



HAL
open science

Effects of muscular and mental fatigue on spatiotemporal gait parameters in dual task walking in young, non-frail and frail older adults

Elodie Piche, Pauline Gerus, Raphaël Zory, Aryn Jaafar, Olivier Guerin, Frédéric Chorin

► To cite this version:

Elodie Piche, Pauline Gerus, Raphaël Zory, Aryn Jaafar, Olivier Guerin, et al.. Effects of muscular and mental fatigue on spatiotemporal gait parameters in dual task walking in young, non-frail and frail older adults. *Aging Clinical and Experimental Research*, 2023, 35 (10), pp.2109-2118. 10.1007/s40520-023-02506-8 . hal-04695434

HAL Id: hal-04695434

<https://hal.science/hal-04695434>

Submitted on 12 Sep 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Effects of muscular and mental fatigue on spatiotemporal gait parameters in dual task walking in young, non-frail and frail older adults

Elodie Piche^{1,2} · Pauline Gerus¹ · Raphaël Zory^{1,4} · Amyn Jaafar² · Olivier Guerin^{2,3} · Frédéric Chorin^{1,2}

Received: 31 March 2023 / Accepted: 12 July 2023

© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2023

Abstract

Background Dual-task (DT) walking is of great interest in clinical evaluation to evaluate frailty or cognitive declines in older adults. Frail older adults are known to adopt different walking strategy to overcome fatigue. However, no studies evaluated the effect of muscular or mental fatigue on dual-task walking strategy and the difference between frail and non-frail older adults.

Aims Evaluate the effect of mental and muscular fatigue on spatio-temporal parameters in dual-task walking in young, non-frail and frail older adults.

Methods 59 participants divided into 20 young (Y) (24.9 ± 3 years old), 20 non-frail (NF) (75.8 ± 4.9 years old) and 19 frail older adults (F) (81 ± 4.7 years old) performed single-task (ST) walking, single-task cognitive (serial subtraction of 3), and dual-task (subtraction + walking) for 1 min at their fast pace. Gait speed, step length, step length variability, stance and swing phase time, single and double support time, cadence, gait speed variability were recorded in single- and dual-task walking. The dual-task effect (DTE) was calculated as $((DT - ST)/ST) \times 100$. Generalized linear mixed models (GLMM) were used to compare the effects of mental and muscular fatigue on gait and cognitive variables between the groups.

Results The DTE walking parameters were worse in F compared to NF or Y but no significant effect of fatigue were highlighted except for swing time and single support time DTEs.

Conclusions The results were mitigated but a clear difference in dual-task spatio-temporal parameters was found between F and NF which brings hope into the capacity of DT to better reveal frailty.

Keywords Frailty · Biomechanics · Dual-task walking · Fatigue

Introduction

A growing body of evidence links gait to cognitive function [1] and suggests that even in healthy young subjects, gait is not automatic, but consumes some amount of attentional resources [2]. Dual tasking paradigms have been used to

study this dependence as it relies upon executive function and the ability to divide attention [3]. When both gait and a secondary task are performed simultaneously and reached the capacity of attentional resources, the performance of at least one of the tasks will deteriorate. Knowing that aging is associated with decreasing mobility and reduced cognitive processing efficiency [4, 5], dual-tasking was found to be more challenging in older adults with greater alteration on spatio-temporal parameters as slower gait speed or wider step width with aging and with dual-tasking [6]. These changes in cognitive or motor performance whilst dual-tasking were found to be able to predict fall risk [7, 8], cognitive status [9] or also frailty status [10]. Frailty is now recognized as a geriatric syndrome which is a result of cumulative declines across multiple physiological systems [11]. Frail older adults are more vulnerable to physiological and psychological stressors, particularly fatigue.

✉ Elodie Piche
piche.e@chu-nice.fr

¹ Université Côte d'Azur, LAMHES, Nice, France

² Université Côte d'Azur, Centre Hospitalier Universitaire de Nice, Clinique Gériatrique du Cerveau et du Mouvement, Nice, France

³ Université Côte d'Azur, CNRS UMR 7284/INSERM U108, Institute for Research on Cancer and Aging Nice (IRCAN), Faculté de médecine, Nice, France

⁴ Institut Universitaire de France, Paris, France

Muscular fatigue has been defined as the fall in maximum force-generating capacity of the muscle, and the failure of the muscle to maintain the required force [12]. It also affects the precision in motor control due to the deteriorated proprioception (e.g., decreased joint position sense, force-matching ability, etc.), movement coordination and reaction time [13, 14]. Consequently, in a fatigue condition, both young and healthy older adults used adaptive strategies to walk with a more cautious pattern by lowering walking speed, reducing step length and/or increasing step width [15, 16]. Thus, inducing a muscular fatigue before a dual-tasking evaluation may probably increase the cognitive-motor interference and the influence on spatio-temporal walking parameters. Only few studies examined the effect of muscular fatigue on dual task walking and even more with the level of frailty. Granacher et al. [17] found that the young adults achieved better cognitive performance post-fatigue at the cost of impaired balance control. However, Kao et al. [18] showed that muscular fatigue did not impact cognitive but motor performance in younger adults. If the results are contradictory and may be confirmed by future studies, no studies focused on comparing the difference of the effect of muscular fatigue between young, healthy older adults and frail older adults. Frail older adults have less muscle mass and strength than the non-frails [19] and have also lower levels of motor processing and slower gait speed [20]. Thus, it could be hypothesized that frail older adults may be more challenged in DT and even more affected by a muscular fatigue during DT than healthy older adults [21]. That would mean that DT could help to better reveal frailty.

While muscular fatigue can directly reduce motor performance in DT due to impairment in force and muscle activation, demanding mental activities can also impact the performance in DT. Indeed, sustaining attention or a mental effort for a prolonged period puts older adults in a fatigued mental state [22, 23] that slows cognitive processes which is often quantified by slowed reaction times [24] alters cortical brain areas and decreases neurotransmitter levels [25, 26]. Such modifications affects cognitive functions known to be involved in gait dual-tasking, resulting in an interference with gait [27]. These interferences resulted in an increase in the coefficient of variation of stride outcomes and other gait parameters [16]. Moreover, Behrens et al. [28] found that the mental fatigue impacted gait parameters in DT (coefficient of variation, stride length and stance time) in old but not in young group which highlight that the effect of mental fatigue on DT is greater with age. However, there is a lack of studies on the effect of mental fatigue in DT especially in frail older adults. The unanswered question is whether frail older adults had similar adaptation in DT to overcome a mental or muscular fatigue compared to healthy older adults or a younger group and if the effect of a muscular or mental

fatigue would be greater in a frail older adults compared to their healthy counterparts.

The purpose of this study was, thus, to investigate how muscular and mental fatigue affects dual task walking performance comparing young, healthy older adults, and frail older adults. For the walking performance, specifically, we explored the effects of mental and muscular fatigue on dual task walking on participant's step length (cm), step length variability (%), stance time and swing time (s), single support time and double support time (s), gait speed (m/s), gait speed variability (%) and cadence (steps/min). These specific variables were chosen for their strong correlation to the level of physical and functional health status [11, 29]. We hypothesized that the three groups would show reduced gait speed, increased gait speed variability and would have worse cognitive performance after reaching both muscular and mental fatigue. We also expected the impact of muscular and mental fatigue to be greater with age and particularly in the frail group.

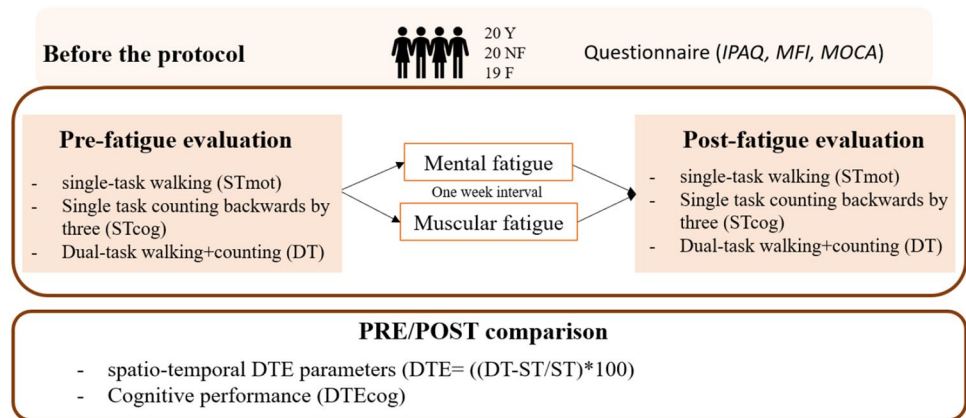
Materials and methods

Participants

Fifty-nine participants were recruited and were divided into three groups. The young group (Y) was composed of 20 participants under 35 years old. The older group was composed of 20 participants aged between 65 and 90 years old without any signs of frailty (NF). The frail older group was composed of 19 older adults between 65 and 90 years old corresponding to the frailty Fried's definition which is to have at least 3 criterions from the five phenotypic components (F). The five components were: (1) unintentional loss of $\geq 5\%$ of body weight in the past year, (2) self-report of feeling "tired all the time" (3) Mean speed to complete a 10 m walk < 1 m/s, (4) Low physical activity and (5) clearly abnormal strength on physical examination [11].

Inclusion criteria were an ability to walk independently for, at least, 50 m and have corrected-to-normal hearing and vision. Participants were excluded if they had a history of neurological disorders, cognitive dysfunction screened with a MOCA score under 23, any orthopedic conditions affecting gait, an acute hospital stay within the last 3 months, or a lower extremity amputation. Their level of physical activity were also assessed through the International Physical Activity Questionnaire (IPAQ) [30] and their initial fatigue was controlled with the Multidimensional Fatigue Inventory (MFI) at the beginning of each protocol (mental and muscular) (MFI_1 and MFI_2 for the first and second visit, respectively) (Fig. 1). The order of the fatigue protocols was randomized with an interval of one week between the two fatigue protocols

Fig. 1 The experimental design protocol for young (Y), non-frail (NF) and frail (F) older adults. STmot, STcog and DT were randomized as well as mental or muscular protocol



(Fig. 1). Participants were evaluated through a randomized 1 min of single-task walking (*STmot*), 1 min of single-task counting backwards by three (*STcog*) and 1 min of both counting and walking (*DT*) before and right after the fatigue protocol. The one-week interval and the randomization were chosen to reduce a possible learning effect of dual-task walking and to ensure a total recovery from the first fatigue protocol. The order chosen in pre-evaluation was the same in post and for the 2nd fatigue protocol one week later. Approval of the study was obtained (n° 2021-A00016-35) and all participants signed the informed consent form.

Dual-task protocol

The dual-task protocol was the same before and after each fatigue protocol. It consists of evaluating the cognitive and motor performance alone (*STcog* and *STmotor*, respectively) and a combination of walking and the secondary cognitive task (*DT*), each during 1 min. The cognitive task was a serial subtraction of 3 from a random number between 150 and 300 [3, 31]. This task was found to be more pertinent and challenging than a verbal fluency or a motor task [32–34]. The cognitive task was performed in a seated position (*STcog*). For the *DT*, participants were instructed to walk continuously without assistance for 1 min along a 10 m walkway (turning at the end each time) at their fastest speed. The fastest speed was chosen rather than a self-selected one as it was proven that the dual-task interference would be greater with increasing the difficulty of the gait task [35, 36]. The 2 first and 2 last steps, considered as acceleration and deceleration phases, were not included in the calculation. No instructions were given regarding which task to prioritize during the *DT* (walking or counting backward) as to not influence the behavior of the participant. At the end of each condition (*STcog*, *STmot*, *DT*), the participant was asked to rate the perceived fatigue the task has given to him/her, named

RPF) with a visual analog scale (VAS) from 0 (no fatigue) to 10 (maximal fatigue). The order of the conditions was randomized and was kept the same before and after the two fatigue protocols.

Mental fatigue protocol

Several mental fatigue protocols have been commonly used in the literature but many are above 60 min which is quite difficult to set up in geriatrics [24, 28]. Recently, a study used a *Psychomotor vigilance task* (PVT) as mental fatigue during 20 min. This task consists of pushing a button when a light turns on the screen. They showed that this task during at least 20 min was sufficient to ensure a mental fatigue [37]. Thus, the mental fatigue of the current study was inspired by the PVT. Participants were asked to visually fixate on a computer screen placed at eye level in front of them while two types of exercises rotated every 5 min during 25 min (exercise 1, 3 and 5 were the same). One of the two exercises was calculation and the participant needed to answer as fast as possible if the first equation was equal, smaller, or greater than the number on the right. The other exercise consisted of clicking to the button “enter” as fast as possible when a circle appears except if the color of the circle was green. Time between each circle varied between 2 and 5 s. The order of the exercises was randomly chosen. Performance over the protocol was registered through correct answers, errors, and reaction time for each exercise along the 25 min fatigue protocol. Immediately after the fatigue protocol, participants were asked to report their level of perceived fatigue on a scale of 1–10 (RPF), with higher numbers indicating greater feelings of fatigue.

Muscular fatigue protocol

After a warm-up of 5 min on an ergocycle (Xercise Cycle Med, Cardiowise®, Germany), participants were asked to perform an isometric maximal voluntary contraction

(MVC) of the knee extensor of the dominant leg on the Biodex dynamometer (Biodex Medical Systems Inc., X2151, Shirley, NY, USA). Immediately after the MVC, participants performed 30 sit-to stand (STS) weighted at 20% of the participant body weight that was proven to induce fatigue [38]. They repeated MVC and STS three times to reach a sufficient muscular fatigue. At the end of each STS, the RPF was also rated as for the mental fatigue. It is important to note that three frail participants were not able to sit and stand with the 20% charge, so they did the protocol only weighted at 10% of BW.

Data analysis

Spatio-temporal gait parameters were obtained with the Optogait system (Optogait, Microgate, Bolzano, Italy) [39]. For this study, a 10-m instrumented walkway was used, consisting of 10 transmission bars and 10 reception bars, with a separation of 120 cm. Each bar (100 cm × 8 cm) contains 96 lights emitters 3 mm from the ground. Optical sensors operate at a frequency of 1000 Hz, with accuracy of 1 cm, to detect spatiotemporal parameters. Finally, the dual-task effect (DTE), which represents a ratio of performance between ST and DT, was calculated for the 10 gait parameters and for the cognitive score (*DTEcog*) as proposed by Plummer et al. [35]:

$$DTE = \frac{(DT - ST)}{ST} \times 100.$$

For gait speed (*DTEmotor*), step length, stance and swing phase time, single support and cadence, negative values indicate that performance deteriorated under DT conditions (i.e., dual-task cost), and positive values represent an improvement in the DT condition relative to ST performance (i.e., dual-task benefit). However, for step length variability, double support, step time variability and speed variability, this is the opposite. The higher the positive value is (or the absolute value for the negative DTE), the higher the performance is deteriorated.

Statistical analysis

Data were tested from normality using Shapiro–Wilk test and from equality of variance with Levene’s test. Mental fatigue was verified through the evaluation of correct answers, errors and reaction time expressed in % of changes between each exercise (1vs3, 1vs5 and 2vs4) with the use of a 2 (TIME: 1vs3, 1vs5) *3(GROUP: Y, NF, F) nonparametric ANOVA (Kruskal–Wallis). Muscular fatigue was verified by applying a 3 (GROUP: Y, NF, F) *2 (TIME: 1vs2, 1vs3) ANOVA on the difference in MVC between each series of STS. The effect of muscular and

mental fatigue on spatiotemporal DTE parameters and *DTEcog* were analyzed using linear mixed models (LMM). For all DTE, normality was not assessed so a gamma regression was applied. The DTEs were translated to their minimal values to have all the DTE positives to be able to use the gamma regression. A random intercept effect structured by participants was included to control for the non-independence of the data and inter-subject variability. The LMM for the analysis of each variable included the level of frailty in the variable GROUP (non-frail (NF) vs. pre-frail (PF) vs. frail (F) participants), FATIGUE (muscular vs mental) and TIME (PRE vs POST fatigue). Also, a Fisher’s LSD correction for multiple comparison was applied and a Tukey’s HSD test was used for post-hoc analysis. LMMs were chosen as they can attain higher statistical power than ANOVA and can reduce type I-error because of the consideration of the sampling variability of both participants and experimental conditions [40, 41]. Statistical analysis was performed using SPSS (IBM Corp. (2015) IBM SPSS Statistics for Windows (V23) Armonk, NY).

Results

Questionnaire

The investigated score in MOCA indicated that the participants in each group were cognitively healthy even if the MOCA score was smaller in F compared to NF (Table 1) ($p = 0.008$). Findings regarding the IPAQ score suggested that Y were significantly more physically active than F ($p = 0.03$) as well as NF compared to F ($p = 0.03$) (Table 1). Also, F were more fatigued than NF or Y with a lower MFI score (Table 1). The MFI_1 score is not significantly different from the MFI_2 ($p = 0.414$, $d = 0.108$) which means that participants were at the same level of perceived fatigue before the two evaluations.

Mental fatigue

A slightly decrease in MVC of 1% was noticed after the mental fatigue and it was significantly different between groups ($F(2,46) = 3.8$, $p = 0.03$) with a higher decrease in MVC of 6% in Y group (Table 2). Concerning the perceived fatigue after the protocol, each groups had a RPF below 5 out of 10 (4.5 ± 1.9) with no significant difference between groups ($p = 0.081$). On average in the three groups, an increase in performance over the exercises was found with an increase in correct answers over the fatigue protocol (from 4.1% in 1 vs 3 to 19.6% in 1 vs

Table 1 Participant's characteristic (mean (SD))

	N=(59)	Y (n=20)	NF (n=20)	F (n=19)	ANOVA
Age (years)	60.2 (26)	24.9 (3)	75.8 (4.9)	81 (4.7)	
Height (cm)	167.4 (10)	172.7 (9)	166.4 (11.3)	162.9 (7)	
Weight (kg)	69.8 (11.7)	68.6 (10.1)	70.8 (13)	70 (12.4)	
MOCA (/30) ^a	26.4 (1.8)	27.2 (1.6)	26.3 (2)	25.6 (1.5)	$H(2)=7.9, p=0.019$
MFI_1 (/100)	75 (11.9)	81.6 (10.5)	78.2 (10.9)	65.5 (7.6)	$F(2.56)=12.3, p<0.01$
MFI_2 (/100)	73.5 (15)	80.2 (14.9)	74.1 (14.4)	66.2 (13.3)	$F(2.56)=4.44, p=0.016$
Score IPAQ ^a	1366.2 (1218.2)	1797.3 (1746.9)	1432.4 (832.1)	842.7 (573.7)	$H(2)=6.878, p=0.032$

The cognitive level score (MOCA), initial perceived fatigue in the first and second evaluation session (MFI_1 and MFI_2, respectively), the level of physical activity (IPAQ) are specified for young (Y), in frail (F) and non-frail (NF) participants.

ANOVA was made with the variable Group (Y, NF, F) as a fixed factor

^aNot normally distributed, a Kruskal Wallis test was performed

Table 2 Mean (SD) of the mental and muscular fatigue protocol and their parameters [maximal voluntary contraction (MVC), rate of perceived fatigue (RPF), correct answers, errors, reaction time expressed in % of change between the 1st and 3rd exercise (1 vs 3) or between the 1st and last exercise (1 vs 5)] in frail (F), non-frail (NF) and young (Y) adults

	Mental fatigue	N=59	Y (n=20)	NF (n=20)	F (n=19)
Pre protocol	MVC (N)	103.5 (39.8)	146.3 (31.2)	87.9 (17.5)	72.8 (20.8)
1 vs 3	Correct answers (%)	4.2 (47)	3.1 (27.7)	- 3.8 (27.7)	13.9 (73.7)
	Errors (%)	- 14.3 (78)	7.6 (90.2)	- 23 (67.2)	- 32 (70.6)
	Reaction time (%)	2.6 (39.3)	- 2 (17.2)	20.2 (51.3)	- 11 (36.4)
1 vs 5	Correct answers (%)	23 (46.8)	16.3 (22.3)	28.2 (39.3)	24.6 (69.4)
	Errors (%)	- 25.8 (69.6)	- 20.3 (78.6)	- 31.3 (67.6)	- 26.4 (63.4)
	Reaction time (%)	1.9 (59.5)	- 6.4 (16.3)	- 8 (22.3)	21.2 (100)
Post protocol	RPF	4.5 (1.9)	5.3 (1.9)	4.2 (2)	4 (1.6)
	MVC (%)	- 0.9 (10.8)	- 6.4 (8.6)	1.9 (12)	2.3 (9.9)
	MVC (N)	102.9 (39)	139.9 (35.6)	90.7 (20.3)	70.7 (15.5)
Muscular fatigue					
Pre protocol	MVC (N)	111.9 (43)	153.7 (37.8)	100.7 (27.5)	77.9 (18.1)
	RPF	6.4 (1.4)	5.2 (1.6)	6.8 (1.5)	7.3 (0.9)
1 vs 2	MVC (%)	- 1.4 (9.1)	- 3 (10.5)	- 1 (10.4)	- 0.00 (5.2)
	RPF (%)	17.2 (15.4)	24.7 (17.3)	13.5 (16.4)	13.1 (8.7)
1 vs 3	MVC (%)	- 6.5 (15.9)	- 6.2 (7.4)	- 10.9 (24.5)	- 1.5 (7.6)
	RPF (%)	34.6 (32.2)	55.5 (28.4)	24.2 (38.2)	23.5 (14.8)
Post protocol	RPF (/10)	5 (1.7)	5.6 (2.1)	4.5 (1.6)	4.8 (1.2)
	MVC (N)	102.1 (39.4)	140.9 (36)	90.8 (21.2)	71.9 (16.2)

5, $H(1)=5.673, p=0.017$), a decrease (not significant) in the number of errors (from 15.8% between the 3rd and 1st exercise to 14.1% between the 5th and 1st) and a decrease in reaction time (from 4% in 3 vs 1 to 13.9% in 5 vs 1).

Muscular fatigue

A significant 6% decrease in MVC ($p<0.001$) occurred after the last series of MVC with a significant increase of 34.5% in RPF averaged over groups ($H(1)=41.595, p<0.001$). The decrease in MVC and increase in MVC was less showed in F group (Table 2).

Cognitive-motor interference (DTEcog and DTEmotor)

The order of the protocols (muscular or mental fatigue) and the order of *STcog*, *STmot* and *DT* inside each protocol did not significantly impact the DTE parameters ($p>0.05$). For cognitive performance (*DTEcog*), a significant effect of FATIGUE was found ($F(1.70)=4.398, p=0.04$). Specifically, *DTEcog* was higher during the muscular fatigue protocol than the mental fatigue. For speed (*DTEmotor*), the analysis showed a significant effect of GROUP ($F(2.223)=14.982, p<0.001$) and Time ($F(1.223)=4.231, p=0.041$). More specifically, DTE was lower in PRE fatigue than in POST ($p=0.042$).

Gait analysis

Single support (%), double support (%) stride length, stride length variability and step time variability were not included in the LMM as they were highly correlated to single support (s), double support (s), step length and cadence, respectively ($R > 0.8$, $p < 0.05$). All the DTE (mean and SD) for the three groups (F, NF, Y) are shown in Table 3. For step length (DTE_{step_length}), a significant effect of GROUP ($F(2.223) = 6.114$, $p = 0.003$) with a significant higher DTE in F compared to Y ($p = 0.004$) as well as in NF compared to Y ($p = 0.003$) was found. Concerning step length variability ($DTE_{step_length_var}$), only a significant effect of GROUP ($F(2.223) = 5.013$, $p = 0.007$) was found. Specifically, only F had higher significant DTE than Y ($p = 0.003$). For stance time (DTE_{stance_time}), the LMM showed only a significant effect of GROUP ($F(2.223) = 30.002$, $p < 0.001$). Specifically, F had higher DTE than T ($p < 0.001$) as well as NF compared to Y ($p < 0.001$) (Fig. 2). In swing time (DTE_{swing_time}), a significant effect of GROUP ($F(2.223) = 3.799$, $p = 0.024$), TIME ($F(1.223) = 4.932$, $p = 0.027$), FATIGUE ($F(1.223) = 6.353$, $p = 0.012$) and the interaction GROUP \times FATIGUE ($F(2.223) = 5.619$, $p = 0.004$) were highlighted. Concerning single support time ($DTE_{single_support_time}$), a significant effect of GROUP

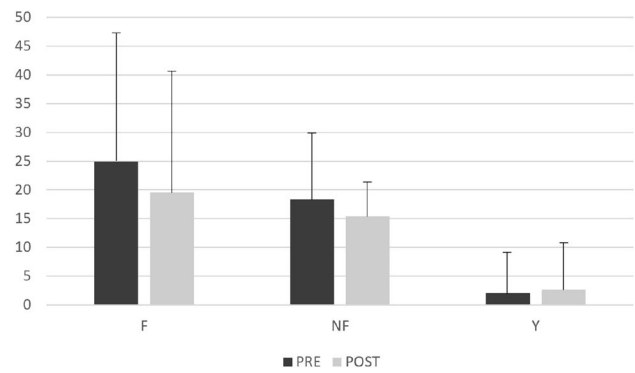


Fig. 2 Mean (SD) DTE_{stance_time} in frail (F) older adults, non-frail (NF) older adults and young participants (Y) before (PRE) and after (POST) fatigue (mental + muscular fatigue)

($F(2.223) = 4.526$, $p = 0.012$), TIME ($F(1.223) = 6.62$, $p = 0.011$) and FATIGUE ($F(1.223) = 13.498$, $p < 0.001$) were found as well as the interaction GROUP \times FATIGUE ($F(2.223) = 5.619$, $p = 0.004$). For double support time ($DTE_{double_support_time}$), only the effect of GROUP was significant ($F(2.222) = 3.466$, $p = 0.033$). Specifically, F had significant higher DTE than Y ($p = 0.032$) as well as NF compared to Y ($p = 0.02$). Concerning speed variability (DTE_{speed_var}), the only significant effect was for

Table 3 Mean (SD) of the DTE in each spatio-temporal parameters before and after the mental and muscular fatigue

Muscular fatigue	Y		NF		F	
	Pre	Post	Pre	Post	Pre	Post
DTE_{step_length}	- 3.1 (3.5)	- 2.9 (3.6)	- 8.6 (4.5)	- 9 (5.2)	- 7.3 (11.2)	- 7.7 (10.3)
$DTE_{step_length_var}$	0.46 (61.5)	7.8 (56.5)	31.2 (90.2)	33.4 (121)	47.6 (85.9)	47.6 (60.3)
DTE_{stance_time}	2.2 (7.3)	2.6 (7.5)	16.7 (9.8)	15.8 (6.8)	23.9 (19.9)	18.6 (15.8)
DTE_{swing_time}	2.8* (3.9)	3.6* (3.9)	11.6* (8.7)	9.4* (4.7)	11.1* (20)	10.2* (19.3)
$DTE_{single_support_time}$	2.8* (4)	3.6 (4)	11.3* (8.2)	9.4 (4.7)	12* (18.9)	8.4 (14.8)
$DTE_{double_support_time}$	22.1 (26.5)	26.6 (30.5)	38.6 (22.4)	40 (21.2)	38.2 (34.3)	38.3 (37.3)
DTE_{motor}	- 6.3 (6.7)	- 7.2 (7.1)	- 19.5 (8)	- 18.8 (6.8)	- 21.1 (12)	- 19.7 (12.1)
DTE_{speed_var}	0.42 (62.8)	25.6 (117.7)	115.6 (261.3)	33.3 (91.5)	89.1 (102.3)	117.9 (129)
$DTE_{cadence}$	- 3.1 (4.7)	- 4.5 (5.3)	- 11.4 (6.2)	- 10.9 (4.5)	- 13.3 (10.4)	- 12.3 (8.8)
DTE_{cog}	- 4.2 (135)	29.8 (131.2)	169.8 (550)	174 (376.5)	- 3 (65.5)	130 (417.4)
Mental fatigue						
DTE_{step_length}	- 3.3 (3.2)	- 2.8 (2.6)	- 10.3 (5.3)	- 7.8 (4.8)	- 7.5 (8.3)	- 7.6 (9.3)
$DTE_{step_length_var}$	- 12.8 (30)	5.8 (91.9)	28.7 (81.7)	28 (97.3)	74.7 (98.3)	66.6 (94.4)
DTE_{stance_time}	2 (7.9)	2.7 (8.6)	20 (13)	15 (5.7)	26 (25.3)	20.6 (25.7)
DTE_{swing_time}	5.5 (4.4)	4.7 (5.8)	12.5 (11.7)	8.7 (4.9)	22.7 (29.4)	13.6 (30.8)
$DTE_{single_support_time}$	5.6 (4.4)	4.6 (5.6)	12.7 (11.1)	8.7 (4.8)	24.1 (33)	17.5 (31.8)
$DTE_{double_support_time}$	20.4 (23.9)	35.3 (33)	45.6 (23.8)	36.3 (16.6)	45.2 (33.3)	44.9 (37.3)
DTE_{motor}	- 8.7 (5.1)	- 7.9 (6.1)	- 21.8 (8)	- 17.2 (6.7)	- 24.7 (11.8)	- 23.3 (9.5)
DTE_{speed_var}	- 17.4 (29.2)	- 12.6 (58.6)	65.4 (142.1)	70.7 (150.3)	108.9 (128)	106.8 (96.2)
$DTE_{cadence}$	- 5.4 (4.2)	- 4.7 (4.9)	- 12.8 (7.4)	- 10.1 (4.6)	- 16.6 (11)	- 14.7 (10.5)
DTE_{cog}	- 10.3 (32.8)	- 12.9 (98.8)	- 23.4 (176.9)	- 17.6 (97.5)	- 31 (90.5)	- 33.9 (65.2)

The DTE are shown for the three groups [young (Y), non-frail (NF) and frail (F) older adults]

GROUP ($F(2.223) = 11.306, p < 0.001$). Concerning cadence ($DTE_{cadence}$), the analysis showed a significant effect of GROUP ($F(2.223) = 11.069, p < 0.001$) and FATIGUE ($F(1.223) = 5.310, p = 0.022$). Specifically, F had lower DTE than Y ($p < 0.001$) as well as NF compared to Y ($p = 0.005$). Also, DTE was higher during the muscular fatigue protocol than the mental fatigue one when grouping F, NF and Y all together ($p = 0.022$).

Discussion

The aim of the present study was to determine the effect of a mental and muscular fatigue on spatiotemporal gait parameters in dual task walking in young, non-frail and frail older adults. We hypothesized that the three groups would show worse DTE in spatio-temporal parameters especially DTE_{motor} and would have worse cognitive performance (DTE_{cog}) after the muscular and mental fatigue. We expected the impact of muscular and mental fatigue on DTE to be greater with age and particularly in the frail group. The results of the present study confirm partly this hypothesis, showing that the DTE in walking parameters were worse in F compared to NF or Y groups but that they were not different after fatigue except for swing time and single support time DTE.

First, one of the most important questions before studying the effect of mental fatigue on physical performance is whether fatigue was successfully induced. Concerning mental fatigue, a low self-reported state of fatigue with the RPF in each group was reported as well as a little decrease in MVC suggesting that the protocol did not induce mental fatigue in the groups. Other studies also reported that the mental fatigue protocol did not seem to exert an effect on either the subjective (RPF) or objective indexes of performance [24, 42]. However, as the mental fatigue has subjective, behavioral and physiological manifestations, the criterion for whether the mental fatigue was well induced is highly debatable [24]. A similar fatigue protocol (a 20 min PVT) induced in young and old participants found that ratings of perceived fatigue (RPF) were significantly higher ($p < 0.001$) after the mental fatigue than ratings at baseline [37]. Unfortunately, the RPF baseline was not measured here which prevents comparison with Morris et al., but it is interesting to see that the 6% decrease in young's MVC is similar to the one of Morris et al. (7% decrease in young too) [37]. Concerning muscular fatigue, the participants were well fatigued as the RPFs were significantly higher ($p < 0.001$) after the fatigue than ratings at baseline in each group, and the MVC significantly decreased through the series of STS especially in Y and NF. However, in the F group, their decrease in MVC were of 1.5% only with a 23.5% increase in RPF which is significantly less than F or NF ($p < 0.05$). This does not necessarily reflect that F were less fatigued

than NF or Y but with aging, the perception of fatigue is affected and an acclimation period is needed to accurately use the RPF [43]. Also, it is well known that, with aging, the ratio slow twitch/fast twitch fibers increased [44], and, as the slow-twitch fibers exhibit good endurance characteristic, muscular endurance is maintained with increased age and may even improve [45].

When focusing on the principal question, which was the effect of the mental and muscular fatigue on the different spatio-temporal DTE during walking, the fatigue did not strongly alter the dual-task walking parameters not cognitive performance (DTE_{cog}). In other words, the effect TIME (pre vs post) was not significant except for DTE_{swing_time} and $DTE_{single_support_time}$ where the DTEs were lower after the fatigue. As the DTEs were positive, before and after fatigue, it means that the participants walked with greater swing time and single support time in DT compared to ST. The decrease in DTE after fatigue means that the difference between DT and ST is reduced. Consequently, both mental and muscular fatigue reduced the difference between ST and DT. Also, swing time and single support time are known to decrease with age which may give the older adults a sense of better walking stability [46]. As the DTE values were positive, it means that, during dual tasking, the need to decrease these parameters for a more cautious gait are inhibited. Moreover, as the DTE value decreased after fatigue, the fatigue protocol reduced this effect of inhibition in dual-tasking as their dual-task walking parameters are closer to their single-task one. These findings are shared with previous studies that found an improvement in walking after fatigue and even more in older adults [17, 47]. Indeed, an increase in stride length and a decrease in stride duration with fatigue caused an increase in gait speed which was even greater in older adults [17, 47]. Walking faster with longer strides length was hypothesized to be a strategy of the older adults to overcome the short walking distance (10 m) and the feeling of physical discomfort (due to the muscle fatigue) [47]. Also, no significant effect of FATIGUE \times TIME was revealed which means that no significant difference in the effect of fatigue on dual task walking strategy between mental or muscular fatigue was highlighted.

Concerning the comparison between the groups, F had their walking parameters more impacted during dual tasking than NF or Y groups. This has been showed through the significant GROUP effect for all spatio-temporal parameters. This is in line with previous studies that highlighted an age-related effect on DTE spatio-temporal parameters [10, 48]. This age-related decrements in DT can be associated to age-related brain modifications that could be structural (E.G loss of the frontal gray matter) [49] or functional (e.g. loss of central neurons). Moreover, with aging, some cognitive functions that are involved in dual-tasking declined such as processing speed [50], working memory [51] or executive

functions [52]. The CRUNCH (Compensation Utilization Of Neural Circuits Hypothesis) model [53] explained that, for reasonable difficulty levels, older adults are able to compensate their cognitive declines but, for high demanding tasks, older adults cannot compensate anymore because of their low level of cognitive resources leading to a decline in performance. Surprisingly, the interaction $\text{GROUP} \times \text{TIME}$ or $\text{GROUP} \times \text{TIME} \times \text{FATIGUE}$ was not significant. In other words, the behavior in DT and the effect of DT on walking performance after fatigue is not significantly different between Y, NF, or F groups. Only a few studies focused on the effect of mental or muscular fatigue on dual-task walking parameters but Behrens et al. [28] also found no significant TIME (pre, post) \times GROUP (young, old) \times FATIGUE (mental, control) interaction between 16 young and 16 old adults. For muscle fatigue, Granacher et al. [17] highlighted that muscle fatigue did not alter the DTE parameters in young and old adults but when looking to the single or dual-task walking parameters alone, they found that fatigue resulted in significant decreases in single-task gait velocity and stride length in young adults, and in significant increases in dual-task gait velocity and stride length in older adults [17]. The high variability in DTE could partially explained why the results are not significant. Also, the lack of studies in this field did not allow much more comparison. Maybe, older adults may have learned how to compensate for age-related and/or fatigue-induced muscle and cognitive deficits leading to similar dual-task effect (DTE) after fatigue.

Some limitations of this study should be mentioned. First, the age difference between NF (75.8 ± 4.9 years old) and F (81 ± 4.7 years old) group could have influenced the results. Indeed, it has previously been shown that spatio-temporal DTE were influenced by age and that, between the 7th decade (70–75 years old) and the 9th (> 80 years old), the DTE are different [10], fatigue and fatigability also differed [54] as well as neuromuscular structure and function (i.e. loss of muscle change, change in muscle fibers' type, loss of motor units (MUs)...) [55]. Consequently, comparison between NF and F should be made carefully as the results could not only be due to the level of frailty but also to their age-related difference. Also, recent studies have shown that DT performance can depend on training and assimilation [56]. It is, thus, important to mention that a learning effect of cognitive and motor tasks could have influenced the results. While the randomization of ST and DT tasks and the order of the fatigue protocols and the setting up of a learning session (counting backwards by three while being seated during 2 mn) before each session were designed to limit and reduce this learning effect, this effect should be considered.

Conclusion

The results of this study demonstrated that the spatio-temporal DTE parameters were more altered in F compared to NF or Y groups but that they were not significantly different after fatigue except for swing time and single support time. This study introduces the possible use of dual-task walking for a better screening of frailty, but more investigations should be made in the efficiency of inducing a fatigue before a dual-task clinical program to better distinguish frailty.

Author contributions All authors contributed to the study design and conception. Material preparation, data collection and analysis were performed by EP and AJ. The first draft of the manuscript was written by EP and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding No funding was received for conducting this study.

Declarations

Conflict of interest The authors have no relevant conflict of interest to disclose.

Ethical approval The study was approved by the CPP (Comité de Protection des Personnes) under the number 2021-A00016-35. All procedures performed in studies involving human participants were in accordance with ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent All the participants signed an informed consent regarding publishing their data and photographs.

References

1. Camicioli R, Howieson DB, Marquis S et al (2003) Independent predictors of cognitive decline in the healthy elderly. *Res Pract Alzheimers Dis* 7:86–92
2. Woollacott M, Shumway-Cook A (2002) Attention and the control of posture and gait: a review of an emerging area of research. *Gait Posture* 16:1–14
3. Yogeve-Seligmann G, Hausdorff JM, Giladi N (2008) The role of executive function and attention in gait. *Mov Disord* 23:329–342
4. Hedden T, Gabrieli JDE (2004) Insights into the ageing mind: a view from cognitive neuroscience. *Nat Rev Neurosci* 5:87–96
5. Wollesen B, Voelcker-Rehage C (2019) Differences in cognitive-motor interference in older adults while walking and performing a visual-verbal stroop task. *Front Aging Neurosci* 11:1–12
6. Fallahtafti F, Boron JB, Venema DM et al (2021) Task specificity impacts dual-task interference in older adults. *Aging Clin Exp Res* 33:581–587
7. Bayot M, Dujardin K, Dissaux L et al (2020) Can dual-task paradigms predict Falls better than single task? A systematic literature review. *Neurophysiol Clin* 50:401–440
8. Beauchet O, Dubost V, Allali G et al (2007) 'Faster counting while walking' as a predictor of falls in older adults. *Age Ageing* 36:418–423

9. Superiore S, Anna S. Alzheimer's & Dementia : The Journal of the Alzheimer ' s Association Innovative Motor Cognitive Dual-Task approaches combining upper and lower limbs may improve dementia early detection
10. Piche E, Chorin F, Gerus P et al (2022) Effects of age, sex, frailty and falls on cognitive and motor performance during dual-task walking in older adults. *Exp Gerontol* 171:112022
11. Fried LP, Tangen CM, Walston J et al (2001) Frailty in older adults: evidence for a phenotype. *J Gerontol Ser A Biol Sci Med Sci* 56:M146–M157
12. Gandevia SC, Allen GM, Butler JE et al (1996) Supraspinal factors in human muscle fatigue: Evidence for suboptimal output from the motor cortex. *J Physiol* 490:529–536
13. Enoka RM, Stuart DG (1992) Neurobiology of muscle fatigue. *J Appl Physiol* 72:1631–1648
14. Abd-Elfattah HM, Abdelazeim FH, Elshennawy S (2015) Physical and cognitive consequences of fatigue: a review. *J Adv Res* 6:351–358
15. Helbostad JL, Leirfall S, Moe-nilssen R et al (2007) *Older Persons* 62:235–236
16. Dos Santos PCR, Barbieri FA, Zijdwind I et al (2019) Effects of experimentally induced fatigue on healthy older adults' gait: a systematic review. *PLoS ONE* 14:1–14
17. Granacher U, Wolf I, Wehrle A et al (2010) Effects of muscle fatigue on gait characteristics under single and dual-task conditions in young and older adults. *J Neuroeng Rehabil* 7:1–12
18. Kao PC, Pierro MA, Booras K (2018) Effects of motor fatigue on walking stability and variability during concurrent cognitive challenges. *PLoS ONE* 13:1–14
19. Cesari M, Leeuwenburgh C, Lauretani F et al (2006) Frailty syndrome and skeletal muscle: Results from the Invecchiare in Chianti study. *Am J Clin Nutr* 83:1142–1148
20. Ferrucci L, Guralnik AJM, Studenski S et al (2004) Delaying functional decline and disability in frail, older persons: a consensus report. *Jags* 52:625–634
21. Theou O, Jones GR, Overend TJ et al (2008) An exploration of the association between frailty and muscle fatigue. *Appl Physiol Nutr Metab* 33:651–665
22. Boksem MAS, Meijman TF, Lorist MM (2005) Effects of mental fatigue on attention: an ERP study. *Cogn Brain Res* 25:107–116
23. Wascher E, Rasch B, Sanger J et al (2014) Frontal theta activity reflects distinct aspects of mental fatigue. *Biol Psychol* 96:57–65
24. Van Cutsem J, Marcora S, De Pauw K et al (2017) The effects of mental fatigue on physical performance: a systematic review. *Sport Med* 47:1569–1588
25. Lorist MM, Boksem MAS, Ridderinkhof KR (2005) Impaired cognitive control and reduced cingulate activity during mental fatigue. *Cogn Brain Res* 24:199–205
26. Arnau S, Mockel T, Rinkenauer G et al (2017) The interconnection of mental fatigue and aging: an EEG study. *Int J Psychophysiol* 117:17–25
27. Allali G, Montembeault M, Simona MB et al (2019) Brain structure covariance associated with gait control in aging. *J Gerontol A Biol Sci Med Sci* 74:705–713
28. Behrens M, Mau-Moeller A, Lischke A et al (2018) Mental fatigue increases gait variability during dual-task walking in old adults. *J Gerontol Ser A Biol Sci Med Sci* 73:792–797
29. Mortaza N, Osman NAA, Mehdikhani N (2014) Are the spatio-temporal parameters of gait capable of distinguishing a faller from a non-faller elderly? *Eur J Phys Rehabil Med* 50:677–691
30. Kim Y, Park I, Kang M (2013) Convergent validity of the International Physical Activity Questionnaire (IPAQ): meta-analysis. *Public Health Nutr* 16:440–452
31. Srygley JM, Mirelman A, Herman T (2009) When does walking alter thinking? Age and task associated findings. *Brain Res* 1253:92–99
32. Ehsani H, Mohler MJ, O'connor K et al (2019) The association between cognition and dual-tasking among older adults: the effect of motor function type and cognition task difficulty. *Clin Interv Aging* 14:659–669
33. Smith E, Cusack T, Blake C (2016) The effect of a dual task on gait speed in community dwelling older adults: a systematic review and meta-analysis. *Gait Posture* 44:250–258
34. Piche E, Gerus P, Chorin F et al (2022) The effect of different dual tasks conditions on gait kinematics and spatio-temporal walking parameters in older adults. *Gait Posture* 95:63–69
35. Plummer-D'Aamato P, Brancato B, Dantowitz M et al (2012) Effects of gait and cognitive task difficulty on cognitive-motor interference in aging. *J Aging Res* 2012:1–8
36. 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
37. Morris AJ, Christie AD (2020) The effect of mental fatigue on neuromuscular function is similar in young and older women. *Brain Sci* 10:191
38. Hatton AL, Menant JC, Lord SR et al (2013) The effect of lower limb muscle fatigue on obstacle negotiation during walking in older adults. *Gait Posture* 37:506–510
39. Lienhard K, Schneider D, Maffiuletti NA (2013) Validity of the Optogait photoelectric system for the assessment of spatiotemporal gait parameters. *Med Eng Phys* 35:500–504
40. Boisgontier MP, Cheval B (2016) The anova to mixed model transition. *Neurosci Biobehav Rev* 68:1004–1005
41. Ma Y, Mazumdar M, Memtsoudis SG (2012) Beyond repeated-measures analysis of variance: advanced statistical methods for the analysis of longitudinal data in anesthesia research. *Reg Anesth Pain Med* 37:99–105
42. Holgado D, Troya E, Perales JC et al (2021) Does mental fatigue impair physical performance? A replication study. *Eur J Sport Sci* 21:762–770
43. Gros Lambert A, Mahon AD (2006) Perceived exertion: influence of age and cognitive development. *Sport Med* 36:911–928
44. Lexell J, Taylor CC, Sjostrom M (1988) What is the cause of the ageing atrophy?. Total number, size and proportion of different fiber types studied in whole vastus lateralis muscle from 15- to 83-year-old men. *J Neurol Sci* 84:275–294
45. Bembem MG (1998) Age-related alterations in muscular endurance. *Sport Med* 25:259–269
46. Afiah IN, Nakashima H, Loh PY et al (2016) An exploratory investigation of changes in gait parameters with age in elderly Japanese women. *Springerplus* 5:1069
47. Barbieri FA, dos Santos PCR, Simieli L et al (2014) Interactions of age and leg muscle fatigue on unobstructed walking and obstacle crossing. *Gait Posture* 39:985–990
48. Lama B, Daniel VKP, Desai P (2018) Impact of dual task performance on fear of fall and gait parameters in elderly. *Int J Physiother Res* 6:2891–2896
49. Beurskens R, Bock O (2012) Age-related deficits of dual-task walking: a review. *Neural Plast* 2012:131608
50. Salthouse TA (1996) The processing-speed theory of adult age differences in cognition. *Psychol Rev* 103:403–428
51. Salthouse TA, Babcock RL (1991) Decomposing adult age differences in working memory. *Dev Psychol* 27:763–776
52. Murman DL (2015) The impact of age on cognition. *Semin Hear* 36:111–121
53. Carp J, Gmeindl L, Reuter-Lorenz PA (2010) Age differences in the neural representation of working memory revealed by multi-voxel pattern analysis. *Front Hum Neurosci* 4:1–10
54. Eldadah BA (2010) Fatigue and fatigability in older adults. *PM R* 2:406–413
55. Power GA, Dalton BH, Rice CL (2013) Human neuromuscular structure and function in old age: a brief review. *J Sport Health Sci* 2:215–226

56. Ruthruff E, Van Selst M, Johnston JC et al (2006) How does practice reduce dual-task interference: integration, automatization, or just stage-shortening? *Psychol Res* 70:125–142

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.