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

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Abstract

Mobile exoskeletons as assistive walking devices can modify body mechanics due to their own weight and restricted range of motion, becoming a potential physical and cognitive load for the user when the support is insufficient, or the power supply has failed. This study investigates the effect of modified leg mechanics on cognitive-motor interference in a controlled dual-task walking setting. Sixteen healthy young adults walked on a treadmill at their preferred walking speed with and without weights attached to their thighs and shanks while performing a visual-verbal Stroop test and a subtraction task. The dependent variables examined were performance on secondary tasks (correct response rates and dual-task effects) and perceived physical and cognitive workload (NASA-TLX). Results show a significant decrease in cognitive performance when walking with weights in the subtraction task, but not in the Stroop test. This suggests that walking with modified leg mechanics shares similar complex neural networks activated in particular during the subtraction task. Perceived cognitive workload increased for both tasks when walking with the weights. These results indicate that modified leg mechanics may impose a cognitive load. Additional analysis of the motion data may provide further insight into task prioritisation during walking with modified leg mechanics.

Introduction

Lower limb exoskeletons as assistive walking devices are being studied and developed for a wide variety of applications (see review in 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 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 (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

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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).

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 Yogev-Seligmann et al. (2012), two main factors contribute to the choice of the task prioritisation 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 (Yogev-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).

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.

Method

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.

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_3)	Control motor condition (ST_4)
Stroop test (STR)	Control cognitive condition (ST_1)	DT_1	DT_3
Subtraction task (SUB)	Control cognitive condition (ST_2)	DT_2	DT_4

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 1). These control conditions are needed to compare task performance under single and dual task conditions.

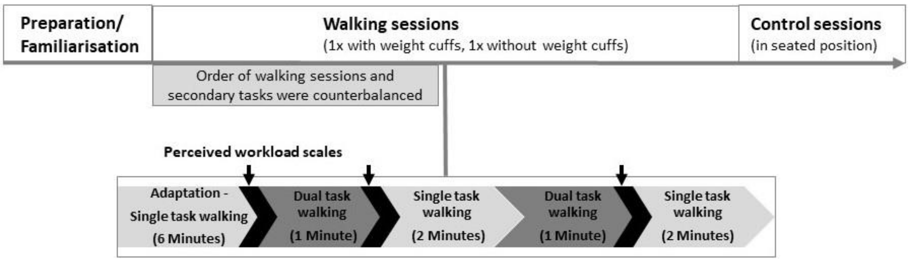


Figure 1. Experimental protocol. Black arrows indicate the times at which the perceived workload subscales were queried during the walking sessions.

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 2 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.

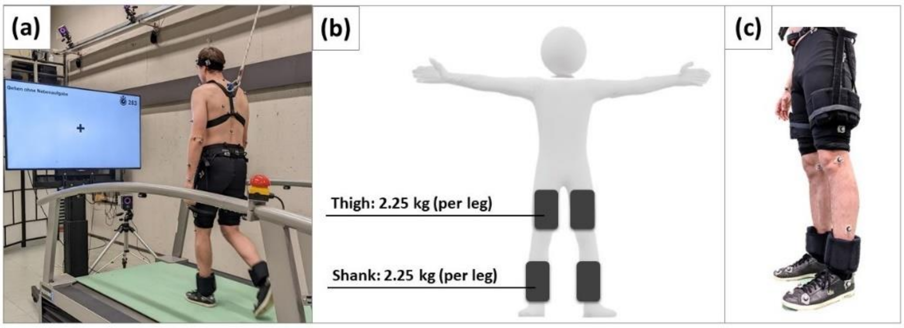


Figure 2. (a) Experimental setup. (b) Schematic representation of the positions of the weight cuffs. (c) Representation of the attachment of the weight cuffs to a participant.

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 3). 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 to 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 3. Exemplary 10x10-matrix of colour words as used in the study.

Walking protocol

Figure 1 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.

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 1 indicates the time of the queries with black arrows.

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:

$$\text{DTE} = \frac{(CRR_{dual\ task} - CRR_{single\ task})}{CRR_{single\ task}} \times 100\% \tag{1}$$

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).

Results

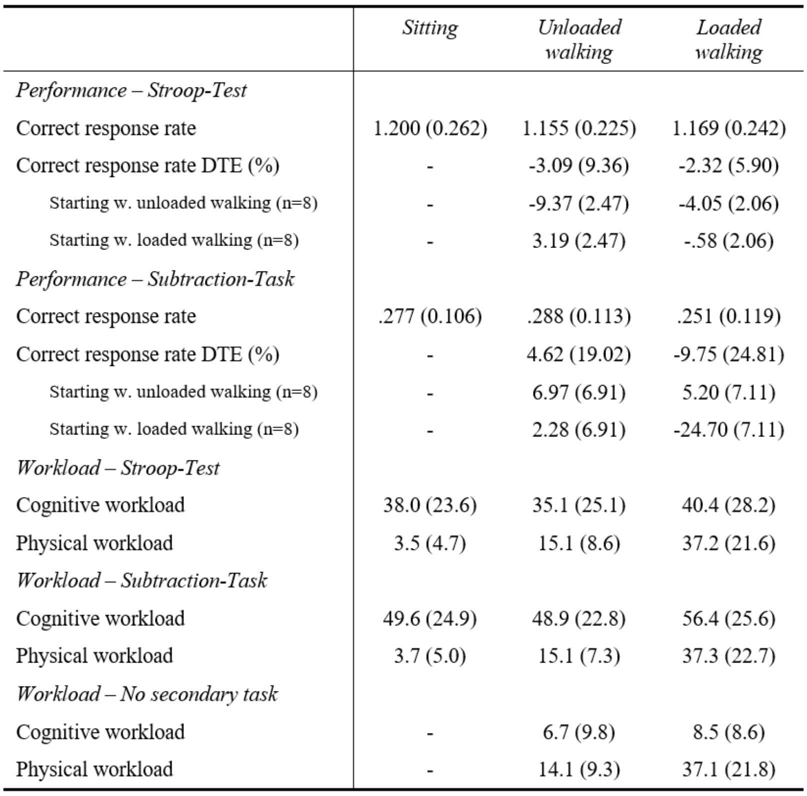
Table 2 shows absolute and relative values for cognitive performance variables and for perceived cognitive and physical workload in each single task and dual task condition.

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 4a, 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*
Performance – Stroop-Test			
Correct response rate	1.200 (0.262)	1.155 (0.225)	1.169 (0.242)
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)
Performance – Subtraction-Task			
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)
Workload – Stroop-Test			
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)
Workload – Subtraction-Task			
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)
Workload – No secondary task			
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, ηp^2 = .392). This indicates that cognitive performance in STR and SUB differed depending on the session order. Figure 4b 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, ηp^2 = .240). This indicates that cognitive performance during unloaded and loaded walking tend to differ depending on the session order (Figure 4b). 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.

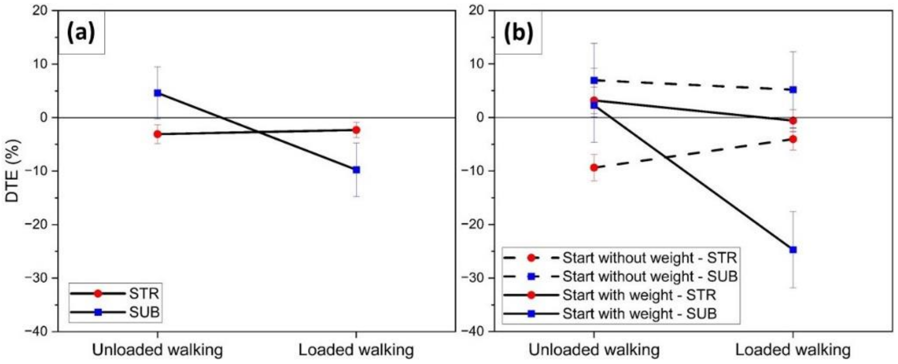


Figure 4. (a) Mean dual task effects (DTE) for STR and SUB in the unloaded and loaded walking condition. (b) Mean DTE for STR and SUB in the unloaded and loaded walking condition for the group of participants who started with unloaded walking (n=8) and the group of participants who started with loaded walking (n=8). Error bars reflect 95% CI.

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

Perceived cognitive workload

There was a significant main effect of *Task Condition* on the perceived cognitive workload (F (1, 15) = 9.257, p = .008, ηp^2 = .382). Reviewing the mean ratings indicated that the SUB was perceived as more cognitively demanding than STR (Figure 5a). There was also a significant main effect of the *Motor Condition* on the perceived cognitive workload (F (2, 30) = 4.155, p = .026, ηp^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, ηp^2 = .049).

Perceived physical workload

There was no significant main effect of *Task Condition* on the perceived physical workload (F (1, 15) < 1, p = .871, ηp^2 = .002), indicating that the type of secondary task had no effect on the perceived physical workload (Figure 5b). There was a significant main effect of the *Motor Condition* on the perceived physical workload (F (1.091, 16.366) = 27.864, p < .001, ηp^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, ηp^2 = .001).

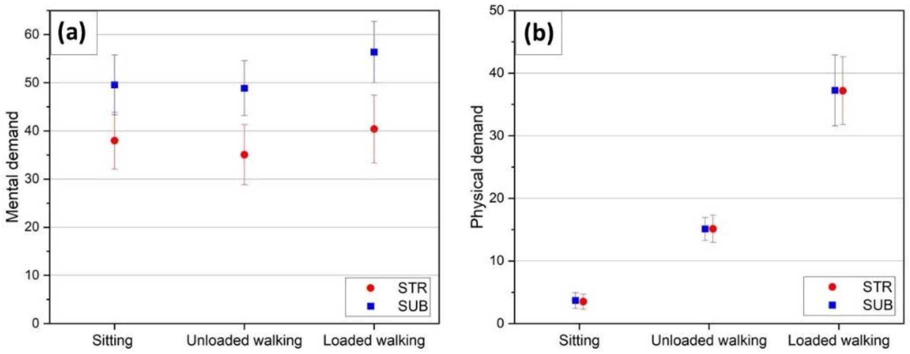


Figure 5. (a) Mean ratings of mental demand. (b) Mean ratings of physical demand. Error bars reflect 95% CI.

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.

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 4a). 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 (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 randomised 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 prioritisation 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 4b). 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).

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.

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.

Acknowledgement

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