait Marker Set (LASI, RASI, LPSI, RSI). This position was compared to the center point of the treadmill to modulate the belt speed. If the participant walked faster than the current belt speed, the algorithm would detect the participant’s position moving forward from center and increase the speed of the treadmill. Conversely, a slower pace would result in a decreased speed to prevent the participant drifting backwards off the treadmill.

The self-paced mode was activated at the beginning of each trial after a short period of fixed paced walking at the participant’s preferred gait speed. We determined preferred gait by starting at slow (~0.5 m/s) and fast (~1.2 m/s) speeds during fixed-paced walking. Participants verbally indicated if the belt speed should be increased or decreased (random increments of 0.05-0.2 m/s) until reaching a comfortable gait speed. This process was repeated three times, and the preferred gait speed was set as the average of the three trials.

Experiment Flow

All dual-task sessions consisted of a single-task walking and CWMS trial followed by three dual-task trials. Participants were not given prioritization instructions between the two tasks and were instructed to answer the CWMS quickly and accurately.

For the motor task baseline, participants performed 2–3 minutes of self-paced walking. For all walking trials, the treadmill slowly ramped up to the participant’s preferred walking pace. After walking for 20–30 seconds at fixed pace, the experimenter activated the self-paced mode. In this way, the participants modulated their own gait speed for the rest of the trial. The D-Flow software recorded the belt speed throughout the trial.

Before any CWMS trials, participants were shown the colors used in the experiment (Red, Blue, Green, Yellow) and performed several practice trials. The experimenter would verbally initiate a three second countdown before the appearance of the first stimulus.

One trial of the cognitive task consisted of 20–22 stimuli of each condition in the order NC, CC, and IC. Immediately after one stimulus condition ended the next began so all three conditions were presented in one continuous trial. Within each stimulus condition, the colors used in the stimulus were pseudo randomized and had an equal number of “yes” and “no” answers. Participants had either unlimited time or 1.5 seconds to respond to each stimulus.

The maximum response time for the time-limited experiment was chosen based on the original implementation of the CWMS[67] while also falling within achievable reaction times for all the participants based on the data from the self-directed time data. Accordingly, for the time-limited protocol each CWMS condition lasted for 30 seconds to match the 20–22 stimuli in the self-directed experiment. In this way, even if the maximum time was reached for each stimulus the overall duration of walking in each trial was kept similar. After 1.5 seconds, if the participant did not respond the next stimulus was automatically triggered and the response was counted as incorrect.

With and without the time-limit, when a response was given to a CWMS stimulus, the experimenter triggered the start of the next stimulus. We recorded participant responses for post processing and timestamps for each stimulus were saved via D-Flow. Outcome measures were reaction time and accuracy. We computed reaction time as the difference between the time a stimulus was presented and the triggering of the next stimulus when a response was heard. Responses that were not a clear “yes” or “no” were counted as incorrect.

Once the participant was familiar with the task, we collected a full trial of CWMS while the participant stood on the treadmill as single-task baseline for the CWMS. After the single-tasks, participants complete three dual-task trials. These trials started the same as the motor baseline but after 10–30 seconds of self-paced walking the experimenter would count down to the start of CWMS. As in the single-task trials, all three conditions were presented one after another in a continuous trial.

Participants took a break after a set of single-task and three dual-task trials, and at this point, the SNP condition was switched from active to inactive or active to inactive. Participants then completed another set of single-task trials and three dual-task trials. Each session of data collection, we alternated the starting SNP condition to account for fatigue across the entire session. In this way, a single session consisted of six dual-task trials, three of each SNP condition.

Data Processing

During each experimental session, limb loss participants performed the following for SNP active and inactive: a single-task walking trial, a single-task CWMS trial while standing , and three dual-task trials,. Able-bodied participants performed only the inactive version of the trials. A single trial with CWMS

featured 20 CWMS stimuli or 30 seconds of stimuli for each stimulus type (NC, CC, IC) depending on whether the CWMS had a time limit or not respectively. Participants completed the following number of sessions with the self-directed CWMS: LL1 four, LL2 seven, LL3 six, AB1 one, and AB2 two. We collected two sessions of the time-limited experiment for LL1–LL3 and one each for AB1 and AB2.

Reaction time, error rates, and gait speed data were exported and processed in RStudio[97]. Gait speed data was trimmed to only include the self-paced portions of the trial during the CWMS stimuli. The speed and reaction times were split into sections for each stimulus condition and averaged across that section. Normality was verified visually with QQ plots and results were reported as reported as mean values ± standard error.

The dual-task effect on reaction time and gait speed was quantified with a dual-task effect (DTE) value. This metric was calculated as a percentage change from the single-task to the dual-task value: DTE = [(dual-task – single-task) / single-task]. Positive DTE values indicate that a metric's value was higher during dual-tasking compared to the single-task value. We pooled the single task gait speed data from sessions with and without the CWMS time-limit since these trials were functionally identical between the two protocols [98] Single-task CWMS metrics were kept separate due to the modified time constraint.

Spatiotemporal parameters were extracted from marker data. We exported marker trajectories for the toe and heel of each foot from Vicon motion capture and identified heel contact and toe off events using a custom MATLAB script. These events were further processed in RStudio to identify gait cycle phases. Stance time was calculated as the time between the heel strike of one foot and its toe off in that same gait cycle. Step lengths were calculated as the distance between heel strikes of one limb and the contralateral heel strike during the same gait cycle. With the self-paced treadmill, we calculated this parameter by summing: (speed x time) between these events and the difference in the anterior-posterior distance. We calculated these parameters for the entire trial of walking and extracted the metrics from the gait cycles belonging to each CWMS condition separately.

For the time-limited experiment, each participant on average featured the following number of gait cycles for each combination of SNP and stimulus condition: LL1 306, LL2 156, LL3 474, AB1 1369, and AB2 670, The data set for the dual-task without a time-limit contained the following average gait cycle counts: LL1 546, LL2 564, LL3 474, AB1 697, and AB2 429.

We performed separate analyses for the dual-task experiment with and without the time-limited CWMS to investigate the role of plantar sensation under varying dual-task prioritization. Specifically, error rate, reaction time DTE , gait speed DTE, and gait kinematic data were analyzed utilizing a two-way analysis of variance (ANOVA) to assess the effect of SNP condition across the stimulus conditions NC, CC, and IC as well as the interaction between these factors. Additionally, we compared limb loss and able bodied error rates with a one-way ANOVA . For all analyses, we performed Tukey post hoc Tukey tests to identify the effect of the SNP and stimulus conditions on performance. Significance level was set at $\alpha < 0.05$ for all tests.

Declarations

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Competing interests: The authors declare no competing interests.

Data availability: The datasets generated and analyzed during the current study are available in the Zenodo repository: https://doi.org/10.5281/zenodo.21444371.

Ethics statement: The studies involving humans were approved by Louis Stokes Cleveland Veterans Affairs Medical Center Institutional Review Board. The studies were conducted in accordance with local legislation, institutional requirements, and in accordance with the principles embodied in the Declaration of Helsinki. The participants provided their written informed consent to participate in this study. Written informed consent was also obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

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Tables

Table 1. Self-directed CWMS error-rates. Participant error rates for the self-directed experiment. No differences were found between SNP conditions when all three CWMS conditions were averaged together.

Participant	Single-Task Error Rate (%)		Dual-Task Error Rate (%)	
	SNP Inactive	SNP Active	SNP Inactive	SNP Active
LL1	4.3 ± 1.7	6.4 ± 1.8	4.1 ± 1.2	4.6 ± 1.9
LL2	4.4 ± 1.0	4.9 ± 1.4	3.9 ± 1.0	3.6 ± 1.0
LL3	11.0 ± 0.9	14.4 ± 1.8	13.8 ± 0.9	12.5 ± 0.6
AB1	1.5 ± 0.8		1.0 ± 0.5	
AB2	3.0 ± 3.0		0.8 ± 0.8	

Table 2. Time-limited CWMS error-rates. Participant error rates for the time-limited experiment. No differences were found between SNP conditions when all three CWMS conditions were averaged together.

Participant	Single-Task Error Rate (%)		Dual-Task Error Rate (%)	
	SNP Inactive	SNP Active	SNP Inactive	SNP Active
LL1	6.8 ± 3.1	3.3 ± 1.2	5.1 ± 2.5	3.6 ± 1.4
LL2	10.4 ± 3.5	15.5 ± 3.8	15.5 ± 3.4	20.7 ± 5.3
LL3	7.8 ± 2.1	4.8 ± 1.4	8.8 ± 2.5	5.5 ± 1.4
AB1	27.0 ± 15.9		32.5 ± 16.4	
AB2	13.9 ± 7.3		13.8 ± 8.8	

Table 3. Participant characteristics. Characteristics of participants enrolled in the study and target nerves where C-FINEs were implanted. Time since amputation is at time of implantation.

Participant	Age (years)	Time since Amputation (years)	Affected Side	Amputation Level	Target Nerves
LL1	63	19	Right	Transtibial	Sciatic, Tibial
LL2	64	16	Right	Transtibial	Sciatic
LL3	55	8	Left	Transfemoral	Sciatic
AB1	59				
AB2	62				

Figures

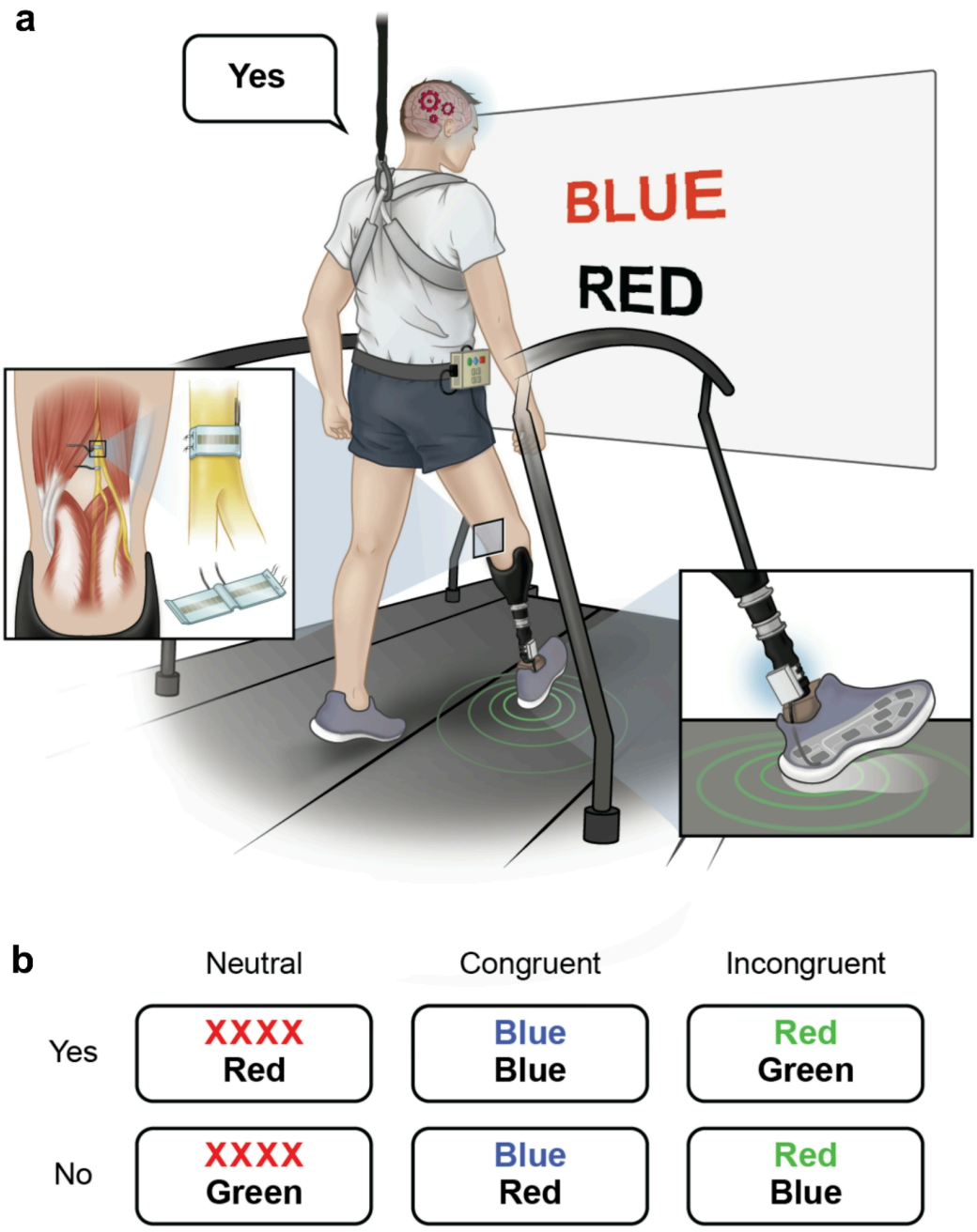

Figure 1

Dual-task experiment. Experimental setup for the dual-task experiments. (**a**) Participants walked on an instrumented self-paced treadmill while responding to the CWMS stimuli. Partcipants with limb loss received peripheral nerve stimulation via implanted cuffs, and the stimulation was mapped to the

pressure distribution under the prosthetic foot measured with a force sensitive resistor. (**b**) Sample CWMS stimuli for each stimulus type and yes /no condition.

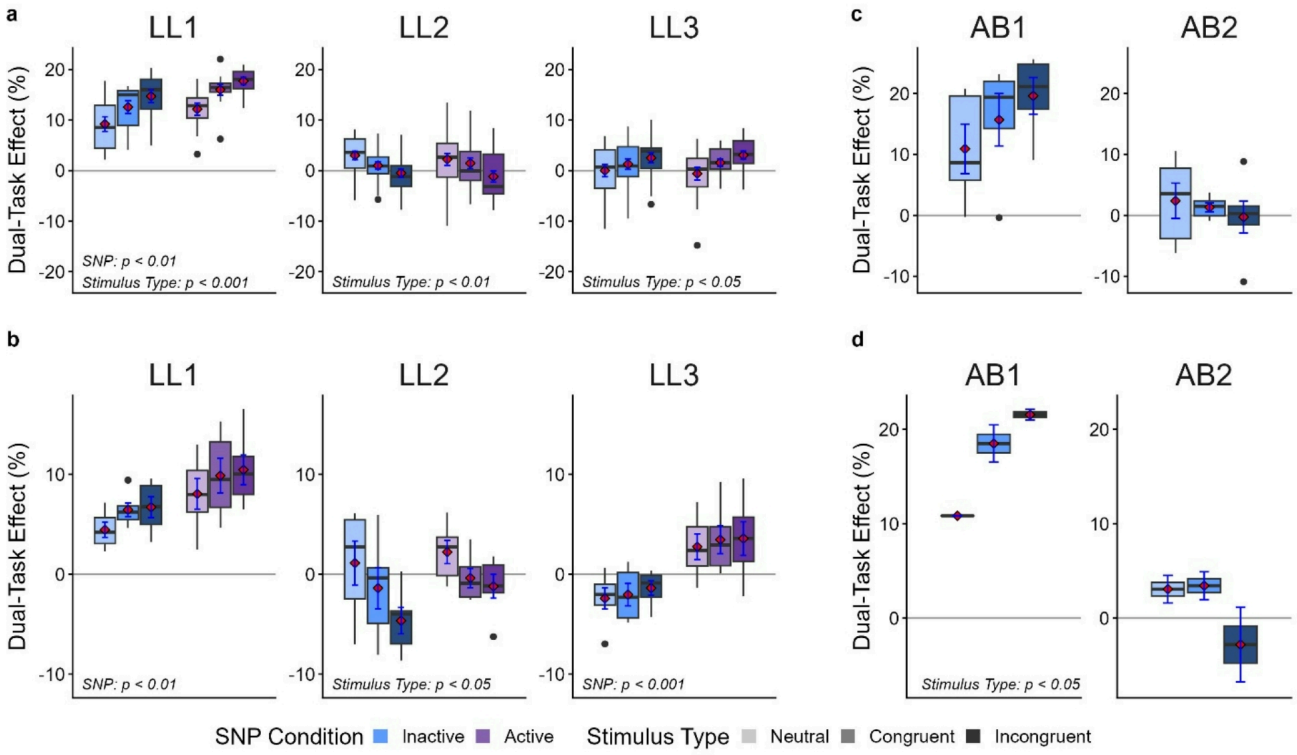

Figure 2

Gait speed dual-task costs. Average gait speed dual-task costs for the (**a**) (**c**) self-directed and (**b**) (**d**) time-limited experiment for each participant. Inactive for AB participants indicates walking with intact sensory feedback. The blue bars and red diamond represent the standard error and mean, respectively. Plot labels indicate the results of a two-way ANOVA (SNP condition x Stimulus Type).

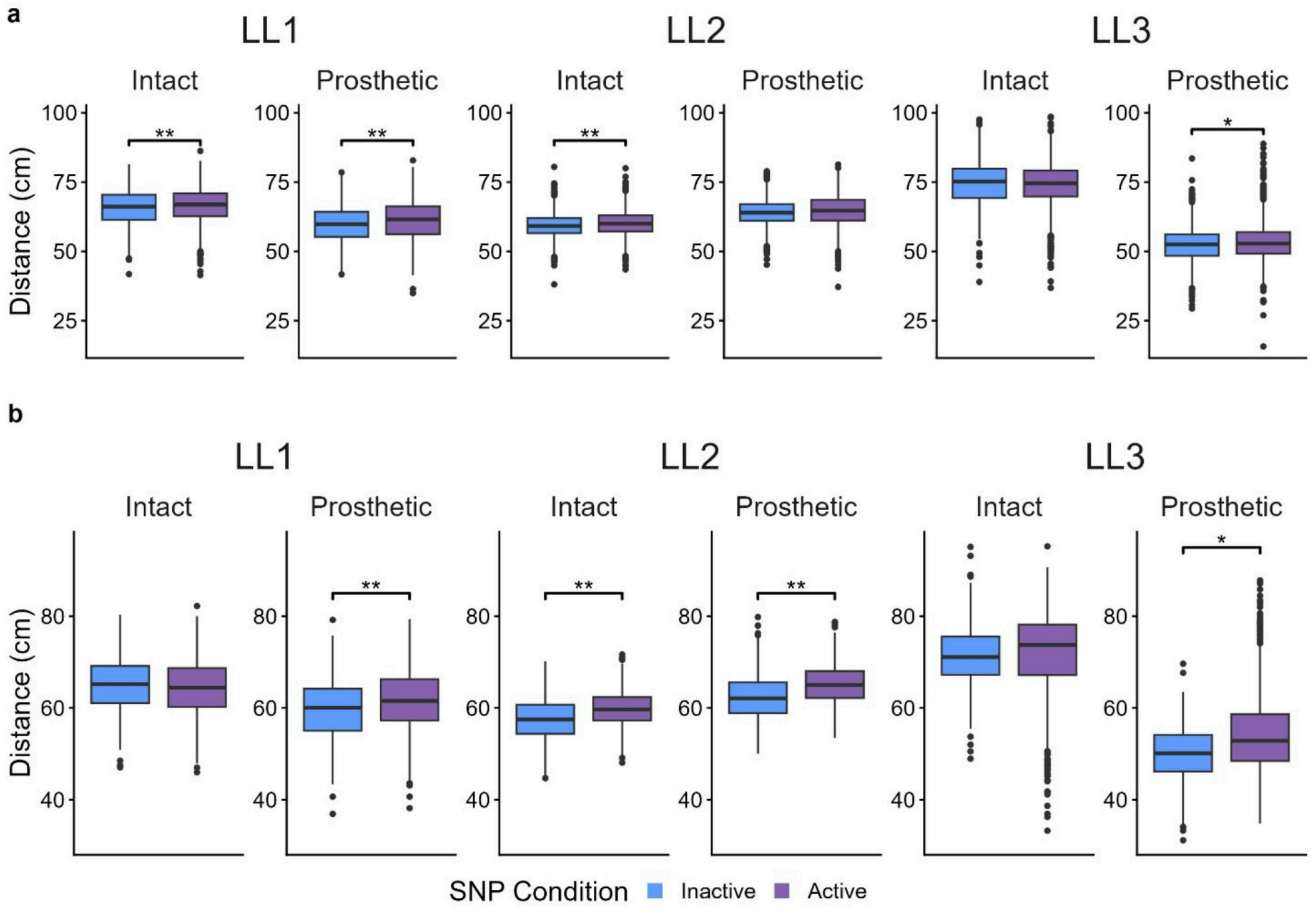

Figure 3

Step lengths during the self-directed experiment. Average step lengths during the (**a**) self-directed and (**b**) time-limited experiments for each participant with limb loss. Tukey post-hoc tests: * $p < 0.05$ and ** $p < 0.01$.

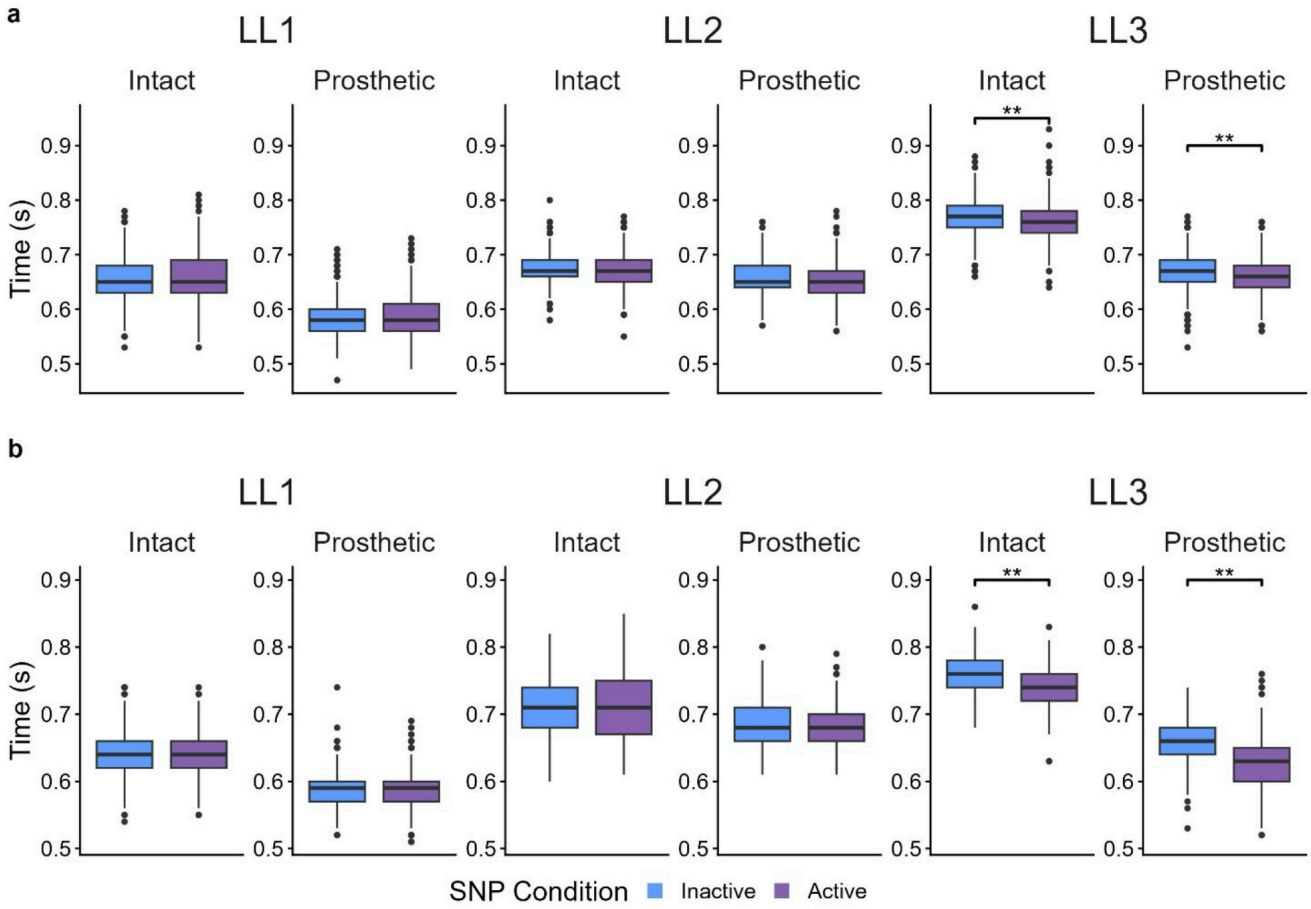

Figure 4

Stance times during the self-directed experiment. Average stance times during the (**a**) self-directed and (**b**) time-limited experiments for each participant with limb loss. Tukey post-hoc tests: * $p < 0.05$ and ** $p < 0.01$.

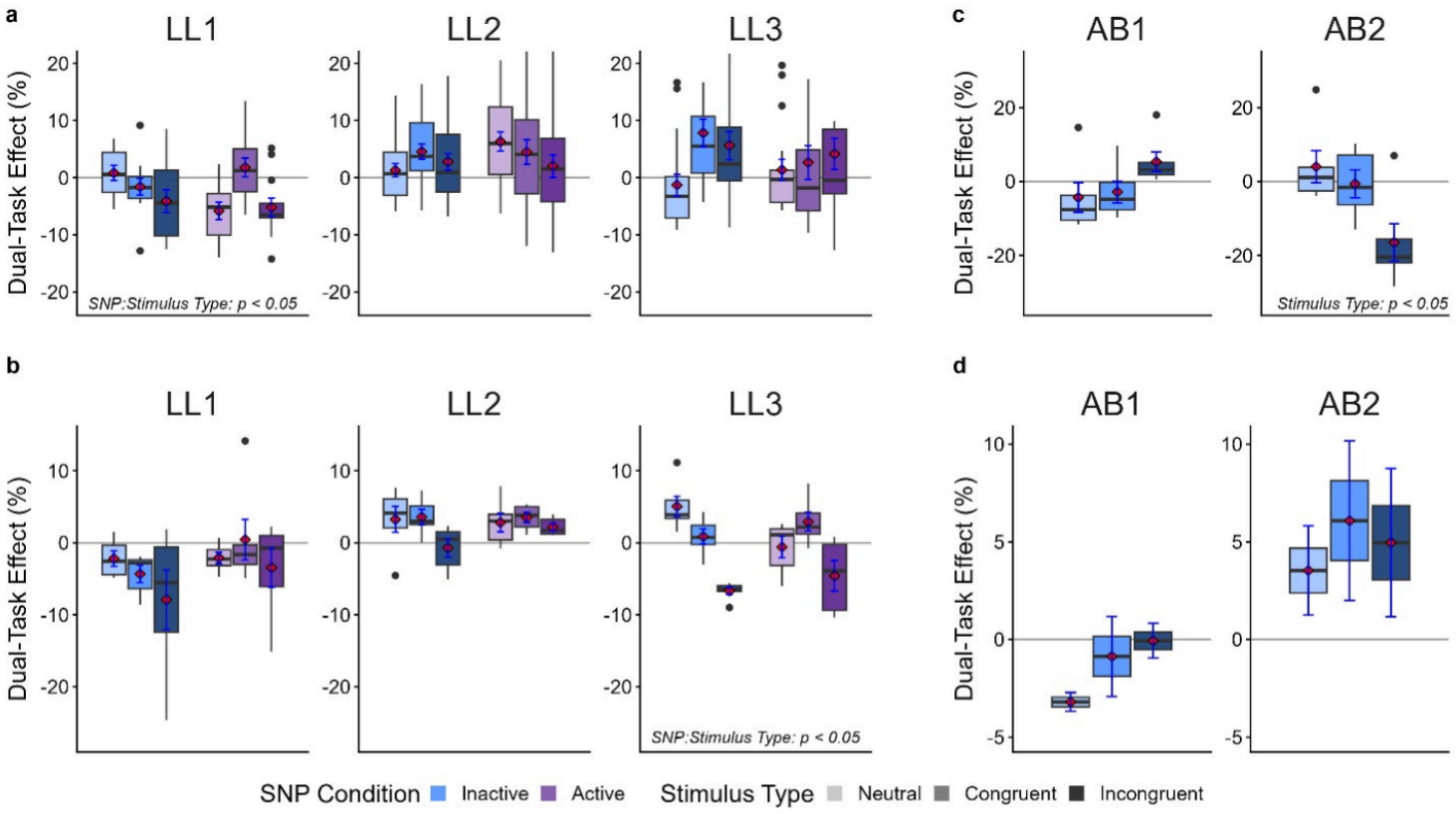

Figure 5

Reaction time dual-task costs. Average reaction time dual-task costs for the (**a**) (**c**) self-directed and (**b**) (**d**) time-limited experiment for each participant. Inactive for AB participants indicates walking with intact sensory feedback. The blue bars and red diamond represent the standard error and mean, respectively. Plot labels indicate the results of a two-way ANOVA (SNP condition x Stimulus Type).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- DualTaskSupplementaryMaterialSciReports.docx