

# **Cognitive-Motor Interference in Human- Exoskeleton Interaction: Evaluating the Cognitive Fit of Lower-Limb Exoskeletons**

Zur Erlangung des akademischen Grades eines

Doktors der Ingenieurwissenschaften (Dr.-Ing.)

von der KIT-Fakultät für Maschinenbau  
des Karlsruher Instituts für Technologie (KIT)

angenommene

Dissertation

von

**Norman Riedel**

Tag der mündlichen Prüfung: 13. April 2026

Erste Gutachterin: Prof. Dr.-Ing. Barbara Deml

Zweiter Gutachter: Prof. Dr. rer. nat. Thorsten Stein



This document is licensed under a Creative Commons Attribution 4.0 International License (CC BY 4.0): <https://creativecommons.org/licenses/by/4.0/deed.en>

# Danksagung

Diese Dissertation wäre ohne die großartige Unterstützung zahlreicher Menschen nicht möglich gewesen. An erster Stelle möchte ich meiner Erstbetreuerin, Prof. Dr.-Ing. Barbara Deml, herzlich danken. Ihre fachliche Unterstützung und motivierende Art haben wesentlich dazu beigetragen, dass diese Arbeit entstehen konnte. Sie hat mir die Freiheiten gegeben, die notwendig waren, um eigene Ideen zu entwickeln und umzusetzen. Ebenso gilt mein besonderer Dank meinem Zweitbetreuer, Prof. Dr. rer. nat. Thorsten Stein, für die exzellente fachliche Unterstützung im Bereich der Sportwissenschaft und Biomechanik. Über die wertvollen fachlichen Impulse hinaus danke ich ihm für die stetige Gesprächsbereitschaft sowie für die Bereitstellung seines Labors und der Messtechnik, welche die essenzielle Grundlage für meine Studien bildeten.

Darüber hinaus geht ein großes Dankeschön an alle Kolleginnen und Kollegen am Institut für Arbeitswissenschaft und Betriebsorganisation (ifab) und des BioMotion Labors für die Unterstützung, Gespräche und die prägende Zeit in Karlsruhe. Michael Herzog danke ich für die gemeinsame Durchführung meiner ersten Studie, die ohne ihn nicht möglich gewesen wäre. Ebenso danke ich Marco Käppler für die zahlreichen, oft langen Gespräche insbesondere zu Beginn und zum Ende meiner Promotionsphase. Sie haben mir nicht nur bei der Themenfindung geholfen, sondern mir auch das Gefühl gegeben, auf dem richtigen Weg zu sein. Sofie Ehrhardt war die beste Bürokollegin, die man sich wünschen kann; danke für die schöne Zeit, die Unterstützung und die hilfreichen Tipps besonders in der finalen Phase meiner Promotion. Den Kollegen aus dem Jubot-Projekt möchte ich für die vielen fachlichen wie auch nicht-fachlichen Gespräche danken, die mir geholfen haben, am Ball zu bleiben. Mein besonderer Dank gilt auch Giorgos Marinou für die gemeinsame Durchführung der zweiten Studie sowie für den anregenden Austausch in Heidelberg und Karlsruhe. Ohne seine Unterstützung wäre diese Studie nicht möglich gewesen. Zudem möchte ich Prof. Dr. Katja Mombaur danken, die durch die Bereitstellung des Exoskeletts für die zweite Studie einen entscheidenden Beitrag geleistet hat. Mein Dank gilt außerdem allen Kolleginnen und Kollegen der Fachgruppe 2.3 Human Factors, Ergonomie der Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA) für die herzliche Aufnahme in das Team und die wertvolle Unterstützung während meiner finalen Promotionsphase.

Ein besonderes Dankeschön geht an meine Eltern Diana und Andreas, die mir diesen Weg ermöglicht und mich in all meinen Vorhaben bestärkt haben. Meiner gesamten Familie sowie meinen Freunden danke ich für den grenzenlosen Rückhalt und die gemeinsamen Momente abseits des akademischen Alltags. Für das sorgfältige Korrekturlesen der Arbeit danke ich insbesondere Arved, Steven und Marco. Schließlich danke ich von Herzen meiner Ehefrau Luana, die mir in allen Höhen und Tiefen ein sicheres Gefühl gegeben hat und stets an mich geglaubt hat.

Dortmund, im Mai 2026

Norman Riedel

# Abstract

**Background & Objective.** Lower-limb exoskeletons have emerged as promising devices both for supporting individuals with mobility impairments and for augmenting the physical capabilities of able-bodied users. To date, most evaluations of lower-limb exoskeletons have focused on physical performance, while the cognitive dimension, referred to as *cognitive fit*, remains underexplored. However, exoskeletons can modify biomechanics through restricted range of motion or added mass, thereby increasing motor control demands. Preserving cognitive capacities is essential for ensuring functional and safe interaction with exoskeletons, particularly in multi-task environments. To address this, the present thesis examines the cognitive fit of exoskeletons by investigating their impact on cognitive and motor performance during dual-task walking, in order to assess the degree of cognitive-motor interference.

**Method.** Two studies were conducted as part of this thesis. In *Study 1*, participants walked on a treadmill both with and without weight cuffs attached to the upper and lower legs, increasing motor demand by modifying body mass and inertia distribution. During these walking conditions, participants performed either a serial subtraction task, a visual-verbal Stroop test or no cognitive secondary task. *Study 2* extended this investigation to an outdoor setting, where participants walked overground with and without a powered lower-limb exoskeleton while performing a serial subtraction task or no cognitive secondary task. Both studies evaluated motor performance through gait parameters, as well as cognitive performance through secondary task outcomes and perceived physical and cognitive workload.

**Results & Discussion.** The results of both studies show that exoskeletons that are insufficiently adapted to the user impose additional physical and cognitive demands and often lead to a posture-first strategy, in which the motor task is prioritized over the cognitive secondary tasks. Study 1 revealed that the type of the secondary task is critical, with cognitive-motor interference being more pronounced during a mental tracking task than during a Stroop test that primarily relies on processing external stimuli. Study 2 showed that short-term adaptation to the powered exoskeleton decreased perceived workload and improved cognitive performance. However, cognitive performance remained below that observed during unassisted walking. Together, the findings indicate that poorly adapted exoskeletons may compromise both cognitive and motor performance, whereas short-term adaptation can mitigate, but not fully eliminate, interference.

**Implication & Outlook.** This thesis contributes to exoskeleton research by introducing a human-centered conceptual framework that explicitly integrates the cognitive dimension into human-exoskeleton interaction. Furthermore, it demonstrates the potential of the *performance operating characteristics framework* as a practical tool for benchmarking exoskeletons, guiding training and fitting exoskeletons to individual needs. Future research should examine lower-limb exoskeletons with adaptive control strategies tailored to specific user groups and incorporate extended training protocols. Advancing knowledge of how different control and design approaches influence motor and cognitive performance during the interaction will be essential for ensuring the safe and effective deployment of exoskeletons in real-world contexts.

# Kurzfassung

**Hintergrund & Zielsetzung.** Exoskelette für die unteren Extremitäten stellen vielversprechende Technologien dar, die sowohl Menschen mit Mobilitätseinschränkungen unterstützen als auch die körperliche Leistungsfähigkeit gesunder Nutzerinnen und Nutzer steigern können. Bisher haben sich die meisten Evaluierungen von Exoskeletten für die unteren Extremitäten auf die physische Leistungsfähigkeit fokussiert, während die kognitive Dimension, hier bezeichnet als kognitive Passung (*cognitive fit*), weitgehend unerforscht bleibt. Exoskelette können jedoch durch eingeschränkten Bewegungsumfang oder zusätzliches Gewicht die Biomechanik verändern und damit die Anforderungen an die motorische Kontrolle erhöhen. Der Erhalt kognitiver Kapazitäten ist entscheidend, um eine funktionale und sichere Interaktion mit Exoskeletten zu gewährleisten, insbesondere wenn diese in komplexen Multitasking-Umgebungen eingesetzt werden. Vor diesem Hintergrund untersucht die vorliegende Arbeit die kognitive Passung von Exoskeletten, indem deren Einfluss auf kognitive und motorische Leistungsfähigkeit beim Gehen unter Dual-Task-Bedingungen analysiert wird, um das Ausmaß der kognitiv-motorischen Interferenz zu bestimmen.

**Methodik.** Im Rahmen dieser Arbeit wurden zwei Studien durchgeführt. In *Studie 1* gingen die Teilnehmenden auf einem Laufband, teils mit, teils ohne Gewichtsmanschetten an Ober- und Unterschenkeln. Die so veränderte Masse- und Trägheitsverteilung führte zu erhöhten motorischen Anforderungen. Währenddessen führten die Teilnehmenden entweder eine serielle Subtraktionsaufgabe, einen visuell-verbale Stroop-Test oder keine kognitive Zusatzaufgabe durch. *Studie 2* erweiterte die Untersuchung in ein Outdoor-Setting, in dem die Teilnehmenden mit und ohne ein aktives Exoskelett für die unteren Extremitäten über eine ebene Oberfläche gingen, während sie entweder eine serielle Subtraktionsaufgabe oder keine kognitive Zusatzaufgabe bearbeiteten. In beiden Studien wurde die motorische Leistung anhand von Gangparametern, die kognitive Leistung anhand der Ergebnisse der Zusatzaufgaben sowie die wahrgenommene physische und kognitive Beanspruchung erfasst.

**Ergebnisse & Diskussion.** Die Ergebnisse beider Studien zeigen, dass unzureichend an die Nutzerinnen und Nutzern angepasste Exoskelette zusätzliche physische und kognitive Anforderungen erzeugen und häufig zu einer Posture-First-Strategie führen, bei der die motorische Aufgabe gegenüber der Bearbeitung kognitiver Aufgaben priorisiert wird. Studie 1 verdeutlichte, dass die

Art der Zusatzaufgabe entscheidend ist. Die kognitiv-motorische Interferenz war bei einer mentalen Tracking-Aufgabe stärker ausgeprägt als bei einer Stroop-Aufgabe, die primär auf der Verarbeitung externer Reize beruht. Studie 2 zeigte, dass eine kurzfristige Adaptation an das aktive Exoskelett die wahrgenommene Beanspruchung verringerte und die kognitive Leistung verbesserte. Dennoch blieb die kognitive Leistung unter dem Niveau des Gehens ohne Exoskelett. Insgesamt weisen die Ergebnisse darauf hin, dass unzureichend adaptierte Exoskelette sowohl die kognitive als auch die motorische Leistungsfähigkeit beeinträchtigen können, während eine kurzfristige Adaptation diese Interferenzen zwar reduzieren, jedoch nicht vollständig aufheben kann.

**Implikation & Ausblick.** Diese Arbeit leistet einen Beitrag zur Exoskelettforschung, indem sie ein nutzerzentriertes Framework etabliert, welches die kognitive Dimension explizit in die Mensch-Exoskelett Interaktion integriert. Darüber hinaus untersucht die Arbeit das *Performance Operating Characteristics*-Framework als Werkzeug für die Praxis, insbesondere für die Bewertung von Exoskeletten, die Gestaltung von Trainingsprogrammen und die individuelle Anpassung von Exoskeletten an die Nutzerinnen und Nutzer. Zukünftige Forschung sollte Exoskelette für die unteren Extremitäten mit adaptiven Steuerungsstrategien untersuchen, die spezifisch auf unterschiedliche Nutzergruppen zugeschnitten sind, und ausführlichere Trainingsprotokolle berücksichtigen. Ein vertieftes Verständnis davon, wie verschiedene Steuerungs- und Designansätze die motorische und kognitive Leistungsfähigkeit in der Interaktion beeinflussen, ist entscheidend für die sichere und effektive Implementierung von Exoskeletten im realen Einsatzkontext.

# List of Publications

This list presents all scientific publications of the doctoral candidate. Publications included in the publication-based doctoral thesis are highlighted in grey.

**Riedel, N.,** Marinou, G., Mombaur, K., & Deml, B. (2025). An outdoor dual-task study on cognitive-motor interference during exoskeleton-assisted walking. *Frontiers in Psychology*, 16, 1583142. <https://doi.org/10.3389/fpsyg.2024.1375029>

**Riedel, N.** & Deml, B. (2025). Assessment of cognitive-motor interference in human-exoskeleton interaction using the Performance-Operating-Characteristics (POC) framework. In D. de Waard, L. Onnasch, M. Liebherr, A. Dettmann, F. Siebert, K. Karrer-Gauß, S. Winkler, A. Toffetti, and M. De Angelis (2025). *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2025 Annual Conference*. (pp. 51-60). Downloaded from <http://hfes-europe.org> (ISSN 2333-4959)

**Riedel, N.,** Käßpler, M., Wetzl, A. & Deml, B. (2025). Ergonomische Herausforderungen bei der Entwicklung von Führerständen für Zweisystem-Bahnen (TramTrains). In GfA, Sankt Augustin (Hrsg.): *Tagungsband 71. GfA-Frühjahrskongress*, S. 438-443, Aachen.

Herzog, M., **Riedel, N.,** Beyerlein, M., Weber, J., Deml, B., & Stein, T. (2024). Adaptation of walking patterns to bilateral loaded walking. *ISBS Proceedings Archive*, 42(1), 382.

**Riedel, N.,** Herzog, M., Stein, T., & Deml, B. (2024). Cognitive-motor interference during walking with modified leg mechanics: a dual-task walking study. *Frontiers in Psychology*, 15, 1375029. <https://doi.org/10.3389/fpsyg.2024.1375029>

**Riedel, N.,** Herzog, M., Stein, T., & Deml, B. (2024). Bewertung von Mensch-Exoskelett-Interaktionen hinsichtlich kognitiv-motorischer Leistungsparameter. In GfA, Sankt Augustin (Hrsg.): *Tagungsband 70. GfA-Frühjahrskongress*, Beitrag D.5.4, Stuttgart.

**Riedel, N.,** Herzog, M., Stein, T., & Deml, B. (2023). Effects of modified leg mechanics on cognitive performance and workload during dual-task walking. In D. de Waard, V. Hagemann, L. Onnasch, A. Toffetti, D. Coelho, A. Botzer, M. de Angelis, K. Brookhuis, and S. Fair-

clough (2023). *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2023 Annual Conference*. (pp. 95-106). Available from <http://hfes-europe.org> (ISSN 2333-4959)

Barisch-Fritz, B., Krafft, J., Rayling, S., Diener, J., Möller, T., Wunsch, K., **Riedel, N.**, ... & Woll, A. (2023). Are nursing home employees ready for the technical evolution? German-wide survey on the status quo of affinity for technology and technology interaction. *Digital Health*, 9. <https://doi.org/10.1177/20552076231218812>

# Contents

Danksagung.....	iii
Abstract.....	v
Kurzfassung .....	vii
List of Publications.....	ix
Contents.....	xi
List of Figures.....	xiii
List of Tables.....	xvi
List of Abbreviations .....	xvii
<b>1 Introduction.....</b>	<b>18</b>
<b>2 Theoretical Background.....</b>	<b>21</b>
2.1 Lower-limb exoskeletons.....	21
2.2 Human-exoskeleton interaction .....	22
2.2.1 Evaluation of human-exoskeleton interaction.....	23
2.2.2 Cognitive fit in human-exoskeleton interaction.....	24
2.3 Cognitive-motor interference.....	25
2.3.1 Theories related to cognitive-motor interference .....	26
2.3.2 Quantification of cognitive-motor interference.....	27
2.3.3 Research related to cognitive-motor interference .....	29
2.3.4 Performance operating characteristics .....	31
<b>3 Research Questions.....</b>	<b>34</b>
<b>4 Study 1 .....</b>	<b>37</b>
4.1 Effects of modified leg mechanics on cognitive performance and workload during dual-task walking.....	38
4.1.1 Introduction.....	38
4.1.2 Method .....	41
4.1.3 Results .....	46
4.1.4 Discussion .....	50

4.1.5	Conclusion.....	52
4.2	Cognitive-motor interference during walking with modified leg mechanics: A dual-task walking study.....	52
4.2.1	Introduction.....	53
4.2.2	Materials and methods.....	55
4.2.3	Results.....	60
4.2.4	Discussion.....	63
4.2.5	Conclusion.....	69
<b>5</b>	<b>Study 2.....</b>	<b>71</b>
5.1	An outdoor dual-task study on cognitive-motor interference during exoskeleton-assisted walking.....	72
5.1.1	Introduction.....	72
5.1.2	Materials and methods.....	74
5.1.3	Results.....	81
5.1.4	Discussion.....	86
5.1.5	Conclusion.....	91
5.2	Assessment of cognitive-motor interference in human-exoskeleton interaction using the Performance-Operating-Characteristics (POC) framework.....	92
5.2.1	Introduction.....	92
5.2.2	Method.....	94
5.2.3	Results.....	96
5.2.4	Discussion.....	98
5.2.5	Conclusion.....	100
<b>6</b>	<b>General Discussion.....</b>	<b>101</b>
6.1	Key findings.....	101
6.2	Theoretical implications.....	103
6.3	Practical implications.....	106
6.4	Conclusion.....	108
	<b>References.....</b>	<b>109</b>

# List of Figures

Figure 1.	Methodological framework to assess cognitive-motor interference in human-exoskeleton interaction. ....	20
Figure 2.	Example of a lower-limb exoskeleton: TWIN exoskeleton. Right image adapted from Semprini et al. (2022). ....	22
Figure 3.	Human-exoskeleton interaction framework for powered exoskeletons with an adaptive control unit. Adapted from Tucker et al. (2015). ....	23
Figure 4.	Exemplary representation of dual-task performance within the POC framework. From Riedel and Deml (2025), adapted from Wickens et al. (1981). ....	32
Figure 5.	Conceptual framework integrating the cognitive dimension in human-exoskeleton interaction.....	34
Figure 6.	Methodological framework with research questions (RQ). ....	35
Figure 7.	Conceptual framework adapted to the methodology of Study 1. ....	37
Figure 8.	Experimental protocol. Black arrows indicate the times at which the perceived workload subscale were queried during the walking sessions. (Riedel et al., 2023) .....	42
Figure 9.	(a) Experimental setup. (b) Schematic representation of the positions of the weight cuffs. (c) Representation of the attachment of the weight cuffs to a participant. (Riedel et al., 2023) .....	43
Figure 10.	Exemplary 10x10-matrix of colour words as used in the study. (Riedel et al., 2023).....	44
Figure 11.	(a) Mean dual task effects (DTE) for STR and SUB in the unloaded and loaded walking condition. (b) Mean DTE for STR and SUB in the unloaded and loaded walking condition for the group of participants who started with unloaded walking (n=8) and the group of participants who startet with loaded walking (n=8). Error bars reflect 95% CI. (Riedel et al., 2023) .....	48

Figure 12.	(a) Mean ratings of mental demand. (b) Mean ratings of physical demand. Error bars reflect 95% CI. (Riedel et al., 2023) .....	49
Figure 13.	Schematic illustration of the protocol of a walking session. The same protocol was performed with and without weight cuffs. (Riedel et al., 2024).....	58
Figure 14.	Coefficients of variation (CV) of (A) step length, (B) stride time, (C) step width, and (D) double support time for loaded and unloaded walking during single task walking (ST), dual-task walking with the Stroop test (STR) and dual-task walking with the subtraction task (SUB). Bars indicate standard errors. (Riedel et al., 2024).....	62
Figure 15.	Mean values of (A) step length, (B) stride time, (C) step width, and (D) double support time for loaded and unloaded walking during single task walking (ST), dual-task walking with the Stroop-Test (STR) and dual-task walking with the Subtraction-Task (SUB). Bars indicate standard errors. (Riedel et al., 2024).....	63
Figure 16.	Conceptual framework adapted to the methodology of Study 2. ....	71
Figure 17.	(A) TWIN lower-limb exoskeleton (adapted from Semprini et al., 2022), (B) setup of the TWIN exoskeleton and the measurement system. FSR, force sensitive resistor; IMU, inertial measurement unit. (Riedel et al., 2025).....	75
Figure 18.	Experimental procedure at the second appointment. (Riedel et al., 2025).....	77
Figure 19.	Gait event detection with the Dual Minima Method based on angular velocity of the shank-mounted IMU. Exemplary extraction of a single step of participant 01 during (A) unassisted walking and (B) exoskeleton-assisted walking. (Riedel et al., 2025).....	80
Figure 20.	Boxplots depicting the (A) coefficient of variation (CV) of stride time, (B) CV of double support time, (C) gait velocity, (D) correct response rate, (E) mental workload and (F) physical workload across different task conditions and walking conditions. The median (horizontal line within the box), the mean (black squares), the interquartile range	

	(box), and the data spread including potential outliers (dots) are shown for each condition. Asterisks (*) indicate statistically significant differences between conditions. (Riedel et al., 2025) .....	85
Figure 21.	Boxplots depicting the (A) coefficient of variation (CV) of stride time, (B) CV of double support time, (C) correct response rate, (D) mental workload and (E) physical workload across the three single task trials. Note that correct response rates were only assessed for the dual-task trials. The median (horizontal line within the box), the mean (black squares), the interquartile range (box), and the data spread including potential outliers (dots) are shown for each condition. Asterisks (*) indicate statistically significant differences between conditions. (Riedel et al., 2025).....	86
Figure 22.	Setup of (A) experiment 1 (from Riedel et al., 2023, 2024) and (B) experiment 2. (Riedel & Deml, 2025).....	95
Figure 23.	Performance-Operating-Characteristics framework showing the effects of (A) surface condition and walking condition and (B) familiarisation on dual-task performance. Single task performance is represented by the dashed lines. The diagonal line represents the Equal Allocation Axis. Data points represent means and bars represent standard errors. mDTE = motor Dual-Task Effect, cDTE = cognitive Dual-Task Effect. (Riedel & Deml, 2025) .....	97

# List of Tables

Table 1. Overview of experimental conditions. ST - single task; DT - dual task. 41

Table 2. Absolute and relative measures of cognitive performance and perceived cognitive and physical workload. Values represent mean (standard deviation). DTE - dual task effects..... 46

Table 3. Intraclass correlation coefficients (ICC) of coefficients of variation (CV) and mean values of gait parameters. .... 59

Table 4. Coefficients of variation and mean values of gait parameters for each experimental condition. .... 61

Table 5. Mean (SD) and median (IQR) of motor performance, cognitive performance, and perceived workload metrics for unassisted and exoskeleton-assisted walking under single-task (ST03) and dual-task (DT03) conditions. .... 81

Table 6. Mean (SD) and median (IQR) of motor performance, cognitive performance, and perceived workload metrics for exoskeleton-assisted walking across the three single-task trials (ST01, ST02, ST03). .... 82

# List of Abbreviations

CMI	Cognitive-Motor Interference
CRR	Correct Response Rate
CV	Coefficient of Variation
DTE	Dual-Task Effect
EEG	Electroenzephalography
fMRI	Functional Magnetic Resonance Imaging
fNIRS	Functional Near-Infrared Spectroscopy
IC	Inertial Contact
ICC	Intraclass Correlation Coefficient
IMU	Inertial Measurement Unit
KIT	Karlsruhe Institute of Technology
MS	Mid Swing
NASA-TLX	NASA-Task Load Index
POC	Performance-Operating-Characteristic
pMCI	Probable Mild Cognitive Impairment
rmANOVA	Repeated-measures Analysis of Variation
RQ	Research Question
RSME	Rating Scale Mental Effort
STR	Stroop test
SUB	Subtraction task
SWAT	Subjective Workload Assessment Technique
TC	Terminal Contact

# 1 Introduction

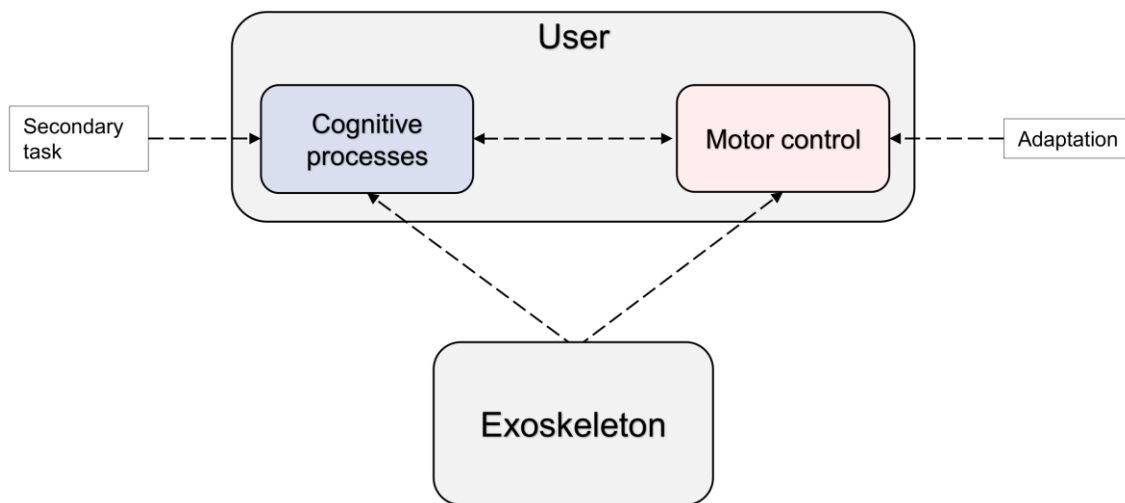
In recent years, the field of wearable robotics or exoskeletons designed to enhance human mobility has witnessed significant advancements. Lower limb exoskeletons have emerged as a potential solution for individuals with mobility impairments, as well as for enhancing the physical capabilities of able-bodied users. These devices, which are worn externally on the legs, aim to assist, augment or restore movement through a combination of mechanical support and sophisticated control systems. Lower-limb exoskeletons not only offer potential rehabilitative benefits but also hold promise for applications in various sectors, including healthcare, military, industrial environments and everyday life (Kalita et al., 2021; Kapsalyamov et al., 2019).

Several technical challenges, such as those related to actuation, materials and power supply, along with the complex requirements of adaptive control, currently limit the deployment of exoskeletons beyond laboratory and clinical settings (Baud et al., 2021; Kalita et al., 2021; Sawicki et al., 2020). Furthermore, Davis et al. (2020) highlight a lack of studies that adopt a human-centered approach, noting that most research remains heavily focused on technical advancements. However, user acceptance, along with the physical and cognitive (i.e., dual-task) demands and biomechanical effects, are key factors in human-exoskeleton interaction research. A recent review on performance evaluation of lower-limb exoskeletons found a strong focus on biomechanical and physiological parameters, while the cognitive aspects have been largely overlooked (Pinto-Fernandez et al., 2020). Initial research at the Massachusetts Institute of Technology introduced the concept of *cognitive fit* in addition to *physical fit* to human-exoskeleton interaction (Stirling et al., 2019). The authors describe cognitive fit as “supporting the perception-cognition-action decision process of the human when wearing the exosystem.” (Stirling et al., 2020, p. 431). This concept emphasizes the necessity of designing exoskeletons that align with the user’s cognitive capabilities to preserve their ability to perform operational tasks in daily life and work environments effectively. Maintaining users’ cognitive abilities is essential for ensuring functional and safe interaction with exoskeletons, particularly in complex, multi-task scenarios.

People often routinely perform multiple tasks simultaneously in daily life, which can lead to performance decline when cognitive resources are insufficient. In scenarios where a motor task is performed alongside a cognitively demanding task, this decline is referred to as *cognitive-motor*

*interference* (Al-Yahya et al., 2011). For instance, studies have demonstrated that both older and younger healthy adults slow down walking speed when engaged in a secondary task (Yogev-Seligmann et al., 2010). Additionally, in complex environments or during challenging motor tasks, individuals tend to allocate greater cognitive resources to perform the motor task to ensure a stable walking pattern, resulting in performance reductions in the secondary task (Yogev-Seligmann et al., 2012). Similarly, exoskeleton use can increase motor control demands required to maintain a stable gait, which can significantly increase cognitive workload (Bequette et al., 2018, 2020) and affect the allocation of cognitive resources between tasks. Due to modified biomechanics, such as restricted range of motion and changes in body mass and inertia caused by the exoskeleton's rigid structures and actuators, users may need to exert greater attentional effort to adjust their muscle activation patterns (Andrade et al., 2024; Jin et al., 2017). While research has examined the cognitive demands of both lower-limb and upper-limb exoskeletons (Marchand et al., 2021), there is a lack of studies evaluating simultaneous cognitive and motor performance during dual-task walking with lower-limb exoskeletons.

This thesis aims to evaluate cognitive fit by examining cognitive-motor interference (CMI) during human-exoskeleton interaction. Using a multimodal experimental approach, both cognitive and motor performance, along with perceived physical and cognitive workload, are assessed in dual-task walking scenarios. The approach combines a walking task with cognitively demanding secondary tasks. Since different types of the secondary tasks interfere differently with walking (Al-Yahya et al., 2011) and an adaptation to exoskeleton-assisted walking improves interaction efficiency (Poggensee & Collins, 2021), this thesis' methodology takes both the type of secondary task and the short-term adaptation phase into account. It provides insights into how exoskeleton use affects cognitive processes, motor control and the allocation of cognitive resources between these domains. The methodological framework of this thesis is illustrated in Figure 1.



**Figure 1.** Methodological framework to assess cognitive-motor interference in human-exoskeleton interaction.

To investigate cognitive-motor interference in human-exoskeleton interaction, two studies were conducted as part of this thesis. In **Study 1**, participants walked on a treadmill both with and without weight cuffs attached to the upper and lower legs, increasing motor demand by altering body mass and inertia distribution. During these walking conditions, participants performed either a serial subtraction task, a visual-verbal Stroop test or no secondary task. **Study 2** extended this investigation to an outdoor setting, where participants walked overground with and without a powered lower-limb exoskeleton while performing a serial subtraction task or no secondary task.

**Chapter 2** provides the theoretical background and current research on lower-limb exoskeletons, human-exoskeleton interaction and cognitive-motor interference. Based on this foundation, **Chapter 3** outlines the research questions and presents the conceptual framework of the thesis. **Chapters 4 and 5** present the publications related to Study 1 and Study 2 as full citations. **Chapter 6** offers a general discussion of the findings, highlighting key findings and their theoretical and practical implications for human-centered exoskeleton design and training.

## 2 Theoretical Background

Chapter 2 outlines the theoretical background of this thesis. Section 2.1 introduces lower-limb exoskeletons, focusing on their purpose and applications in mobility support and augmentation. Section 2.2 addresses human-exoskeleton interaction, its evaluation and the role of cognitive fit of exoskeletons alongside physical fit. Section 2.3 focuses on cognitive-motor interference as a means to assess cognitive fit, addressing the effects of simultaneous cognitive and motor demands on user performance. The section concludes by presenting the performance operating characteristics (POC) framework as a tool for visualizing these performance dynamics. Together, these sections provide the conceptual basis for the experiments presented in this thesis.

### 2.1 Lower-limb exoskeletons

Lower-limb exoskeletons are wearable robotic systems designed to restore, assist or augment the biomechanical functions of the user's legs. In addition to the distinction between passive and active lower-limb exoskeletons, the literature further classifies these devices according to criteria such as actuation method, control strategy, power source, mechanical design, sensor technology and field of application (Baud et al., 2021; Dollar & Herr, 2008; Kalita et al., 2021; Kapsalyamov et al., 2019). Baud et al. (2021) classified lower-limb exoskeletons to fully mobilizing and partially assisting exoskeletons. Exoskeletons for full mobilization such as the ReWalk (Esquenazi et al., 2012), eLEGs (Strausser & Kazerooni, 2011) and TWIN (Laffranchi et al., 2021) (see Figure 2) are commonly used in rehabilitation, particularly for individuals who are unable to initiate or control their own movements. These systems often employ relatively simple control strategies to guide the user's limbs through fixed trajectories using position control. This strategy is straightforward to implement, as it relies on pre-defined motion patterns rather than real-time adaptations. Exoskeletons designed for partial assistance such as the BLEEX (Kazerooni & Steger, 2006) and the HAL (Sankai, 2011) address a broader range of use cases and end users, including supporting individuals with residual mobility or augmenting physical performance in healthy individuals. These devices require more adaptive control strategies to interact effectively with the user and respond to complex, real-world environments. Adaptive strategies integrate information about the user's state and intent, environmental factors and the system's own

state to adjust its assistance (Tucker et al., 2015). However, implementing these advanced control strategies is challenging due to the complex nature of the interaction (Baud et al., 2021). Understanding the interaction between the user and the exoskeleton is crucial for developing effective and safe control strategies and refining exoskeleton design.



Figure 2. Example of a lower-limb exoskeleton: TWIN exoskeleton. Right image adapted from Semprini et al. (2022).

## 2.2 Human-exoskeleton interaction

Human-exoskeleton interaction describes the physical and cognitive interplay between the exoskeleton, the user and the environment. Adapted from Tucker et al. (2015), Figure 3 shows a human-exoskeleton interaction framework for a partially assisting exoskeleton with an adaptive control. This framework integrates four subsystems: the user, the exoskeleton, the environment and the control unit. These subsystems communicate through either physical interactions (thick arrows) or signal-level exchanges (thin arrows).

**The user** interacts directly with the mechanical structure of the exoskeleton. This interaction is bidirectional: the user's movements and biomechanical signals (e.g., joint angles, muscle activity) influence the exoskeleton's behavior, while the exoskeleton provides support in the form of

physical assistance. The user's state and intent in form of sensor data is transmitted to the control unit for processing and real-time adaptation of the exoskeleton's behavior. **The exoskeleton** subsystem comprises the mechanical and actuation components that provide physical assistance to the user. It executes control commands received from the control unit and provides feedback on its current state (e.g., joint positions, motor torques or force exerted). This feedback mechanism ensures control and allows the system to adapt dynamically to changes in user behavior or environmental conditions. **The control unit** acts as the central component, synthesizing data from the user, exoskeleton and environment to generate control commands.

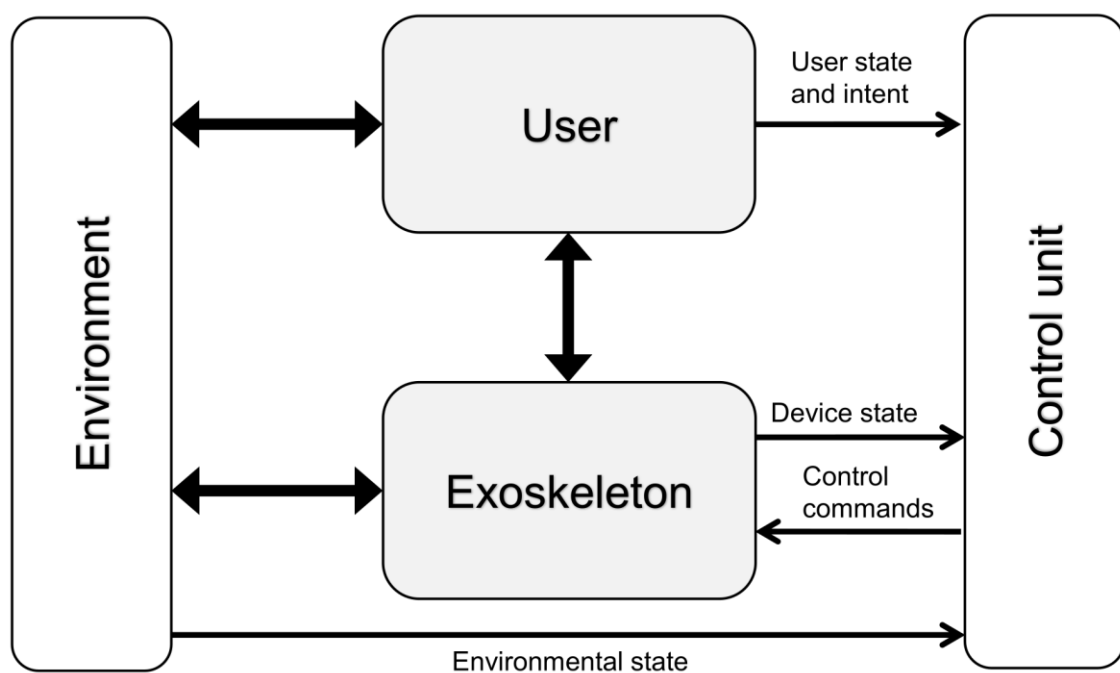


Figure 3. Human-exoskeleton interaction framework for powered exoskeletons with an adaptive control unit. Adapted from Tucker et al. (2015).

### 2.2.1 Evaluation of human-exoskeleton interaction

The evaluation of human-exoskeleton interaction is critical for demonstrating the effectiveness of exoskeletons and guiding their design and control. Pinto-Fernandez et al. (2020) reviewed the existing literature on the performance evaluation of lower-limb exoskeletons. They categorized studies based on the motor skills assessed and the performance indicators employed. The motor skills predominantly evaluated include walking tasks such as overground walking, treadmill walking and navigating irregular terrain, along with other functional activities such as standing and

sit-to-stand transitions. Performance indicators were systematically classified into three categories: goal-level (e.g., maximum speed or minimum time, distance achievable by the device, stability, endurance, versatility and dependability), kinematics and kinetics (e.g., spatiotemporal parameters, joint or limb kinematics and kinetics, symmetry, coordination and human likeness) and human-robot interaction (e.g., metabolic cost, ergonomics, comfort, muscle effort, interaction forces, cognitive effort and safety). The results highlight that most studies prioritize the evaluation of physiological and biomechanical parameters during straight walking tasks. Sawicki et al. (2020) also report that when the primary objective of an exoskeleton is to reduce physical effort, the metabolic cost serves as a gold-standard metric.

Several limitations in current evaluation methods have been identified. Pinto-Fernandez et al. (2020) and Sawicki et al. (2020) highlight the need to move beyond controlled lab settings and assess exoskeleton performance in realistic environments. Evaluating performance across different motor tasks is essential to ensure the practical applicability of these devices. At the same time it is important to develop standards and benchmarks to enhance comparability of results between exoskeletons (Torricelli et al., 2020). Furthermore, the cognitive aspects of human-exoskeleton interaction, particularly the cognitive workload associated with their operation, remain insufficiently investigated (Pinto-Fernandez et al., 2020). To address this, Stirling et al. (2020; 2019) emphasize the need to include the paradigm of cognitive fit in addition to physical fit in the design and evaluation of exoskeletons.

### 2.2.2 Cognitive fit in human-exoskeleton interaction

Cognitive fit refers to the alignment between the exoskeleton's design and the user's cognitive processes required for goal-oriented tasks and seamless interaction. Various human factor concepts help to understand and evaluate cognitive fit in human-exoskeleton interaction, including mental models, attention, workload and situation awareness (Stirling et al., 2019). In the context of human-exoskeleton interaction, *mental models* are internal representations that individuals develop to understand and predict how the device operates. Effective cognitive fit supports the development of accurate mental models, enabling users to anticipate system behavior and make informed decisions. *Attention* refers to the process of directing awareness toward a specific element in the environment and can be defined as the information processing capacity of an individual (Woollacott & Shumway-Cook, 2002). Understanding how attention is allocated and the

factors that influence shifts in focus during exoskeleton operation is crucial to evaluate human-exoskeleton interaction. *Cognitive workload* is defined as the total amount of cognitive resources required to perform tasks, including operating the exoskeleton. *Situation awareness* involves understanding the environment, recognizing changes and predicting future states. Effective cognitive fit ensures that the user can maintain high situation awareness, particularly in complex scenarios.

Cognitive fit develops dynamically as the user adapts to the exoskeleton. Rasmussen's (1983) behavioral levels provide a useful framework for understanding this process. In the *knowledge-based behavior* stage, the user relies on conscious reasoning to interact with the exoskeleton. Errors may be more frequent as the user develops a mental model of the system and learns to coordinate movements. With practice, they transition to *rule-based behavior*, relying on established rules and procedures. This reduces cognitive demand, as tasks become more familiar and efficient. Finally, in the *skill-based behavior* stage, interactions with the exoskeleton become automatic, requiring minimal conscious attention.

Assessing workload and attentional processes provides an effective way to measure the cognitive fit of exoskeleton designs and evaluates changes over time. Accordingly, this thesis focuses on evaluating cognitive-motor interference as a means to infer cognitive workload and attentional processes in dual-task scenarios.

## 2.3 Cognitive-motor interference

Cognitive-motor interference (CMI) refers to the interaction and potential conflict that arises when cognitive and motor tasks are performed simultaneously. This thesis focuses on walking as the motor task under investigation. Walking is characterized by a cyclical and reciprocal pattern of limb movement that is consistent among healthy individuals. It relies on the continuous integration of sensory information from visual, proprioceptive, and vestibular systems (Beurskens & Bock, 2012). However, in healthy individuals, gait control is predominantly automatic, reflecting the nervous system's capacity to maintain steady-state locomotion with minimal use of attentional resources (Clark, 2015).

The complexity of human locomotion becomes apparent in cases of pathological gait or when individuals must adapt to novel contexts, such as navigating uneven terrain, performing dual

tasks or utilizing assistive technologies like orthoses and lower-limb exoskeletons. Dual-task research has demonstrated that walking and cognitive processes are interdependent (Al-Yahya et al., 2011; Bayot et al., 2018; Woollacott & Shumway-Cook, 2002) and walking closely relates to executive functions and divided attention (Springer et al., 2006; Yogev-Seligmann et al., 2008). Brain-imaging studies have found that walking engages brain regions associated with higher-order cognitive control (Dennis Hamacher et al., 2015). For instance, gait speed control areas appear to share neural networks with executive functions, particularly involving the prefrontal cortex (Al-Yahya et al., 2011). Various theories exist to explain the mechanisms underlying CMI (Lacour et al., 2008; Leone et al., 2017; Wollesen et al., 2016; Yogev-Seligmann et al., 2008).

### 2.3.1 Theories related to cognitive-motor interference

The most popular theories used to explain CMI are capacity sharing, bottleneck and cross-talk theories (Leone et al., 2017). *Capacity sharing theories* suggest that cognitive and motor tasks share a limited pool of resources that can be flexibly shifted. The *central capacity theory* suggests that attention is a single resource pool that can be allocated to various tasks, with performance depending on the total demand on this shared resource (Kahneman, 1973). In contrast, the *multiple resource theory* posits that attention consists of several separate pools tied to specific modalities (e.g., visual, auditory), processing stages or response types, allowing tasks using different resources to interfere less with one another than tasks drawing on the same resource (Wickens, 2002). The *bottleneck theory* focuses on a structural limitation in information processing rather than a limited resource capacity (Pashler, 1994). This structural limitation or bottleneck is believed to occur at the response selection stage. When two tasks require a response, the response selection for the second task must wait until the response selection for the first task is complete. The *cross-talk theory* proposes that crosstalk arises when the processing of one task interacts with the processing of another task, even if there are no resource limitations (Navon & Gopher, 1979; Navon & Miller, 1987). This theory suggests that limitations in cognitive processing are not just about the quantity of resources or structural bottlenecks but also about the nature and relationship of the information being processed.

Several theories directly address CMI, considering both task-related and individual-related factors. For instance, the degree of interference and the prioritization of tasks depends on factors

such as individual characteristics (e.g., age, physical fitness, cognitive abilities) and the complexity of the tasks involved (Yogev-Seligmann et al., 2012). The *task prioritization model* posits that cognitive resources are allocated based on an individual's postural reserve and hazard estimation (Yogev-Seligmann et al., 2012). Postural reserve encompasses all factors that ensure effective postural control, reflecting an individual's "capacity to respond most effectively to a postural threat" (Yogev-Seligmann et al., 2012, p. 766). Hazard estimation involves cognitive self-awareness, including the evaluation of environmental risks and personal limitations. Young, healthy adults are generally believed to have an intact postural reserve and effective hazard estimation, enabling them to focus on secondary tasks without compromising their gait performance. The *dual-process model*, also known as the *U-shaped non-linear interaction model* (Huxhold et al., 2006), describes a U-shaped relationship between cognitive task difficulty and motor performance. According to this model, simple cognitive tasks improve motor performance by promoting an external focus of attention. In contrast, complex tasks lead to competition for cognitive resources, resulting in decreased motor performance (Decker et al., 2016; Lövdén et al., 2008). The *supra-postural task model* (Stoffregen et al., 2007; Stoffregen et al., 2000; Stoffregen et al., 1999) explains changes in motor performance from a situational awareness perspective rather than task difficulty. According to this model, motor performance may align with the goals of a secondary task, such as stabilizing head motion during walking while focusing on specific visual stimuli in the environment.

### **2.3.2 Quantification of cognitive-motor interference**

Methods to quantify cognitive workload or attentional processes include subjective self-reports, physiological measures and task performance measures (Dehais et al., 2020; Marchand et al., 2021; M. S. Young et al., 2015). These methods are similarly applicable to quantify CMI.

*Subjective measures* rely on individuals' self-reports of their demands during a task using questionnaires such as the NASA Task Load Index (NASA-TLX) (Hart & Staveland, 1988), the Rating Scale Mental Effort (RSME) (Zijlstra, 1993) or the Subjective Workload Assessment Technique (SWAT) (Reid & Nygren, 1988). Although these questionnaires provide valuable insight into perceived workload, they may be influenced by individual biases or rely on retrospective interpretation, making them most effective when complemented by objective measures (M. S. Young et al., 2015).

*Physiological measures* provide objective measures of mental workload by analyzing the body or brain responses to task demands (Charles & Nixon, 2019). These include electrocardiac activity (e.g., heart rate, heart rate variability), respiration measures (e.g., respiratory rate, airflow, volume or gas composition), skin-based measures (e.g., electrodermal activity, skin conductance), blood pressure, ocular metrics (e.g., blink rate, blink duration, pupil size) and brain activity (e.g., electroencephalography [EEG], functional magnetic resonance imaging [fMRI]), functional near-infrared spectroscopy [fNIRS]). However, a notable limitation of physiological measures is their susceptibility to errors, particularly when transitioning from controlled laboratory settings to real-world environments (Charles & Nixon, 2019).

*Performance measures* are central to evaluating CMI, particularly within dual-task paradigms. Performance in cognitive tasks such as serial subtractions, Stroop tests, n-back tasks or Go/No-Go tasks is typically evaluated through behavioral parameters, including reaction time, response accuracy and response speed. Motor performance during walking can be assessed using spatio-temporal gait parameters, as well as more complex measures of stability, coordination and rhythmicity, such as Lyapunov coefficients, Floquet multipliers and the harmonic ratio. Among spatio-temporal gait parameters, gait velocity is the most frequently measured in dual-task experiments, alongside other parameters like cadence, stride length and stride time (Al-Yahya et al., 2011). Analyzing stride-to-stride variability is particularly important for evaluating motor control. Low variability suggests reliance on automatic motor processes, while high variability indicates attentional involvement in motor control (Hausdorff, 2005, 2007; Newell & Corcos, 1993; Springer et al., 2006). For instance, high gait variability is associated with an increased risk of falls in older adults (Hausdorff et al., 2001; Maki, 1997; Pieruccini-Faria et al., 2020).

A widely used metric for quantifying the relative decline in cognitive or motor performance between single-task and dual-task conditions is the dual-task effect (DTE) (Kelly et al., 2010):

$$DTE = \frac{(Parameter_{dual\ task} - Parameter_{single\ task})}{Parameter_{single\ task}} \times 100\%$$

Negative DTE values indicate interference, suggesting that task demands exceeded available cognitive resources or that resources were reallocated due to changes in task prioritization.

### 2.3.3 Research related to cognitive-motor interference

**Ageing and neurological disorders.** Cognitive-motor interference has been extensively studied in clinical and epidemiological contexts, particularly using the dual-task walking paradigm. This approach has shown the impact of age-related cognitive decline and neurological disorders on the interaction between cognitive and motor functions (Beurskens & Bock, 2012; Kelly et al., 2012). Age-related changes in brain structure, particularly in the prefrontal cortex, contribute to a decline in executive functions and attentional capacities, which are critical for handling simultaneous cognitive and motor tasks (Yogev-Seligmann et al., 2008). Lundin-Olsson et al. (1997) demonstrated that older adults who were unable to walk while talking were significantly more prone to falls. Springer et al. (2006) support this link, reporting increased gait variability under dual-task conditions in fall-prone individuals compared to non-fallers.

Gait impairments in individuals with neurological disorders are also exacerbated under dual-task conditions (Kelly et al., 2012; Klotzbier & Schott, 2017). For instance, Klotzbier and Schott (2017) found that older adults with probable mild cognitive impairment (pMCI) exhibited significantly greater motor dual-task costs compared to both younger adults and healthy older adults. Additionally, the study identified distinct patterns of attentional resource allocation. Participants with pMCI prioritized the cognitive task over the motor task to a greater extent than the control groups, thereby increasing their risk of falls.

**Task complexity.** Beyond individual characteristics, the type and complexity of motor and cognitive tasks significantly influence CMI (Yogev-Seligmann et al., 2012). Al-Yahya et al. (2011) classified cognitive tasks into five categories: reaction time, decision-making, mental tracking, working memory and verbal fluency, emphasizing the varying cognitive demands and processes involved. For instance, tasks involving internal cognitive processes, such as mental tracking, tend to interfere stronger with walking than reaction time or verbal fluency tasks. This is supported by Patel et al. (2014), who observed that CMI during dual-task walking varies based on the type and perceived complexity of the cognitive task.

More complex motor tasks typically demand increased cognitive resources, as demonstrated by heightened activity in cortical and subcortical regions, including the motor cortex, thalamus, basal ganglia, parietal lobule, and the frontal and occipital lobules (Godde & Voelcker-Rehage, 2010; Dennis Hamacher et al., 2015). Maintaining a stable gait, even during relatively simple

walking tasks, requires a considerable allocation of conscious attention, which increases with motor task complexity (Clark, 2015). Numerous studies have explored the effects of motor task complexity on CMI in both healthy individuals and individuals with neurological disorders (Kao & Pierro, 2022; Kelly et al., 2010; McFadyen et al., 2009; Reiser et al., 2019; Timmermans et al., 2018). Timmermans et al. (2018) investigated CMI in stroke patients during walking through both real and virtual obstacle environments. Their results demonstrated that obstacle negotiation, regardless of modality, led to significantly greater CMI compared to unobstructed walking. Although overall interference levels were comparable between the real and virtual conditions, notable differences emerged in task prioritization. Participants prioritized motor performance in the real obstacle environment, reflecting stronger adherence to the *posture-first* strategy (Shumway-Cook et al., 1997). Complementary findings were reported by Reiser et al. (2019) in a mobile EEG study with healthy young adults. Findings showed that increasing walking complexity in an outdoor walking scenario was associated with a reduction in parietal P3 amplitude. This reduction suggests that more complex motor conditions increase cognitive demand, thereby limiting the capacity available for secondary cognitive tasks. Correspondingly, participants reported higher subjective workload and exhibited reduced cognitive task performance as walking complexity increased.

**Lower-limb exoskeletons.** Operating a lower-limb exoskeleton can be considered a complex motor task, as it may impact natural walking patterns by restricting joint movement and changing mass distribution (Jin et al., 2017). These biomechanical changes require users to adapt their neuromuscular control strategies, thereby increasing attentional demands to ensure stable walking (Andrade et al., 2024). Bequette et al. (2020) found that, during a simulated patrol task, some participants exhibited slower reaction times in a concurrent visual search task while using a powered lower-limb exoskeleton, with performance decrements more pronounced under powered conditions. Furthermore, subjective workload ratings, as assessed by the NASA-TLX, were significantly higher during both powered and unpowered exoskeleton-assisted walking compared to unassisted walking. The authors also highlighted the inter-individual variability in performance parameters. Consistent with this observation, Leibman et al. (2022) reported variability in cognitive performance across participants. Their study utilized a dual-task protocol combining a visual attention task with a physical peg-in-hole activity, requiring squatting or overhead work, while using either shoulder-mounted or lower-limb exoskeletons. The findings suggested that these differences not only varied between participants but also between different

types of exoskeletons. Using the same experimental paradigm, Leibman and Choi (2025) examined mean task performance and intra-individual variability in both motor and cognitive tasks. Regarding the squatting task involving a passive lower-limb exoskeleton they found increased motor performance variability, i.e. greater inconsistency in completing one trial, but no impact on the cognitive performance. The authors posited that the minimal cognitive load imposed by the exoskeleton could be attributed to the simplicity and passive nature of the device, as well as the relatively static nature of the task. The studies mentioned above did not involve an adaptation period. However, adaptation has shown to improve muscle recruitment patterns (Gordon & Ferris, 2007) and reduce energy costs (Poggensee & Collins, 2021). Higher levels of physical effort have been associated with a shift from automaticity to executive control, thereby increasing cognitive demands (Clark, 2015). Afzal et al. (2017) conducted a study involving eight individuals with multiple sclerosis who underwent up to 15 training sessions walking with and without a lower-limb exoskeleton while performing a reaction time task. Preliminary results revealed no significant differences in reaction times between assisted and unassisted conditions, suggesting that exoskeleton use may not necessarily impose additional cognitive load.

Findings across studies vary substantially and are difficult to directly compare due to inter-individual differences and heterogeneity in experimental protocols, including variations in familiarization periods, exoskeleton types and the specific motor and cognitive tasks employed. No study to date has comprehensively evaluated cognitive and motor performance concurrently in dual-task walking with a lower-limb exoskeleton. Existing work often isolates either motor or cognitive performance, without systematically investigating the interplay between cognitive processes and motor control. To address this gap, the present thesis proposes a novel conceptual framework that explicitly integrates CMI as a central construct in the investigation of human-exoskeleton interaction, with a focus on lower-limb exoskeletons during walking (see Figure 5).

### **2.3.4 Performance operating characteristics**

The performance operating characteristics (POC) framework, first introduced by Norman and Bobrow (1975), provides a method to evaluate how performance on two or more simultaneous tasks varies in relation to changes in resource allocation. The POC framework can serve as a visual-descriptive tool to examine how cognitive resources are distributed across concurrent

tasks which can be valuable when investigating CMI. At the core of this framework lies a distinction between resource-limited and data-limited processing (Norman & Bobrow, 1975). A task is defined as *resource-limited* if its performance can be improved through the allocation of additional cognitive resources. In contrast, a task is *data-limited* when its performance is constrained solely by the quality or quantity of available sensory information. In such cases, further increases in resource allocation do not lead to a performance increase. POCs are particularly meaningful when at least one of the tasks is resource-limited, creating a functional interdependence between them. When two resource-limited tasks are performed concurrently, the principle of complementarity applies: allocating more resources to one task results in fewer resources available for the other (Norman & Bobrow, 1976). Consequently, performance decrements or improvements across tasks can be plotted within a shared resource-performance space. Within the context of the POC framework, Wickens et al. (1981) illustrate dual-task performance as a single point. This point reflects the relative performance decrements in each task when performed simultaneously, as compared to their respective single-task baselines (see Figure 4).

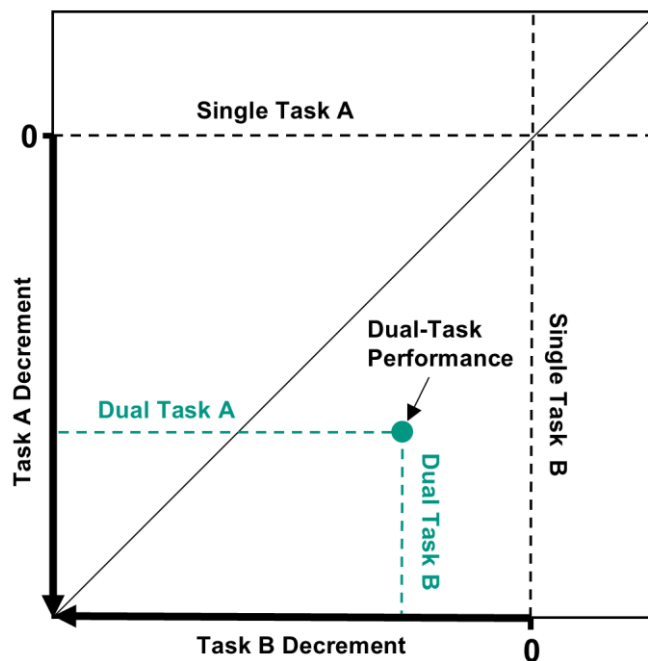


Figure 4. Exemplary representation of dual-task performance within the POC framework. From Riedel and Deml (2025), adapted from Wickens et al. (1981).

A shift toward the upper-right corner of the plot reflects improvements in both tasks, indicating more efficient resource allocation or reduced interference. When the point moves closer to one

of the single-task performance boundaries, represented by black dashed lines, this suggests a prioritization of the corresponding task.

In the context of CMI, Kelly et al. (2010) applied the POC framework to investigate dual-task performance using a walking paradigm. Their study examined how instructed attentional focus and task difficulty influenced performance on both walking and a secondary cognitive task in healthy young adults. By plotting performance within the POC space, the authors were able to quantify the degree of dual-task interference and track how performance shifted under different instructional and task-load conditions. Expanding on this approach, the POC has considerable potential for application in the domain of human-exoskeleton interaction. It provides a method to assess how different exoskeleton systems influence user performance and how performance patterns change throughout the adaptation phase.

### 3 Research Questions

Assessing cognitive-motor interference is particularly relevant in human-exoskeleton interaction, where the user must not only perform motor tasks but also engage in cognitive processes such as decision-making, navigation or interaction with the control system. The dual demands on cognitive resources can lead to reduced performance in either or both domains, posing challenges for user safety and system efficiency. For instance, users navigating uneven terrain may experience an increased cognitive load as they focus on interpreting environmental cues while simultaneously coordinating their movements with the exoskeleton.

To account for the cognitive aspects of human-exoskeleton interaction, the framework shown in Figure 3 has been expanded integrating the methodological framework shown in Figure 1. The resulting conceptual framework shown in Figure 5 shifts the focus from purely physical interaction (thick arrows) to include the cognitive interplay (dashed arrows) between the user and the exoskeleton. Recognizing that exoskeletons may introduce cognitive demands, this framework aims to capture the dynamic allocation of cognitive resources between motor control and other cognitive processes during exoskeleton operation. In this thesis, the allocation of cognitive resources was assessed using both motor and cognitive performance measures. Motor performance was evaluated via gait parameters, cognitive performance via secondary task outcomes and perceived physical and cognitive workload were included as subjective indicators.

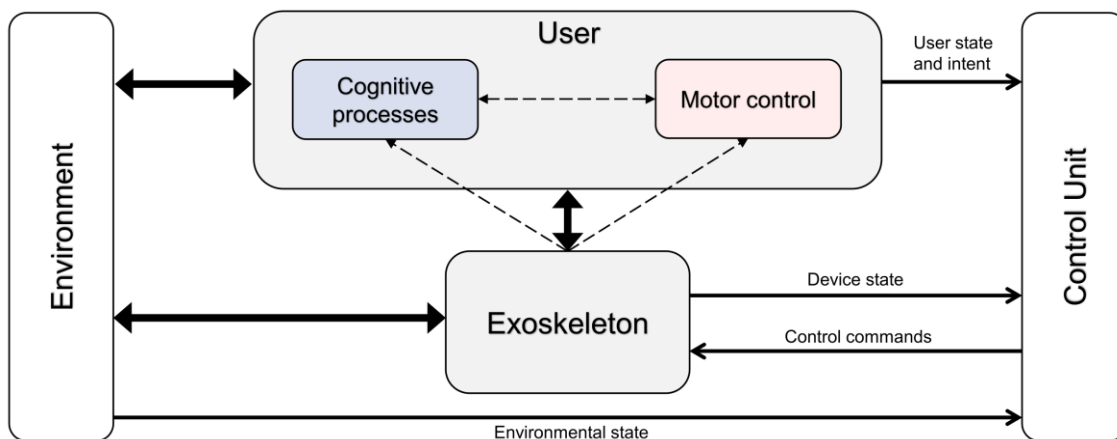
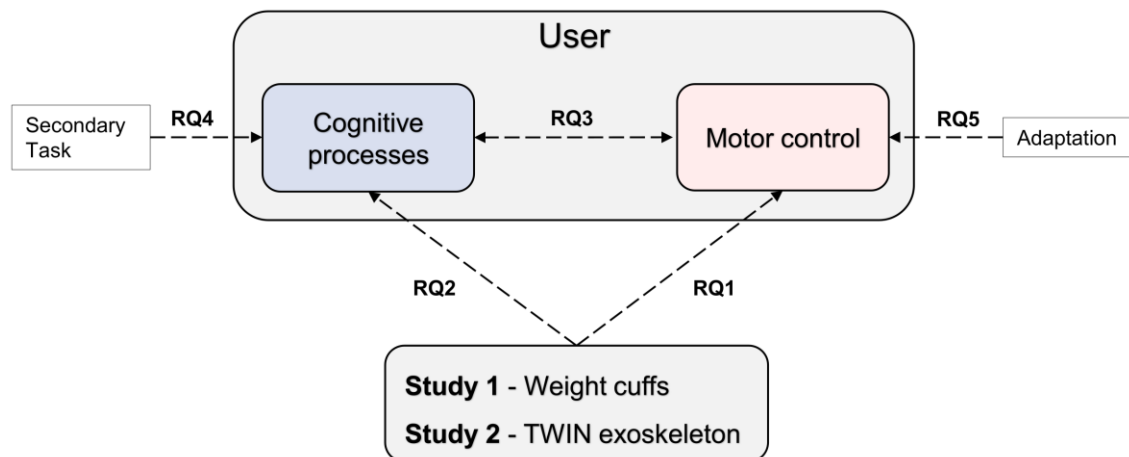


Figure 5. Conceptual framework integrating the cognitive dimension in human-exoskeleton interaction.

Drawing from the literature outlined above, five general research questions (RQs) were derived (see Figure 6):

- RQ1.** How does exoskeleton use influence motor performance (motor control) during walking?
- RQ2.** How does exoskeleton use influence cognitive performance (cognitive processes) during walking?
- RQ3.** How does exoskeleton use influence the allocation of cognitive resources during walking?
- RQ4.** How does the type of the secondary cognitive task modulate cognitive resource allocation during exoskeleton-assisted walking?
- RQ5.** How does short-term adaptation to exoskeleton use influence cognitive resource allocation during walking?



**Figure 6. Methodological framework with research questions (RQ).**

As outlined in the introduction, this thesis comprises two studies. Research Questions 1 to 3 were addressed in both studies. Study 1 additionally focused on Research Question 4, examining the influence of different secondary tasks. Study 2 further addressed Research Question 5, investigating the role of short-term adaptation<sup>1</sup> to exoskeleton-assisted walking. Notably, Study 1

<sup>1</sup> Short-term adaptation refers to early adjustments occurring over limited practice, while familiarization refers to initial exposure and full adaptation refers to long-term changes after extensive training. In this thesis, *short-term adaptation* and *familiarization* are used interchangeably to describe early adjustments over short practice periods (minutes to hours).

utilized weight cuffs to passively modify leg mechanics, rather than employing a powered exoskeleton. As exoskeletons can modify leg mechanics via rigid structures, this setup provides insight into passive exoskeletal effects.

Chapters 4 and 5 provide brief overviews of Studies 1 and 2, respectively, and include full citations of the associated publications. The publications have been incorporated into the overall structure of this thesis, with chapter, figure and table numbering adjusted for consistency and readability. Furthermore, certain figures were removed to eliminate redundancies across the dissertation. While the formatting has thus been adapted, the texts themselves are reproduced in their original published form. As a result, some publications are written in British English and others in American English. All literature references are presented in APA 7 format, consistent with the rest of the thesis. All co-authors of the published papers have declared that they will not use the publication in the context of another academic examination.

## 4 Study 1

In the first study, sixteen participants walked on a treadmill at their preferred walking speed under two conditions: with and without weight cuffs attached to their upper and lower legs. During walking, they simultaneously performed a subtraction task, a Stroop test or no additional task. The objective was to examine how modified leg mechanics, induced by the passive loading of weight cuffs, and varying cognitive demands influence motor and cognitive performance, as well as perceived workload. Since exoskeletons can modify leg mechanics through rigid structural components (Jin et al., 2017), this experimental setup provides insight into the potential effects of passive exoskeletal elements, excluding the influence of active actuator support. Accordingly, the conceptual framework presented in Figure 5 was adapted in Figure 7 to reflect the passive nature of the methodological manipulation, omitting any interaction with a control unit typically found in powered exoskeletons.

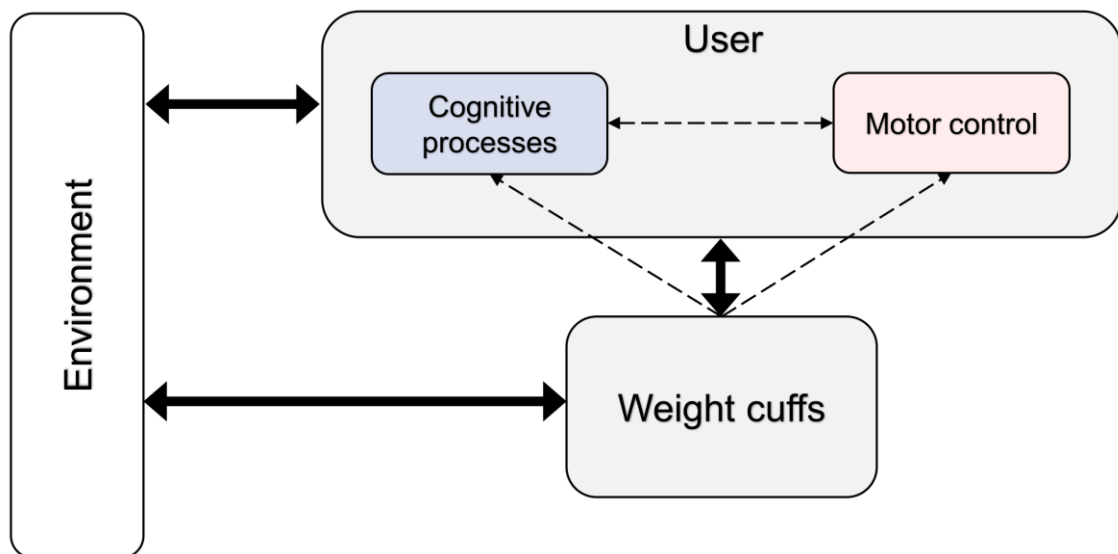


Figure 7. Conceptual framework adapted to the methodology of Study 1.

Study 1 resulted in two publications. The first focused on cognitive performance during the secondary tasks, as well as participants perceived mental and physical workload (see Section 4.1). The second publication built upon these findings by examining motor performance parameters,

including gait variability and mean gait parameters (see Section 4.2). Together, these publications provide an integrated analysis of cognitive and motor performance to assess cognitive-motor interference.

## 4.1 Effects of modified leg mechanics on cognitive performance and workload during dual-task walking

The following subsections (4.1.1 Introduction, 4.1.2 Method, 4.1.3 Results, 4.1.4 Discussion and 4.1.5 Conclusion) are full citations from the publication:

**Riedel, N.**, Herzog, M., Stein, T., & Deml, B. (2023). Effects of modified leg mechanics on cognitive performance and workload during dual-task walking. In D. de Waard, V. Hagemann, L. Onnasch, A. Toffetti, D. Coelho, A. Botzer, M. de Angelis, K. Brookhuis, and S. Fairclough (2023). *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2023 Annual Conference*. (pp. 197-211). Downloaded from <http://hfes-europe.org> (ISSN 2333-4959)

### 4.1.1 Introduction

“Lower limb exoskeletons as assistive walking devices are being studied and developed for a wide variety of applications (see review in A. J. Young & Ferris, 2017). There are a few lower limb exoskeletons, especially in the field of rehabilitation, which are already being used in practical applications using predetermined trajectories (see review in Di Shi et al., 2019). The trajectories are collected from healthy persons normal gait data and restrict the user's motion accordingly to these trajectories. However, there is still a need for research and development before mobile exoskeletons for daily activities and highly dynamic applications successfully move from the laboratory environment to the field (A. J. Young & Ferris, 2017). As this transition gets closer, human factor aspects must receive greater attention in the development and evaluation of exoskeletons (Stirling et al., 2019). Davis et al. (2020) identified three key research areas to inform human-centred design of exoskeletons: user acceptance, physical and mental load (dual demands), and biomechanical effects (e.g., kinematics, kinetics). To date, most research has quantified the effects of lower limb exoskeletons using biomechanical and physiological indicators. In contrast, the investigation of cognitive workload in human-exoskeleton interaction has barely

been considered (Pinto-Fernandez et al., 2020). The analysis of cognitive workload in the context of human-exoskeleton interaction is crucial, because the user's cognitive abilities must be maintained such that operational activities can be performed appropriately (Stirling et al., 2020). A field study with soldiers demonstrated that wearing a lower limb exoskeleton resulted in slowed reaction times in a visual search task for some subjects (Bequette et al., 2018, 2020). This study provides preliminary hints that wearing an exoskeleton during early adaptation may place a cognitive load on the user. The authors suggest that some subjects showed increased cognitive workload due to the interaction with the mechanical properties (weight, bulk, range of motion) and some due to the actively applied assistance (actuators, control strategy).

#### **4.1.1.1 Dual-task walking**

There are different methods to assess cognitive workload. In the context of assistive wearable devices, dual-task paradigms and subjective assessments are predominantly used (Marchand et al., 2021). Dual-task paradigms are of interest in the study of human-exoskeleton interaction, as simultaneous cognitive and motor tasks have been shown to be interdependent (Al-Yahya et al., 2011; Woollacott & Shumway-Cook, 2002). In this context, the literature refers to cognitive-motor interference. Interferences occur when the capacity of limited cognitive resources is reached and is indicated by reductions in performance in the motor or cognitive task, or even in both tasks. The investigation of cognitive-motor interferences is widely used in clinical and epidemiological studies to investigate the influence of age-related factors and neurological diseases on cognitive and motor performance (Beurskens & Bock, 2012; Raffegeau et al., 2019). Motor control to maintain postural stability is thought to require more conscious attention in elderly than in healthy young adults (Lundin-Olsson et al., 1997). However, significant effects of dual task walking on motor or cognitive parameters have also been found in healthy young adults (Patel et al., 2014; Szturm et al., 2013; Yogev-Seligmann et al., 2010).

The extent of cognitive-motor interference is also determined by how the brain prioritises the individual tasks. The allocation of cognitive resources or task prioritisation depends on various factors, such as individual characteristics or task complexity (Kelly et al., 2012; Yogev-Seligmann et al., 2008, 2012). The traditional theory to explain task prioritisation in dual-task walking is the posture first principle, which postulates that healthy subjects prioritise the motor task over the cognitive task to avoid threats like falling when no specific instructions are given (Shumway-

Cook et al., 1997). More recently, research suggests a more complex interplay of individual factors. According to the integrated model of task prioritisation of Yogeve-Seligmann et al. (2012), two main factors contribute to the choice of the task prioritization strategy. One factor is the postural reserve “that reflects the individual’s capability to respond most effectively to a postural threat”. The second factor is hazard estimation that involves different aspects of self-awareness such as the ability to estimate environmental hazards and being aware of self-limitations. These factors together with other factors such as expertise, personality and the nature of the secondary task determine the choice of the prioritisation strategy. Healthy young adults who have a high postural reserve and high hazard estimation prioritise the cognitive task without reductions in gait performance (Yogeve-Seligmann et al., 2012). However, more complex environments or motor tasks can demand the postural reserve, resulting in a shift of attention to the motor task to avoid potentially critical hazards. As a result, less cognitive resources are available to perform the secondary task, which can lead to a reduction in performance (Bequette et al., 2020). Studies using neural correlates support this hypothesis by reporting significant changes in brain activity with varying complexity of the cognitive task (Hill et al., 2013) or motor task (Reiser et al., 2019).

#### **4.1.1.2 Present study**

Using a dual-task walking paradigm, the present study investigates under controlled laboratory conditions the extent to which modified leg mechanics affect motor and cognitive performance while walking on a treadmill. Weight cuffs bilaterally attached to the thighs and shanks of the participants manipulate the mechanical properties and add complexity to the motor task.

The present paper shows preliminary results examining cognitive performance in secondary tasks and perceived workload. It was hypothesised that walking with modified leg mechanics demands the postural reserve and consequently reduces cognitive performance compared to normal walking (H1) and increases perceived cognitive (H2) and physical workload (H3) compared to normal walking or sitting.

## 4.1.2 Method

### 4.1.2.1 Participants

Sixteen healthy young adults (age:  $M = 24.1$ ,  $SD = 3.4$ ; height:  $M = 172.9$  cm,  $SD = 8.8$  cm; mass:  $M = 65.1$  kg,  $SD = 10.4$  kg; sex: 9 female, 7 male) were recruited among students of the Karlsruhe Institute of Technology. Participants completed a medical history screening and were excluded from the study if musculoskeletal, neurological, or cardiovascular disease or red-green weakness was present that could affect walking secondary task performance. Written informed consent was obtained in accordance with approved institutional review board procedures. The ethics committee of the Karlsruhe Institute of Technology approved the study.

### 4.1.2.2 Experimental procedures

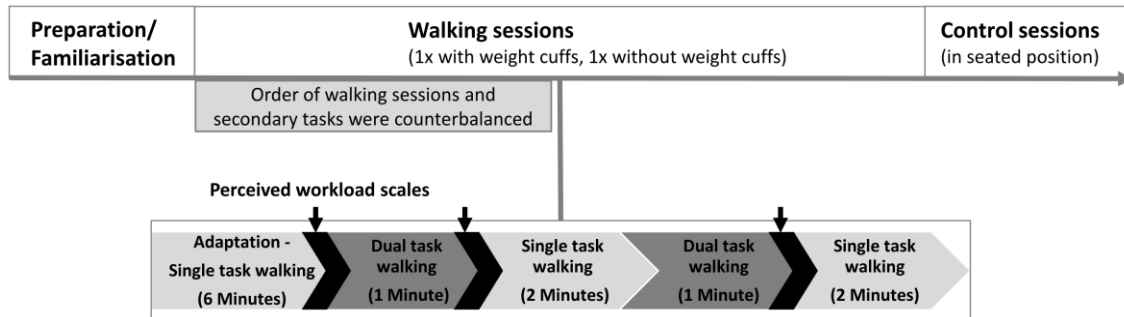
In this experiment with a 3x3 within-subjects design, participants walked on a treadmill with and without weight cuffs bilaterally attached to the thigh and shank (*Motor Condition*: sitting, unloaded walking, loaded walking) and simultaneously performed cognitively demanding secondary tasks (*Cognitive Condition*: no secondary task, visual-verbal Stroop test [STR], descending subtraction task [SUB]). Table 1 gives an overview of the experimental conditions including four single task and four dual task conditions.

**Table 1.** Overview of experimental conditions. ST - single task; DT - dual task

	Sitting	Unloaded walking	Loaded walking
No secondary task	-	Control motor condition (ST <sub>3</sub> )	Control motor condition (ST <sub>4</sub> )
Stroop test (STR)	Control cognitive condition (ST <sub>1</sub> )	DT <sub>1</sub>	DT <sub>3</sub>
Subtraction task (SUB)	Control cognitive condition (ST <sub>2</sub> )	DT <sub>2</sub>	DT <sub>4</sub>

First, for familiarisation, the two secondary tasks were performed in a seated position. After a six-minute familiarisation period of walking on the treadmill (Meyer et al., 2019) and the determination of the preferred gait speed according to the procedure proposed by Jordan et al. (2007), the unloaded and loaded walking sessions were carried out in a counterbalanced order. Finally, the two secondary tasks were performed again in a seated position as single task control

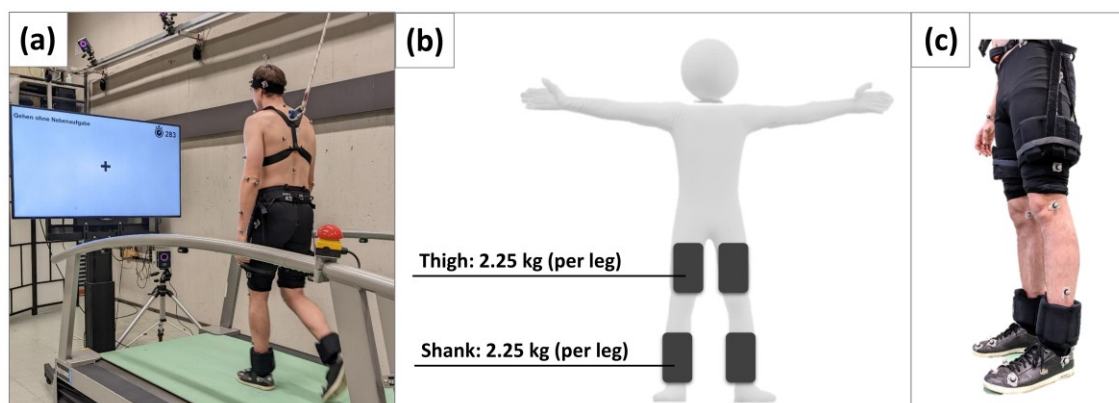
condition (Figure 8). These control conditions are needed to compare task performance under single and dual task conditions.



**Figure 8.** Experimental protocol. Black arrows indicate the times at which the perceived workload subscale were queried during the walking sessions. (Riedel et al., 2023)

#### 4.1.2.3 Motor main task

As a motor task, participants walked on a treadmill (h/p/cosmos, model: saturn 300/100) with and without weight cuffs bilaterally attached to the thigh and shank, each weighing 2.25 kg (total weight: 9 kg). The individual preferred gait speed ( $M = 4.1$  km/h,  $SD = 0.3$  km/h) was kept constant for both sessions. A custom developed hip belt was used to attach the weight cuffs to the thigh. Two Velcro straps were attached to the hip belt on each side of the leg, into which the weight cuffs could be hooked. Figure 9 illustrates the experimental setup, the positions of the weight cuffs and shows how they were attached to a participant along with the hip belt. The Velcro straps could be adjusted in height so that the lower edge of the weight cuffs was positioned 10 cm above the knee joint axis for each participant. A safety harness secured participants while walking on the treadmill. Whole-body movements were recorded using an infrared camera system (Vicon Motion Systems Ltd.) with sixteen cameras. The marker setup includes 56 markers. In the present paper, motor performance is not investigated. However, extensive data sets are available and may be analysed further.



**Figure 9.** (a) Experimental setup. (b) Schematic representation of the positions of the weight cuffs. (c) Representation of the attachment of the weight cuffs to a participant. (Riedel et al., 2023)

#### 4.1.2.4 Cognitive secondary task

In a meta-analysis, Al-Yahya et al. (2011) found that cognitive tasks disturb walking more when internal rather than external interfering factors are involved. Based on the type of mental processes required to perform the tasks, the authors established classifications. Two cognitive tasks from different classifications were used in this study: A visual-verbal version of the Stroop test (STR) (Stroop, 1935) as a decision-making task involving external interfering factors and a descending subtraction task (SUB) as a mental tracking task involving only internal interfering factors.

In STR, a 10x10-matrix of colour words (red, blue, green, yellow) with incongruent word and colour information was presented for 60 seconds (Figure 10). To avoid learning effects, there were five different matrices, which were presented in random order. Participants were instructed to name the respective font colour of the words as quickly as possible and without error. Participants started in the left top corner and continued column wise to the right. Cognitive performance was determined by the correct response rate (CRR). According Galletly and Brauer (2005), this is calculated by multiplying the response rate (responses per second) and the accuracy (percent of correct responses).

In SUB, a random three-digit number between 201 and 999 was presented. The participants were asked to serially subtract the number 7 for 60 seconds starting with the presented number. The CRR was again used as the outcome measure. Both tasks were performed in a seated position (cognitive control condition) and during unloaded and loaded walking. For familiarisation, the participants first completed a 20-second test trial, followed by a 60-second training trial in a

seated position for both tasks. While seated, the tasks were presented on a 22-inch monitor at a distance of approximately 80 cm from the participant. While walking on the treadmill, a 65-inch monitor was used at a distance of 240 cm from the participant. The monitor height was set so that the top edge was at the eye level of the participant. Participants' responses were recorded for analysis via a recording device (Sony, model: ICD- UX570) with a clip-on microphone (Phillips, model: LFH9173/00).

ROT	GELB	ROT	BLAU	ROT	ROT	GRÜN	GELB	BLAU	GRÜN
BLAU	BLAU	GRÜN	GELB	GELB	BLAU	GELB	ROT	ROT	ROT
ROT	ROT	ROT	GRÜN	BLAU	GELB	GRÜN	BLAU	ROT	BLAU
GRÜN	GELB	GRÜN	ROT	GRÜN	GRÜN	BLAU	GELB	GRÜN	GELB
GELB	GELB	ROT	BLAU	ROT	ROT	ROT	GRÜN	GELB	BLAU
ROT	GRÜN	GRÜN	GELB	GELB	GELB	GRÜN	GELB	GRÜN	GRÜN
BLAU	BLAU	GELB	ROT	ROT	GRÜN	BLAU	ROT	BLAU	GRÜN
GRÜN	ROT	BLAU	GRÜN	GRÜN	ROT	ROT	BLAU	GELB	BLAU
GELB	GELB	GRÜN	GELB	BLAU	GELB	GELB	GRÜN	ROT	GELB
ROT	GRÜN	ROT	BLAU	GRÜN	BLAU	BLAU	GELB	BLAU	ROT

Figure 10. Exemplary 10x10-matrix of colour words as used in the study. (Riedel et al., 2023)

#### 4.1.2.5 Walking protocol

Figure 8 shows the protocol of a walking session. Both walking sessions (unloaded and loaded walking) started with a six-minute block of single task walking (motor control condition). This block controlled for possible adaptation effects to ensure that participants did not have to use cognitive resources to adapt to unfamiliar walking conditions. Noble and Prentice (2006) showed that adaptation is completed after 45-50 strides when walking with unilateral weights. This was followed by the first secondary task for 60 seconds. To counteract cognitive fatigue, a two-minute block of single task walking followed before the second secondary task was presented for 60 seconds. Sessions ended with another two-minute block of single task walking. In total, this protocol lasted 12 minutes each. The order of walking sessions and appearance of secondary

tasks were counterbalanced to account for fatigue and learning effects. No specific instructions were provided regarding which task to prioritise.

#### 4.1.2.6 Subjective measures

Immediately after each of the eight experimental conditions (Table 1), the two subscales Mental Demand and Physical Demand of the NASA-TLX (Hart & Staveland, 1988) were queried. Here, participants were presented with the subscale description along with the scale (0 – low demand, 100 – high demand) and had to verbally indicate the number that was appropriate for them. While walking on the treadmill, participants had 30 seconds per subscale to give a response. Figure 8 indicates the time of the queries with black arrows.

#### 4.1.2.7 Dependent variables and statistics

The effects of the experimental conditions on cognitive performance and perceived workload were determined using the CRR and ratings of NASA-TLX subscales, respectively. To assess relative change of the CRR the dual task effects (DTE) were calculated (Kelly et al., 2010). Negative values represent a reduction under dual task conditions; positive values represent an improvement under dual task conditions. Since a lower CRR represents a reduction in task performance, the DTEs are calculated as follows:

$$DTE = \frac{(CRR_{dual\ task} - CRR_{single\ task})}{CRR_{single\ task}} \times 100\%$$

The Kolmogorov-Smirnov test was used to test the data for normal distribution. In the ratings on perceived workload, the assumption of normal distribution was violated in three out of twelve conditions. Since rmANOVAs are considered robust to violations of the normal distribution, the parametric tests were nevertheless used (Vasey & Thayer, 1987). Homogeneity of variances was tested using Levene's test based on the median and homogeneity of covariances was calculated by Box's test. Sphericity of the data was tested with the Mauchly test. When this assumption was violated, degrees of freedom were adjusted with the Greenhouse-Geisser correction. For all statistics, significance level was set a priori as  $\alpha = .05$ . Bonferroni correction was applied to post hoc comparisons. Effect sizes are given as partial eta squares with  $\eta_p^2 = .01$  indicating a small effect,  $\eta_p^2 = .06$  a medium effect and  $\eta_p^2 = .14$  a large effect (Cohen, 1988). Statistics were evaluated using SPSS 28 (IBM Statistics Armonk).

A 2x2x2-mixed-ANOVA with within-factors *Task Condition* (STR, SUB) and *Motor Condition* (Unloaded walking, loaded walking) and between-factor *Session Order* (Start with unloaded walking, start with loaded walking) was conducted to test differences in DTE (H1). Since the analysis of the descriptive data indicated order effects, this was exploratively included in the statistical model. The between-factor *Session Order* was used to investigate whether it makes a difference if the walking session is started with unloaded or loaded walking. Two 2x3-rmANOVAs were conducted with within-factors *Task Condition* (STR, SUB) and *Motor Condition* (Sitting, unloaded walking, loaded walking) to test differences of perceived cognitive (H2) and physical workload (H3).

### 4.1.3 Results

Table 2 shows absolute and relative values for cognitive performance variables and for perceived cognitive and physical workload in each single task and dual task condition.

#### 4.1.3.1 Cognitive performance

Analysis of DTE showed no significant main effects of *Task Condition* ( $F(1, 14) < 1, p = .974, \eta_p^2 < .000$ ), *Walking Condition* ( $F(1, 14) = 2.79, p = .117, \eta_p^2 = .166$ ) and *Session Order* ( $F(1, 14) = 2.20, p = .160, \eta_p^2 = .136$ ).

There was a significant interaction effect between *Walking Condition* and *Task Condition* ( $F(1, 14) = 5.65, p = .032, \eta_p^2 = .287$ ). This indicates that the cognitive performance in the different walking conditions differed according to the type of task performed. Reviewing the interaction graph in Figure 11a, this suggests that cognitive performance in SUB decreases from unloaded to loaded walking, whereas cognitive performance in STR shows no differences from unloaded to loaded walking.

**Table 2.** Absolute and relative measures of cognitive performance and perceived cognitive and physical workload. Values represent mean (standard deviation). DTE - dual task effects.

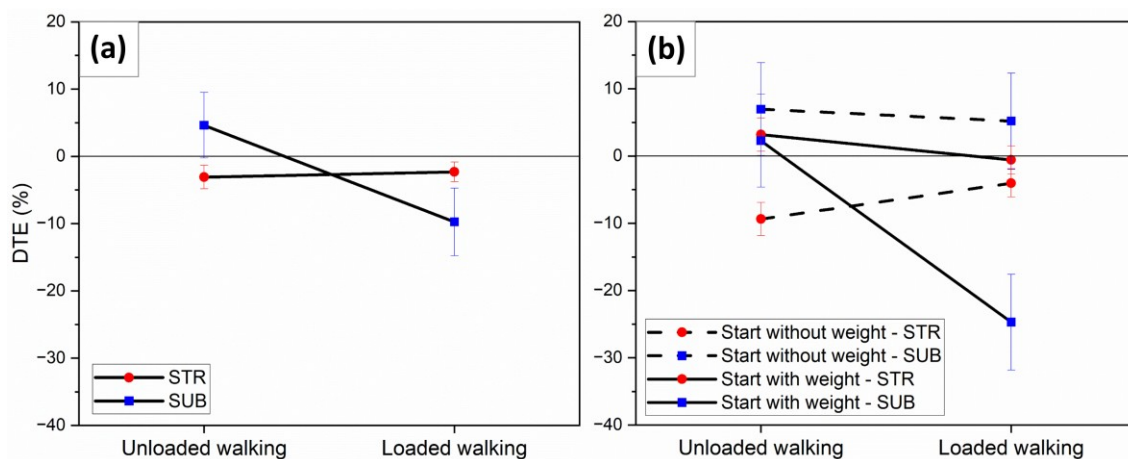
	Sitting	Unloaded walking	Loaded walking
<b>Performance – Stroop-Test</b>			
Correct response rate	1.200 (0.262)	1.155 (0.225)	1.169 (0.242)

	<b>Sitting</b>	<b>Unloaded walking</b>	<b>Loaded walking</b>
Correct response rate DTE (%)	-	-3.09 (9.36)	-2.32 (5.90)
Starting w. unloaded walking (n=8)	-	-9.37 (2.47)	-4.05 (2.06)
Starting w. loaded walking (n=8)	-	3.19 (2.47)	-.58 (2.06)
<b>Performance – Subtraction-Task</b>			
Correct response rate	.277 (0.106)	.288 (0.113)	.251 (0.119)
Correct response rate DTE (%)	-	4.62 (19.02)	-9.75 (24.81)
Starting w. unloaded walking (n=8)	-	6.97 (6.91)	5.20 (7.11)
Starting w. loaded walking (n=8)	-	2.28 (6.91)	-24.70 (7.11)
<b>Workload – Stroop-Test</b>			
Cognitive workload	38.0 (23.6)	35.1 (25.1)	40.4 (28.2)
Physical workload	3.5 (4.7)	15.1 (8.6)	37.2 (21.6)
<b>Workload – Subtraction-Task</b>			
Cognitive workload	49.6 (24.9)	48.9 (22.8)	56.4 (25.6)
Physical workload	3.7 (5.0)	15.1 (7.3)	37.3 (22.7)
<b>Workload – No secondary task</b>			
Cognitive workload	-	6.7 (9.8)	8.5 (8.6)
Physical workload	-	14.1 (9.3)	37.1 (21.8)

There was a significant interaction effect between *Task Condition* and *Session Order* ( $F(1, 14) = 9.03$ ,  $p = .009$ ,  $\eta_p^2 = .392$ ). This indicates that cognitive performance in STR and SUB differed depending on the session order. Figure 11b shows the mean DTE for each dual task condition for the group of participants who started with unloaded walking and the group of participants who started with loaded walking. The interaction graph revealed a disordinal interaction suggesting that starting with loaded walking strongly reduces cognitive performance for SUB and

only slightly for STR. Starting with unloaded walking seems to have the opposite effect, suggesting a reduced cognitive performance in STR and a slightly increased cognitive performance in SUB.

The interaction effect between *Walking Condition* and *Session Order* showed a statistical trend ( $F(1, 14) = 4.43, p = .054, \eta_p^2 = .240$ ). This indicates that cognitive performance during unloaded and loaded walking tend to differ depending on the session order (Figure 11b). The interaction graph revealed a disordinal interaction suggesting that starting with loaded walking decreases the cognitive performance during loaded walking and has only small positive effects on cognitive performance during unloaded walking. In contrast to this, starting with unloaded walking has only small effects on cognitive performance for both walking conditions.



**Figure 11. (a) Mean dual task effects (DTE) for STR and SUB in the unloaded and loaded walking condition. (b) Mean DTE for STR and SUB in the unloaded and loaded walking condition for the group of participants who started with unloaded walking ( $n=8$ ) and the group of participants who started with loaded walking ( $n=8$ ). Error bars reflect 95% CI. (Riedel et al., 2023)**

The three-way interaction *Walking Condition*  $\times$  *Task Condition*  $\times$  *Session Order* was not significant ( $F(1, 14) = 1.60, p = .227, \eta_p^2 = .102$ ).

#### 4.1.3.2 Perceived cognitive workload

There was a significant main effect of *Task Condition* on the perceived cognitive workload ( $F(1, 15) = 9.257, p = .008, \eta_p^2 = .382$ ). Reviewing the mean ratings indicated that the SUB was perceived as more cognitively demanding than STR (Figure 12a). There was also a significant main effect of the *Motor Condition* on the perceived cognitive workload ( $F(2, 30) = 4.155, p = .026, \eta_p^2 = .217$ ). Post-hoc analysis revealed that perceived cognitive workload was not significantly

different from control condition to unloaded walking (MDiff = 1.81, 95%-CI [-2.46, 6.08],  $p = .813$ ) and to loaded walking (MDiff = -4.59, 95%-CI [-11.78, 2.59],  $p = .317$ ). The difference of perceived cognitive workload between unloaded and loaded walking showed a statistical trend (MDiff = -6.41, 95%-CI [-13.07, 0.26],  $p = .062$ ), suggesting a higher perceived cognitive workload in loaded compared to unloaded walking. There was no significant interaction effect between *Task Condition* and *Motor Condition* ( $F(2, 30) < 1$ ,  $p = .474$ ,  $\eta_p^2 = .049$ ).

#### 4.1.3.3 Perceived physical workload

There was no significant main effect of *Task Condition* on the perceived physical workload ( $F(1, 15) < 1$ ,  $p = .871$ ,  $\eta_p^2 = .002$ ), indicating that the type of secondary task had no effect on the perceived physical workload (Figure 12b). There was a significant main effect of the *Motor Condition* on the perceived physical workload ( $F(1.091, 16.366) = 27.864$ ,  $p < .001$ ,  $\eta_p^2 = .650$ ). Post-hoc analysis revealed that perceived physical workload significantly increased from control condition to unloaded walking (MDiff = -11.53, 95%-CI [-15.22, -7.85],  $p < .001$ ) and to loaded walking (MDiff = -33.63, 95%-CI [-48.76, -18.49],  $p < .001$ ). The differences between unloaded and loaded walking were also significant (MDiff = -22.09, 95%-CI [-36.70, -7.49],  $p = .003$ ). There was no significant interaction effect between *Task Condition* and *Motor Condition* ( $F(2, 30) < 1$ ,  $p = .991$ ,  $\eta_p^2 = .001$ ).

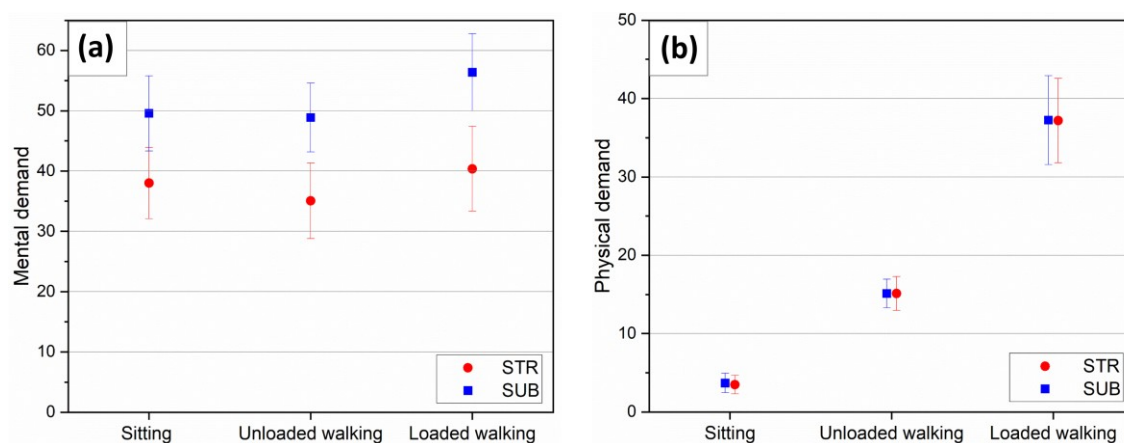


Figure 12. (a) Mean ratings of mental demand. (b) Mean ratings of physical demand. Error bars reflect 95% CI. (Riedel et al., 2023)

#### **4.1.4 Discussion**

The present paper investigated effects of modified leg mechanics on cognitive performance and perceived workload while walking on a treadmill using a dual-task paradigm. It was hypothesised that walking with modified leg mechanics reduces cognitive performance compared to normal walking (H1) and increases perceived cognitive (H2) and physical workload (H3) compared to normal walking or sitting. Additionally, possible order effects on cognitive performance were exploratively investigated.

##### **4.1.4.1 Cognitive performance (H1)**

Cognitive performance in the secondary tasks was assessed via the correct response rates. To account for relative changes from dual task walking compared to single task while sitting, the dual task effects were calculated. The results provide mixed support for the hypotheses H1. There is no simple main effect of modified leg mechanics on cognitive performance in the different dual task conditions. However, a significant interaction effect suggests that walking with modified leg mechanics decreased cognitive performance in SUB, but not in STR, indicating an increased cognitive load due to the added weights (Figure 11a). In agreement with the task prioritisation framework proposed by Yogev-Seligmann et al. (2012), this finding suggests that the type of secondary task and the complexity of the motor task as a threat to postural stability affects allocation of attention in healthy young adults. Walking with modified leg mechanics seems to threaten postural stability, so maintaining the stability of the otherwise largely automated process of walking requires conscious attention. This allocation of attention to walking could explain the reduction in performance in the secondary task. According to a meta-analysis by Al-Yahya et al. (2011), tasks that require memorizing information and simultaneously performing internal, mental processes, such as SUB, interfere stronger with gait performance than tasks involving external stimuli. Mental tracking tasks, such as SUB, appear to share similar complex neural networks to those activated during walking (Al-Yahya et al., 2011). In particular, the prefrontal cortex was found to be involved in locomotion and dual tasking (Dennis Hamacher et al., 2015; Holtzer et al., 2011). Hill et al. (2013) reported that walking while serially subtracting 7 increased the prefrontal cortex activity compared to walking while counting backwards by 1 in young adults. This supports the results of the present paper that SUB required a significant amount of cognitive resources that may have interfered with loaded, but not with unloaded walking.

In fact, unloaded walking slightly improved performance in SUB compared to single task. Similar dual task benefits in normal walking were found in a previous study (Yogev-Seligmann et al., 2010). Practice effects can be excluded because all experimental conditions were counterbalanced, the starting number was randomized in SUB and the single task session was always performed after the dual task sessions. Therefore, the activity of (unloaded) walking itself may be the reason for the improved performance in SUB. According to the Yerkes-Dodson law (Yerkes & Dodson, 1908), performance increases with physiological or mental arousal, while performance decreases when the level of arousal is too low, as may be the case in the seated condition, or too high, as may be the case in the loaded walking condition.

As the present paper has not investigated motor dual task effects, no conclusive statements can be made about cognitive-motor interferences and task prioritization strategies. For example, in agreement with the results of the present study, Patel et al. (2014) reported higher cognitive costs for the subtraction task compared to the Stroop test. However, they also reported higher motor costs for the Stroop test compared to the subtraction task. Additional analysis of the motion data may provide further insight into task prioritisation strategies.

The descriptive data of the cognitive performance showed that especially subjects who started with loaded walking showed reduced performance in SUB during loaded walking. For this reason, the between-subjects factor *Session Order* was included in the statistical model as an exploratory measure. In fact, interaction effects could be found that suggest an influence of the session order (Figure 11b). In particular, participants who started with the most complex dual task condition (loaded walking with SUB) showed cognitive performance reductions during loaded walking, while participants who started with unloaded walking even showed a little performance improvement. The interplay of novelty and complexity of the dual-task condition might have been perceived as an increased hazard for postural stability, which requires an intact hazard estimation. Interestingly, participants who started with unloaded walking showed slightly reduced dual task performance in STR while participants who started with loaded walking showed almost no change in dual task performance compared to single task. It is possible that different prioritisation strategies were adopted depending on the complexity of the motor task in the first attempt. Another explanation are the individual differences in the cognitive and motor abilities of the participants, which may mask the effects of the experimental manipulation due to the small sample in the present study (Bequette et al., 2020).

#### 4.1.4.2 Perceived Workload (H2 & H3)

Perceived physical and cognitive workload were assessed with the respective subscales of the NASA-TLX in all experimental conditions. As hypothesised the perceived physical workload increased significantly from sitting to unloaded walking to loaded walking, validating the experimental manipulation. Perceived cognitive workload showed a statistical trend, indicating an increased cognitive workload in loaded walking compared to unloaded walking. Bequette et al. (2020) reported similar results: Completing an obstacle course with a powered and unpowered exoskeleton was rated as significantly more cognitively demanding than completing the course without an exoskeleton. The course involved more complex motor tasks, which is presumably why the influence of the modified leg mechanics due to the exoskeleton on the perceived cognitive workload is stronger than in the present study.

#### 4.1.5 Conclusion

The present paper suggests an increased cognitive workload during walking with modified leg mechanics in the early adaptation phase. However, cognitive performance reductions do not occur in general, but seem to be caused by an interplay of external factors (e.g., complexity of the motor/cognitive task, task order). The perceived cognitive workload also increases, although not significantly. The results highlight the relevance of assessing cognitive workload when evaluating exoskeletons and other wearable devices. In order to be able to make further statements about task prioritisation and attention allocation, motor performance must be evaluated in addition to cognitive performance.”

## 4.2 Cognitive-motor interference during walking with modified leg mechanics: A dual-task walking study

The following subsections (4.2.1 Introduction, 4.2.2 Materials and methods, 4.2.3 Results, 4.2.4 Discussion and 4.2.5 Conclusion) are full citations from the publication:

**Riedel, N., Herzog, M., Stein, T., & Deml, B. (2024).** Cognitive-motor interference during walking with modified leg mechanics: a dual-task walking study. *Frontiers in psychology, 15*, 1375029. <https://doi.org/10.3389/fpsyg.2024.1375029>

### 4.2.1 Introduction

“In daily life, we frequently engage in multiple tasks simultaneously. This can lead to impairments when cognitive resources are insufficient to handle these tasks at the same time. In situations involving both motor and cognitive tasks, this impairment is referred to as cognitive-motor interference. The analysis of cognitive-motor interference using a dual-task walking approach is widely used in clinical and epidemiological research (as reviewed in Al-Yahya et al., 2011; Bayot et al., 2018). This approach has proven effective in revealing aging effects (as reviewed in Beurskens & Bock, 2012) and effects due to neurodegenerative diseases such as Parkinson’s disease (as reviewed in Kelly et al., 2012) on cognitive and motor performance. However, this approach could also be useful to evaluate human-exoskeleton interaction. In this context, studies have either focused on biomechanical and physiological effects (as reviewed in Pinto-Fernandez et al., 2020) or cognitive effects (Bequette et al., 2020; Upasani & Srinivasan, 2023), but not the combined effects, i.e., the cognitive-motor interference.

According to Yogev-Seligmann et al. (2012), two main factors determine the extent of interference and prioritization of tasks in dual-task walking. The first factor *postural reserve* includes all individual aspects that ensure postural control and reflects the “capability to respond most effectively to a postural threat” (Yogev-Seligmann et al., 2012, p. 766). The second factor *hazard estimation* refers to the cognitive capability of self-awareness including the estimation of environmental hazards and self-limitations. Young healthy adults are assumed to have an intact postural reserve and hazard estimation, which allows them to concentrate on performing secondary tasks without impairing their gait performance. However, studies have also shown that interference in dual-task walking can also be observed in healthy young subjects (Daniel Hamacher, Koch, et al., 2019; Patel et al., 2014; Wrightson & Smeeton, 2017). External factors, such as complex environmental influences or challenging motor tasks can demand the postural reserve (Yogev-Seligmann et al., 2012). This can result in a larger proportion of conscious attention being allocated to the motor task to maintain a stable gait. Kao and Pierro (2022) investigated cognitive-motor interference during walking with and without continuous treadmill platform sways and found that participants prioritized the walking task during the perturbed walking condition. Reiser et al. (2019) found a decrease in the parietal P3 amplitude with increasing movement complexity in an outdoor environment using mobile electroencephalography. This suggests that there is a higher cognitive workload associated with increasing movement complexity.

In the field of dual-task studies, examining gait parameters provides insight into the complex relationship between motor performance and cognitive demands. Al-Yahya et al. (2011) conducted a meta-analysis that highlighted the effects of dual-tasking on various mean and variability gait parameters. Gait variability is considered an indicator of motor control (Hausdorff, 2005; Newell & Corcos, 1993). Low variability suggests reliance on automatic processes, whereas high variability signifies the engagement of attentional resources in motor control. Studies have linked high gait variability to negative health outcomes, including falls in older adults and various comorbidities (Pieruccini-Faria et al., 2020). According to Tian et al. (2017), temporal and spatial gait variability parameters may be associated with brain areas related to sensorimotor integration and coordination in older adults. The addition of cognitively demanding secondary tasks or physical perturbations that engage the same brain areas can cause interferences that lead to changes in gait variability. While some studies report an increase in gait variability among healthy older adults when faced with a secondary task (as reviewed in Smith et al., 2017), others demonstrate a decrease (Decker et al., 2016; Daniel Hamacher, Hamacher, et al., 2019; Lövdén et al., 2008). This divergence in findings is attributed to a shift in attentional focus from walking to the secondary task, facilitating more automated walking patterns. The Dual-Process Model, initially proposed by Huxhold et al. (2006) in the context of standing balance control, provides a framework for understanding these observations. According to this model, simple cognitive tasks promote an external focus of attention, thereby enhancing automated motion execution and reducing variability. Conversely, complex cognitive tasks lead to competition for attentional resources, outweighing the benefits of an external focus and resulting in increased variability. Thus, a U-shaped relationship emerges between gait variability and cognitive task difficulty, with variability being high during single-task walking, decreasing with a simple secondary task, and increasing again with a complex secondary task.

Considering that factors such as physical effort, modified biomechanical structures and the use of assistive devices are supposed to increase the use of attention-demanding cognitive resources (Clark, 2015), the dual-task walking approach and the Dual-Process Model can provide valuable insights in the context of human-exoskeleton interaction. Findings are important for evaluating the current state of cognitive and motor adaptation to a system, as well as to develop and evaluate appropriate training interventions. In a field study with participants completing an obstacle course, Bequette et al. (2020) reported slowed reaction times in a visual search task for

some participants when wearing a powered lower limb exoskeleton. The overall perceived workload assessed with the NASA-TLX was significantly higher in powered and unpowered walking compared to walking without the exoskeleton. Riedel et al. (2023) investigated effects of modified leg mechanics using weight cuffs attached to both upper and lower legs on cognitive performance and perceived workload during dual-task walking on a treadmill. Participants who started with the loaded walking condition showed significant performance decrements on a subtraction task during loaded but not during unloaded walking. Consistent with Bequette et al. (2020), physical and mental demand assessed with the NASA-TLX increased during loaded walking, however not significantly for mental demand.

This study aims to examine the effects of modified leg mechanics on cognitive-motor interference in dual-task walking. Riedel et al. (2023) initially analyzed subjective measures and behavioral parameters. However, motion data can also provide valuable information regarding cognitive-motor interference. The present paper analyzed gait variability, as an indicator of motor control, to investigate its relation to cognitive task difficulty and to determine whether lower extremity loading modifies this relationship. Additionally, the impact on the gait pattern, as represented by the mean values of spatio-temporal gait parameters was investigated. Weight cuffs attached bilaterally to the thighs and shanks manipulated the biomechanics of the musculoskeletal system and added complexity to the motor task. According to the Dual-Process Model, it was hypothesized that loaded walking would exhibit a U-shaped relationship between gait variability and cognitive task difficulty, unlike unloaded walking (H1a). We predicted that gait variability would be higher during loaded walking compared to unloaded walking (H1b). Furthermore, changes were anticipated in the overall gait pattern, as indicated by mean spatio-temporal gait parameters, due to the weight cuffs (H2a) and the performance of secondary tasks (H2b).

## 4.2.2 Materials and methods

For the analysis of motor performance under different single and dual-task walking situations, a  $2 \times 3$  within-subject experimental design was employed with two *Walking Conditions* (unloaded walking, loaded walking) and three *Task Conditions* (no secondary task, visual-verbal Stroop test, serial subtraction task).

#### 4.2.2.1 Participants

Sixteen healthy young adults participated in the study. Only 15 participants (age:  $24.3 \pm 3.5$  years; stature:  $1.73 \pm 0.09$  m; body mass:  $66 \pm 10.1$  kg; physical activity:  $3.2 \pm 0.3$  days/week and  $183 \pm 25$  min/week) were used for the analysis due to incomplete recording of motion data for one individual. The participants, consisting of eight females and seven males, were selected from the student population of the Karlsruhe Institute of Technology. Individuals with red-green visual impairment were excluded from the study. This research complied with the American Psychological Association Code of Ethics and was approved by the Ethics Committee of the Karlsruhe Institute of Technology. All participants provided written informed consent prior to participation.

#### 4.2.2.2 Apparatus

Participants walked on a treadmill (h/p/cosmos Saturn; Nussdorf-Traunstein, Germany) with and without weight cuffs bilaterally attached to the thigh and shank (see Figure 9). The total weight of the four weight cuffs was 9 kg (2.25 kg each), which is typical for lower-limb, gait-assisting exoskeletons (Bortole et al., 2013). A custom hip belt was designed to secure the weight cuffs to the thigh. The hip belt was a climbing harness without the leg elements. It consisted of a padded hip belt with side loops to which two Velcro straps were attached on each side. The weight cuffs were hooked onto the Velcro straps to prevent them from slipping down during movement. The Velcro straps could be adjusted in height, ensuring that the lower edge of the weight cuffs was positioned 10 cm above each participant's knee joint axis. The weight of powered exoskeletons is strongly centered on the motors, which are located at the joints. A position close to the knee joint axis was chosen, which also ensures that movement is not restricted. For safety, a harness was used to secure participants during treadmill walking. In front of the treadmill a 65-inch monitor was mounted at a distance of 240 cm from the participants. The top edge of the monitor was set at the eye level of each participant. The monitor was used to display the current task to be performed, including the presentation of the stimuli of the secondary tasks. Participants were instructed to keep their eyes at the monitor to ensure an upright posture. An infrared camera system (Vicon Motion Systems; Oxford Metrics Group, Oxford, UK) equipped with 16 cameras (200 Hz) was employed to capture whole-body movements, using a modified Master-Motor-Map marker-setup with 56 markers (Mandery et al., 2016).

#### 4.2.2.3 Secondary tasks

A wide variety of cognitive tasks exists that assess different cognitive functions. Al-Yahya et al. (2011) established a classification based on the type of mental processes required to perform the task. In this study, two cognitive tasks from different classifications were used: a visual-verbal version of the Stroop test (STR) (Stroop, 1935) as a discrimination task involving response inhibition and a serial subtraction task (SUB) as a mental tracking task.

STR involved the presentation of a  $10 \times 10$  matrix containing color words (red, blue, green, and yellow) with incongruent word and color information, which was displayed on the monitor in front of the treadmill for a duration of 60 s (see Figure 10). To avoid learning effects, there were five different matrices, which were presented in random order. Participants were instructed to name the respective font color of the words as quickly as possible and without error. Participants started in the left top corner and continued column wise to the right. During SUB, a random three-digit number ranging from 201 to 999 was presented to the participants. They were then instructed to perform serial subtractions of seven from the presented number continuously for 60 s.

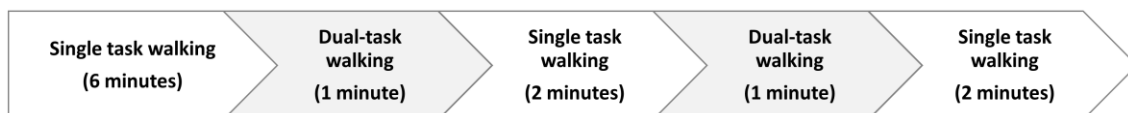
Riedel et al. (2023) reported the average score of the mental demand subscale of the NASA-TLX during unloaded single task walking (Score: 7), dual-task walking with STR (Score: 35) and dual-task walking with SUB (Score: 49). As these scores were significantly different from each other, STR is considered the simple secondary task and SUB is considered the difficult secondary task.

#### 4.2.2.4 Procedure

For familiarization, participants first performed each secondary task for 80 s while seated. Afterwards they walked for 6 min on the treadmill according to recommendations by Meyer et al. (2019), before the preferred gait speed of  $1.14 \pm 0.08$  m/s ( $4.1 \pm 0.3$  km/h) was determined using the method suggested by Jordan et al. (2007). The determined speed was maintained constant for all experimental conditions.

The two walking sessions followed in a balanced order, each lasting 12 min in total. One session involved unloaded walking and one loaded walking. Figure 13 shows the protocol of a walking session. Both walking sessions started with a 6-min block of single task walking. This first block was intended to control adaptation processes, especially in the loaded walking session, and to

ensure that subjects did not have to use cognitive resources to adapt to unfamiliar motor conditions. For example, adaptation to walking with unilateral attached weights is assumed to be completed after 45 - 50 strides (Noble & Prentice, 2006). This was followed by the first dual-task walking block for 1 min. To counteract cognitive fatigue, a 2-min block of single task walking followed before the second dual-task walking block was performed for 1 min. The sessions ended with another 2-min block of single task walking. The order of secondary tasks' appearance has also been counterbalanced. No specific instructions were provided regarding which task to prioritize during dual-task walking. After the loaded walking session, an additional 18-min session followed, which was used to investigate (re-)adaptation processes. However, this session is not relevant for this paper. After the walking sessions, the secondary tasks were again performed while seated and served as control conditions.



**Figure 13.** Schematic illustration of the protocol of a walking session. The same protocol was performed with and without weight cuffs. (Riedel et al., 2024)

#### 4.2.2.5 Data processing and statistical analysis

The motion data was post-processed using Vicon Nexus 2.14.0 and Matlab R2023a (The MathWorks, Natick, MA, United States). The marker trajectories were smoothed in Matlab using a 6 Hz fourth order Butterworth low-pass filter (Gordon & Ferris, 2007). In each trial, the first and last 5 s were then cut off and the first 30 strides were extracted from the remaining section for the calculation of the mean values and coefficients of variation (CV) of step length, step width, stride time, and double support time. For single task walking, the last minute of the first 6-min block was considered for analysis. Segmentation of strides was performed according to Noble and Prentice (2006). The step length was determined as the anterior-posterior distance between the right and left heel markers at each heel contact. The step width was calculated using the medio-lateral distance between the right and left heel markers at each heel contact. The time between ipsilateral heel contacts represents the stride time, while the time at which both feet are in contact with the ground represents the double support time. The reliability of gait variability parameters is an ongoing discussion in the literature. Recommendations for the minimum number of strides to capture to reliably assess variability vary widely between six strides (Lord

et al., 2011) up to more than a hundred strides (Hollman et al., 2010). Here, within-session reliability was assessed with the intraclass correlation coefficients (ICC) of all mean values and CV for single task walking (see Table 3). ICC values and their corresponding 95% confidence intervals were derived using a mean-rating ( $k = 3$ ), absolute-agreement, 2-way mixed-effects model. Reliability values below 0.5 indicate poor reliability, values between 0.5 and 0.75 suggest moderate reliability, values between 0.75 and 0.9 indicate good reliability, while values greater than 0.90 indicate excellent reliability (Koo & Li, 2016).

**Table 3.** Intraclass correlation coefficients (ICC) of coefficients of variation (CV) and mean values of gait parameters.

	Loaded walking	Unloaded walking
<b>CV</b>		
Step length	0.866 [0.687, 0.951]	0.857 [0.658, 0.948]
Step width	0.933 [0.824, 0.976]	0.941 [0.823, 0.980]
Stride time	0.837 [0.618, 0.941]	0.675 [0.213, 0.883]
Double support time	0.924 [0.818, 0.972]	0.618 [0.153, 0.856]
<b>Mean values</b>		
Step length	0.978 [0.947, 0.992]	0.997 [0.993, 0.999]
Step width	0.983 [0.949, 0.994]	0.984 [0.962, 0.994]
Stride time	0.986 [0.966, 0.995]	0.995 [0.989, 0.998]
Double support time	0.992 [0.981, 0.997]	0.997 [0.992, 0.999]

ICC and their corresponding 95% confidence intervals were derived using a mean-rating ( $k = 3$ ), absolute-agreement, 2-way mixed-effects model. Values represent ICC of gait parameters during single task walking. The 95% confidence interval are presented in parentheses.

Data were tested for normal distribution using the Kolmogorov-Smirnov test. In contrast to the mean values, some CV showed a skewed, non-normal distribution. Since repeated measures ANOVAs (rmANOVA) are considered robust to violations of the normal distribution if the sphericity assumption is met (Blanca et al., 2023; Schmider et al., 2010) and transformations have considerable shortcomings (Blanca et al., 2017; Feng et al., 2014) parametric models were applied to the original data. The assumption of sphericity was tested with the Mauchly test, and in cases of violation, degrees of freedom were adjusted using the Greenhouse-Geisser correction. The significance level for all statistical analyses was set a priori at  $\alpha = 0.05$  and post hoc pairwise comparisons were Bonferroni corrected. Effect sizes are reported as partial eta squares ( $\eta_p^2$ ).

Values between 0.01 and 0.06 indicate a small effect, values between 0.06 and 0.14 indicate a medium effect, and values above 0.14 indicate a large effect (Cohen, 1988). Two 2×3-rmANOVAs for each gait parameter with within-factors *Walking Condition* (unloaded walking, loaded walking) and *Task Condition* (no secondary task, STR, SUB) were conducted to test differences in CV and mean values. The statistical analysis was performed using SPSS Statistics 28.0 (IBM, Armonk, NY, United States).

## 4.2.3 Results

### 4.2.3.1 Variability of gait parameters

The 2 × 3-rmANOVA revealed that there was not a statistically significant interaction between *Walking Condition* and *Task Condition* for all gait variability parameters: Step length (F [1.31, 18.21] = 1.37,  $p = 0.268$ ,  $\eta_p^2 = 0.09$ ), step width (F [2, 28] = 1.19,  $p = 0.319$ ,  $\eta_p^2 = 0.08$ ), stride time (F [2, 28] = 0.51,  $p = 0.608$ ,  $\eta_p^2 = 0.04$ ) and double support time (F [2, 28] = 1.03,  $p = 0.369$ ,  $\eta_p^2 = 0.07$ ). It is important to note, that in this case step length variability violated normal distribution and sphericity assumption.

A significant main effect of *Walking Condition* on CV of step length (F [1, 14] = 5.67,  $p < 0.032$ ,  $\eta_p^2 = 0.29$ ) was found. Step length variability increased during loaded walking (see Figure 14; Table 4). No significant main effects of *Walking Condition* were found for stride time (F [1, 14] = 4.06,  $p < 0.064$ ,  $\eta_p^2 = 0.23$ ), double support time (F [1, 14] = 2.83,  $p = 0.115$ ,  $\eta_p^2 = 0.17$ ) and step width (F [1, 14] = 0.12,  $p = 0.736$ ,  $\eta_p^2 < 0.01$ ). However, variability in stride time and double support time showed statistical trends that also indicate an increase in variability during loaded walking, supporting hypothesis H1b.

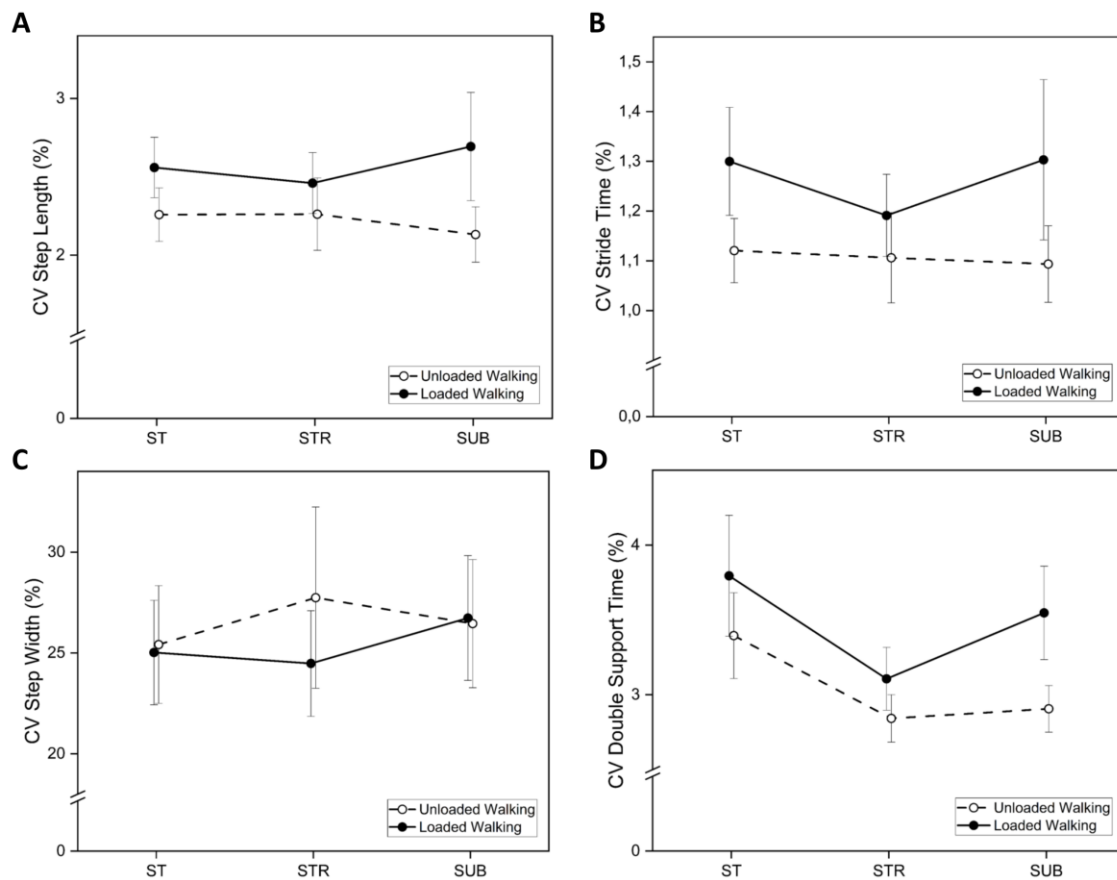
There was a significant main effect of *Task Condition* on double support time variability (F [2, 28] = 4.31,  $p = 0.023$ ,  $\eta_p^2 = 0.24$ ). Bonferroni-corrected post-hoc analysis revealed a statistical trend for differences from single task (ST) to STR (MDiff = 0.62, 95%-CI [-0.03, 1.28],  $p = 0.066$ ). Inspection of Figure 14 suggests that variability in double support time is lower when walking while performing the STR task compared to single task walking. As hypothesized (H1a) variability increased again during SUB for loaded, but not unloaded walking, leading to a U-shaped curve. Variability in double support time was not significantly different from ST to SUB (MDiff = 0.37, 95%-CI [-0.29, 1.03],  $p = 0.455$ ) and from STR to SUB (MDiff = -0.25, 95%-CI [-0.62, 0.12],

$p = 0.255$ ). There were no significant main effects of *Task Condition* on CV of step length ( $F [2, 28] = 0.06$ ,  $p = 0.943$ ,  $\eta_p^2 < 0.01$ ), step width ( $F [2, 28] = 0.74$ ,  $p = 0.486$ ,  $\eta_p^2 = 0.05$ ) and step time ( $F [2, 28] = 0.35$ ,  $p = 0.707$ ,  $\eta_p^2 = 0.02$ ).

**Table 4.** Coefficients of variation and mean values of gait parameters for each experimental condition.

	Loaded walking			Unloaded walking		
	Single task	Dual-task (STR)	Dual-task (SUB)	Single task	Dual-task (STR)	Dual-task (SUB)
<b>CV</b>						
Step length (%)	2.6 (0.7)	2.5 (0.8)	2.7 (1.3)	2.3 (0.7)	2.3 (0.9)	2.1 (0.7)
Step width (%)	25.0 (10.0)	24.5 (10.1)	26.7 (12.0)	25.4 (11.3)	27.7 (17.4)	26.5 (12.3)
Stride time (%)	1.3 (0.4)	1.2 (0.3)	1.3 (0.6)	1.1 (0.2)	1.1 (0.4)	1.1 (0.3)
Double support time (%)	3.8 (1.6)	3.1 (0.8)	3.5 (1.2)	3.4 (1.1)	2.8 (0.6)	2.9 (0.6)
<b>Mean values</b>						
Step length (mm)	631 (37)	632 (38)	631 (35)	604 (4.1)	603 (43)	604 (41)
Step width (mm)	102 (28)	101 (27)	100 (27)	87 (2.4)	90 (26)	92 (27)
Stride time (ms)	1208 (83)	1203 (65)	1201 (63)	1147 (67)	1142 (57)	1148 (54)
Double support time (ms)	356 (10)	354 (9)	354 (8)	377 (9)	372 (8)	373 (8)

Values represent group mean (standard deviation). STR = Stroop-Test; SUB = Subtraction-Task; CV = Coefficient of Variation.



**Figure 14.** Coefficients of variation (CV) of (A) step length, (B) stride time, (C) step width, and (D) double support time for loaded and unloaded walking during single task walking (ST), dual-task walking with the Stroop test (STR) and dual-task walking with the subtraction task (SUB). Bars indicate standard errors. (Riedel et al., 2024)

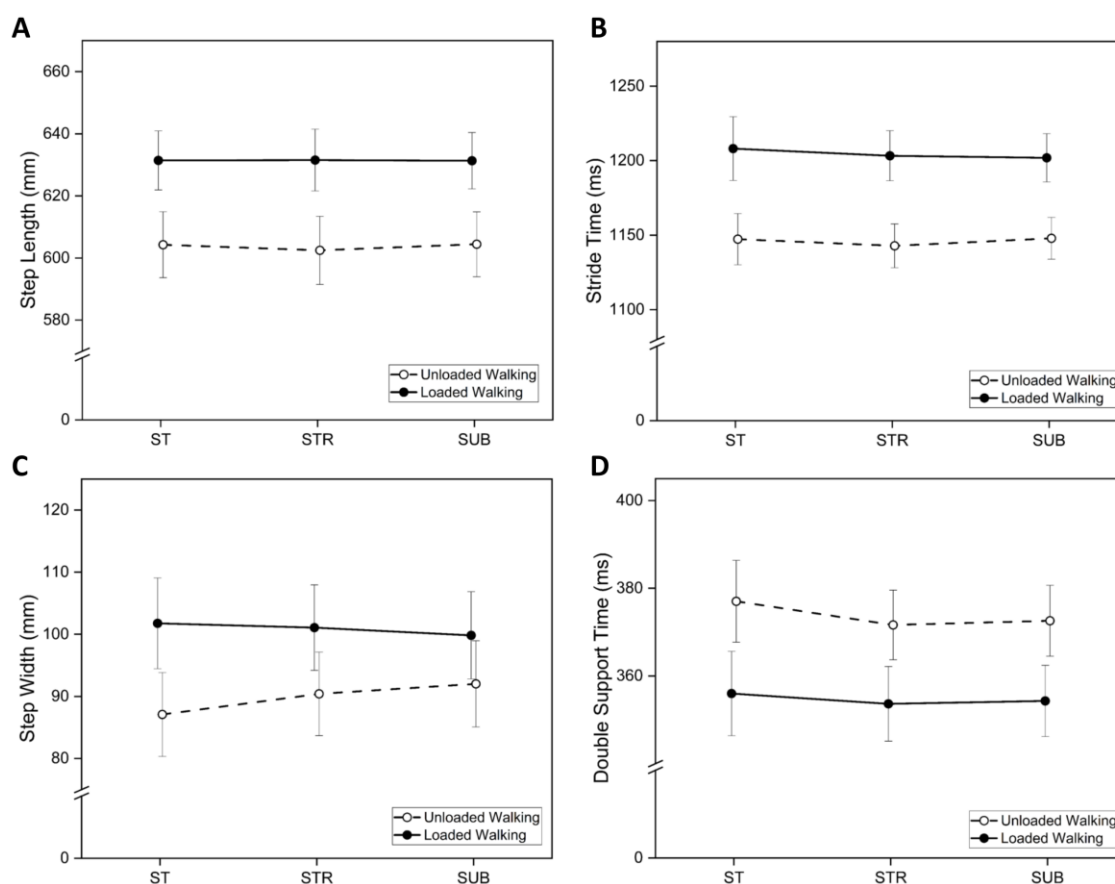
#### 4.2.3.2 Mean values of gait parameters

The interaction between *Walking Condition* and *Task Condition* was not significant for all mean gait parameters: Step length ( $F [2, 28] = 0.39, p = 0.683, \eta_p^2 = 0.03$ ), step width ( $F [1.35, 18.84] = 2.21, p = 0.149, \eta_p^2 = 0.14$ ), stride time ( $F [2, 28] = 1.09, p = 0.349, \eta_p^2 = 0.07$ ) and double support time ( $F [2, 28] = 0.91, p = 0.414, \eta_p^2 = 0.06$ ).

The  $2 \times 3$ -rmANOVA showed significant main effects of *Walking Condition* on mean values of step length ( $F [1, 14] = 98.49, p < 0.001, \eta_p^2 = 0.88$ ), stride time ( $F [1, 14] = 65.56, p < 0.001, \eta_p^2 = 0.82$ ), step width ( $F [1, 14] = 4.72, p = 0.047, \eta_p^2 = 0.25$ ) and double support time ( $F [1,$

14] = 30.60,  $p < 0.001$ ,  $\eta_p^2 = 0.69$ ). In line with hypothesis H2a, loaded walking resulted in increased step length, step width, and stride time, while decreasing double support time compared to unloaded walking (see Figure 15; Table 4).

There were no significant main effects of *Task Condition* on mean values of step length ( $F [1.40, 19.53] = 0.06$ ,  $p = 0.888$ ,  $\eta_p^2 < 0.01$ ), step width ( $F [2, 28] = 0.29$ ,  $p = 0.754$ ,  $\eta_p^2 = 0.02$ ), stride time ( $F [1.29, 18.01] = 0.27$ ,  $p = 0.670$ ,  $\eta_p^2 = 0.02$ ) and double support time ( $F [1.26, 17.68] = 1.45$ ,  $p = 0.251$ ,  $\eta_p^2 = 0.09$ ). This means that hypothesis H2b cannot be confirmed.



**Figure 15.** Mean values of (A) step length, (B) stride time, (C) step width, and (D) double support time for loaded and unloaded walking during single task walking (ST), dual-task walking with the Stroop-Test (STR) and dual-task walking with the Subtraction-Task (SUB). Bars indicate standard errors. (Riedel et al., 2024)

#### 4.2.4 Discussion

This study aimed to examine the effects of modified leg mechanics on cognitive-motor interference in dual-task walking. For this purpose, a within-subject experimental design was employed. Participants walked on a treadmill with and without weight cuffs bilaterally attached to their

thighs and shanks under different cognitive demand levels. The study investigated the effects of physical load (weight cuffs) and cognitive load (secondary tasks) on variability, as a measure of motor control, and mean values of step length, stride time, step width and double support time. The study found that walking with modified leg mechanics in challenging dual-task situations could lead to an increase in cognitive-motor interference. Additionally, participants seemed to prioritize maintaining their posture over the cognitive task in challenging dual-task situations during walking with modified leg mechanics.

#### **4.2.4.1 Dual-process account observed for double support time variability during loaded walking**

Literature supports a dual-process account in dual-task walking (Decker et al., 2016; Lövdén et al., 2008; Verrel et al., 2009). Accordingly, simple secondary tasks seem to promote an external focus of attention resulting in reduced gait variability compared to single-task walking. Conversely, complex secondary tasks lead to a competition for cognitive resources, potentially resulting in increased gait variability (U-shaped relationship). The model also proposes that the interplay between external focus and resource competition is influenced by age. The hypothesis was that modified leg mechanics demands the postural reserve to a similar extent as aging. In the conducted study, participants rated the Stroop test (STR) as less mentally demanding than the subtraction task (SUB) (Riedel et al., 2023). Consequently, it was anticipated that variability would decrease for the STR task (which involves an external focus of attention) and increase for the SUB task (where cognitive resource competition occurs) during loaded walking (H1a).

However, this was solely evident in the case of double support time (DST) variability (see Figure 14). The other variability parameters showed a similar pattern resembling a U-shaped curve, yet lacked significant effects. DST variability decreased from single task walking to walking while concurrently performing the STR task, both for unloaded and loaded walking, indicating an externalized focus of attention. Conversely, in the more cognitively demanding SUB task, DST variability continued to be lower for unloaded walking, but increased for loaded walking. This observation suggests that competition for cognitive resources outweighs the benefits of an external attentional focus when walking with weight cuffs in cognitively demanding situations. Lövdén et al. (2008) observed that the beneficial effect of an external focus of attention persists among young, healthy adults even when confronted with complex secondary tasks. However, this did not hold true for older adults. Decker et al. (2016) reported similar results regarding step

length and step time. For step width, they identified a U-shaped pattern in both younger and older adults. This implies that increased cognitive demand influences balance control in individuals of all ages, while affecting the regulation of rhythmic step patterns exclusively in older adults. Like step width, DST is related to balance control (Gabell & Nayak, 1984). Therefore, the results of the present study imply that increased cognitive demands during loaded dual-task walking primarily impact balance control in healthy young adults. However, step width did not show the expected pattern.

Regardless of the cognitive demand, variability in step length was higher during loaded walking than during unloaded walking. This supports hypothesis H1b. Modified leg mechanics seem to influence gait variability to a similar extent as age-related effects. For instance, Decker et al. (2016) reported that older adults demonstrated increased variability in step length and step time than younger adults.

#### **4.2.4.2 Mental tracking rather than inhibitory control interferes with motor control**

The results also suggest that mental tracking, rather than inhibitory control, may interfere with motor control during loaded walking. This is in line with the findings of Kao and Pierro (2022). Tasks requiring memorization of information while simultaneously engaging in internal mental processes, such as serial subtraction, have a greater interference effect on gait performance. Such mental tracking tasks are suggested to engage neural networks that overlap with those involved in locomotion (Al-Yahya et al., 2011). Specifically, the prefrontal cortex has been implicated in both locomotion and dual-tasking (Dennis Hamacher et al., 2015; Holtzer et al., 2011). However, contrasting findings exist. Serial subtraction did not consistently yield the greatest cognitive-motor interferences in studies involving different cognitive tasks (Bartolo et al., 2021; Patel et al., 2014). Patel et al. (2014) observed that performing a Stroop test resulted in more interference with walking at preferred speed compared to a serial subtraction task, a word list generation task, and a simple reaction time task. Zoccatelli et al. (2010) demonstrated that the Stroop test activates several brain regions, including the dorsolateral prefrontal cortex and the anterior cingulate cortex. According to Patel et al. (2014), the neural activation pattern in the Stroop test indicates that it requires more processing resources than the other tasks studied. This contrasts with the subjective ratings of the cognitive demands of the participants in the present study. Explanations for the differing findings could be task-specific factors. The SUB task in this study, involving the subtraction of sevens from a random three digit number, may have

been more complex than in the study by Patel et al. (2014), requiring more cognitive resources. Furthermore, in the visual-verbal STR task, participants had to focus on the monitor in front of the treadmill on which the stimulus was presented, while in the SUB task, participants had the flexibility to shift their visual focus away from the monitor despite instructions to the contrary. To focus on the letters of the stimuli in the STR task participants had to stabilize themselves potentially leading to reduced variability. This aligns with the Supra Postural Task Model (Stof-fregen et al., 2000), which could offer an alternative explanation for the reduced variability during dual-task walking.

#### **4.2.4.3 Shift to a posture first strategy during demanding dual-task situations**

From the perspective of the Task Prioritization Framework proposed by Yogev-Seligmann et al. (2012), the shift of attention to the cognitive task (external focus) can be interpreted as the adoption of a “posture second” strategy. However, during loaded walking while performing the SUB task the positive impact of an external focus was nullified. This suggests a reallocation of attentional resources toward the motor task, indicating a shift toward a “posture first” strategy. Such a strategy is adopted when hazards are detected, aiming to stabilize walking and to prevent injuries (Shumway-Cook et al., 1997). Nonetheless, the extent of perceived postural threat influences the amount of attentional resources allocated to the motor task (Yogev-Seligmann et al., 2012). Riedel et al. (2023) reported that during loaded walking, participants who initiated with loaded walking experienced a substantial reduction in cognitive performance for the SUB task (i.e., fewer subtractions per period). In contrast, those who initiated with unloaded walking showed a slight improvement in cognitive performance during loaded walking. Starting with the dual-task conditions involving the simple motor task (unloaded walking) allowed participants some time to become familiar with the dual-task conditions involving the challenging motor task (loaded walking). It appears that these participants perceived the postural threat as less severe compared to those who initiated with loaded walking. Consequently, they allocated fewer attentional resources to the motor task. For both participant groups the shift toward a “posture first” strategy was successful, as evidenced by the fact that DST variability did not surpass the levels observed in the single-task condition. Decker et al. (2016) and Lövdén et al. (2008) reported similar observations. However, it seems that in contrast to the participants who initiated with unloaded walking, the participants who initiated with loaded walking did not have sufficient cognitive resources left to perform the SUB task, which led to the observed cognitive performance decrements (Riedel et al., 2023). Consistent with this, prior research has shown that

when confronted with more complex motor tasks, such as responding to unexpected perturbations (Mersmann et al., 2013) or adapting to asymmetric split-belt conditions (Hinton et al., 2020), healthy young adults prioritize maintaining their posture as their primary strategy.

Interestingly, this pattern was not observed during unloaded walking, suggesting that modifications in leg mechanics increase the postural threat and demand the postural reserve of healthy young adults. However, the results also suggest that familiarization alters the perceived threat and thus the amount of cognitive resources allocated to the motor task. Further studies are needed to investigate the time for familiarization with modified leg mechanics or powered exoskeletons, which is crucial for the design of effective training interventions.

#### **4.2.4.4 Gait pattern influenced by modified leg mechanics but not secondary tasks**

Weight cuffs attached to the legs not only increase metabolic rate (Royer & Martin, 2005) but also shift the center of mass of the leg segments and change the overall moment of inertia of the leg (Browning et al., 2007). In this study, participants showed increased step length, step width, and stride time, while double support time decreased, which provides support for hypothesis H2a. However, the present findings challenge the established paradigm of the inverted pendulum hypothesis, which posits that during the stance phase of gait, the human body exhibits behavior analogous to an inverted pendulum, with the body's center of mass oscillating over the supporting foot akin to a pendulum. This hypothesis suggests that alterations in gait primarily arise from variations in segment length rather than changes in mass. For example, Iosa et al. (2016) demonstrated significant modification of the gait ratio through artificial extension of the lower leg segment, while the addition of 1 kg weights to the lower legs did not yield significant modifications. Similarly to the present study, Browning et al. (2007) observed an increase in stride length and swing time when using foot weights of 4 kg and 8 kg. These weights likely affected the center of mass and inertia properties of body segments, potentially contributing to the observed changes in gait pattern, which are expected to occur mainly during the swing phase. Due to the changed moment of inertia, the leg swings further forward, resulting in an extended step length and stride time. The double support time decreased, indicating an extended swing time and single-leg stance, which could pose higher demands on balance control. A wider step width was presumably adopted to increase the base of support as a possible stabilizing strategy. However, it is also conceivable that the weight cuffs imposed physical constraints

on the participants, causing them to increase their step width. Browning et al. (2007) also suggest a shift in strategy with higher weights, prioritizing foot control over energy conservation, as a possible explanation. This implies a reevaluation of the mechanisms underlying locomotor control under varying loads or modified leg mechanics, as it may be the case when wearing an exoskeleton. Jin et al. (2017) reported similar effects. The authors investigated the impact of added masses on walking using pelvic, thigh, and shank cuffs. They found that the weight and inertia of an exoskeleton led to an increased step length, a reduction in step height, and a decreased maximum knee flexion. A comparison of the different loading conditions was made between normal walking and walking with a powered lower limb exoskeleton, revealing that active support could only partially restore normal walking parameters. Specifically, gait parameters primarily affected by inertia such as step length could not be restored.

Contrary to the hypothesis H2b, increased cognitive load did not affect mean gait parameters, aligning with findings from Szturm et al. (2013). In a study involving dual-task treadmill walking, the mean values for step time, swing time, and double support time showed no statistically significant differences between single-task and dual-task walking conditions. However, variability measures increased during dual-task walking. It is plausible that in the context of treadmill-based dual-task walking, the mechanical support provided by the treadmill serves as a regulating mechanism, ensuring the stability of the gait pattern (Wrightson et al., 2020).

#### **4.2.4.5 Limitations**

Effects due to increased cognitive demand often showed no significance in gait parameters. It is possible that the postural reserve of healthy young adults is high enough so that only a small part of attention needs to be allocated to the motor task, even during loaded walking. This could be promoted by the chosen methodology as studies found that treadmill walking increases automaticity (Baek et al., 2023) and enhances cognitive performance (Penati et al., 2020) compared to overground walking. Thumm et al. (2018) reported that in people with Parkinson's disease, prefrontal cortex activity was lower when walking on a treadmill than when walking on the ground. Therefore, the generalizability of the results on overground walking is limited (Wrightson et al., 2020). By keeping the gait velocity constant, the consistent strategy of reducing gait velocity during dual-task overground walking (Al-Yahya et al., 2011) was prevented. However, it is essential to note that treadmill walking facilitates the collection of a larger number of steps, thus improving the reliability of variability parameters—a well-documented issue in

clinical research (Hollman et al., 2010). In this study, 30 strides per condition were analyzed and most parameters showed at least moderate to excellent reliability, while only two parameters showed poor to good reliability (see Table 3). Furthermore, to ensure reliable assessment of performance in the secondary tasks, this study necessitated continuous walking, which would not have been feasible with short overground trials of 5 - 10 m. However, future studies should prioritize overground walking studies to ensure the transferability of the results to real life. Furthermore, it is important to investigate normalized gait parameters to enhance comparability between studies. Additionally, the secondary tasks used in this study demand different cognitive functions, such as mental tracking in the SUB task and inhibitory control in the STR task (Bayot et al., 2018). For future investigations into cognitive-motor interference, it is recommended to employ secondary tasks that allow for parametric manipulation of cognitive demands, such as the n-back task (Conway et al., 2005). The n-back task requires participants to determine if each stimulus in a sequence matches the one that appeared n items before. As n increases, the task becomes progressively more challenging. The general task remains unchanged, ensuring consistent assessment of the same cognitive function. Another limitation to consider is the moderate sample size ( $n = 15$ ) in this study. Individual outliers caused greater and overlapping variance in the data, as demonstrated in Figure 14. However, these outliers were not excluded from the analysis, as the extreme values were not caused by measurement errors but rather corresponded to the natural behavior of these individuals.

#### **4.2.5 Conclusion**

The findings of the study show that walking with modified leg mechanics could increase cognitive-motor interference for healthy young adults in challenging dual-task situations. In challenging dual-task situations, effects of cognitive resource competition outweighed the benefits of an external attentional focus during walking with modified leg mechanics. Interestingly, this pattern was not observed during normal walking, suggesting that modifications in leg mechanics increase the postural threat and demand the postural reserve of healthy young adults. However, the results also suggest that familiarization can alter the perceived threat and thus the amount of cognitive resources allocated to the motor task. In this study, physical effort and biomechanics were passively manipulated using weight cuffs, with both factors known to affect automated walking (Clark, 2015). In contrast to the passive weight cuffs, powered lower limb exoskeletons could compensate for the physical effort (Jin et al., 2017), but controlling the exoskeleton can

add cognitive demands and thus deteriorate automated walking. The methodology employed in this study can serve as a conceptual framework for exploring the mechanisms underlying cognitive-motor interference in the domain of human-exoskeleton interaction.”

## 5 Study 2

Building on the findings of Study 1, which examined the effects of passively modified leg mechanics using weight cuffs in a controlled treadmill setting, Study 2 employed a powered exoskeleton in an outdoor, overground walking experiment with twenty healthy young adults. Participants performed a serial subtraction task while walking, both unassisted and while wearing the powered lower-limb exoskeleton TWIN (Laffranchi et al., 2021). Cognitive and motor performance, along with perceived workload, were measured and compared across conditions and over time to evaluate the effects of short-term adaptation. The TWIN exoskeleton operates under full position control, executing predefined movement trajectories without adapting to the user's intentions. The control unit receives only the trunk's inclination angle as input from the user. A slight forward inclination of the trunk serves as the trigger for initiating the step sequence. Accordingly, the conceptual framework from Figure 5 was adapted in Figure 16 to reflect the static nature of the control unit.

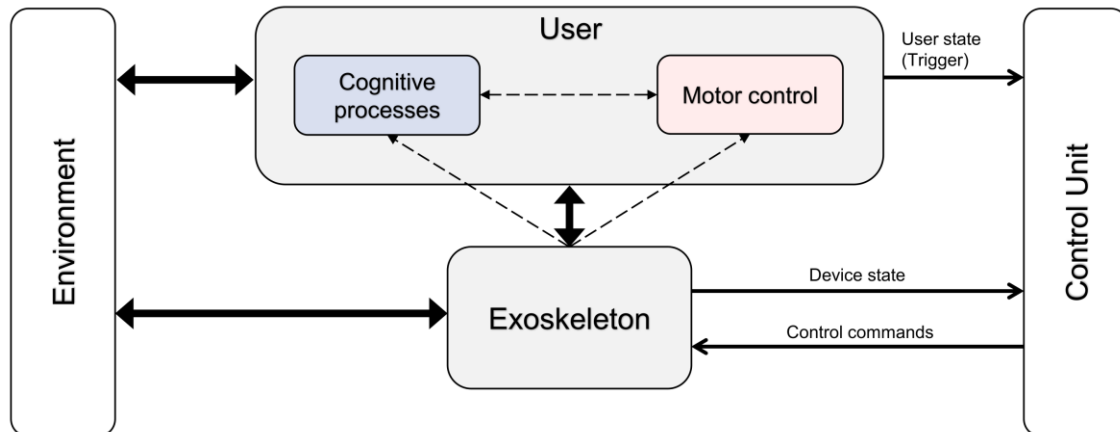


Figure 16. Conceptual framework adapted to the methodology of Study 2.

Data from this study contributed to two publications. The first examined cognitive and motor performance, as well as perceived workload, across experimental conditions and over time (see Section 5.1). The second publication integrated data of both Study 1 and Study 2 to explore the applicability of the performance operating characteristics (POC) framework in the context of human-exoskeleton interaction (see Section 5.2).

## 5.1 An outdoor dual-task study on cognitive-motor interference during exoskeleton-assisted walking

The following subsections (5.1.1 Introduction, 5.1.2 Materials and methods, 5.1.3 Results, 5.1.4 Discussion and 5.1.5 Conclusion) are full citations from the publication:

**Riedel, N.**, Marinou, G., Mombaur, K., & Deml, B. (2025). An outdoor dual-task study on cognitive-motor interference during exoskeleton-assisted walking. *Frontiers in Psychology*, *16*, 1583142. <https://doi.org/10.3389/fpsyg.2025.1583142>

### 5.1.1 Introduction

“In recent years, the integration of lower-limb exoskeletons as walking assistance devices has opened new avenues for enhancing mobility. Given the demographic shift toward an aging population, exoskeletons offer a promising solution to help the elderly maintain autonomy and independence in their everyday life (Kapsalyamov et al., 2019). Although lower-limb exoskeletons are currently available for use in controlled clinical and laboratory settings, their application in real-world environments remains a work in progress (Sawicki et al., 2020). Current performance evaluations of lower-limb exoskeletons predominantly focus on biomechanical and physiological parameters, often neglecting the cognitive aspects of the interaction (Pinto-Fernandez et al., 2020). However, Stirling et al. (2020) emphasize the importance of evaluating the cognitive fit in addition to the static and dynamic fit of an exoskeleton to ensure that the cognitive abilities necessary for other relevant tasks are fully available even when using an exoskeleton. Therefore, in addition to the technical challenges that have been identified (e.g., Di Shi et al., 2019; Kapsalyamov et al., 2019), the cognitive-motor interferences that arise from human-exoskeleton interaction remain a critical area of investigation.

Dual-task walking paradigms are an established approach to investigate cognitive-motor interference, particularly in clinical and epidemiological research (Al-Yahya et al., 2011; Beurskens & Bock, 2012; Kelly et al., 2012). In dual-task scenarios, limited cognitive resources can lead to performance declines in one or both tasks, influenced by individual characteristics and task complexity (Yogev-Seligmann et al., 2012). For instance, healthy young adults can allocate attention to a secondary task while maintaining a stable gait due to their high postural reserve. The pos-

tural reserve is defined as the capacity to respond optimally to a postural threat (Yogev-Seligmann et al., 2012). In contrast, elderly individuals, due to age-related cognitive decline, need to allocate more attentional resources to the motor task (Yogev-Seligmann et al., 2012). A motor task with increased balance control requirements, such as walking with an exoskeleton, may be perceived as a postural threat. Such complex motor tasks may cause attentional resources to be allocated to the motor task at the expense of the cognitive task, even in healthy young adults (Bequette et al., 2020; Hinton et al., 2020; Kao & Pierro, 2022; Mersmann et al., 2013; Reiser et al., 2019; Riedel et al., 2024).

To assess cognitive-motor interference and task prioritization, it is necessary to quantify both cognitive performance and motor performance using a multimodal approach. Cognitive performance is often measured using behavioral parameters like secondary task performance, whereas motor performance in dual-task walking studies is mainly evaluated through various gait parameters. Gait velocity is the most common parameter for assessing motor performance. Individuals generally slow down when a secondary task is introduced, especially if it involves complex neural networks that are interconnected with motor control, like mental tracking (Al-Yahya et al., 2011). Another key indicator of motor control is stride-to-stride variability (Hausdorff, 2005). Low variability indicates the reliance on automatic processes, while high variability suggests the engagement of attentional resources in motor control.

Powered lower-limb exoskeletons typically feature rigid segments and active joints, which can restrict the range of motion and modify mass and inertia distribution (Jin et al., 2017). It has been hypothesized that walking with an exoskeleton requires increased attentional resources to generate the appropriate muscle recruitment patterns necessary for maintaining a stable gait (Andrade et al., 2024). Additionally, imprecise application of active support can disrupt natural motion execution, requiring simultaneous control of both the device and the user's own motion, thereby increasing cognitive load (Clark, 2015) and physical load in terms of fatigue and metabolic costs (Stirling et al., 2020). Bequette et al. (2020) found that wearing a powered lower-limb exoskeleton led to slower reaction times in a visual search task for some participants. Moreover, the perceived workload, as measured by the NASA-TLX, was significantly higher during both powered and unpowered walking compared to walking without the exoskeleton.

This study employed the powered lower-limb exoskeleton TWIN (Laffranchi et al., 2021) (see Figure 17) to investigate cognitive-motor interference and short-term familiarization effects in

an outdoor dual-task walking experiment with a cohort of healthy young adults. The TWIN utilizes position control with predefined gait trajectories, requiring users to synchronize their movements with the exoskeleton. The *primary hypothesis (H1)* of this study postulates that cognitive-motor interference increases during exoskeleton-assisted walking compared to unassisted walking, resulting in decreased cognitive performance, motor performance, or both. Additionally, it was hypothesized that perceived mental and physical workload increase. However, research on adaptation to exoskeleton walking has shown improved muscle recruitment patterns (Gordon & Ferris, 2007; Jacobs et al., 2018) and significant reductions in energy costs (Poggensee & Collins, 2021). Clark (2015) provides evidence that excessive physical exertion requires more cognitive resources. This suggests that greater alignment with the exoskeleton's assistance may result in a reduction in cognitive demands. The *secondary hypothesis (H2)* predicted that short-term, within-session familiarization during exoskeleton-assisted walking improves both cognitive and motor performance and decreases perceived workload. The investigation of familiarization with lower-limb exoskeletons is extended through a complementary study by Marinou et al. (manuscript in preparation), where biomechanical metrics are established as familiarization indicators, quantifying familiarization through single and dual task conditions by systematically measuring variables such as stride duration, crutch ground reaction forces and foot center of pressure. Together, these studies enhance the understanding of familiarization by integrating both cognitive and biomechanical insights, thereby advancing research on the broader impacts of exoskeleton use on human performance.

## **5.1.2 Materials and methods**

### **5.1.2.1 Participants**

Twenty healthy young adults (age:  $25.3 \pm 4.1$  years; stature:  $1.73 \pm 0.10$  m; body mass:  $69 \pm 12.1$  kg; 10 female, 10 male) participated in the study. The participants were students at the Karlsruhe Institute of Technology (KIT). Participants had to be between 1.55 and 1.90 m tall and weigh < 100 kg so that the exoskeleton could be adjusted accordingly. This research was conducted in accordance with the American Psychological Association Code of Ethics and received approval from the KIT-Ethics Committee. Prior to participation, all subjects provided written informed consent.

### 5.1.2.2 Apparatus

Data collection took place at the KIT sports facilities on a 25 m track in a covered open-air hall. During the walking sessions, the powered lower-limb exoskeleton TWIN was used, along with a measurement system that included various inertial, force, and pressure sensors (see Figure 17).

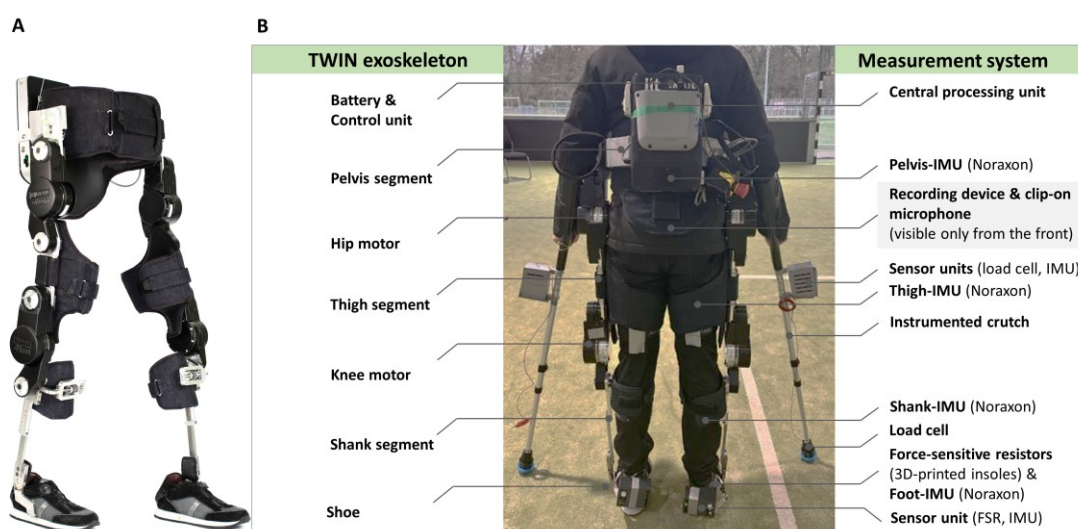


Figure 17. (A) TWIN lower-limb exoskeleton (adapted from Semprini et al., 2022), (B) setup of the TWIN exoskeleton and the measurement system. FSR, force sensitive resistor; IMU, inertial measurement unit. (Riedel et al., 2025)

#### 5.1.2.2.1 TWIN exoskeleton

The TWIN was developed at the IIT-INAIL Rehab Technologies Lab with the primary objective of assisting the ambulation of spinal cord injury patients. It was designed to operate in full position control, generating predefined movement trajectories that can be modified based on gait parameter inputs by the operator (Vassallo et al., 2020). Based on Vassallo et al. (2020), a predetermined trajectory (T3) is incorporated in the TWIN's high-level control, chosen based on the merits of joint angle minimization during walking as to maximize user comfort, and heel-strike phase accentuation to avoid stumbling during gait, thus increasing system stability. The modular structure of the TWIN comprises four actuated joints at the hips and knees and five rigid components at the pelvis, as well as right and left components for the thighs and shanks with padded braces. The rigid components are available in different sizes, allowing for individual anthropometrical fitting of the exoskeleton. The controller and batteries are located at the lower back. While the exoskeleton provides rigid support, the hip and knee joints allow for minor ranges of motion for internal and external rotations. Additionally, the ankle joint incorporates a variable

elastic element to accommodate variations in dorsiflexion and extension. Consequently, despite the predefined joint trajectories, the user can introduce within-step variability.

The gait parameters for the trajectory generation can be controlled through a mobile device using a custom app. TWIN can operate in two walking modes: manual and automatic. In manual mode, an external person triggers each step via the app. In automatic mode, an inertial measurement unit (IMU) located at the back element of the TWIN initiates a step sequence upon detecting a slight forward shift of the trunk. The sequence continues until the user returns to an upright position, with the final step safely bringing the feet together. Since the range of motion is primarily restricted to the sagittal plane (flexion-extension), this can challenge both static and dynamic balance, necessitating the use of forearm crutches.

#### 5.1.2.2.2 Measurement System

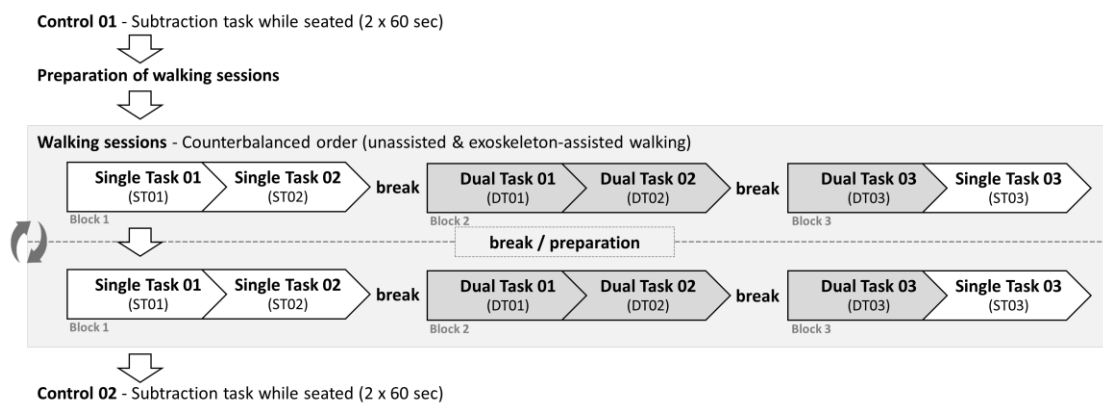
Kinematics were assessed at 200 Hz using a Noraxon Ultium Motion IMU system with MyoResearch 3.20.40 software, incorporating seven IMUs at the feet, shanks, thighs, and pelvis (Noraxon U.S.A. Inc., Scottsdale, AZ). Following the instructions provided by Noraxon, lower-limb sensors were affixed to a Velcro strap that was fastened around the corresponding body segment. The pelvis sensor was attached directly to the skin via an adhesive. In order to capture the participant's responses in the secondary task for the analysis of the cognitive performance, a recording device (Sony, model: ICDUX570) with a clip-on microphone (Phillips, model: LFH9173/00) was used.

The crutches used in this study were instrumented with load cells and IMUs. Additionally, force-sensitive resistors within a 3D-printed insole were placed in the exoskeleton shoes (Marinou et al., 2025). The data collected from these sensors helped generate the biomechanical metrics used as familiarization indicators in the parallel study by Marinou et al. (manuscript in preparation).

#### 5.1.2.3 Procedure

The study involved two separate appointments. During the initial preparation appointment, participants provided written informed consent and anthropometric measurements were taken to ensure the exoskeleton was individually fitted. Participants received detailed instructions on how to use the exoskeleton and crutches before taking a maximum of five steps with the exoskeleton in manual mode, limiting familiarization effects prior to data collection.

Data collection during the second appointment took place at least 14 days after the initial appointment. The exoskeleton and the instrumented crutches were preadjusted based on the measured individual anthropometric parameters. The procedure at the second appointment is illustrated schematically in Figure 18.



**Figure 18. Experimental procedure at the second appointment. (Riedel et al., 2025)**

The cognitive task was initially performed while seated to allow for familiarization with the task. Participants performed a serial subtraction task in which they were given a random three-digit number between 301 and 999 and instructed to subtract 7 repeatedly as quickly and accurately as possible. Participants performed two trials, each lasting 60 s (Control 01). After each trial, participants rated their perceived mental and physical workload using the respective NASA-TLX subscales (Hart & Staveland, 1988).

Noraxon IMUs were attached and calibrated dynamically in accordance with the walking calibration instructions. First, subjects stood still for 2.5 s with their arms at their sides and their feet close to shoulder-width apart. They then walked for 15 s at a self-selected speed, made a 180° turn, walked back to the starting position, and stood still another 2.5 s in the same initial posture. After the calibration, participants engaged in two walking sessions, an unassisted walking session and an exoskeleton-assisted walking session, in a counterbalanced order. Both sessions comprised of three blocks with two walking trials of 25 m each. After the first walking trial in each block, participants turned 180° and walked back after an obligatory short break (~2 min), followed by an obligatory longer break (~5 min) between blocks. Both walking trials of the first block were carried out without a cognitive task, i.e. single-task walking (ST01 and ST02). In the second block, the participants performed the subtraction task in both walking trials, i.e. dual-task walking (DT01 and DT02). In the third block, the first walking trial included the subtraction

task, whereas the second walking trial did not (DT03 and ST03). In the short and long breaks between trials, the participants again rated their perceived mental and physical workload.

During the unassisted walking session, only the lower-limb IMUs and audio recorder were utilized. Participants walked at their preferred walking speed at an average of  $1.31 \pm 0.08$  m/s ( $4.72 \pm 0.29$  km/h). In contrast, during the exoskeleton-assisted walking session, the entire measurement system was employed. Participants were first fitted with the exoskeleton while seated, including replacing their shoes with the exoskeleton's integrated shoes. Subsequently, the foot IMUs were transferred to the TWIN shoes. This was followed by a recapitulation of the instructions for using the exoskeleton in automatic mode. Finally, the pressure sensors, IMUs on the crutches, and load cells were calibrated. The average walking speed across exoskeleton conditions was  $0.10 \pm 0.01$  m/s ( $0.36 \pm 0.03$  km/h). Several factors influence exoskeleton-assisted walking speed, with the control strategy being a primary contributor, which allows for pre-programmed step parameters. This includes parameters such as step velocity and inter-step timing, while anthropometric scaling further influences timing by adjusting step length based on the user's segment lengths. These factors likely contributed to reduced walking speeds, as participants needed to synchronize with the exoskeleton's movements, although they retained some control over step timing by leaning back.

After the two walking sessions, participants performed the subtraction task while seated to assess cognitive performance without the motor task (Control 02). As at the beginning, there were two 60-s trials. The second appointment took a maximum of 180 min.

#### **5.1.2.4 Data processing**

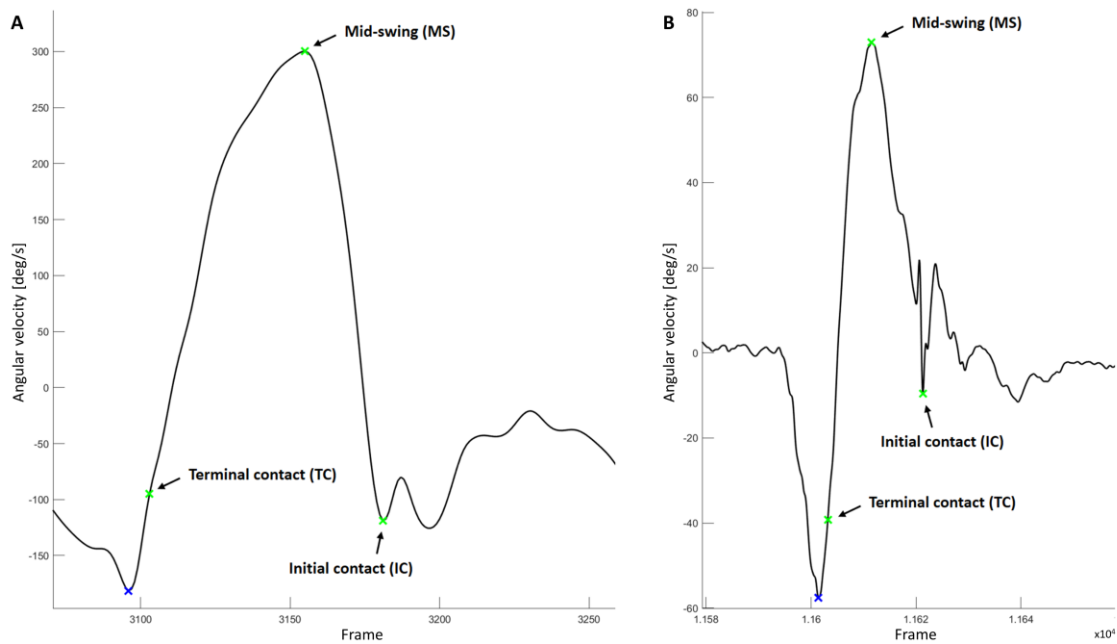
To quantify cognitive performance, the correct response rates (CRR) were calculated. According to Galletly and Brauer (2005), this is determined by multiplying the response rate (subtractions per second) by the accuracy (percentage of correct subtractions). During the exoskeleton-assisted walking trials, data were collected from a 60-s segment following an initial 60 s of walking. For unassisted walking trials, the entire duration was used.

To evaluate the motor performance, stride time, double support time and gait velocity were calculated using MATLAB R2023a (The MathWorks, Natick, MA, United States). Stride time is the duration of one complete gait cycle, from initial contact of one foot to its subsequent contact. Double support time is the phase within the gait cycle when both feet are simultaneously in

contact with the ground. For stride time and double support time, the mean values and coefficients of variation (CV) were determined. The CV were calculated by dividing the standard deviation by the mean and multiplying by 100.

Gait event detection was conducted using the Dual Minima Method, which relies on the angular velocity measured by gyroscopes mounted on the shank (Aminian et al., 2002; Bötzel et al., 2016; Greene et al., 2010; Salarian et al., 2004). After applying a 20 Hz, 4th-order low-pass Butterworth filter to the angular velocity data, local maxima were identified as mid-swing (MS). Initially, the preceding and following local minima below zero were marked as initial contact (IC) and terminal contact (TC), respectively. While IC detection was accurate, TC was found to occur later than initially detected (Bötzel et al., 2016). Following Bötzel et al. (2016), TC was defined as the midpoint between the minimum and the zero-crossing (see Figure 19). Since symmetry was assumed, the stride time was calculated based on the right side. For each walking trial, the first and last two strides were excluded from the analysis to account for acceleration and deceleration effects. The analysis was based on an average of 23 strides performed with the exoskeleton and 15 strides without it.

Gait velocity was calculated by dividing the distance walked by the time taken. The distance was assessed based on the pelvis IMU trajectory calculated via double integration in Noraxon MyoResearch. The magnitude of the resulting trajectory was calculated in the antero-posterior and medio-lateral directions. Due to the progressive accelerometer drift of the Noraxon IMUs during the lengthy exoskeleton-assisted walking trials, the gait velocity data were extracted only for the first single- (ST01) and dual-task (DT01) trials.



**Figure 19.** Gait event detection with the Dual Minima Method based on angular velocity of the shank-mounted IMU. Exemplary extraction of a single step of participant 01 during (A) unassisted walking and (B) exoskeleton-assisted walking. (Riedel et al., 2025)

### 5.1.2.5 Statistical analysis

Normality of the data was assessed using the Kolmogorov-Smirnov test. Given that repeated measures ANOVAs (rmANOVA) are robust to deviations from normality when the sphericity assumption is satisfied (Blanca et al., 2023; Schmider et al., 2010), parametric models were employed. If both assumptions were violated, non-parametric models were used instead. Sphericity was evaluated with the Mauchly test, and when violated, the Greenhouse-Geisser correction was applied. All statistical tests were conducted with a significance level of  $\alpha = 0.05$ , with Bonferroni corrections applied to post-hoc pairwise comparisons. The effect sizes are reported as partial eta squared ( $\eta_p^2$ ). Measurement errors in certain trials led to data loss, reducing the sample size for some parameters. The specific sample sizes are indicated in the results section through the reported degrees of freedom and are annotated in each plot shown in Figure 20 and Figure 21. The statistical analyses were conducted using SPSS Statistics 29.0 (IBM, Armonk, NY, USA).

To test the first hypothesis,  $2 \times 2$ -rmANOVAs were performed for stride time variability, double support time variability, gait velocity, and perceived mental and physical workload. The analyses included two within-subject factors: *Walking Condition* (Unassisted walking, exoskeleton-assisted walking) and *Task Condition* (Single-task, dual-task). Data from the third block (DT03,

ST03) were used for the analysis, as the first two blocks functioned as a familiarization phase (see Figure 18). However, gait velocity analysis included data from ST01 and DT01, as described above. A  $1 \times 3$ -rmANOVA was conducted on CRR, including the dual-task conditions and the second seated control condition (Control 02) as levels.

To test the second hypothesis,  $1 \times 3$ -rmANOVAs or non-parametric Friedman tests were conducted on the three single-task trials during exoskeleton-assisted walking, examining stride time variability, double support time variability, CRR, and perceived mental and physical workload. The analyses included *Time Condition* (ST01, ST02, ST03) as a within-subject factor. CRR was assessed exclusively during the dual-task trials (DT01, DT02, DT03).

### 5.1.3 Results

Table 5 presents the mean (SD) and median (IQR) for motor performance, cognitive performance, and perceived workload parameters in Block 3 (ST03, DT03) for both unassisted and exoskeleton-assisted walking, with corresponding boxplots depicted in Figure 20. Additionally, Table 6 presents the mean (SD) and median (IQR) of dependent variables for exoskeleton-assisted walking across the three single-task trials (ST01, ST02, ST03), with boxplots depicted in Figure 21.

**Table 5.** Mean (SD) and median (IQR) of motor performance, cognitive performance, and perceived workload metrics for unassisted and exoskeleton-assisted walking under single-task (ST03) and dual-task (DT03) conditions.

	Unassisted walking		Exoskeleton-assisted walking	
	ST03	DT03	ST03	DT03
<b>Motor performance</b>				
CV Stride time (%)	1.2 (0.4)   1.2 (0.9-1.5)	2.2 (0.9)   2.0 (1.5-2.8)	3.4 (1.7)   3.6 (1.5-4.6)	3.0 (1.6)   2.9 (1.8-4.2)
CV Double support time (%)	3.5 (1.5)   3.1 (2.6-4.0)	4.4 (1.7)   4.6 (3.4-5.4)	4.6 (2.6)   4.5 (2.1-5.6)	4.3 (2.3)   4.4 (2.3-6.5)
Gait velocity (m/s)	1.39 (0.21)   1.37 (1.23-1.47) <sup>1</sup>	1.26 (0.25)   1.24 (1.04-1.41) <sup>1</sup>	0.09 (0.03)   0.10 (0.07-0.12) <sup>1</sup>	0.11 (0.02)   0.11 (0.10-0.12) <sup>1</sup>

	Unassisted walking		Exoskeleton-assisted walking	
	ST03	DT03	ST03	DT03
<b>Cognitive performance</b>				
Correct response rate	-	0.35 (0.09)   0.33 (0.29-0.42)	-	0.30 (0.10)   0.28 (0.22-0.36)
<b>Perceived workload</b>				
Mental workload	2.2 (3.3)   0.0 (0.0-5.0)	41.0 (23.2)   35.0 (21.3-60.0)	17.0 (12.3)   12.5 (10.0-20.0)	59.9 (21.2)   60.0 (42.5-75.0)
Physical workload	7.8 (6.4)   8.0 (2.5-10.0)	7.1 (6.4)   5.0 (2.3-10.0)	25.3 (16.2)   20.0 (12.0-40.0)	25.9 (15.7)   20.0 (15.0-39.3)

n = 20, 1: n = 16 and based on ST01, DT01. CV – Coefficient of Variation; ST – Single Task; DT – Dual Task

**Table 6.** Mean (SD) and median (IQR) of motor performance, cognitive performance, and perceived workload metrics for exoskeleton-assisted walking across the three single-task trials (ST01, ST02, ST03).

	Exoskeleton-assisted walking		
	ST01	ST02	ST03
<b>Motor performance</b>			
CV Stride time (%)	4.2 (2.5)   3.7 (2.0-6.4) <sup>1</sup>	3.3 (1.7)   3.1 (1.8-4.1) <sup>1</sup>	2.9 (1.7)   2.6 (1.4-4.4) <sup>1</sup>
CV Double support time (%)	5.9 (3.7)   5.3 (2.3-9.8) <sup>1</sup>	4.8 (2.4)   4.3 (3.0-6.3) <sup>1</sup>	4.0 (2.3)   3.6 (1.9-5.6) <sup>1</sup>
<b>Cognitive performance</b>			
Correct response rate	0.26 (0.08)   0.24 (0.20-0.28) <sup>2</sup>	0.30 (0.08)   0.27 (0.25-0.35) <sup>2</sup>	0.30 (0.10)   0.28 (0.22-0.36) <sup>2</sup>
<b>Perceived workload</b>			
Mental workload	28.3 (12.2)   27.5 (20.0-40.0)	24.9 (12.1)   22.5 (15.0-30.0)	17.0 (12.0)   12.5 (10.0-20.0)
Physical workload	31.9 (14.7)   25.0 (20.0-40.0)	28.0 (11.4)   27.5 (20.0-40.0)	25.3 (15.8)   20.0 (12.0-40.0)

n = 20, 1: n = 15, 2: based on DT01, DT02, DT03. CV – Coefficient of Variation; ST – Single Task

### 5.1.3.1 Motor performance

The  $2 \times 2$ -rmANOVAs conducted to test H1 revealed that there was a statistically significant interaction between the effects of *Walking Condition* and *Task Condition* for stride time variability [ $F(1,19) = 15.30, p < 0.001, \eta_p^2 = 0.45$ ] and gait velocity [ $F(1,19) = 34.98, p < 0.001, \eta_p^2 = 0.65$ ].

Simple main effects tests indicated that stride time variability was significantly higher during exoskeleton-assisted walking than during unassisted walking in the single-task condition ( $p < 0.001$ ). However, there were no significant differences during the dual-task condition ( $p = 0.062$ ). Stride time variability during unassisted walking increased significantly from single-task to dual-task condition ( $p < 0.001$ ), whereas it reduced on average during exoskeleton-assisted walking, however not significantly ( $p = 0.165$ ). For gait velocity, simple main effects tests showed that participants reduced their speed from single-task to dual-task condition during unassisted walking ( $p < 0.001$ ). In contrast, gait velocity during exoskeleton-assisted walking increased from single-task to dual-task condition ( $p = 0.018$ ). The gait velocity during unassisted walking, under both single-task ( $p < 0.001$ ) and dual-task conditions ( $p < 0.001$ ), was significantly greater compared to exoskeleton-assisted walking. For double support time variability the rmANOVA showed no significant interaction effects [ $F(1,19) = 3.85$ ,  $p = 0.065$ ,  $\eta_p^2 = 0.17$ ]. However, the statistical trend indicates a similar pattern observed for stride time variability. The main effects for *Walking Condition* [ $F(1,19) = 0.86$ ,  $p = 0.365$ ,  $\eta_p^2 = 0.04$ ] and *Task Condition* [ $F(1,19) = 0.66$ ,  $p = 0.426$ ,  $\eta_p^2 = 0.03$ ] were also not significant.

The  $1 \times 3$ -rmANOVAs conducted to test H2 revealed no significant effects of *Time Condition* for stride time variability [ $F(1.30,18.17) = 2.94$ ,  $p = 0.095$ ,  $\eta_p^2 = 0.17$ ] and double support time variability [ $F(1.29,18.02) = 2.38$ ,  $p = 0.136$ ,  $\eta_p^2 = 0.15$ ]. The statistical trends in stride time variability and double support time variability indicate a reduction in variability from the first to the third trial.

### 5.1.3.2 Cognitive performance

The  $1 \times 3$ -rmANOVA showed a significant effect for CRR [ $F(2,38) = 5.50$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.38$ ]. Post-hoc tests revealed that CRR was significantly lower during exoskeleton-assisted walking compared to both unassisted walking ( $p = 0.018$ ) and the seated control condition ( $p < 0.001$ ). No significant differences were found between unassisted walking and the seated control condition ( $p = 0.347$ ).

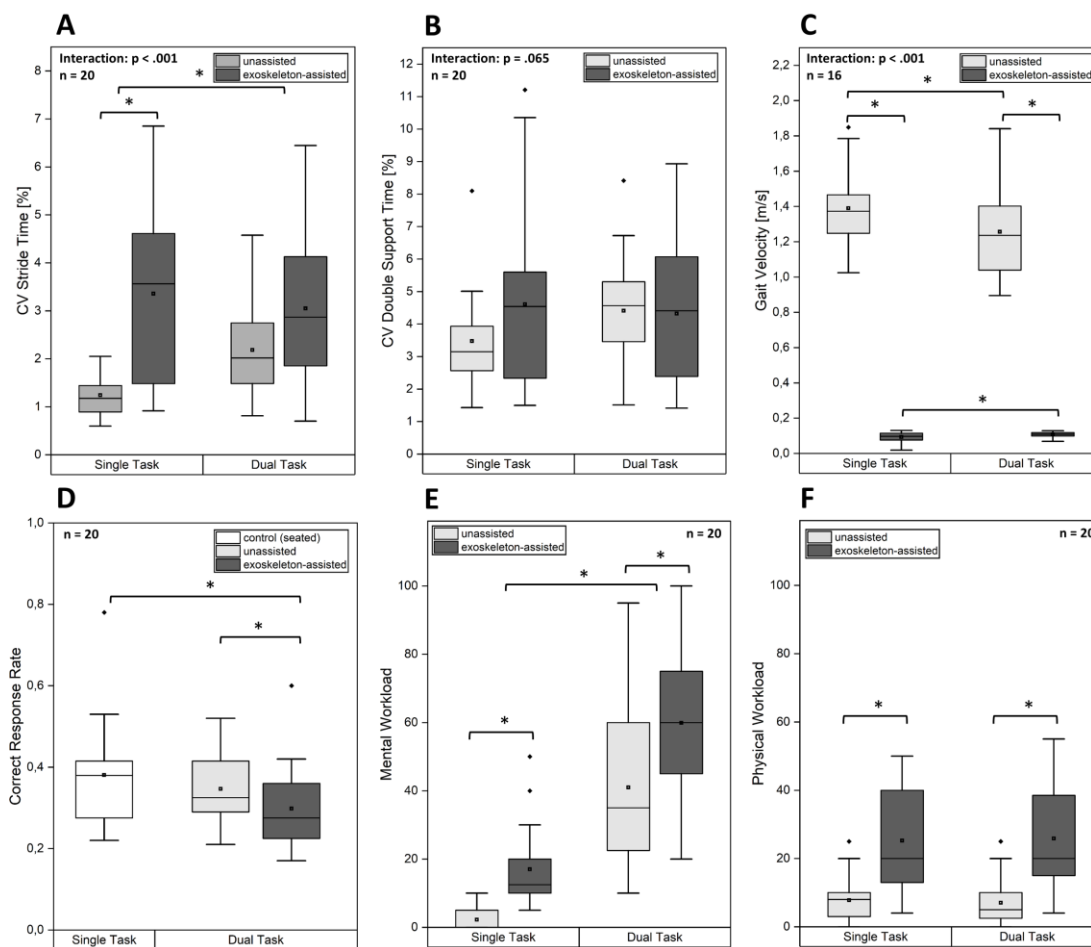
A significant effect of *Time Condition* was observed [ $F(2,38) = 5.50$ ,  $p = 0.008$ ,  $\eta_p^2 = 0.23$ ], indicating an increase in CRR from the first to the third trial during exoskeleton-assisted walking. Post-hoc analyses showed that CRR was significantly higher in the third trial compared to the

first ( $p = 0.005$ ), while no significant differences were observed between the first and second trial ( $p = 0.066$ ) or between the second and third trial ( $p = 1.00$ ).

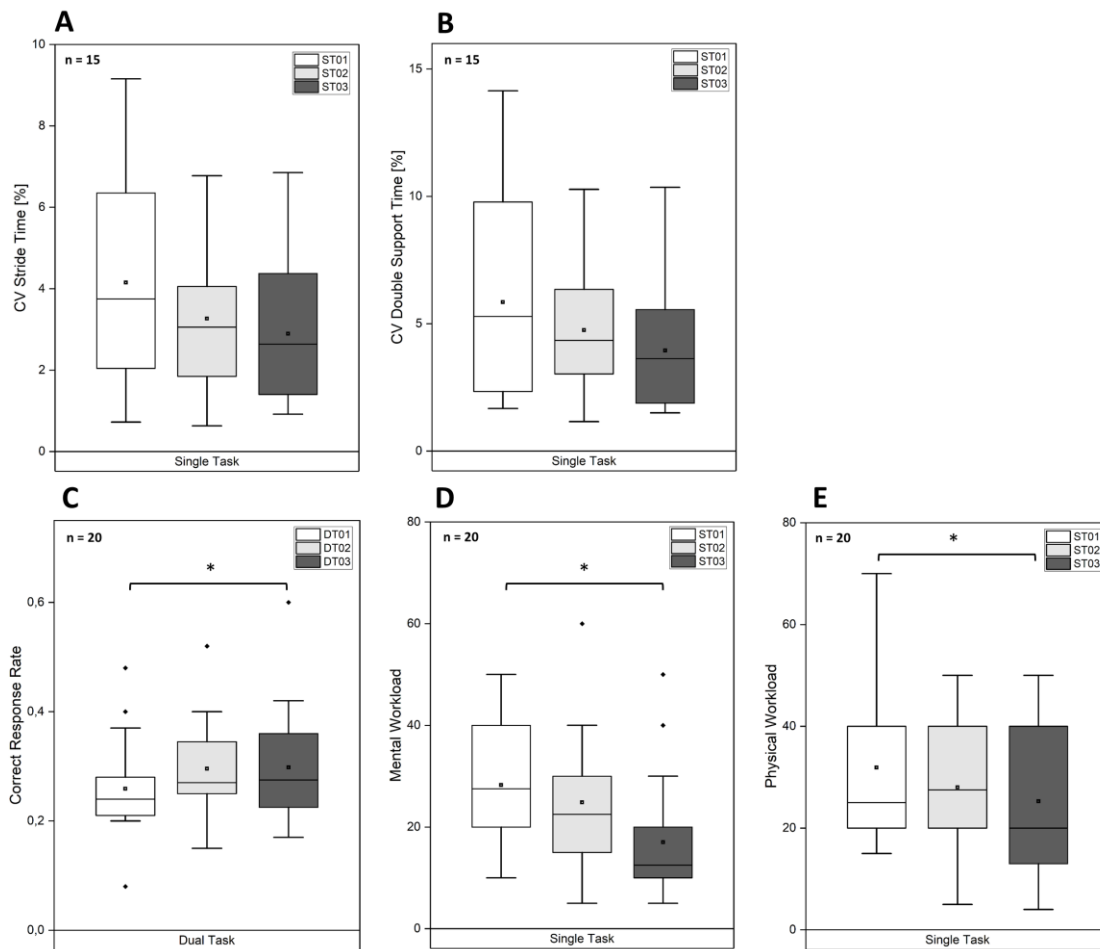
### 5.1.3.3 Perceived workload

There was no significant interaction between *Walking Condition* and *Task Condition* for perceived mental workload [ $F(1,19) = 0.97$ ,  $p = 0.337$ ,  $\eta_p^2 = 0.05$ ] and physical workload [ $F(1,19) = 1.21$ ,  $p = 0.285$ ,  $\eta_p^2 = 0.06$ ]. However, there were significant main effects of *Walking Condition* on mental workload [ $F(1,19) = 44.58$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.70$ ] and physical workload [ $F(1,19) = 27.56$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.59$ ], indicating an increase of perceived mental and physical workload during exoskeleton-assisted walking compared to unassisted walking. *Task Condition* had a significant effect on mental workload [ $F(1,19) = 79.77$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.81$ ], but no effect on physical workload [ $F(1,19) = 0.01$ ,  $p = 0.914$ ,  $\eta_p^2 = 0.00$ ]. This shows that the subtraction task in the dual-task condition increased mental workload as intended, without affecting physical workload.

The Friedman test revealed significant effects of *Time Condition* on perceived mental workload [ $\chi^2(2) = 17.10$ ,  $p < 0.001$ ] and physical workload [ $\chi^2(2) = 9.10$ ,  $p = 0.011$ ]. Dunn-Bonferroni post-hoc tests indicated that both mental workload ( $p < 0.001$ ) and physical workload ( $p = 0.027$ ) decreased significantly from the first to the third trial. The differences between the first and the second trial were not significant for mental workload ( $p = 0.342$ ) and physical workload ( $p = 0.707$ ). Similarly, no significant differences were found between the second and the third trial for mental workload ( $p = 0.066$ ) and physical workload ( $p = 0.464$ ).



**Figure 20.** Boxplots depicting the (A) coefficient of variation (CV) of stride time, (B) CV of double support time, (C) gait velocity, (D) correct response rate, (E) mental workload and (F) physical workload across different task conditions and walking conditions. The median (horizontal line within the box), the mean (black squares), the interquartile range (box), and the data spread including potential outliers (dots) are shown for each condition. Asterisks (\*) indicate statistically significant differences between conditions. (Riedel et al., 2025)



**Figure 21.** Boxplots depicting the (A) coefficient of variation (CV) of stride time, (B) CV of double support time, (C) correct response rate, (D) mental workload and (E) physical workload across the three single task trials. Note that correct response rates were only assessed for the dual-task trials. The median (horizontal line within the box), the mean (black squares), the interquartile range (box), and the data spread including potential outliers (dots) are shown for each condition. Asterisks (\*) indicate statistically significant differences between conditions. (Riedel et al., 2025)

### 5.1.4 Discussion

This study employed a dual-task paradigm to investigate cognitive-motor interference (H1) and short-term familiarization effects (H2) in an outdoor walking experiment with a powered lower-limb exoskeleton. In contrast to unassisted walking, introducing the secondary task during exoskeleton-assisted walking slightly increased gait velocity and decreased stride time variability. Concurrently, cognitive performance declined during exoskeleton-assisted walking, suggesting a shift to a *posture-first* strategy. Short-term familiarization was observed through reduced per-

ceived workload and improved cognitive performance throughout the session. However, cognitive performance remained inferior to the seated control condition and unassisted walking, suggesting that walking with the exoskeleton still requires significant attentional resources.

#### **5.1.4.1 Introduction of a cognitive task increased gait velocity and decreased stride time variability in exoskeleton-assisted walking**

Previous studies have shown that gait velocity decreases under dual-task conditions, suggesting that higher-order cognitive processes are involved (Al-Yahya et al., 2011). In line with this, the present study found a significant decrease in gait velocity during unassisted walking with a subtraction task (−9%). However, gait velocity increased during dual-task exoskeleton-assisted walking (+22%), suggesting that, despite the mechanical constraints imposed by the TWIN, gait patterns were modified—possibly through increased stride length. In a self-paced treadmill walking study by Gupta et al. (2023), healthy adults exhibited a tendency to shift toward a preferred walking velocity while performing a secondary task, suggesting that walking at a preferred velocity may require less attentional effort in dual-task scenarios. It can therefore be hypothesized that participants walking at low speeds with the exoskeleton exhibit similar behavior.

Similarly, stride time variability increased from single- to dual-task conditions during unassisted walking (+83%) but slightly decreased during exoskeleton-assisted walking (−12%), contradicting the initial hypothesis that motor interference increases during exoskeleton-assisted walking. Stride time variability was significantly higher during exoskeleton-assisted walking compared to unassisted walking in single-task conditions, but no differences emerged in the dual-task condition. The introduction of a secondary task appeared to enhance motor performance during exoskeleton-assisted walking, consistent with participants' feedback that it shifted their attention away from the exoskeleton. This shift in attention may have reduced exploratory behavior compared to single-task walking, potentially decreasing resistance against the exoskeleton and promoting more automatic compliance with the predefined gait trajectories.

Treadmill studies have shown that externalizing the focus of attention in this way can reduce gait variability during simple secondary tasks, as it promotes more automatic gait execution (Decker et al., 2016; Lövdén et al., 2008; Riedel et al., 2024). Such findings have not been replicated for overground walking, raising questions about their transferability (Hybart et al., 2023; Wrightson et al., 2020). However, similar to a treadmill, the TWIN induces a rhythmic regulating

mechanism through predefined trajectories, haptic cues via the transmission of forces and torques (Wu et al., 2022), and auditory cues as the device beeps before the initiation of each step. There is evidence that rhythmic auditory stimulation can lead to increased gait speed and stride length, as well as reduced gait variability in individuals with Parkinson's disease (Hausdorff et al., 2007; Pau et al., 2016). Moreover, studies with lower-limb exoskeletons show that external cues can improve motor performance (Kim et al., 2022; Wu et al., 2022). From an ergonomic perspective, the results suggest that providing direct feedback through external cues may benefit exoskeleton users—particularly when their attention is externally directed, as often occurs in real-world contexts.

#### **5.1.4.2 Differing prioritization strategies for unassisted walking and exoskeleton-assisted walking**

Reduced gait velocity and increased stride time variability during unassisted walking suggest that participants prioritized the cognitive task over the motor task, employing a *posture-second* strategy (Yogev-Seligmann et al., 2012). This is supported by the results of cognitive performance, as correct response rates (CRR) did not differ significantly from the seated control condition. In contrast, CRR significantly decreased during exoskeleton-assisted walking (−14%), indicating that fewer cognitive resources were allocated to the secondary task. This suggests a shift to a *posture-first* strategy. Conversely, participant feedback indicated that the dual-task condition led to more automated walking, as they did not consciously think about walking, suggesting that a *posture-second* strategy may also be present during exoskeleton-assisted walking. However, walking with the exoskeleton and coordinating with external cues still required considerable attentional resources, contributing to the observed decline in cognitive performance. This implies that only a portion of attentional resources was allocated to the secondary task, with the primary focus remaining on the motor task. This shift toward a *posture-first* strategy implies that participants perceived exoskeleton-assisted walking as a postural threat, which is consistent with the fact that the TWIN restricts natural movement. This underscores the need for enhancing the intuitiveness of the exoskeleton's operation through the incorporation of adaptive control systems (Baud et al., 2021) and mechanical designs that permit natural joint motion without limiting degrees of freedom (Dežman et al., 2024).

In human-robot interaction research, particularly in non-physically coupled systems, the ability of a robot to anticipate human behavior has been shown to improve efficiency (Huang & Mutlu,

2016). A key challenge involves the integration of intent recognition that infer user intent and dynamically adapt the level of exoskeletal assistance. The effectiveness of these mechanisms is closely tied to the concept of mental models, the user's internal understanding of how the exoskeleton functions (Stirling et al., 2019). Discrepancies between the user's mental model and the system's embedded model can result in reduced performance. Empirical evidence indicates that both the type of the control strategy (Zhang et al., 2015) and the temporal dynamics of assistance (Ding et al., 2016) are critical determinants of user performance, potentially due to their varying degrees of congruence with the user's mental model. Future investigations should systematically examine which adaptive control strategies best match user's mental models under various task demands.

Participants in this study reported significantly higher physical and mental workload during exoskeleton-assisted walking compared to unassisted walking, suggesting that the exoskeleton imposes greater demands on both cognitive and motor control systems. While cognitive performance declined, motor performance improved. These findings indicate that, although external rhythmic cues can enhance motor performance, walking with the exoskeleton and coordinating with these cues still require substantial attentional resources. The integration of multimodal feedback systems, including visual, auditory, and haptic cues that are easy to interpret, may help reduce cognitive workload during exoskeleton use (Wu et al., 2022) and warrants further investigation in future studies.

#### **5.1.4.3 Short-term familiarization effects in exoskeleton-assisted walking**

To test the second hypothesis regarding short-term, within-session familiarization effects during exoskeleton-assisted walking, the dependent variables were assessed across three consecutive single-task trials (see Figure 18). Each exoskeleton trial lasted ~3 - 4 min, with the entire session spanning around 20 min. Participants reported a significant reduction in both perceived physical and mental workload throughout the session, indicating familiarization. These results align with those of (Marinou et al., 2022), who found that participants began exhibiting familiarization effects with the TWIN exoskeleton within 10 - 20 min of walking.

In addition, the cognitive performance increased significantly from the first to the third trial, supporting the hypothesis that greater alignment with the exoskeleton's assistance reduces cognitive load. However, cognitive performance remained inferior to both seated control and un-

assisted walking conditions, suggesting that walking with the exoskeleton still requires significant attentional resources. The dependent variables showed no significant differences between the second and third trials, indicating that familiarization effects plateaued after the second trial. However, long-term study designs are required to ascertain whether familiarization has been fully completed or not. The time required for familiarization can vary depending on several factors, including the complexity of the exoskeleton (e.g., the number of assisted joints and the magnitude of assistance) and the individual characteristics of the user (Poggensee & Collins, 2021). In line with the recommendations of Poggensee and Collins (2021), designs of future experiments investigating human-exoskeleton interaction should ensure that participants are thoroughly familiarized.

#### **5.1.4.4 Limitations**

The participants in this study did not represent the intended target user group for the TWIN exoskeleton, which intentionally interfered with natural walking. The use of healthy young adults as participants limits the generalizability of the results, as cognitive-motor challenges may differ in clinical populations. While assessing the efficacy of a specific exoskeleton ideally necessitates the recruitment of individuals from the target user group, such an objective was beyond the scope of the current investigation. Future research should include individuals with spinal cord injury or other relevant clinical populations to enhance the ecological validity of the results. All participants were novices with the TWIN exoskeleton. Although the study controlled for familiarization effects before examining cognitive-motor interference, the results do not allow for a definitive conclusion regarding whether the familiarization process was fully completed, highlighting the need for a longer familiarization period. Additionally, participants had to coordinate their movements with both the exoskeleton and crutches, thereby introducing additional cognitive and motor demands. Another important factor to consider is the substantial difference in gait velocity between unassisted and exoskeleton-assisted walking, as gait velocity influences gait variability. Jordan et al. (2007) provide evidence that gait variability tends to decrease as walking speed increases. The observed differences in motor performance in response to the secondary task can be interpreted independently of gait velocity within each walking condition. However, the overall increase in gait variability during exoskeleton-assisted walking as compared to unassisted walking may be due to the slower walking speed rather than being attributable solely to the use of the exoskeleton.

Additionally, the subtraction task had a predictive rhythmic pattern, which may have led participants to synchronize their response speed with the exoskeleton's gait cycle, despite instructions to perform the task as quickly and accurately as possible (Bartolo et al., 2021). Exploratory t-tests revealed a significant reduction in response rate from unassisted walking (0.36 responses/s) to exoskeleton-assisted walking (0.31 responses/s), while accuracy remained relatively unchanged (unassisted walking: 97.69%; exoskeleton-assisted walking: 96.78%). Using unpredictable stimuli may help address this potential confounding factor. For example, Reiser et al. (2022) jittered the stimulus interval by  $\pm 250$  ms. In outdoor experiments, responding to jittered auditory stimuli may provide a viable alternative. Finally, randomizing the initial number on each trial in the subtraction task may have introduced variability in task complexity across trials. This approach was intended to reduce predictability and reduce the potential for rehearsal effects.

### 5.1.5 Conclusion

This study employed a dual-task paradigm to investigate cognitive-motor interference and short-term familiarization effects in an outdoor walking experiment with healthy adults using the TWIN lower-limb exoskeleton. The findings indicate the adoption of different prioritization strategies for unassisted and exoskeleton-assisted walking. Specifically, introducing a secondary task during exoskeleton-assisted walking slightly increased gait velocity and decreased stride time variability, possibly due to the partial allocation of attentional resources enhancing coordination with the exoskeleton's external rhythmic cues. However, cognitive performance declined compared to both the seated control and unassisted walking conditions, indicating a *posture-first* strategy. Short-term familiarization during exoskeleton-assisted walking reduced perceived workload and improved cognitive performance. Nonetheless, performance remained below that of control conditions, suggesting that walking with the exoskeleton still requires significant attentional resources. These findings should be interpreted with caution, given the limited familiarization period and the exclusive focus on healthy young adults. Further research is needed to validate these preliminary results across larger and more diverse populations, and to examine the effects of extended training periods. Future studies should also explore adaptive control and user feedback systems to enhance the efficiency of human-exoskeleton interaction. Ultimately, the results underscore the importance of designing exoskeletons with a good cognitive fit to

support the perception-cognition-action decision process of the exoskeleton user (Stirling et al., 2020).”

## **5.2 Assessment of cognitive-motor interference in human-exoskeleton interaction using the Performance-Operating-Characteristics (POC) framework**

The following subsections (5.2.1 Introduction, 5.2.2 Method, 5.2.3 Results, 5.2.4 Discussion and 5.2.5 Conclusion) are full citations from the publication:

**Riedel, N. & Deml, B. (2025).** Assessment of cognitive-motor interference in human-exoskeleton interaction using the Performance-Operating-Characteristics (POC) framework. In D. de Waard, L. Onnasch, M. Liebherr, A. Dettmann, F. Siebert, K. Karrer-Gauß, S. Winkler, A. Toffetti, and M. De Angelis (2025). *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2025 Annual Conference*. (pp. 51-60). Downloaded from <http://hfes-europe.org> (ISSN 2333-4959)

### **5.2.1 Introduction**

“Lower-limb exoskeletons are wearable robotic devices designed to provide support to the legs during locomotion. However, the rigid structure and mass of these devices can alter body mechanics and impose additional physical and cognitive demands on the user (Jin et al., 2017). These challenges become particularly pronounced when actuated joint assistance is insufficient and disrupts the user’s natural movement pattern. While previous studies have primarily focused on the biomechanical and physiological effects of lower-limb exoskeletons, the cognitive aspects associated with their use are widely overlooked (Pinto-Fernandez et al., 2020). However, assessing the cognitive fit of exoskeletons is crucial to ensure a safe and efficient interaction, allowing users to allocate sufficient cognitive resources to other relevant tasks (Stirling et al., 2020). For instance, Bequette et al. (2020) found that individuals using a powered lower-limb exoskeleton exhibited delayed reaction times in a visual search task, and subjective workload

assessments via the NASA-Task Load Index (NASA TLX) (Hart & Staveland, 1988) revealed significantly higher perceived workload during both powered and unpowered exoskeleton-assisted walking compared to unassisted walking.

Dual-task paradigms provide a methodological approach to examining the interaction between cognitive processing and motor control during locomotion. Performing a cognitively demanding task while walking can lead to cognitive-motor interference (CMI), where performance in one or both tasks is reduced due to competition for limited cognitive resources (Al-Yahya et al., 2011). According to Norman and Bobrow (1975), a task is considered resource-limited when its performance improves as more cognitive resources are allocated to it, and vice versa. The Performance-Operating-Characteristics (POC), developed by Norman and Bobrow (1975), provides a framework for understanding performance trade-offs under conditions of divided attention. Wickens et al. (1981) further reported that the efficiency of dual-task performance can be represented as a single point within the POC framework. That point represents the decrement in both tasks relative to their respective single-task performance (see Figure 4). Shifts to the upper right corner represent performance improvements, and vice versa. Shifts toward the black dashed lines (single task performance) indicate a prioritisation of that task, i.e., the allocation of greater resources to that task. In this way, the POC framework offers a visual-descriptive representation of CMI. Kelly et al. (2010) applied this framework to dual-task walking to investigate the influence of instructions and task difficulty on CMI. The authors suggest that the POC framework can be used to investigate how individual, environmental, and task characteristics influence dual-task performance.

Building upon these recommendations, this work evaluates the applicability of the POC framework in the context of human-exoskeleton interaction through two experiments employing a dual-task walking paradigm. In the first experiment, participants walked on a treadmill under two conditions: with and without weight cuffs affixed to the upper and lower limbs (Riedel et al., 2023, 2024). In the second experiment, participants engaged in overground walking both with and without the assistance of a powered lower-limb exoskeleton (Riedel et al., 2025). This work examines the effects of various walking conditions (unloaded walking, loaded walking, and exoskeleton-assisted walking) along with different surface conditions (treadmill and overground walking) on overall CMI using the POC framework. Additionally, it explores the impact of familiarisation on exoskeleton-assisted walking.

## 5.2.2 Method

In the following the methods and materials of both experiments are briefly described. For a detailed description, please refer to the referenced papers.

### 5.2.2.1 Experiment 1

In the first experiment fifteen healthy young adults (age:  $24.3 \pm 3.5$  years; stature:  $1.73 \pm 0.09$  m; body mass:  $66 \pm 10.1$  kg, 8 females, 7 males) walked on a treadmill at their preferred walking speed with and without weight cuffs bilaterally attached to the thigh and shank, each weighting 2,25 kg (see Figure 22A). The experiment employed a within-subjects design to analyse cognitive and motor performance under different walking conditions (unloaded walking, loaded walking) and cognitive task demands (no secondary task, Stroop test, serial subtraction). Participants underwent a structured protocol with alternating single- and dual-task walking phases. Walking was tracked using an infrared camera system (Vicon Motion Systems; Oxford Metrics Group, Oxford, UK) and secondary task performance was recorded via a microphone. Dependent variables include mean values and variability (coefficients of variation) of step length, step width, stride time and double support time. Additionally, secondary task performance as correct response rates (CRR) and perceived workload (NASA TLX) were assessed.

### 5.2.2.2 Experiment 2

In the second experiment twenty healthy young adults (age:  $25.3 \pm 4.1$  years; stature:  $1.73 \pm 0.10$  m; body mass:  $69 \pm 12.1$  kg; 10 females, 10 males) walked overground with and without the powered lower-limb exoskeleton TWIN (Laffranchi et al., 2021) (see Figure 22B). Due to incomplete data only fifteen participants were included to calculate the parameters for the POC. The experiment employed a within-subjects design to analyse cognitive and motor performance under different walking conditions (unassisted walking, exoskeleton-assisted walking) and cognitive task demands (no secondary task, serial subtraction). Participants underwent a structured protocol with alternating single- and dual-task walking phases. Walking was tracked using a Noraxon Ultium Motion IMU system (Noraxon U.S.A. Inc., Scottsdale, AZ) and secondary task performance was recorded via a microphone. Dependent variables include mean gait velocity and variability (coefficients of variation) of stride time and double support time. Additionally, secondary task performance as CRR and perceived workload (NASA TLX) were assessed.

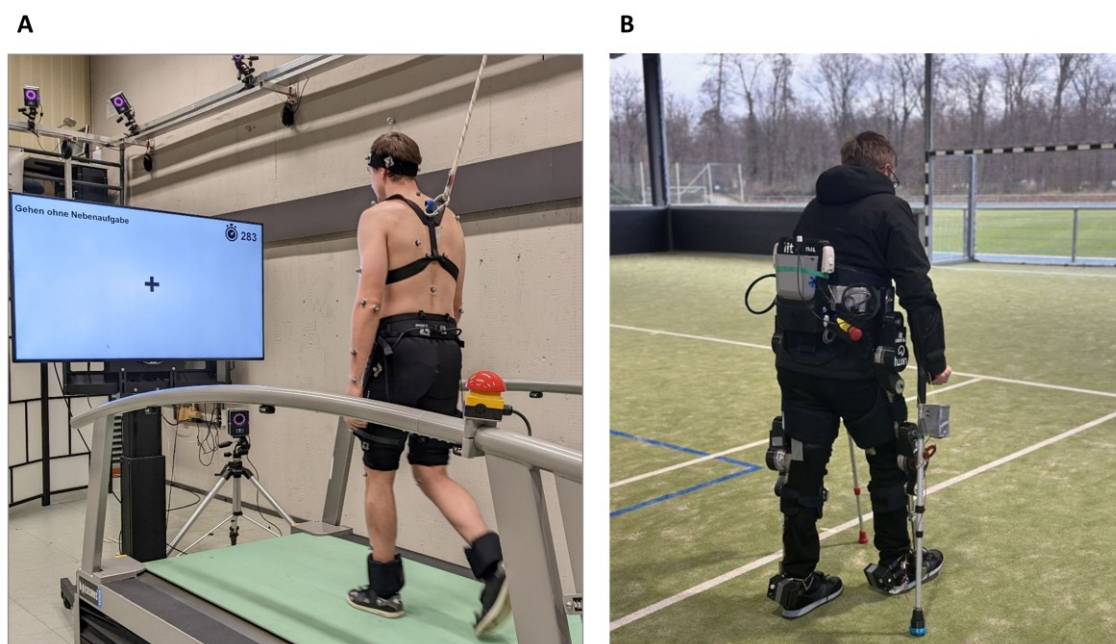


Figure 22. Setup of (A) experiment 1 (from Riedel et al., 2023, 2024) and (B) experiment 2. (Riedel & Deml, 2025)

### 5.2.2.3 Data processing and statistical analysis

To prepare the data of both experiments for the POC framework, dual-task effects (DTE) were calculated for motor performance (mDTE) and cognitive performance (cDTE). DTE compare single-task performance to dual-task performance and were calculated for each experimental condition using the following formula:

$$\text{DTE} = - \frac{(\text{Parameter}_{\text{dual task}} - \text{Parameter}_{\text{single task}})}{\text{Parameter}_{\text{single task}}} \times 100\%$$

For data comparability between the experiments, mDTE was derived using the same motor parameters assessed in both studies: the coefficient of variation of stride time and double support time. Step-by-step variability is considered an indicator of gait quality (Hausdorff, 2005); therefore, greater variability was assumed to indicate reduced motor performance. The DTE of each parameter was calculated for each participant, and the mean and standard error were determined. The mean DTE values of both gait parameters were then combined and averaged to obtain the composite mDTE.

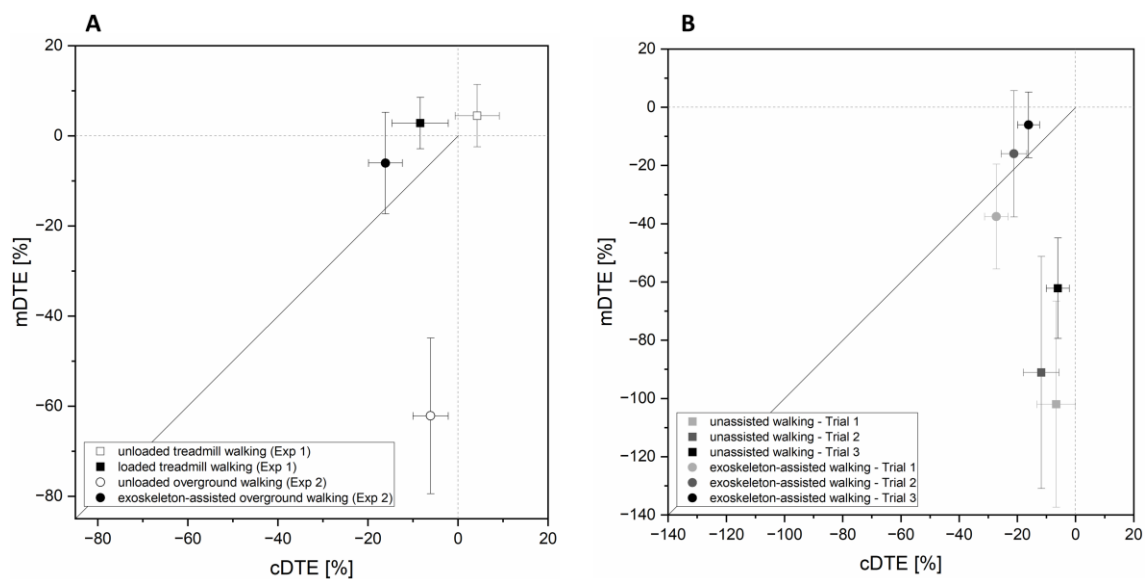
Cognitive performance in each experimental condition was assessed based on the correct response rate (CRR) in the serial subtraction task (subtracting the number 7 from a randomly selected three-digit number). This metric was computed as the product of responses per second

and the percentage of correct responses. To quantify cDTE, the CRR while walking (dual task) was compared to the CRR while sitting (single task). In this case, the negative sign in the formula was omitted, as a higher CRR reflects improved cognitive performance. Negative DTE values thus indicate a decline in performance under dual-task conditions. To visualise the results within the POC framework, the mean and standard error of mDTE and cDTE were plotted against each other.

The Kolmogorov-Smirnov test was used to assess data normality, while sphericity was evaluated with Mauchly's test. If sphericity was violated, the Greenhouse-Geisser correction was applied. Statistical tests were performed at a significance level of  $\alpha = 0.05$ . All analyses were conducted using SPSS Statistics 29.0 (IBM, Armonk, NY, USA). The effects of *walking condition* (unloaded walking, modified walking) and *surface condition* (treadmill walking, overground walking) on mDTE and cDTE were analysed using a 2x2 repeated-measures ANOVA with data from both experiments. The *modified walking* level combines loaded walking from Experiment 1 and exoskeleton-assisted walking from Experiment 2. The effect of *familiarisation* (Trial 1, Trial 2, Trial 3) on cDTE values was examined using 1x3 repeated-measures ANOVAs for unassisted walking and exoskeleton-assisted walking. Since mDTE values were not normally distributed, the Friedman test was used instead. Only data from the second experiment were included in the familiarisation analysis.

### 5.2.3 Results

Figure 23A illustrates the effects of surface condition and walking condition on dual-task performance using the POC framework. Figure 23B illustrates the effects of familiarisation on dual-task performance for unassisted walking and exoskeleton-assisted walking.



**Figure 23. Performance-Operating-Characteristics framework showing the effects of (A) surface condition and walking condition and (B) familiarisation on dual-task performance. Single task performance is represented by the dashed lines. The diagonal line represents the Equal Allocation Axis. Data points represent means and bars represent standard errors. mDTE = motor Dual-Task Effect, cDTE = cognitive Dual-Task Effect. (Riedel & Deml, 2025)**

The surface condition influenced mDTE ( $p = .013$ ), with larger costs for overground walking (-34.1%) than for treadmill walking (3.6%). The walking condition also influenced mDTE ( $p = .040$ ), with larger costs for unloaded walking (-28.9%) than for modified walking (-1.6%). There was an interaction between surface condition and walking condition for mDTE, with a greater effect of walking condition on mDTE during overground walking ( $p = .014$ ). The surface condition did not affect cDTE ( $p = .077$ ). The statistical trend indicates larger costs for overground walking (-11.1%) than for treadmill walking (-2.1%). The walking condition also did not affect cDTE ( $p = .064$ ). The statistical trend indicates larger costs for modified walking (-12.3%) than for unloaded walking (-0.9%). There was no interaction between surface condition and walking condition on cDTE ( $p = .699$ ).

Familiarisation decreased mDTE from trial to trial during exoskeleton-assisted walking (Trial 1: -37.5%; Trial 2: -16.0; Trial 3: -6.1%;  $p = .038$ ) but had no impact on unassisted walking (Trial 1: -102.0%; Trial 2: -91.1; Trial 3: -62.2%;  $p = .627$ ). Familiarisation also decreased cDTE from trial to trial during exoskeleton-assisted walking (Trial 1: -27.2%; Trial 2: -21.1; Trial 3: -16.1%;  $p = .026$ ) but had no impact on unassisted walking (Trial 1: -6.7%; Trial 2: -11.8; Trial 3: -6.1%;  $p = .532$ ).

## 5.2.4 Discussion

This work presents the Performance-Operating-Characteristics (POC) framework as a visual-descriptive assessment method for use in the context of human-exoskeleton interaction. POCs were developed to investigate whether two tasks influence each other and how the performance of one task changes as a function of the performance of another. The results highlight performance differences across surface, walking and familiarisation conditions.

### 5.2.4.1 Surface and walking condition effects

Motor dual-task performance (mDTE) significantly declined during overground walking, whereas it slightly improved during treadmill walking. This aligns with previous findings that treadmill walking enhances gait automaticity (Baek et al., 2023) and cognitive performance (Penati et al., 2020) by inducing a more rhythmic gait pattern. In contrast, cognitive dual-task performance (cDTE) did not differ significantly between treadmill and overground walking, though a statistical trend suggests greater cognitive performance declines during overground walking. Consistent with existing literature, these results reaffirm that treadmill walking is not directly comparable to overground walking (Wrightson et al., 2020). The greatest reduction in mDTE was observed during unloaded overground walking, supporting prior research showing that individuals slow down when performing a secondary task (Al-Yahya et al., 2011). However, in the exoskeleton condition, the overground walking effects on mDTE were less pronounced, likely due to the exoskeleton's motion constraints and its induction of a more rhythmic gait pattern, similar to treadmill walking. The TWIN exoskeleton used in the second experiment operated with a full position control strategy with predefined movement trajectories.

For overground walking, the results suggest that prioritisation strategies vary depending on the walking condition. During unloaded walking, participants adopted a posture-second strategy, with data points falling below the Equal Allocation Axis. Conversely, during exoskeleton-assisted walking, participants appeared to prioritise the motor task, shifting towards a posture-first strategy, as indicated by data points above the Equal Allocation Axis in the POC framework. According to Yogeve-Seligmann et al. (2012), attentional focus shifts toward maintaining gait stability when walking becomes more challenging. This implies that participants may have perceived exoskeleton-assisted walking as a greater postural challenge, requiring increased cognitive resource allocation to maintain stability.

#### 5.2.4.2 Familiarisation effects

During exoskeleton-assisted walking, both mDTE and cDTE significantly decreased from trial 1 to trial 3, indicating short-term familiarisation effects. While this study examined only three time points within a relatively short period (>30 minutes), a more comprehensive POC analysis could provide deeper insights into how priorities shift during the familiarisation process. It is plausible that full familiarisation may require a substantially longer duration than the timeframe assessed in the second experiment (Poggensee & Collins, 2021). For instance, this timeframe depends on the complexity of the exoskeleton system and individual user characteristics. Ideally, upon full familiarisation, the POC curve would reach the intersection of the two dashed lines, indicating the elimination of dual-task costs. Tracking performance changes over time could be especially valuable for evaluating the intuitiveness and efficiency of different exoskeleton systems. The POC framework could help designers refine exoskeleton control algorithms to minimise cognitive demand and enhance user experience. The high degree of individual variability observed underscores the need for user-specific POC assessments, which could guide the development of personalised exoskeleton settings. Although POC analyses provide important insights, they can be complex and time-intensive. However, on an individual level, the automation of DTE calculations using a standardised method could streamline POC computation. This approach could help reduce fall risk by ensuring users reach an adequate level of adaptation before relying on the device. Clear thresholds for acceptable DTE values should be established, defining when the training phase is complete and the exoskeleton is safe for independent use. This involves establishing a set of appropriate parameters that are then combined to calculate the composite DTE.

#### 5.2.4.3 Limitations

POCs are highly sensitive to the parameters used to calculate DTE and the nature of the secondary task employed, making their interpretation complex and requiring careful consideration when drawing conclusions. Additionally, confounding factors such as fatigue and motivation can influence performance, further complicating POC analysis. These factors may also contribute to the high variability observed among participants. Norman and Bobrow (1976) highlight the “distinction between the theoretical concept of a resource and the behavioural concept of performance” (p. 509). If the relation between performance and resource is nonlinear, interpreting POCs becomes even more challenging.

Furthermore, variations in the experimental protocols, particularly regarding the familiarisation period, necessitate caution when comparing data across experiments, such as in the analysis of surface and walking condition effects. The examples presented in this study primarily aim to demonstrate the potential application of POCs in human-exoskeleton interaction research.

### **5.2.5 Conclusion**

The POC framework can provide valuable insights into cognitive-motor interferences in human-exoskeleton interaction and how attentional resources are shifted during the familiarisation process. While the POC framework has limitations, it provides a promising human-centred tool for evaluating human-exoskeleton interactions. Future research should leverage this framework to investigate extended familiarisation periods, assess diverse performance metrics, and establish a standardised protocol to enhance comparability across studies and exoskeleton systems.”

## 6 General Discussion

To advance research on the cognitive fit of exoskeletons, this thesis proposes a conceptual framework focused on cognitive-motor interference in human-exoskeleton interaction (see Figure 5). Two studies were conducted using a dual-task walking paradigm to assess motor and cognitive performance as well as perceived workload. Study 1 involved interaction with leg weight cuffs (see Chapter 4), while Study 2 examined the use of a powered lower-limb exoskeleton (see Chapter 5). Section 6.1 summarizes the key findings from both studies in relation to research questions RQ1 - RQ5. Section 6.2 discusses the theoretical implications and outlines directions for future research aimed at addressing the studies' limitations. Section 6.3 focuses on the practical implications for exoskeleton design and training. Finally, Section 6.4 provides the overall conclusion.

### 6.1 Key findings

**RQ1 - Effects of an exoskeleton on motor performance during walking.** Across both studies, the use of an exoskeleton or weight cuffs consistently increased perceived physical workload compared to normal walking, independent of additional cognitive load from a secondary task. Analysis of gait parameters revealed distinct effects for the two motor conditions of the two studies. When walking with weight cuffs, variability in step length, and to a lesser extent stride time and double support time, was higher than during unloaded walking, regardless of cognitive demand. In exoskeleton-assisted walking, stride time variability was significantly higher than during unassisted walking under single-task conditions, but this difference disappeared in dual-task conditions. Notably, stride time variability increased from single- to dual-task conditions during unassisted walking (+83%), whereas it slightly decreased during exoskeleton-assisted walking (-12%). A comparable effect was observed for gait velocity, which decreased under dual-task conditions in unassisted walking yet increased in exoskeleton-assisted walking.

**RQ2 - Effects of an exoskeleton on cognitive performance during walking.** Walking with an exoskeleton was perceived as cognitively more demanding than unassisted walking. Walking with weight cuffs showed a statistical trend in the same direction. In line with the subjective ratings, exoskeleton-assisted walking resulted in a significant decline in cognitive performance on the

serial subtraction task compared to unassisted walking, suggesting increased cognitive load due to the exoskeleton. For walking with weight cuffs, an interaction effect was observed. Cognitive performance decreased only in the subtraction task, but not in the Stroop test, indicating that the impact varied depending on the type of the secondary task (see RQ4).

**RQ3 - Allocation of cognitive resources between motor and cognitive processes.** Both studies indicated that increased motor demands shift the focus of attention toward maintaining postural stability, consistent with a posture-first strategy, often at the expense of cognitive task performance. Walking with the weight cuffs led to a reallocation of attention to posture during demanding dual-task conditions, particularly in the subtraction task, as indicated by a decreased cognitive performance. Similarly, exoskeleton-assisted walking decreased correct response rates by 14%, indicating reduced cognitive resource allocation to the secondary task, while concurrently increasing gait velocity and slightly reducing gait variability. In contrast, unassisted walking under dual-task conditions was associated with reduced gait velocity and increased stride-time variability, without impairing cognitive performance, consistent with a posture-second strategy.

**RQ4 - Effects of secondary task type on cognitive resource allocation.** In Study 1, double-support time variability decreased from single-task walking to walking while performing the Stroop test, in both unloaded and loaded conditions. The decreased variability suggests more automated walking, consistent with a shift in attentional focus toward the secondary task (externalized attentional focus). In contrast, during the more cognitively demanding subtraction task, double-support time variability decreased for unloaded walking but remained unchanged under loaded walking. This pattern indicates that, when walking with weight cuffs, competition for cognitive resources can outweigh the benefits of an external attentional focus in high-demand cognitive contexts. Moreover, the results suggest that mental tracking (subtraction task), rather than inhibitory control (Stroop test), imposes greater interference on motor control. In line with these findings, participants rated the Stroop test as less mentally demanding than the subtraction task.

**RQ5 - Effects of adaptation on cognitive resource allocation.** In Study 2, short-term adaptation to exoskeleton-assisted walking was shown by reduced perceived mental and physical workload and improved cognitive performance across trials. However, cognitive performance remained below seated control and unassisted walking, suggesting that full adaptation may require

longer-term exposure. Gait variability did not significantly decrease but showed a statistical trend toward reduction. The improved cognitive performance and unchanged motor performance indicates a shift from a posture-first to a posture-second strategy, likely as perceived postural threat diminished over time.

## 6.2 Theoretical implications

**Research gap and novel framework.** This thesis addresses a critical research gap by being among the first to investigate exoskeleton-assisted walking while concurrently assessing both cognitive and motor performance. This dual focus enables inferences about cognitive-motor interference (CMI) and the allocation of attentional resources during exoskeleton-assisted walking. The assessment of CMI has a long tradition in clinical and epidemiological research, where it has been widely employed to examine the impact of age-related cognitive decline and neurological disorders on the interaction between cognitive and motor functions (Beurskens & Bock, 2012; Kelly et al., 2012). By transferring this approach to the domain of human-exoskeleton interaction, the present thesis contributes to the emerging literature on cognitive fit of exoskeletons, an aspect that has been largely neglected in prior work, which has predominantly emphasized static and dynamic fit (Pinto-Fernandez et al., 2020; Stirling et al., 2020). Here, cognitive fit is operationalized through the assessment of CMI, with particular emphasis on attentional resource allocation and overall workload as key human factors. Nevertheless, cognitive fit should be conceptualized more broadly. Beyond attentional demands and workload, future research must extend this framework to include additional human factors such as mental models and situational awareness. For instance, research regarding mental models should investigate the alignment between the user's internal anticipation of assistance and the exoskeleton's actual control strategy. Simultaneously, studies on situational awareness should assess whether the physical interface of an exoskeleton compromises the user's perception of the environment. Such an expanded perspective would provide a more comprehensive understanding of human-exoskeleton interaction and support the development of human-centered systems.

The present thesis provides a conceptual framework adapted from the control framework of Tucker et al. (2015). This framework represents the interaction between the human, the exoskeleton, the control unit and the environment by explicitly integrating the cognitive dimension of human-exoskeleton interaction (see Figure 5). This human-centered conceptual framework

offers a foundation for future research aimed at evaluating exoskeleton systems across diverse motor tasks, user populations and design configurations. In this way, it can serve as a tool for benchmarking exoskeleton systems. Torricelli et al. (2020) highlighted the importance of benchmarking exoskeletons not only from the perspective of functional performance but also by incorporating user experience and methodological considerations. The framework developed in this thesis enables an integrated evaluation approach that combines functional performance with cognitive aspects, while simultaneously providing a methodological structure through the dual-task paradigm.

**Empirical support for the task prioritization model.** The findings of both studies provide empirical support for the task prioritization model, which posits that cognitive resources are allocated according to an individual's postural reserve, defined as the capacity to maintain effective postural control, and hazard estimation, referring to the awareness of environmental risks and personal limitations (Yogev-Seligmann et al., 2012). The observed shift from a *posture-second* to a *posture-first* strategy during loaded or exoskeleton-assisted walking suggests that increased postural threat induces reallocation of attentional resources toward motor control to maintain stability and prevent potential falls. Consistent with this notion, other studies examining the impact of complex motor tasks on CMI have also reported a shift toward a posture-first strategy (Kao & Pierro, 2022; Mersmann et al., 2013; Reiser et al., 2019). These findings align with the hypothesis that increased physical exertion reduces the automaticity of walking (Clark, 2015).

Furthermore, Bequette et al. (2020) demonstrated that performance in a visual detection task decreased significantly when participants operated a powered exoskeleton, whereas no such deterioration occurred in the unpowered condition. This suggests that the operation of complex exoskeleton systems demands increased attentional resources. In the second study presented in this thesis, the applied powered exoskeleton was non-adaptive and restricted the range of motion, which likely disrupted natural walking execution. Consequently, future research should systematically investigate the influence of different control strategies, particularly adaptive approaches and design solutions that minimize interference with natural movement. These considerations are critical for optimizing resource allocation during exoskeleton-assisted walking. Ideally, exoskeleton users should be able to adopt a *posture-second* strategy, whereby walking with the exoskeleton becomes as automated as normal walking, thus preserving sufficient cognitive resources to perform concurrent tasks in the environment.

**Short-term adaptation effects.** Prior research has shown that adaptation processes reduce physical exertion during exoskeleton use (Gordon & Ferris, 2007; Poggensee & Collins, 2021), which suggests that training can also reduce cognitive demands. In line with this, the findings of study 2 indicate that short-term adaptation influences patterns of resource allocation. The improved cognitive performance and unchanged motor performance indicates a shift from a *posture-first* to a *posture-second* strategy. Nevertheless, cognitive performance did not reach the level observed in unassisted walking, implying that exoskeleton-assisted walking still required substantial attentional resources. Following the recommendations of Poggensee and Collins (2021), individuals should ideally receive training with the exoskeleton prior to assessments of human-exoskeleton interaction. This allows them to progress from Rasmussen's knowledge-based stage of behavior to the rule-based stage, at which motor control becomes more automated and cognitive load is reduced. Future longitudinal research should further investigate the transition from rule-based to skill-based behavior, with a particular focus on the factors that facilitate these shifts. These include individual characteristics, such as cognitive capacity and motor skills, as well as design-related features, such as adaptability and feedback modalities. Furthermore, such studies should examine how CMI changes across the different stages.

**Impact of secondary task type.** Consistent with the dual-process model (Huxhold et al., 2006), double support time (DST) variability decreased during the simpler Stroop test for both loaded and unloaded walking, indicating an external attentional focus and greater gait automaticity. Conversely, during the more demanding subtraction task, DST variability did not decrease under loaded conditions. This suggests that when cognitive and physical demands are high, competition for cognitive resources outweighs the benefits of an external focus. The stronger interference observed with the subtraction task compared to the Stroop test in Study 1 aligns with previous findings indicating that mental tracking tasks, meaning those requiring continuous information maintenance and internal processing such as the subtraction task, interfere with walking more strongly than tasks involving external stimuli (Al-Yahya et al., 2011). This increased interference is likely attributable to the engagement of overlapping neural networks between mental tracking and locomotion, particularly within the prefrontal cortex (Dennis Hamacher et al., 2015; Holtzer et al., 2011). This effect has not yet been examined in the context of lower-limb exoskeletons. To advance understanding of the underlying mechanisms, neurophysiological methods such as electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) can be used. For example, Zhu et al. (2021) examined the effects of a passive upper-body

exoskeleton using a dual-task paradigm and fNIRS methodology. Applying these methods in exoskeleton-assisted walking paradigms would provide critical insights into how cognitive and motor processes interact under varying task demands.

**Treadmill vs. overground walking.** The results of Study 1 indicate that treadmill walking promotes rhythmic gait patterns, which may facilitate more automated locomotion. This effect likely arises because the treadmill provides mechanical support that stabilizes gait, serving as a regulating mechanism (Wrightson et al., 2020). Such treadmill-induced automaticity can mask the effects of increased cognitive demand (Baek et al., 2023; Penati et al., 2020). Consequently, treadmill findings may have limited generalizability to overground walking. Therefore, treadmill-based assessments may not fully represent overground exoskeleton use and should be interpreted with caution when evaluating human-exoskeleton interaction.

### 6.3 Practical implications

**Performance operating characteristics framework in human-exoskeleton interaction.** A central practical implication of this thesis is the application of the performance operating characteristics (POC) framework to the domain of human-exoskeleton interaction. The POC framework offers a visual approach to simultaneously assess cognitive and motor performance under varying task demands (Norman & Bobrow, 1975). Kelly et al. (2010) already emphasized its potential for evaluating complex dual-task walking scenarios. This thesis used the framework by demonstrating how loaded walking (Study 1) and exoskeleton-assisted walking (Study 2), in combination with secondary cognitive task demands, affect both motor and cognitive performance in healthy young adults. By plotting performance within the POC space, it was possible to quantify the degree of dual-task interference and track how performance shifted under different motor and cognitive task conditions. One important application lies in the comparative evaluation of different exoskeleton systems, control strategies or design settings. By mapping cognitive and motor performance within a standardized framework, POC analysis could provide a robust benchmark for rating the impact of exoskeleton systems on human performance. Moreover, the inter-individual variability underscores the importance of fitting exoskeleton use to the specific needs and capacities of each user. User-specific POCs offer a valuable tool for tracking individual adaptation and training progress over time. For instance, monitoring changes in POC measures can help identify the optimal point at which an exoskeleton may be used safely and effectively in daily

activities. When integrated into real-time monitoring systems, POC analysis could further enable adaptive feedback during training or rehabilitation, allowing for the personalization of assistance settings.

**Reducing cognitive-motor interference through rhythmic external cues.** Exoskeleton-assisted dual-task walking was associated with improved motor performance, characterized by increased gait velocity and slightly reduced stride-time variability. These improvements may arise from rhythmic external cues provided by the exoskeleton through haptic and auditory feedback. Such mechanisms are thought to promote gait automaticity in a manner similar to treadmill walking. In line with this, findings from rhythmic auditory stimulation research show that such external cues can increase gait speed and stride length while reducing variability, particularly in individuals with impaired motor control (Hausdorff et al., 2007; Pau et al., 2016). External rhythmic cues therefore represent a promising strategy for promoting automated exoskeleton-assisted walking (Wu et al., 2022). Future research should examine how multimodal feedback strategies (visual, auditory, haptic) influence exoskeleton-assisted walking and adaptation, with direct implications for system design.

**Recommendations for exoskeleton training.** The findings of this thesis highlight several important recommendations for developing exoskeleton training protocols. First, extended training sessions are essential. Although short-term familiarization effects can be observed within approximately 30 minutes, these initial improvements are insufficient to fully mitigate the cognitive demands associated with exoskeleton use. This underscores the need for prolonged adaptation periods before optimal performance in daily activities can be expected. Training protocols should therefore include a structured progression that allows users to transition from knowledge-based control to rule-based and ultimately to skill-based control, making walking increasingly automatic. These findings also highlight the need to manage user expectations prior to the initial use of the exoskeleton.

Second, employing a dual-task paradigm may facilitate exoskeleton familiarization. Findings from Study 1, in line with previous research (Decker et al., 2016; Lövdén et al., 2008), showed that diverting attentional focus from walking to a concurrent secondary task reduced gait variability, provided that motor task demands remained below a threshold where competition for cognitive resources occurred. Participant feedback from Study 2 further supported this obser-

vation, with several participants reporting that performing a secondary task diminished exploratory behavior during exoskeleton-assisted walking, thereby promoting more automatic locomotion. These conditions appear to help users operate the exoskeleton without overanalyzing their movements. Moreover, controlled dual-task walking scenarios could better prepare individuals for real-world environments, where attentional resources are often divided. This approach has already shown benefits in clinical populations (Fritz et al., 2015; Ghai et al., 2017) and should be integrated into exoskeleton training.

## 6.4 Conclusion

This thesis examined the cognitive fit of exoskeletons by investigating their impact on cognitive and motor performance while walking in dual-task conditions, in order to assess the degree of cognitive-motor interference. Across two dual-task walking studies using weight cuffs and a powered lower-limb exoskeleton, the findings demonstrate that devices not well adapted to the user can increase both physical and cognitive workload, often prompting a posture-first strategy that prioritizes posture control at the expense of cognitive performance. While short-term adaptation to the powered exoskeleton showed measurable benefits, cognitive performance did not reach the level of unassisted walking.

This work contributes to exoskeleton research by introducing a human-centered conceptual framework that explicitly integrates the cognitive dimension into human-exoskeleton interaction and by demonstrating the potential of the performance operating characteristics framework as a practical tool for benchmarking exoskeletons, guiding training and fitting exoskeletons to individual needs. These contributions establish cognitive fit as a critical dimension in exoskeleton research and design. Looking ahead, advancing knowledge of how different control and design approaches influence motor and cognitive performance during human-exoskeleton interaction will be essential for ensuring the safe and effective deployment of exoskeletons in real-world contexts.

# References

- Afzal, T., Kern, M., Tseng, S.-C., Lincoln, J., Francisco, G., & Chang, S.-H. (2017). Cognitive demands during wearable exoskeleton assisted walking in persons with multiple sclerosis. In *2017 International Symposium on Wearable Robotics and Rehabilitation (WeRob)* (pp. 1–2). IEEE. <https://doi.org/10.1109/WEROB.2017.8383853>
- Al-Yahya, E., Dawes, H., Smith, L., Dennis, A., Howells, K., & Cockburn, J. (2011). Cognitive motor interference while walking: a systematic review and meta-analysis. *Neuroscience and Biobehavioral Reviews*, *35*(3), 715–728. <https://doi.org/10.1016/j.neubio-rev.2010.08.008>
- Aminian, K., Najafi, B., Büla, C., Leyvraz, P.-F., & Robert, P. (2002). Spatio-temporal parameters of gait measured by an ambulatory system using miniature gyroscopes. *Journal of Biomechanics*, *35*(5), 689–699. [https://doi.org/10.1016/S0021-9290\(02\)00008-8](https://doi.org/10.1016/S0021-9290(02)00008-8)
- Andrade, R. M., Sapienza, S., Mohebbi, A., Fabara, E. E., & Bonato, P. (2024). Overground Walking With a Transparent Exoskeleton Shows Changes in Spatiotemporal Gait Parameters. *IEEE Journal of Translational Engineering in Health and Medicine*, *12*, 182–193. <https://doi.org/10.1109/JTEHM.2023.3323381>
- Baek, C. Y., Kim, H. D., Yoo, D. Y., Kang, K. Y., & Woo Lee, J. (2023). Effect of automaticity induced by treadmill walking on prefrontal cortex activation and dual-task performance in older adults. *PloS One*, *18*(8), 287252. <https://doi.org/10.1371/journal.pone.0287252>
- Bartolo, D. de, Giorgi, C. de, Compagnucci, L., Betti, V., Antonucci, G., Morone, G., Paolucci, S., & Iosa, M. (2021). Effects of cognitive workload on heart and locomotor rhythms coupling. *Neuroscience Letters*, *762*, 136140. <https://doi.org/10.1016/j.neulet.2021.136140>
- Baud, R., Manzoori, A. R., Ijspeert, A., & Bouri, M. (2021). Review of control strategies for lower-limb exoskeletons to assist gait. *Journal of Neuroengineering and Rehabilitation*, *18*(1), 119. <https://doi.org/10.1186/s12984-021-00906-3>
- Bayot, M., Dujardin, K., Tard, C., Defebvre, L., Bonnet, C. T [Cédric T.], Allart, E., & Delval, A. (2018). The interaction between cognition and motor control: A theoretical framework

- for dual-task interference effects on posture, gait initiation, gait and turning. *Neurophysiologie Clinique = Clinical Neurophysiology*, 48(6), 361–375.  
<https://doi.org/10.1016/j.neucli.2018.10.003>
- Bequette, B., Norton, A., Jones, E., & Stirling, L. (2018). The Effect of a Powered Lower-Body Exoskeleton on Physical and Cognitive Warfighter Performance. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 62(1), 1663–1667.  
<https://doi.org/10.1177/1541931218621377>
- Bequette, B., Norton, A., Jones, E., & Stirling, L. (2020). Physical and Cognitive Load Effects Due to a Powered Lower-Body Exoskeleton. *Human Factors*, 62(3), 411–423.  
<https://doi.org/10.1177/0018720820907450>
- Beurskens, R., & Bock, O. (2012). Age-related deficits of dual-task walking: a review. *Neural Plasticity*, 2012, 131608. <https://doi.org/10.1155/2012/131608>
- Blanca, M. J., Alarcón, R., Arnau, J., Bono, R., & Bendayan, R. (2017). Non-normal data: Is ANOVA still a valid option? *Psicothema*, 29(4), 552–557.  
<https://doi.org/10.7334/psicothema2016.383>
- Blanca, M. J., Arnau, J., García-Castro, F. J., Alarcón, R., & Bono, R. (2023). Non-normal Data in Repeated Measures ANOVA: Impact on Type I Error and Power. *Psicothema*, 35(1), 21–29. <https://doi.org/10.7334/psicothema2022.292>
- Bortole, M., del Ama, A., Rocon, E., Moreno, J. C [J. C.], Brunetti, F., & Pons, J. L [J. L.] (2013). A robotic exoskeleton for overground gait rehabilitation. In *2013 IEEE International Conference on Robotics and Automation (ICRA 2013)* (pp. 3356–3361). IEEE.  
<https://doi.org/10.1109/ICRA.2013.6631045>
- Bötzel, K., Marti, F. M., Rodríguez, M. Á. C., Plate, A., & Vicente, A. O. (2016). Gait recording with inertial sensors – How to determine initial and terminal contact. *Journal of Biomechanics*, 49(3), 332–337. <https://doi.org/10.1016/j.jbiomech.2015.12.035>
- Browning, R. C., Modica, J. R., Kram, R., & Goswami, A. (2007). The effects of adding mass to the legs on the energetics and biomechanics of walking. *Medicine and Science in Sports and Exercise*, 39(3), 515–525. <https://doi.org/10.1249/mss.0b013e31802b3562>
- Charles, R. L., & Nixon, J. (2019). Measuring mental workload using physiological measures: A systematic review. *Applied Ergonomics*, 74, 221–232.  
<https://doi.org/10.1016/j.apergo.2018.08.028>

- Clark, D. J. (2015). Automaticity of walking: functional significance, mechanisms, measurement and rehabilitation strategies. *Frontiers in Human Neuroscience*, *9*, 246.  
<https://doi.org/10.3389/fnhum.2015.00246>
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2. ed.). Erlbaum.  
<https://doi.org/10.4324/9780203771587>
- Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review*, *12*(5), 769–786. <https://doi.org/10.3758/bf03196772>
- Davis, K. G., Reid, C. R., Rempel, D. D., & Treaster, D. (2020). Introduction to the Human Factors Special Issue on User-Centered Design for Exoskeleton. *Human Factors*, *62*(3), 333–336. <https://doi.org/10.1177/0018720820914312>
- Decker, L. M., Cignetti, F., Hunt, N., Potter, J. F., Stergiou, N., & Studenski, S. A. (2016). Effects of aging on the relationship between cognitive demand and step variability during dual-task walking. *Age (Dordrecht, Netherlands)*, *38*(4), 363–375.  
<https://doi.org/10.1007/s11357-016-9941-y>
- Dehais, F., Lafont, A., Roy, R., & Fairclough, S [Stephen] (2020). A Neuroergonomics Approach to Mental Workload, Engagement and Human Performance. *Frontiers in Neuroscience*, *14*, 268. <https://doi.org/10.3389/fnins.2020.00268>
- Dežman, M., Marquardt, C., & Asfour, T. (2024). Ankle Exoskeleton with a Symmetric 3 DoF Structure for Plantarflexion Assistance. In *2024 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 3227–3233). IEEE.  
<https://doi.org/10.1109/ICRA57147.2024.10609991>
- Di Shi, Zhang, W [Wuxiang], Zhang, W [Wei], & Ding, X. (2019). A Review on Lower Limb Rehabilitation Exoskeleton Robots. *Chinese Journal of Mechanical Engineering*, *32*(1).  
<https://doi.org/10.1186/s10033-019-0389-8>
- Ding, Y., Panizzolo, F. A., Sivi, C., Malcolm, P., Galiana, I., Holt, K. G., & Walsh, C. J. (2016). Effect of timing of hip extension assistance during loaded walking with a soft exosuit. *Journal of Neuroengineering and Rehabilitation*, *13*(1), 87.  
<https://doi.org/10.1186/s12984-016-0196-8>
- Dollar, A. M., & Herr, H. (2008). Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art. *IEEE Transactions on Robotics*, *24*(1), 144–158.  
<https://doi.org/10.1109/TRO.2008.915453>

- Esquenazi, A., Talaty, M., Packel, A., & Saulino, M. (2012). The ReWalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury. *American Journal of Physical Medicine & Rehabilitation, 91*(11), 911–921. <https://doi.org/10.1097/PHM.0b013e318269d9a3>
- Feng, C., Wang, H., Lu, N., Chen, T., He, H., Lu, Y., & Tu, X. M. (2014). Log-transformation and its implications for data analysis. *Shanghai Archives of Psychiatry, 26*(2), 105–109. <https://doi.org/10.3969/j.issn.1002-0829.2014.02.009>
- Fritz, N. E., Cheek, F. M., & Nichols-Larsen, D. S. (2015). Motor-Cognitive Dual-Task Training in Persons With Neurologic Disorders. *Journal of Neurologic Physical Therapy, 39*(3), 142–153. <https://doi.org/10.1097/NPT.000000000000090>
- Gabell, A., & Nayak, U. S. (1984). The effect of age on variability in gait. *Journal of Gerontology, 39*(6), 662–666. <https://doi.org/10.1093/geronj/39.6.662>
- Galletly, R., & Brauer, S. G. (2005). Does the type of concurrent task affect preferred and cued gait in people with Parkinson's disease? *Australian Journal of Physiotherapy, 51*(3), 175–180. [https://doi.org/10.1016/S0004-9514\(05\)70024-6](https://doi.org/10.1016/S0004-9514(05)70024-6)
- Ghai, S., Ghai, I., & Effenberg, A. O. (2017). Effects of dual tasks and dual-task training on postural stability: a systematic review and meta-analysis. *Clinical Interventions in Aging, Volume 12*, 557–577. <https://doi.org/10.2147/CIA.S125201>
- Godde, B., & Voelcker-Rehage, C [Claudia] (2010). More automation and less cognitive control of imagined walking movements in high- versus low-fit older adults. *Frontiers in Aging Neuroscience, 2*. <https://doi.org/10.3389/fnagi.2010.00139>
- Gordon, K. E., & Ferris, D. P. (2007). Learning to walk with a robotic ankle exoskeleton. *Journal of Biomechanics, 40*(12), 2636–2644. <https://doi.org/10.1016/j.jbiomech.2006.12.006>
- Greene, B. R., McGrath, D., O'Neill, R., O'Donovan, K. J., Burns, A., & Caulfield, B. (2010). An adaptive gyroscope-based algorithm for temporal gait analysis. *Medical & Biological Engineering & Computing, 48*(12), 1251–1260. <https://doi.org/10.1007/s11517-010-0692-0>
- Gupta, A., Kelty-Stephen, D. G., Mangalam, M., McKindles, R. J., & Stirling, L. (2023). Walking speed and dual task input modality impact performance on a self-paced treadmill. *Applied Ergonomics, 109*, 103986. <https://doi.org/10.1016/j.apergo.2023.103986>

- Hamacher, D [Daniel], Hamacher, D [Dennis], Müller, R., Schega, L., & Zech, A. (2019). The Effect of a Cognitive Dual Task on the Control of Minimum Toe Clearance While Walking. *Motor Control, 23*(3), 344–353. <https://doi.org/10.1123/mc.2018-0006>
- Hamacher, D [Daniel], Koch, M., Löwe, S., & Zech, A. (2019). Less noise during dual-task walking in healthy young adults: an analysis of different gait variability components. *Experimental Brain Research, 237*(12), 3185–3193. <https://doi.org/10.1007/s00221-019-05664-2>
- Hamacher, D [Dennis], Herold, F., Wiegel, P., Hamacher, D [Daniel], & Schega, L. (2015). Brain activity during walking: A systematic review. *Neuroscience and Biobehavioral Reviews, 57*, 310–327. <https://doi.org/10.1016/j.neubiorev.2015.08.002>
- Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In *Advances in Psychology. Human Mental Workload* (pp. 139–183). Elsevier. [https://doi.org/10.1016/S0166-4115\(08\)62386-9](https://doi.org/10.1016/S0166-4115(08)62386-9)
- Hausdorff, J. M. (2005). Gait variability: methods, modeling and meaning. *Journal of Neuroengineering and Rehabilitation, 2*, 19. <https://doi.org/10.1186/1743-0003-2-19>
- Hausdorff, J. M. (2007). Gait dynamics, fractals and falls: finding meaning in the stride-to-stride fluctuations of human walking. *Human Movement Science, 26*(4), 555–589. <https://doi.org/10.1016/j.humov.2007.05.003>
- Hausdorff, J. M., Lowenthal, J., Herman, T., Gruendlinger, L., Peretz, C., & Giladi, N. (2007). Rhythmic auditory stimulation modulates gait variability in Parkinson's disease. *The European Journal of Neuroscience, 26*(8), 2369–2375. <https://doi.org/10.1111/j.1460-9568.2007.05810.x>
- Hausdorff, J. M., Rios, D. A., & Edelberg, H. K. (2001). Gait variability and fall risk in community-living older adults: A 1-year prospective study. *Archives of Physical Medicine and Rehabilitation, 82*(8), 1050–1056. <https://doi.org/10.1053/apmr.2001.24893>
- Hill, A., Bohil, C., Lewis, J., & Neider, M. (2013). Prefrontal Cortex Activity During Walking While Multitasking. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 57*(1), 1224–1228. <https://doi.org/10.1177/1541931213571272>
- Hinton, D. C., Conradsson, D., Bouyer, L., & Paquette, C. (2020). Does dual task placement and duration affect split-belt treadmill adaptation? *Gait & Posture, 75*, 115–120. <https://doi.org/10.1016/j.gaitpost.2019.10.005>

- Hollman, J. H., Childs, K. B., McNeil, M. L., Mueller, A. C., Quilter, C. M., & Youdas, J. W. (2010). Number of strides required for reliable measurements of pace, rhythm and variability parameters of gait during normal and dual task walking in older individuals. *Gait & Posture, 32*(1), 23–28. <https://doi.org/10.1016/j.gaitpost.2010.02.017>
- Holtzer, R., Mahoney, J. R., Izzetoglu, M., Izzetoglu, K., Onaral, B., & Verghese, J. (2011). fNIRS study of walking and walking while talking in young and old individuals. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 66*(8), 879–887. <https://doi.org/10.1093/gerona/qlr068>
- Huang, C.-M., & Mutlu, B. (2016). Anticipatory robot control for efficient human-robot collaboration. In *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI)* (pp. 83–90). IEEE. <https://doi.org/10.1109/HRI.2016.7451737>
- Huxhold, O., Li, S.-C., Schmiedek, F., & Lindenberger, U. (2006). Dual-tasking postural control: aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Research Bulletin, 69*(3), 294–305. <https://doi.org/10.1016/j.brainresbull.2006.01.002>
- Hybart, R., Ferris, D., & Di Marco, R. (2023). Gait variability of outdoor vs treadmill walking with bilateral robotic ankle exoskeletons under proportional myoelectric control. *PloS One, 18*(11), e0294241. <https://doi.org/10.1371/journal.pone.0294241>
- Iosa, M., Morone, G., Bini, F., Fusco, A., Paolucci, S., & Marinuzzi, F. (2016). The connection between anthropometry and gait harmony unveiled through the lens of the golden ratio. *Neuroscience Letters, 612*, 138–144. <https://doi.org/10.1016/j.neulet.2015.12.023>
- Jacobs, D. A., Koller, J. R., Steele, K. M., & Ferris, D. P. (2018). Motor modules during adaptation to walking in a powered ankle exoskeleton. *Journal of Neuroengineering and Rehabilitation, 15*(1), 2. <https://doi.org/10.1186/s12984-017-0343-x>
- Jin, X., Cai, Y., Prado, A., & Agrawal, S. K. (2017). Effects of exoskeleton weight and inertia on human walking. In *2017 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 1772–1777). IEEE. <https://doi.org/10.1109/ICRA.2017.7989210>
- Jordan, K., Challis, J. H., & Newell, K. M. (2007). Walking speed influences on gait cycle variability. *Gait & Posture, 26*(1), 128–134. <https://doi.org/10.1016/j.gaitpost.2006.08.010>
- Kahneman, D. (1973). *Attention and effort*. Prentice-Hall series in experimental psychology. Prentice-Hall Inc.

- Kalita, B., Narayan, J., & Dwivedy, S. K. (2021). Development of Active Lower Limb Robotic-Based Orthosis and Exoskeleton Devices: A Systematic Review. *International Journal of Social Robotics*, 13(4), 775–793. <https://doi.org/10.1007/s12369-020-00662-9>
- Kao, P.-C., & Pierro, M. A. (2022). Motor adaptation to cognitive challenges and walking perturbations in healthy young adults. *Gait & Posture*, 92, 167–175. <https://doi.org/10.1016/j.gaitpost.2021.11.030>
- Kapsalyamov, A., Jamwal, P. K., Hussain, S., & Ghayesh, M. H. (2019). State of the Art Lower Limb Robotic Exoskeletons for Elderly Assistance. *IEEE Access*, 7, 95075–95086. <https://doi.org/10.1109/ACCESS.2019.2928010>
- Kazerooni, H., & Steger, R. (2006). The Berkeley Lower Extremity Exoskeleton. *Journal of Dynamic Systems, Measurement, and Control*, 128(1), 14–25. <https://doi.org/10.1115/1.2168164>
- Kelly, V. E., Eusterbrock, A. J., & Shumway-Cook, A [Anne] (2012). A review of dual-task walking deficits in people with Parkinson’s disease: motor and cognitive contributions, mechanisms, and clinical implications. *Parkinson’s Disease*, 2012, 918719. <https://doi.org/10.1155/2012/918719>
- Kelly, V. E., Janke, A. A., & Shumway-Cook, A [Anne] (2010). Effects of instructed focus and task difficulty on concurrent walking and cognitive task performance in healthy young adults. *Experimental Brain Research*, 207(1-2), 65–73. <https://doi.org/10.1007/s00221-010-2429-6>
- Kim, M., Jeong, H., Kantharaju, P., Yoo, D., Jacobson, M., Shin, D., Han, C., & Patton, J. L. (2022). Visual guidance can help with the use of a robotic exoskeleton during human walking. *Scientific Reports*, 12(1), 3881. <https://doi.org/10.1038/s41598-022-07736-w>
- Klotzbier, T. J., & Schott, N. (2017). Cognitive-Motor Interference during Walking in Older Adults with Probable Mild Cognitive Impairment. *Frontiers in Aging Neuroscience*, 9, 350. <https://doi.org/10.3389/fnagi.2017.00350>
- Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine*, 15(2), 155–163. <https://doi.org/10.1016/j.jcm.2016.02.012>
- Lacour, M., Bernard-Demanze, L., & Dumitrescu, M. (2008). Posture control, aging, and attention resources: models and posture-analysis methods. *Neurophysiologie Clinique = Clinical Neurophysiology*, 38(6), 411–421. <https://doi.org/10.1016/j.neucli.2008.09.005>

- Laffranchi, M., D'Angella, S., Vassallo, C., Piezzo, C., Canepa, M., Giuseppe, S. de, Di Salvo, M., Succi, A., Cappa, S., Cerruti, G., Scarpetta, S., Cavallaro, L., Boccardo, N., D'Angelo, M., Marchese, C., Saglia, J. A., Guanziroli, E., Barresi, G., Semprini, M., . . . Michieli, L. de (2021). User-Centered Design and Development of the Modular TWIN Lower Limb Exoskeleton. *Frontiers in Neurorobotics*, *15*, 709731.  
<https://doi.org/10.3389/fnbot.2021.709731>
- Leibman, D., & Choi, H. (2025). Going beyond the mean in examining the effects of exoskeleton use on motor and attentional task performance. *Applied Ergonomics*, *129*, 104567.  
<https://doi.org/10.1016/j.apergo.2025.104567>
- Leibman, D., Mitchell, D. B., & Choi, H. (2022). Impacts of Enhanced Physical Abilities via Exoskeletons on Attentional Performance and Workload. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *66*(1), 280–284.  
<https://doi.org/10.1177/1071181322661344>
- Leone, C., Feys, P., Moumdjian, L., D'Amico, E., Zappia, M., & Patti, F. (2017). Cognitive-motor dual-task interference: A systematic review of neural correlates. *Neuroscience and Biobehavioral Reviews*, *75*, 348–360. <https://doi.org/10.1016/j.neubiorev.2017.01.010>
- Lord, S., Howe, T., Greenland, J., Simpson, L., & Rochester, L. (2011). Gait variability in older adults: a structured review of testing protocol and clinimetric properties. *Gait & Posture*, *34*(4), 443–450. <https://doi.org/10.1016/j.gaitpost.2011.07.010>
- Lövdén, M., Schaefer, S., Pohlmeier, A. E., & Lindenberger, U. (2008). Walking variability and working-memory load in aging: a dual-process account relating cognitive control to motor control performance. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, *63*(3), 121–128. <https://doi.org/10.1093/geronb/63.3.P121>
- Lundin-Olsson, L., Nyberg, L., & Gustafson, Y. (1997). “Stops walking when talking” as a predictor of falls in elderly people. *The Lancet*, *349*(9052), 617.  
[https://doi.org/10.1016/S0140-6736\(97\)24009-2](https://doi.org/10.1016/S0140-6736(97)24009-2)
- Maki, B. E. (1997). Gait changes in older adults: Predictors of falls or indicators of fear. *Journal of the American Geriatrics Society*, *45*(3), 313–320. <https://doi.org/10.1111/j.1532-5415.1997.tb00946.x>
- Mandery, C., Terlemez, O., Do, M., Vahrenkamp, N., & Asfour, T. (2016). Unifying Representations and Large-Scale Whole-Body Motion Databases for Studying Human Motion. *IEEE Transactions on Robotics*, *32*(4), 796–809. <https://doi.org/10.1109/TRO.2016.2572685>

- Marchand, C., Graaf, J. B., & Jarrassé, N. (2021). Measuring mental workload in assistive wearable devices: a review. *Journal of Neuroengineering and Rehabilitation*, *18*(1), 160. <https://doi.org/10.1186/s12984-021-00953-w>
- Marinou, G., Kourouma, I., & Mombaur, K. (2025). Development and Validation of a Modular Sensor-Based System for Gait Analysis and Control in Lower-Limb Exoskeletons. *Sensors (Basel, Switzerland)*, *25*(8). <https://doi.org/10.3390/s25082379>
- Marinou, G., Sloom, L., & Mombaur, K. (2022). Towards efficient lower-limb exoskeleton evaluation: Defining biomechanical metrics to quantify assisted gait familiarization. In *2022 9th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)* (pp. 1–8). IEEE. <https://doi.org/10.1109/BioRob52689.2022.9925360>
- McFadyen, B. J., Hegeman, J., & Duysens, J. (2009). Dual task effects for asymmetric stepping on a split-belt treadmill. *Gait & Posture*, *30*(3), 340–344. <https://doi.org/10.1016/j.gaitpost.2009.06.004>
- Mersmann, F., Bohm, S., Bierbaum, S., Dietrich, R., & Arampatzis, A. (2013). Young and old adults prioritize dynamic stability control following gait perturbations when performing a concurrent cognitive task. *Gait & Posture*, *37*(3), 373–377. <https://doi.org/10.1016/j.gaitpost.2012.08.005>
- Meyer, C., Killeen, T., Easthope, C. S., Curt, A., Bolliger, M., Linnebank, M., Zörner, B., & Filli, L. (2019). Familiarization with treadmill walking: How much is enough? *Scientific Reports*, *9*(1), 5232. <https://doi.org/10.1038/s41598-019-41721-0>
- Navon, D., & Gopher, D. (1979). On the economy of the human-processing system. *Psychological Review*, *86*(3), 214–255. <https://doi.org/10.1037/0033-295X.86.3.214>
- Navon, D., & Miller, J. (1987). Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, *13*(3), 435–448. <https://doi.org/10.1037//0096-1523.13.3.435>
- Newell, K. M., & Corcos, D. M. (1993). *Variability and motor control*. Human Kinetics Publishers.
- Noble, J. W., & Prentice, S. D. (2006). Adaptation to unilateral change in lower limb mechanical properties during human walking. *Experimental Brain Research*, *169*(4), 482–495. <https://doi.org/10.1007/s00221-005-0162-3>
- Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology*, *7*(1), 44–64. [https://doi.org/10.1016/0010-0285\(75\)90004-3](https://doi.org/10.1016/0010-0285(75)90004-3)

- Norman, D. A., & Bobrow, D. G. (1976). On the analysis of performance operating characteristics. *Psychological Review*, *83*(6), 508–510. <https://doi.org/10.1037/0033-295X.83.6.508>
- Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychological Bulletin*, *116*(2), 220–244. <https://doi.org/10.1037/0033-2909.116.2.220>
- Patel, P., Lamar, M., & Bhatt, T. (2014). Effect of type of cognitive task and walking speed on cognitive-motor interference during dual-task walking. *Neuroscience*, *260*, 140–148. <https://doi.org/10.1016/j.neuroscience.2013.12.016>
- Pau, M., Corona, F., Pili, R., Casula, C., Sors, F., Agostini, T., Cossu, G., Guicciardi, M., & Murgia, M. (2016). Effects of Physical Rehabilitation Integrated with Rhythmic Auditory Stimulation on Spatio-Temporal and Kinematic Parameters of Gait in Parkinson’s Disease. *Frontiers in Neurology*, *7*. <https://doi.org/10.3389/fneur.2016.00126>
- Penati, R., Schieppati, M., & Nardone, A. (2020). Cognitive performance during gait is worsened by overground but enhanced by treadmill walking. *Gait & Posture*, *76*, 182–187. <https://doi.org/10.1016/j.gaitpost.2019.12.006>
- Pieruccini-Faria, F., Sarquis-Adamson, Y., Anton-Rodrigo, I., Noguerón-García, A., Bray, N. W., Camicioli, R., Muir-Hunter, S. W., Speechley, M., McIlroy, B., & Montero-Odasso, M. (2020). Mapping Associations Between Gait Decline and Fall Risk in Mild Cognitive Impairment. *Journal of the American Geriatrics Society*, *68*(3), 576–584. <https://doi.org/10.1111/jgs.16265>
- Pinto-Fernandez, D., Torricelli, D., Del Sanchez-Villamanan, M. C., Aller, F., Mombaur, K., Conti, R., Vitiello, N., Moreno, J. C [Juan C.], & Pons, J. L [Jose Luis] (2020). Performance Evaluation of Lower Limb Exoskeletons: A Systematic Review. *IEEE Transactions on Neural Systems and Rehabilitation Engineering : A Publication of the IEEE Engineering in Medicine and Biology Society*, *28*(7), 1573–1583. <https://doi.org/10.1109/TNSRE.2020.2989481>
- Poggensee, K. L., & Collins, S. H. (2021). How adaptation, training, and customization contribute to benefits from exoskeleton assistance. *Science Robotics*, *6*(58). <https://doi.org/10.1101/2021.04.25.440289>

- Raffegeau, T. E., Krehbiel, L. M., Kang, N., Thijs, F. J., Altmann, L. J. P., Cauraugh, J. H., & Hass, C. J. (2019). A meta-analysis: Parkinson's disease and dual-task walking. *Parkinsonism & Related Disorders*, *62*, 28–35.  
<https://doi.org/10.1016/j.parkreldis.2018.12.012>
- Rasmussen, J. (1983). Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man, and Cybernetics*, *SMC-13*(3), 257–266. <https://doi.org/10.1109/TSMC.1983.6313160>
- Reid, G. B., & Nygren, T. E. (1988). The Subjective Workload Assessment Technique: A Scaling Procedure for Measuring Mental Workload. In *Advances in Psychology. Human Mental Workload* (Vol. 52, pp. 185–218). Elsevier. [https://doi.org/10.1016/S0166-4115\(08\)62387-0](https://doi.org/10.1016/S0166-4115(08)62387-0)
- Reiser, J. E., Arnau, S., Rinckenauer, G., Wascher, E., & Di Russo, F. (2022). Did you even see that? Visual sensory processing of single stimuli under different locomotor loads. *PLoS One*, *17*(5), e0267896. <https://doi.org/10.1371/journal.pone.0267896>
- Reiser, J. E., Wascher, E., & Arnau, S. (2019). Recording mobile EEG in an outdoor environment reveals cognitive-motor interference dependent on movement complexity. *Scientific Reports*, *9*(1), 13086. <https://doi.org/10.1038/s41598-019-49503-4>
- Riedel, N., & Deml, B. (2025). Assessment of cognitive-motor interference in human-exoskeleton interaction using the Performance-Operating-Characteristics (POC) framework. In D. de Waard, L. Onnasch, M. Liebherr, A. Dettmann, F. Siebert, K. Karrer-Gauß, S. Winkler, A. Toffetti, & M. de Angelis (Eds.), *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2025 Annual Conference* (pp. 51-60). <https://www.hfes-europe.org/wp-content/uploads/2025/05/Riedel2025.pdf>
- Riedel, N., Herzog, M., Stein, T., & Deml, B. (2023). Effects of modified leg mechanics on cognitive performance and workload during dual-task walking. In D. de Waard, V. Hagemann, L. Onnasch, A. Toffetti, D. Coelho, A. Botzer, M. de Angelis, K. Brookhuis, & S. Fairclough (Eds.), *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2023 Annual Conference* (pp. 197–211). <https://www.hfes-europe.org/wp-content/uploads/2023/05/Riedel2023.pdf>
- Riedel, N., Herzog, M., Stein, T., & Deml, B. (2024). Cognitive-motor interference during walking with modified leg mechanics: A dual-task walking study. *Frontiers in Psychology*, *15*, 1375029. <https://doi.org/10.3389/fpsyg.2024.1375029>

- Riedel, N., Marinou, G., Mombaur, K., & Deml, B. (2025). An outdoor dual-task study on cognitive-motor interference during exoskeleton-assisted walking. *Frontiers in Psychology, 16*, 1583142. <https://doi.org/10.3389/fpsyg.2025.1583142>
- Royer, T. D., & Martin, P. E. (2005). Manipulations of leg mass and moment of inertia: effects on energy cost of walking. *Medicine and Science in Sports and Exercise, 37*(4), 649–656. <https://doi.org/10.1249/01.mss.0000159007.56083.96>
- Salarian, A., Russmann, H., Vingerhoets, F., Dehollain, C., Blanc, Y., Burkhard, P. R., & Aminian, K. (2004). Gait Assessment in Parkinson's Disease: Toward an Ambulatory System for Long-Term Monitoring. *IEEE Transactions on Biomedical Engineering, 51*(8), 1434–1443. <https://doi.org/10.1109/TBME.2004.827933>
- Sankai, Y. (2011). HAL: Hybrid Assistive Limb Based on Cybernetics. In B. Siciliano, O. Khatib, F. Groen, M. Kaneko, & Y. Nakamura (Eds.), *Springer Tracts in Advanced Robotics. Robotics Research* (Vol. 66, pp. 25–34). Springer Berlin Heidelberg. [https://doi.org/10.1007/978-3-642-14743-2\\_3](https://doi.org/10.1007/978-3-642-14743-2_3)
- Sawicki, G. S., Beck, O. N., Kang, I., & Young, A. J. (2020). The exoskeleton expansion: Improving walking and running economy. *Journal of Neuroengineering and Rehabilitation, 17*(1), 25. <https://doi.org/10.1186/s12984-020-00663-9>
- Schmider, E., Ziegler, M., Danay, E., Beyer, L., & Bühner, M. (2010). Is It Really Robust? *Methodology, 6*(4), 147–151. <https://doi.org/10.1027/1614-2241/a000016>
- Semprini, M., Lencioni, T., Hinterlang, W., Vassallo, C., Scarpetta, S., Maludrottu, S., Iandolo, R., Carè, M., Laffranchi, M., Chiappalone, M., Ferrarin, M., Michieli, L. de, & Jonsdottir, J. (2022). User-centered design and development of TWIN-Acta: A novel control suite of the TWIN lower limb exoskeleton for the rehabilitation of persons post-stroke. *Frontiers in Neuroscience, 16*, 915707. <https://doi.org/10.3389/fnins.2022.915707>
- Shumway-Cook, A [A.], Woollacott, M [M.], Kerns, K. A., & Baldwin, M. (1997). The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 52*(4), 232–240. <https://doi.org/10.1093/gerona/52A.4.M232>
- Smith, E., Cusack, T., Cunningham, C., & Blake, C. (2017). The Influence of a Cognitive Dual Task on the Gait Parameters of Healthy Older Adults: A Systematic Review and Meta-Analysis. *Journal of Aging and Physical Activity, 25*(4), 671–686. <https://doi.org/10.1123/japa.2016-0265>

- Springer, S., Giladi, N., Peretz, C., Yogev, G., Simon, E. S., & Hausdorff, J. M. (2006). Dual-tasking effects on gait variability: the role of aging, falls, and executive function. *Movement Disorders : Official Journal of the Movement Disorder Society*, *21*(7), 950–957.  
<https://doi.org/10.1002/mds.20848>
- Stirling, L., Kelty-Stephen, D., Fineman, R., Jones, M. L. H., Daniel Park, B.-K., Reed, M. P., Parham, J., & Choi, H. J. (2020). Static, Dynamic, and Cognitive Fit of Exosystems for the Human Operator. *Human Factors*, *62*(3), 424–440.  
<https://doi.org/10.1177/0018720819896898>
- Stirling, L., Siu, H. C., Jones, E., & Duda, K. (2019). Human Factors Considerations for Enabling Functional Use of Exosystems in Operational Environments. *IEEE Systems Journal*, *13*(1), 1072–1083. <https://doi.org/10.1109/JSYST.2018.2821689>
- Stoffregen, T. A., Hove, P., Bardy, B. G [Benoît G.], Riley, M., & Bonnet, C. T [Cedrick T.] (2007). Postural stabilization of perceptual but not cognitive performance. *Journal of Motor Behavior*, *39*(2), 126–138. <https://doi.org/10.3200/JMBR.39.2.126-138>
- Stoffregen, T. A., Pagulayan, R. J., Bardy, B. G [Benoît G.], & Hettinger, L. J. (2000). Modulating postural control to facilitate visual performance. *Human Movement Science*, *19*(2), 203–220. [https://doi.org/10.1016/S0167-9457\(00\)00009-9](https://doi.org/10.1016/S0167-9457(00)00009-9)
- Stoffregen, T. A., Smart, L. J., Bardy, B. G [Benoît G.], & Pagulayan, R. J. (1999). Postural stabilization of looking. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1641–1658. <https://doi.org/10.1037/0096-1523.25.6.1641>
- Strausser, K. A., & Kazerooni, H. (2011). The development and testing of a human machine interface for a mobile medical exoskeleton. In *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems* (pp. 4911–4916). IEEE.  
<https://doi.org/10.1109/IROS.2011.6095025>
- Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 643–662. <https://doi.org/10.1037/h0054651>
- Szturm, T., Maharjan, P., Marotta, J. J., Shay, B., Shrestha, S., & Sakhalkar, V. (2013). The interacting effect of cognitive and motor task demands on performance of gait, balance and cognition in young adults. *Gait & Posture*, *38*(4), 596–602.  
<https://doi.org/10.1016/j.gaitpost.2013.02.004>

- Thumm, P. C., Maidan, I., Brozgol, M., Shustak, S., Gazit, E., Shema Shiratzki, S., Bernad-Elazari, H., Beck, Y., Giladi, N., Hausdorff, J. M., & Mirelman, A. (2018). Treadmill walking reduces pre-frontal activation in patients with Parkinson's disease. *Gait & Posture*, *62*, 384–387. <https://doi.org/10.1016/j.gaitpost.2018.03.041>
- Tian, Q., Chastan, N., Bair, W.-N., Resnick, S. M., Ferrucci, L., & Studenski, S. A. (2017). The brain map of gait variability in aging, cognitive impairment and dementia—A systematic review. *Neuroscience & Biobehavioral Reviews*, *74*, 149–162. <https://doi.org/10.1016/j.neubiorev.2017.01.020>
- Timmermans, C., Roerdink, M., Janssen, T. W. J., Meskers, C. G. M., & Beek, P. J. (2018). Dual-Task Walking in Challenging Environments in People with Stroke: Cognitive-Motor Interference and Task Prioritization. *Stroke Research and Treatment*, *2018*, 7928597. <https://doi.org/10.1155/2018/7928597>
- Toricelli, D., Rodriguez-Guerrero, C., Veneman, J. F., Crea, S., Briem, K., Lenggenhager, B., & Beckerle, P. (2020). Benchmarking Wearable Robots: Challenges and Recommendations From Functional, User Experience, and Methodological Perspectives. *Frontiers in Robotics and AI*, *7*, 561774. <https://doi.org/10.3389/frobt.2020.561774>
- Tucker, M. R., Olivier, J., Pagel, A., Bleuler, H., Bouri, M., Lambercy, O., Del Millán, J. R., Riemer, R., Vallery, H., & Gassert, R. (2015). Control strategies for active lower extremity prosthetics and orthotics: A review. *Journal of Neuroengineering and Rehabilitation*, *12*(1), 1. <https://doi.org/10.1186/1743-0003-12-1>
- Upasani, S., & Srinivasan, D. (2023). Gaze Behavior and Mental Workload While Using a Whole-Body Powered Exoskeleton: A Pilot Study. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. Advance online publication. <https://doi.org/10.1177/21695067231192201>
- Vasey, M. W., & Thayer, J. F. (1987). The continuing problem of false positives in repeated measures ANOVA in psychophysiology: a multivariate solution. *Psychophysiology*, *24*(4), 479–486. <https://doi.org/10.1111/j.1469-8986.1987.tb00324.x>
- Vassallo, C., Giuseppe, S. de, Piezzo, C., Maludrottu, S., Cerruti, G., D'Angelo, M. L., Gruppioni, E., Marchese, C., Castellano, S., Guanziroli, E., Molteni, F., Laffranchi, M., & Micheli, L. de (2020). Gait patterns generation based on basis functions interpolation for the TWIN lower-limb exoskeleton. In *2020 IEEE International Conference on Robotics*

- and Automation (ICRA)* (pp. 1778–1784). IEEE.  
<https://doi.org/10.1109/ICRA40945.2020.9197250>
- Verrel, J., Lövdén, M., Schellenbach, M., Schaefer, S., & Lindenberger, U. (2009). Interacting effects of cognitive load and adult age on the regularity of whole-body motion during treadmill walking. *Psychology and Aging, 24*(1), 75–81.  
<https://doi.org/10.1037/a0014272>
- Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science, 3*(2), 159–177. <https://doi.org/10.1080/14639220210123806>
- Wickens, C. D., Mountford, S. J., & Schreiner, W. (1981). Multiple Resources, Task-Hemispheric Integrity, and Individual Differences in Time-Sharing. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 23*(2), 211–229.  
<https://doi.org/10.1177/001872088102300209>
- Wollesen, B., Voelcker-Rehage, C [C.], Regenbrecht, T., & Mattes, K. (2016). Influence of a visual-verbal Stroop test on standing and walking performance of older adults. *Neuroscience, 318*, 166–177. <https://doi.org/10.1016/j.neuroscience.2016.01.031>
- Woollacott, M [Marjorie], & Shumway-Cook, A [Anne] (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait & Posture, 16*(1), 1–14.  
[https://doi.org/10.1016/S0966-6362\(01\)00156-4](https://doi.org/10.1016/S0966-6362(01)00156-4)
- Wrightson, J. G., Schäfer, L., & Smeeton, N. J. (2020). Dual-task prioritization during over-ground and treadmill walking in healthy adults. *Gait & Posture, 75*, 109–114.  
<https://doi.org/10.1016/j.gaitpost.2019.08.007>
- Wrightson, J. G., & Smeeton, N. J. (2017). Walking modality, but not task difficulty, influences the control of dual-task walking. *Gait & Posture, 58*, 136–138.  
<https://doi.org/10.1016/j.gaitpost.2017.07.042>
- Wu, M. I., Stegall, P., Siu, H. C., & Stirling, L. (2022). Impact of Haptic Cues and an Active Ankle Exoskeleton on Gait Characteristics. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 66*(3), 904–915. <https://doi.org/10.1177/00187208221113625>
- Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology, 18*(5), 459–482.  
<https://doi.org/10.1002/cne.920180503>

- Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement Disorders : Official Journal of the Movement Disorder Society*, 23(3), 329–42472. <https://doi.org/10.1002/mds.21720>
- Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2012). Do we always prioritize balance when walking? Towards an integrated model of task prioritization. *Movement Disorders: Official Journal of the Movement Disorder Society*, 27(6), 765–770. <https://doi.org/10.1002/mds.24963>
- Yogev-Seligmann, G., Rotem-Galili, Y., Mirelman, A., Dickstein, R., Giladi, N., & Hausdorff, J. M. (2010). How does explicit prioritization alter walking during dual-task performance? Effects of age and sex on gait speed and variability. *Physical Therapy*, 90(2), 177–186. <https://doi.org/10.2522/ptj.20090043>
- Young, A. J., & Ferris, D. P. (2017). State of the Art and Future Directions for Lower Limb Robotic Exoskeletons. *IEEE Transactions on Neural Systems and Rehabilitation Engineering : A Publication of the IEEE Engineering in Medicine and Biology Society*, 25(2), 171–182. <https://doi.org/10.1109/TNSRE.2016.2521160>
- Young, M. S., Brookhuis, K. A., Wickens, C. D., & Hancock, P. A. (2015). State of science: mental workload in ergonomics. *Ergonomics*, 58(1), 1–17. <https://doi.org/10.1080/00140139.2014.956151>
- Zhang, J., Cheah, C. C., & Collins, S. H. (2015). Experimental comparison of torque control methods on an ankle exoskeleton during human walking. In *2015 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 5584–5589). IEEE. <https://doi.org/10.1109/ICRA.2015.7139980>
- Zhu, Y., Weston, E. B., Mehta, R. K., & Marras, W. S. (2021). Neural and biomechanical tradeoffs associated with human-exoskeleton interactions. *Applied Ergonomics*, 96, 103494. <https://doi.org/10.1016/j.apergo.2021.103494>
- Zijlstra, F. (1993). *Efficiency in Work Behavior: A Design Approach for Modern Tools*, Delft: Delft University Press.
- Zoccatelli, G., Beltramello, A., Alessandrini, F., Pizzini, F. B., & Tassinari, G. (2010). Word and position interference in stroop tasks: A behavioral and fMRI study. *Experimental Brain Research*, 207(1-2), 139–147. <https://doi.org/10.1007/s00221-010-2433-x>