Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

The Differential Impact of Cognitive Versus Motor Dual-Tasks on Lower Limb Neuromuscular Control during Gait: A Cognitive-Load Perspective

Sara Sadeghi
Bu-Ali Sina University
Behrouz Hajilou
behrouz.hajiloo@yahoo.com
Research Institute for Education
Behnam Behrad
Research Institute for Education

Article

Keywords: Cognitive dual-task, Motor dual-task, Cognitive-motor interference, Attention, Electromyography, Gait

Posted Date: March 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8464573/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Dual-tasking during gait represents a classic paradigm of cognitive-motor interference, primarily driven by competition for limited central executive resources. While both cognitive and motor secondary tasks disrupt gait, their specific neuromuscular signatures remain poorly differentiated. This study compared the effects of cognitive versus motor dual-tasks on lower limb muscle activity, interpreting findings through cognitive-load theories. Twenty-four healthy adults walked under single-task (normal gait), cognitive dual-task (serial subtraction by threes), and motor dual-task (carrying a full glass of water) conditions. Surface electromyography recorded activity from eight lower limb muscles. Muscle activity intensity was analyzed using repeated-measures ANOVA. Dual-tasking significantly altered muscle activity compared to normal walking (except rectus femoris). A key finding was the distinct pattern elicited by the cognitive task: the medial gastrocnemius, soleus, and tibialis anterior showed significantly higher activity during the cognitive dual-task compared to both the motor dual-task and normal walking. Conversely, the motor dual-task primarily increased activity in the vastus medialis, vastus lateralis, and hamstrings. The pronounced effect of the cognitive task suggests a high demand on central executive resources, leading to compensatory distal stiffening. This underscores cognitive load as a primary driver of gait interference, advocating for task-specific assessment in fall risk evaluation and rehabilitation.

1. Introduction

Human motor performance is fundamentally constrained by limited attentional and cognitive processing resources. Foundational cognitive theories, such as the Limited Capacity Model [1] and Multiple Resource Theory [2], posit that attention comprises finite neural resources. When two tasks compete for these shared or overlapping resources, performance in one or both domains deteriorates—a phenomenon termed dual-task interference. This is particularly salient in cross-modal dual-tasks, where an automatic motor task like walking is paired with a cognitively demanding secondary task [3–4].

Walking, often considered automatic, requires supraspinal monitoring and executive function, especially in complex environments [5]. Introducing a secondary task forces the division of attention, leading to measurable costs. Neuroimaging studies consistently show increased activation in executive brain regions, notably the prefrontal cortex (PFC), during dual-task gait, reflecting this neural resource competition [6]. The behavioral outcomes—reduced gait speed, increased stride variability, and elevated fall risk—are well-documented, particularly in populations with compromised cognitive resources [7–9].

While the detrimental effects of dual-tasking on spatiotemporal gait parameters are established, the specific neuromuscular adaptations to different types of secondary tasks remain unclear [10]. According to Multiple Resource Theory [2], a cognitive secondary task (e.g., mental arithmetic) and a motor secondary task (e.g., carrying an object) likely compete with the primary gait task for different resource pools (verbal/executive vs. visuomotor/spatial). This differential competition should theoretically manifest as distinct patterns of muscle activity. However, a precise mapping of cognitive load onto specific lower limb muscle activation strategies is lacking.

Therefore, this study aimed to investigate and compare the effects of cognitive and motor dual-tasks on lower limb muscle activity during gait. We sought to interpret electromyography (EMG) findings within established cognitive frameworks. We hypothesized that: 1) Both dual-task conditions would alter muscle activity compared to single-task walking, but 2) The cognitive secondary task would elicit a unique activation pattern, reflecting a greater demand on central executive control and a distinct compensatory neuromuscular strategy compared to the motor secondary task.

2. Methods

2.1. Participants

Twenty-four healthy individuals (12 men, 12 women; mean age = 24.3 ± 2.1 years) participated voluntarily. Sample size was determined using G*Power software (effect size f = 0.8, power = 0.95, α = 0.05). Inclusion criteria included no history of neurological or musculoskeletal disorders and being injury-free for the past six months. Postural alignment was screened via the New York Posture Rating Chart [11]. The study was approved by the Research Ethics Committee of Hamedan University of Medical Sciences (IR.BASU.REC.044.1402) and all subjects gave written informed consent. The study was conducted according to the Declaration of Helsinki. The authors declare that all research was done in conformity with all relevant guidelines/regulations.

2.2. Procedure

2.2.1. Surface Electromyography

Muscle activity was recorded from eight muscles of the dominant leg (preferred kicking leg): rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), lateral hamstring (LH; biceps femoris), medial hamstring (MH; semitendinosus/semimembranosus), medial gastrocnemius (GM), soleus (SO), and tibialis anterior (TA). Following standard skin preparation, Ag/AgCl electrodes were placed according to SENIAM recommendations. Participants walked barefoot along a 15-meter pathway at a self-selected speed [12]. Six trials per condition were recorded. Using foot-switch data, three clean gait cycles (heel-strike to subsequent heel-strike of the same foot) per trial were extracted for analysis.

2.2.2. Task Conditions

Single-Task (ST): Normal walking. Cognitive Dual-Task (CDT): Walking while performing serial subtraction by threes aloud from a random number. This secondary task was selected for its high demand on working memory (phonological loop) and executive attention [13]. Motor Dual-Task (MDT): Walking while carrying a full glass of water with the elbow flexed at 90°, without arm-to-body contact. This secondary task primarily challenges visuomotor attention, postural stabilization, and inhibitory control [14]. For all dual-task trials, participants were instructed to prioritize walking safety while performing the secondary task to the best of their ability. Condition order was randomized.

2.2.3. Data Processing

Raw EMG signals were bandpass filtered (10–500 Hz), full-wave rectified, and smoothed using a 4th-order Butterworth low-pass filter (6 Hz). Data were normalized using the submaximal method (peak activity within each extracted gait cycle) to express activity as a percentage. Gait cycles were time-normalized to 101 data points. The average normalized activity for each muscle in each condition was used for statistical analysis [15].

2.2.4. Statistical Analysis

Normality was confirmed using the Shapiro-Wilk test. Muscle activity intensity across the three conditions was compared using repeated-measures ANOVA. Bonferroni post-hoc tests identified pairwise differences. Analyses used SPSS v.24 ($\alpha = 0.05$).

3. Results

The mean and standard deviation of normalized muscle activity intensity are presented in Table 1 and Fig. 1. Repeated-measures ANOVA revealed a significant main effect of condition for all muscles except the rectus femoris ($p > 0.05$). Post-hoc comparisons detailed the distinct patterns: VL, VM, MH, LH: Activity was significantly higher in both dual-task conditions compared to single-task walking (all $p < 0.001$). For MH and LH, activity was also significantly higher during the MDT compared to the CDT ($p < 0.001$). GM, SO, TA: These distal muscles showed a divergent response. Their activity was significantly higher during the CDT compared to both single-task walking ($p < 0.001$) and the MDT (GM: $p = 0.016$; SO & TA: $p < 0.001$). Activity during the MDT was not significantly different from single-task walking.

Table 1
Mean (± SD) of Normalized Muscle Activity Intensity (%)

Muscle	Single-Task	Cognitive Dual-Task	Motor Dual-Task	F-value	p-value	η^2
Rectus Femoris	0.31 ± 0.04	0.28 ± 0.06	0.46 ± 0.03	1.64	0.200	0.060
Vastus Lateralis	0.32 ± 0.08	0.32 ± 0.05	0.30 ± 0.07	0.26	0.760	0.012
Vastus Medialis	0.39 ± 0.04	0.33 ± 0.05	0.50 ± 0.01	1.01	0.370	0.042
Medial Hamstring	0.27 ± 0.04	0.28 ± 0.05	0.18 ± 0.03	1.57	0.220	0.064
Lateral Hamstring	0.20 ± 0.01	0.33 ± 0.03	0.12 ± 0.06	5.66	0.010*	0.198
Med. Gastrocnem.	0.25 ± 0.01	0.34 ± 0.06	0.21 ± 0.01	1.64	0.200	0.067
Soleus	0.09 ± 0.02	0.09 ± 0.07	0.08 ± 0.02	0.11	0.890	0.005
Tibialis Anterior	0.16 ± 0.09	0.18 ± 0.07	0.16 ± 0.09	2.35	0.100	0.093
Note: Post-hoc results for significant main effects are described in text.						

4. Discussion

This study investigated the neuromuscular correlates of dual-task interference, contrasting cognitive versus motor secondary tasks. The results confirm our hypotheses, demonstrating that the nature of the secondary task dictates specific patterns of muscle activity alteration, interpretable through cognitive and neuroscientific frameworks.

The most salient finding was the differential impact of the two secondary tasks. The cognitive secondary task (serial subtraction) selectively increased activity in the ankle plantar flexors (GM, SO) and dorsiflexor (TA). This pattern suggests a task-specific compensatory strategy. Under high cognitive load —which heavily engages the PFC and working memory—the motor system may adopt a stiffening strategy at the ankle. This potentially compensates for reduced attentional resources available for continuous gait adjustments by simplifying control at a distal joint, enhancing mechanical stability at the cost of metabolic efficiency [8]. This aligns perfectly with the Limited Capacity Theory [1]; the excessive demand on central executive resources degrades automated gait control, necessitating a less efficient, more consciously controlled strategy reflected in altered muscle activation.

In contrast, the motor secondary task (carrying a glass) primarily increased activity in the quadriceps and hamstrings. This likely reflects a direct biomechanical and postural adaptation to maintain whole-body balance while managing an external object. The demand here is more local, related to visuospatial attention and limb control, and may share fewer central executive resources with gait compared to the cognitive task, as predicted by Multiple Resource Theory [2]. The observed pattern is consistent with the capacity-sharing model, where individuals dynamically reallocate, attention based on task priority, here likely prioritizing postural stability [16].

The divergent muscle patterns likely stem from different loci of neural competition. The cognitive task induces “central” interference at the PFC level, disrupting the executive oversight of gait [1]. The ankle muscle changes are a downstream consequence of this high-level disruption. The motor task may cause more “peripheral” or “subcortical” interference, related to integrating additional afferent feedback and managing limb dynamics, manifesting as increased proximal muscle activity to control the center of mass. Neuroimaging studies support this, showing that different secondary tasks activate overlapping but distinct neural networks during walking [17].

Our finding that cognitive tasks perturb distal muscle control extends the work of Song et al (2020). It also offers a resolution for apparent contradictions in the literature [18]. the degree and pattern of interference are inherently task-dependent. A motor task requiring fine manual control may disrupt gait kinematics, while a cognitive task taxing working memory may disrupt neuromuscular coordination.

Clinically, this underscores that not all dual-tasks are equivalent. Fall risk assessments should consider the type of secondary task used [19]. The pronounced effect of cognitive loading suggests that gait assessment under cognitive stress could be a sensitive tool for detecting subtle executive function deficits [20]. Furthermore, rehabilitation can be tailored: cognitive dual-tasks may train executive-

attentional components of gait control, while motor dual-tasks may train limb-coordination and dynamic balance [20].

This study used single exemplars of cognitive and motor tasks. Future work should vary task difficulty within each modality to map the resource competition landscape more finely. Concurrent measurement of brain activity (e.g., fNIRS) with EMG would directly link PFC activation to muscle synergy changes. Finally, investigating these effects in clinical populations is crucial for translational impact.

5. Conclusion

This study demonstrates that cognitive and motor dual-tasks induce qualitatively different patterns of lower limb muscle activity during gait. The specific increase in ankle muscle activity under cognitive load points to a unique interference mechanism rooted in competition for central executive resources. These findings shift the perspective from viewing dual-tasking as a uniform source of gait degradation to understanding it as a probe for specific cognitive-motor integration processes. Emphasizing the primary role of cognitive load, this research highlights the critical importance of secondary task selection in both assessment and intervention paradigms aimed at improving safe mobility in complex, real-world environments.

Declarations

Acknowledgements The authors express their gratitude to the subjects who participated in this study.

Author contributions SS and BE contributed to the conception, design of the work and data collection; BB contributed to draft the manuscript; BH and BB contributed to interpretation of data, SS contributed to review and editing the manuscript and contributed to critical revisions of the manuscript. All authors reviewed the manuscript.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability

The data used and analyzed for the current study are available from the corresponding author upon reasonable request.

Declarations Competing interests

The authors declare no competing interests.

Additional information Correspondence and requests for materials should be addressed to B.H.

References

1. Ninio, A. & Kahneman, D. Reaction time in focused and in divided attention. *J. Exp. Psychol.* **103**, 394 (1974).
2. Wickens, C. D. Processing resources in attention. In Varieties of attention (eds (eds Parasuraman, R. & Davies, D. R.) 63–102 (Academic, (1984).
3. Sadeghi, S., Hajilou, B. & Rohbanfard, H. The Effect of Cognitive and Motor Dual Tasks on the Synergy of Lower Limb Muscles During Walking. *Mot. Control* 1–12 (2024).
4. Al-Yahya, E. et al. Cognitive motor interference while walking: A systematic review and meta-analysis. *Neurosci. Biobehav Rev.* **35**, 715–728 (2011).
5. Yogev-Seligmann, G., Hausdorff, J. M. & Giladi, N. The role of executive function and attention in gait. *Mov. Disord*. **23**, 329–342 (2008).
6. Holtzer, R. et al. fNIRS study of walking and walking while talking in young and old individuals. *J. Gerontol. Biol. Sci. Med. Sci.* **66**, 879–887 (2011).
7. Mirelman, A. et al. Addition of a non-walking task to a walking test to detect dual-task interference in aging and neurodegenerative diseases. *J. Neuroeng. Rehabil*. **17**, 66 (2020).
8. Hausdorff, J. M. et al. Dual-task decrements in gait: Contributing factors among healthy older adults. *J. Gerontol. Biol. Sci. Med. Sci.* **75**, 799–806 (2020).
9. Dawi, N. M. et al. Analysis of the correlation between muscle reaction and stride interval variability in single-task and dual-task walking. *Fractals* **29**, 2150272 (2021).
10. Walsh, G. S. Dynamics of modular neuromotor control of walking and running during single and dual task conditions. *Neuroscience* **465**, 1–10 (2021).
11. Hajilou, B., Esmaeili, H. & Anbarian, M. Effect of foot type on electromyography characteristics and synergy of lower limb muscles during running. *Sci. Rep.* **14**, 25221 (2024).
12. Murley, G. S., Menz, H. B., Landorf, K. B. & Bird, A. R. Reliability of lower limb electromyography during overground walking: A comparison of maximal- and sub-maximal normalisation techniques. *J. Biomech.* **43**, 749–756 (2010).
13. Zukowski, L. A. et al. Dual-tasking impacts gait, cognitive performance, and gaze behavior during walking in a real-world environment in older adult fallers and non-fallers. *Exp. Gerontol.* **150**, 111342 (2021).
14. Song, Q. et al. Effects of a Dual-Task Paradigm and Gait Velocity on Dynamic Gait Stability during Stair Descent. *Appl. Sci.* **10**, 1979 (2020).
15. Serrancolí, G., Monllau, J. C. & Font-Llagunes, J. M. Analysis of muscle synergies and activation-deactivation patterns in subjects with anterior cruciate ligament deficiency during walking. *Clin. Biomech.* **31**, 65–73 (2016).
16. Leone, C. et al. Cognitive-motor dual-task interference: A systematic review of neural correlates. *Neurosci. Biobehav Rev.* **75**, 348–360 (2017).
17. Kahya, M. et al. Brain activity during dual task gait and balance in aging and age-related neurodegenerative conditions: a systematic review. *Exp. Gerontol.* **128**, 110756 (2019).

18. Nohelova, D., Bizovska, L., Vuillerme, N. & Svoboda, Z. Gait Variability and Complexity during Single and Dual-Task Walking on Different Surfaces in Outdoor Environment. *Sensors* **21**, 4792 (2021).
19. Magnani, R. M. et al. Local dynamic stability and gait variability during attentional tasks in young adults. *Gait Posture*. **55**, 105–108 (2017).
20. Taylor, M. E. et al. Gait parameter risk factors for falls under simple and dual task conditions in cognitively impaired older people. *Gait Posture*. **37**, 126–130 (2013).

Figures

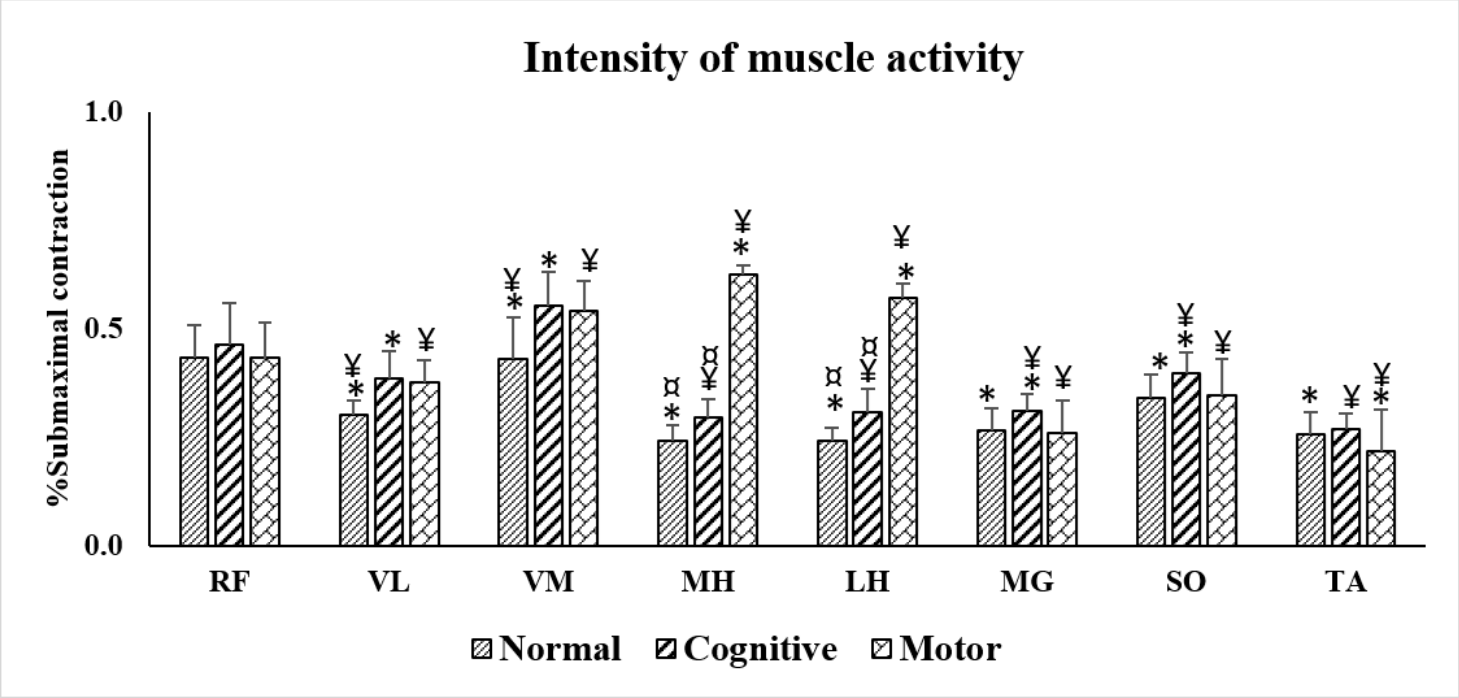


Figure 1

Mean and standard deviation of muscle activity intensity during normal, cognitive, and motor gait

**, ¥, ¤= significantly different*