



HAL
open science

Impact of Overweight on Spatial–Temporal Gait Parameters During Obstacle Crossing in Young Adults: A Cross-Sectional Study

Matthias Chardon, Fabio Augusto Barbieri, Clint Hansen, Pascal Petit,
Nicolas Vuillerme

► **To cite this version:**

Matthias Chardon, Fabio Augusto Barbieri, Clint Hansen, Pascal Petit, Nicolas Vuillerme. Impact of Overweight on Spatial–Temporal Gait Parameters During Obstacle Crossing in Young Adults: A Cross-Sectional Study. *Sensors*, 2024, 24 (23), pp.7867. 10.3390/s24237867 . hal-04844215

HAL Id: hal-04844215

<https://hal.science/hal-04844215v1>

Submitted on 17 Dec 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.



Distributed under a Creative Commons Attribution 4.0 International License

Article

Impact of Overweight on Spatial–Temporal Gait Parameters During Obstacle Crossing in Young Adults: A Cross-Sectional Study

Matthias Chardon ^{1,2}, Fabio Augusto Barbieri ^{2,*}, Clint Hansen ^{1,3}, Pascal Petit ¹ and Nicolas Vuillerme ^{1,4,*}

¹ AGEIS, Université Grenoble Alpes, 38000 Grenoble, France; matthias.chardon@univ-grenoble-alpes.fr (M.C.); c.hansen@neurologie.uni-kiel.de (C.H.); pascal.petit@univ-grenoble-alpes.fr (P.P.)

² Human Movement Research Laboratory (MOVI-LAB), Department of Physical Education, São Paulo State University (UNESP), Bauru 17011180, SP, Brazil

³ Department of Neurology, Kiel University, 24105 Kiel, Germany

⁴ Institut Universitaire de France, 75005 Paris, France

* Correspondence: fabio.barbieri@unesp.br (F.A.B.); nicolas.vuillerme@univ-grenoble-alpes.fr (N.V.)

Abstract: Background: Overweight may present an additional challenge when crossing obstacles. More specifically it may affect adequate foot clearance to reduce the risk of obstacle contact. Thus, the objective of this study was to compare obstacle clearance and spatial–temporal gait parameters during obstacle crossing in young adults with normal body weight and overweight. **Methods:** Twenty-eight and fifteen individuals were categorized into normal body mass index (18.5–25 kg/m²) and overweight (25–30 kg/m²), respectively. The participants walked along a walkway at their preferred speed and stepped over an obstacle. Spatial–temporal parameters were calculated during the approaching (stride before obstacle) and the crossing (step over the obstacle) phases. Additionally, the leading and trailing foot placements prior to and after the obstacle and toe clearance were calculated. **Results:** No significant differences were found for the approach, the crossing phases and leading and trailing toe clearance. Analysis of foot placement distance prior to and after the obstacle showed that, compared to the individuals with normal body weight, overweight individuals significantly increased the leading foot placement distance prior to the obstacle (+7 cm, ↑ 6.7%) and increased the trailing foot placement distance after the obstacle (+8.1 cm, ↑ 9%). **Conclusions:** Our findings indicated that overweight individuals have a different obstacle crossing behavior regarding foot placement distance prior to and after the obstacle compared to normal-weight individuals without differences in spatial–temporal gait parameters or toe clearances. However, the results did not suggest that participants with overweight show a higher risk of tripping.

Keywords: overweight; obstacle crossing; gait; clearance



Citation: Chardon, M.; Barbieri, F.A.; Hansen, C.; Petit, P.; Vuillerme, N. Impact of Overweight on Spatial–Temporal Gait Parameters During Obstacle Crossing in Young Adults: A Cross-Sectional Study. *Sensors* **2024**, *24*, 7867. <https://doi.org/10.3390/s24237867>

Academic Editor: Giovanni Saggio

Received: 23 October 2024

Revised: 4 December 2024

Accepted: 5 December 2024

Published: 9 December 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Overweight and obesity have become a significant problem worldwide, with the obesity prevalence having nearly tripled in the last 50 years [1]. The body mass index (BMI) is commonly used to assess overweight (BMI between 25 and 29.9 kg/m²) and obesity (BMI ≥ 30 kg/m²). Overweight and obesity impose functional limitations by the additional loading of the increased body mass to the locomotor system, resulting in gait alterations and aberrant mechanism in posture and balance [2–8]. Although the question of whether and how overweight and obesity could affect gait during unobstructed walking in adults has received a large interest in the past few decades (for recent reviews, see [9–11]), not much is reported about how overweight and obesity could impact gait under more challenging conditions, such as crossing an obstacle while walking. However, it is probable that excess body weight may present an additional challenge when crossing obstacles and ensuring adequate foot clearance. A systematic review on the influence of overweight and obesity

on obstacle crossing performance [12] identified a small number of published studies that have specifically compared obstacle crossing during walking in obese or overweight adults to those with normal body weight ($n = 3$) [13–15]. Despite this small number of published studies and their heterogeneity, the results of this review suggested that overweight and obesity significantly impacted gait patterns during obstacle crossing in adults.

Compared to normal-body-weight adults, overweight or obese adults exhibit lower velocity [13,15], shorter step length, lower cadence, larger step width, less time spent in single-limb support, more time spent in double support [13] and a reduced swing time (as a percentage of the gait cycle) [15] during obstacle crossing. At this point, however, the three studies that investigated the effects of overweight or obesity on gait behavior during obstacle crossing have certain limitations; we were particularly concerned about two of them.

First, none of the studies examined the distance from the foot to the obstacle, which is called “horizontal and vertical foot–obstacle clearance distances” or “toe/heel clearance”. These parameters are usually considered as a critical parameter in a variety of obstacle crossing tasks (e.g., for reviews, see [16,17]). More largely, it is further recognized that since the foot clearance is the safety margin in the obstacle crossing task, decreasing the clearance might lead to a higher risk of tripping over an obstacle (e.g., [18–20]). In addition, foot placement prior to and after the obstacles may be fundamental, since errors may result in a misstep [21]. An optimal foot placement to the obstacle allows enough time to flex the limb and clear the obstacle [21], especially when body limitations are present as in obesity.

Second, none of the above-mentioned studies specifically compared obstacle crossing during walking between normal-body-weight (BMI of 18.5–24.9 kg/m²) vs. overweight individuals (BMI of 25.0–29.9 kg/m²). Therefore, potential differences in obstacle clearance and spatial–temporal gait parameters during obstacle crossing among overweight individuals remain unknown, even though differences compared to normal-weight individuals have been demonstrated during flat-ground walking [22].

Silva et al. (2017) [14] and Desrochers et al. (2021) [13] compared a group of normal-body-weight participants to a group of obese participants (BMI ≥ 27 [14] or 30 kg/m² [13]), which according to the WHO classification combines both overweight and obese individuals (mean BMI: 29.9 ± 2.5 kg/m²) [23]. Gill (2019) [15] included the so-called “Overweight/Class I obesity” group (BMI of 25–34.9 kg/m²) that hence brought together overweight individuals (BMI of 25.0–29.9 kg/m²) and obese individuals (BMI of 30.0–34.9 kg/m²). All of the studies highlighted group differences in the spatial–temporal parameters when comparing the overweight and normal-body-weight participants.

Consequently, the aim of the present study is to compare obstacle clearance and spatial–temporal gait parameters during an obstacle crossing task in normal-body-weight and overweight young adults. We hypothesized that overweight impacts gait behavior during obstacle crossing, particularly on obstacle clearance parameters by reducing foot clearances, which might lead to an increased risk of tripping.

2. Materials and Methods

This study is a secondary analysis of previous studies performing obstacle crossing tasks [24–26]. Data from forty-three participants in these studies were analyzed. Only healthy participants aged 20–39 years were included in this analysis [24], specifically those in the healthy control group, excluding participants with multiple sclerosis [25,26]. No new data were collected for this specific analysis.

2.1. Participants

Based on the classifications for BMI recommended by the World Health Organization (WHO) [27], the 43 participants were categorized into two groups of (1) 28 (65%) individuals with normal body weight (BMI of 18.5 to <24.9 kg/m²) and (2) 15 (35%) overweight individuals (BMI of 25 to <29.9 kg/m²). Apart from their weight status, participants were considered healthy (i.e., no participant with multiple sclerosis was included). The sub-

jects were informed about the experimental procedures (University Institution Review Board CAAE#99191318.0.0000.5398) and signed informed consent forms. Also, the experiment was performed in accordance with the Declaration of Helsinki and Brazilian ethical regulations.

2.2. Obstacle Crossing Task

Participants were instructed to walk barefoot at a self-selected speed along a 8.5 m long * 1.5 m [25] or 3.5 m [26] wide wooden pathway and to step over an obstacle (height = 15 cm, width = 80 cm, thickness = 2 cm, foam material [25]) without making contact, positioned in the middle of the pathway. The pathway was covered with a 3 mm thick black rubber carpet [24]. Three trials were performed. The starting point of each trial was adjusted to ensure that the obstacle was crossed with the right leg as the leading limb and that two strides were completed prior to the obstacle crossing.

2.3. Data Collection

Kinematic data were captured using a system of ten infrared cameras (Vicon Motion System[®], Oxford, UK, 200 Hz). Two markers were attached at the top of the obstacle. Additional markers were positioned as follows: on the lateral aspect of the calcaneus and the head of the second metatarsus of the right limb, and on the medial aspect of the calcaneus and the head of the second metatarsus of the left limb. The limbs were conventionally labeled: the leading foot was defined as the first to cross the obstacle, and the trailing foot as the second. Gait signals were processed using a fifth-order low-pass Butterworth filter (6 Hz, zero-lag).

Figure 1 illustrates the obstacle clearance outcomes evaluated. The following parameters were analyzed:

- Spatial-temporal gait parameters: stride length, width, duration, velocity and double-support time during the approach phase (stride before the obstacle) and the crossing phase (step over the obstacle);
- Leading and trailing foot placement prior to the obstacle (horizontal distance of the leading and trailing foot from the second metatarsal marker to the obstacle prior to crossing);
- Leading and trailing vertical toe foot clearance during obstacle crossing (vertical distance of the second metatarsal marker from the top of the obstacle for the leading and trailing foot during crossing);
- Leading and trailing foot placement after the obstacle (horizontal distance of the leading and trailing foot from the heel marker to the obstacle after crossing).

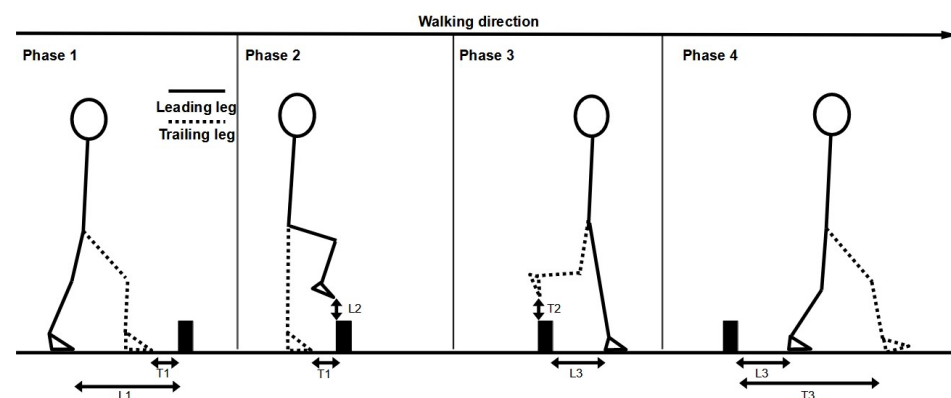


Figure 1. Description of the different phases of the obstacle crossing task and the obstacle clearance parameters. L1: leading foot horizontal distance prior to the obstacle (cm); L2: leading foot toe clearance (vertical distance between the foot marker and the obstacle) (cm); L3: leading foot horizontal distance after the obstacle (cm); T1: trailing foot horizontal distance prior to the obstacle (cm); T2: trailing foot toe clearance (cm); T3: trailing foot horizontal distance after the obstacle (cm).

2.4. Statistical Analysis

All statistical analyses were performed using R software 4.2.2[®] (R Core Team, Vienna, Austria) for Windows 10©. Vargha and Delaney's A (VDA) was calculated using the effect size package [28]. For each participant, the mean trial value of each gait parameter was used. In a previous analysis, we demonstrated that gait and clearance parameters were reliable across three trials [29]. In addition, for data analysis, previous studies commonly used the mean of the three trials of gait outcomes in obstacle crossing tasks [30–34].

Due to skewed, non-normal or multimodal distributions, the outcomes were evaluated with nonparametric methods [35]. The Wilcoxon–Mann–Whitney rank sum test was used to test whether there were differences in socio-demographics, anthropometrics and gait parameters between the two groups. The Wilcoxon effect size (ES) and its 95% confidence interval were computed to quantify the difference between the two groups beyond p -value interpretation. To that end, the Vargha and Delaney's A statistic (VDA) was used. VDA is a standardized quantification of the difference between the two groups. VDA indicates the likelihood that a randomly chosen value from one group exceeds a randomly chosen value from the other group. A value of 0.50 reflects stochastic equality between the two groups. A value of 1 signifies that the first group (individuals with normal body weight) consistently outperforms the second group (overweight individuals) in stochastic terms. A value of 0 indicates complete stochastic domination by the second group (overweight individuals). Vargha and Delaney (2000) suggested an ES of 0.45–0.55 as a negligible effect, 0.56–0.63 (or 0.35–0.44) as a small effect, 0.64–0.70 (or 0.30–0.34) as a medium effect and >0.70 (or <0.30) as a large effect [36]. The type I error rate was set at $\alpha = 0.05$.

3. Results

3.1. Socio-Demographic and Anthropometric Characteristics

Table 1 presents the results from the Wilcoxon–Mann–Whitney rank sum tests examining differences between the two groups.

Age and the body height did not significantly differ between the two groups ($p > 0.05$), while body mass and BMI did. Overweight individuals had a significantly higher body mass ($p < 0.01$) and BMI ($p < 0.01$) than individuals with normal body weight.

3.2. Spatial–Temporal Gait Parameters During the Approaching and Crossing Phases

There were no significant differences between the two groups in any of the spatial–temporal step parameters studied in both the approaching and crossing phases ($p > 0.05$). Figure 2 presents the distributions of horizontal and vertical foot clearance parameters measured in normal body weight (in grey) and overweight young adults (in green) as a raincloud plot. Additionally, individual box plots illustrating the variance of all clearance parameters for both groups are provided as supplementary material.

3.3. Leading and Trailing Foot Placement Relative to the Obstacle

The leading foot horizontal distance prior to the obstacle and trailing foot horizontal distance after the obstacle were significantly longer in overweight individuals than in individuals with a normal body weight ($p = 0.03$ and $p = 0.02$, respectively).

There was no significant difference between the two groups in the trailing foot horizontal distance prior to the obstacle and leading foot horizontal distance after the obstacle ($p > 0.05$) (Table 1 and Figure 2).

3.4. Leading and Trailing Vertical Toe Clearance During Obstacle Crossing

There were no significant differences between the two groups in the leading and trailing vertical toe clearance during obstacle crossing ($p > 0.05$).

3.5. Obstacle Contacts

There was no contact with the obstacle during all trials in both groups.

Table 1. Group differences regarding socio-demographic and anthropometric characteristics, spatial–temporal gait parameters and obstacle clearance parameters.

Condition	Parameter	18.5 ≤ BMI < 25 kg/m ²			25 ≤ BMI < 30 kg/m ²			W	p	Effect Size (VDA)
		n	Mean ± SD	Median [IQR]	n	Mean ± SD	Median [IQR]			
Socio-demographic	Age (years)	28	28.3 ± 6.12	27.9 [8.25]	15	30.6 ± 5.39	31 [6]	154	0.156	0.367 [0.218; 0.546]
Anthropometric	Body height (m)	28	1.76 ± 0.0666	1.77 [0.113]	15	1.78 ± 0.0618	1.77 [0.09]	187	0.566	0.445 [0.278; 0.625]
Anthropometric	Body mass (kg)	28	70.8 ± 6.78	70.8 [9.41]	15	86.5 ± 6.15	87.9 [5.3]	13	5.51 × 10⁷	0.031 [0.0151; 0.0623]
Anthropometric	BMI (kg/m²)	28	22.8 ± 1.72	23.5 [1.55]	15	27.4 ± 1.41	26.9 [2.4]	0	9.22 × 10⁸	0 [0; 0]
Spatial–temporal gait parameters	Stride length (cm)	28	129 ± 9.85	127 [15.2]	15	135 ± 10.8	139 [16.9]	141	0.0808	0.336 [0.195; 0.513]
	Stride width (cm)	28	10.5 ± 2.49	10.2 [2.41]	15	11.8 ± 2.28	11.6 [3.46]	147	0.112	0.35 [0.206; 0.528]
Approaching phase	Stride double-support time (s)	28	0.361 ± 0.0512	0.35 [0.0567]	15	0.344 ± 0.0447	0.333 [0.0533]	263.5	0.177	0.627 [0.447; 0.778]
	Stride duration (s)	28	1.1 ± 0.116	1.09 [0.0742]	15	1.09 ± 0.0986	1.05 [0.12]	240	0.452	0.571 [0.391; 0.735]
	Stride velocity (cm/s)	28	119 ± 14.6	119 [14.1]	15	125 ± 15.8	123 [18.3]	160	0.21	0.381 [0.228; 0.561]
Spatial–temporal gait parameters	Step length (cm)	28	72.1 ± 9.18	71.7 [12.7]	15	75.3 ± 8.59	78.4 [13.4]	160	0.21	0.381 [0.228; 0.561]
	Step width (cm)	28	10.1 ± 2.7	9.45 [3.32]	15	10.6 ± 3.4	11.1 [3.37]	175	0.384	0.417 [0.256; 0.598]
Crossing phase	Step double-support time (s)	28	0.211 ± 0.033	0.207 [0.0317]	15	0.204 ± 0.0359	0.2 [0.0483]	235.5	0.524	0.561 [0.38; 0.726]
	Step duration (s)	28	0.636 ± 0.0547	0.645 [0.0683]	15	0.623 ± 0.0813	0.59 [0.0933]	249.5	0.32	0.594 [0.413; 0.753]
	Step velocity (cm/s)	28	115 ± 17	113 [22.6]	15	123 ± 21.3	125 [26.5]	158	0.192	0.376 [0.225; 0.556]

Table 1. Cont.

Condition	Parameter	$18.5 \leq \text{BMI} < 25 \text{ kg/m}^2$			$25 \leq \text{BMI} < 30 \text{ kg/m}^2$			W	p	Effect Size (VDA)
		n	Mean \pm SD	Median [IQR]	n	Mean \pm SD	Median [IQR]			
Obstacle clearance	Trailing foot—horizontal distance prior to obstacle (cm)	28	42.4 \pm 8.77	42.7 [10.4]	15	45 \pm 9.19	47.5 [9.54]	163	0.239	0.388 [0.234; 0.569]
parameters	Trailing foot—horizontal distance after obstacle (cm)	28	90 \pm 8.21	89.6 [11.9]	15	98.1 \pm 11.6	95.7 [15.5]	122	0.0245	0.29 [0.164; 0.46]
	Trailing foot—toe clearance (cm)	28	32 \pm 7.07	31.1 [11.6]	15	31.7 \pm 6.61	30 [7.51]	208	0.97	0.495 [0.32; 0.671]
	Leading foot—horizontal distance prior to obstacle (cm)	28	105 \pm 8.91	106 [9.28]	15	112 \pm 8.88	110 [13.4]	123	0.0263	0.293 [0.166; 0.463]
	Leading foot—horizontal distance after obstacle (cm)	28	25.1 \pm 5.75	24.8 [8.3]	15	27.3 \pm 6.95	24.2 [7.01]	172	0.343	0.41 [0.25; 0.591]
	Leading foot—toe clearance (cm)	28	10.1 \pm 4.27	9.38 [4.04]	15	10.4 \pm 4.67	10.9 [5.18]	195	0.715	0.464 [0.294; 0.643]

Note: IQR—interquartile range; SD—arithmetic standard deviation; VDA—Vargha and Delaney's A statistic. Blue background—negligible effect size; green background—small effect size; yellow background—moderate/medium effect size; red background—large effect size.

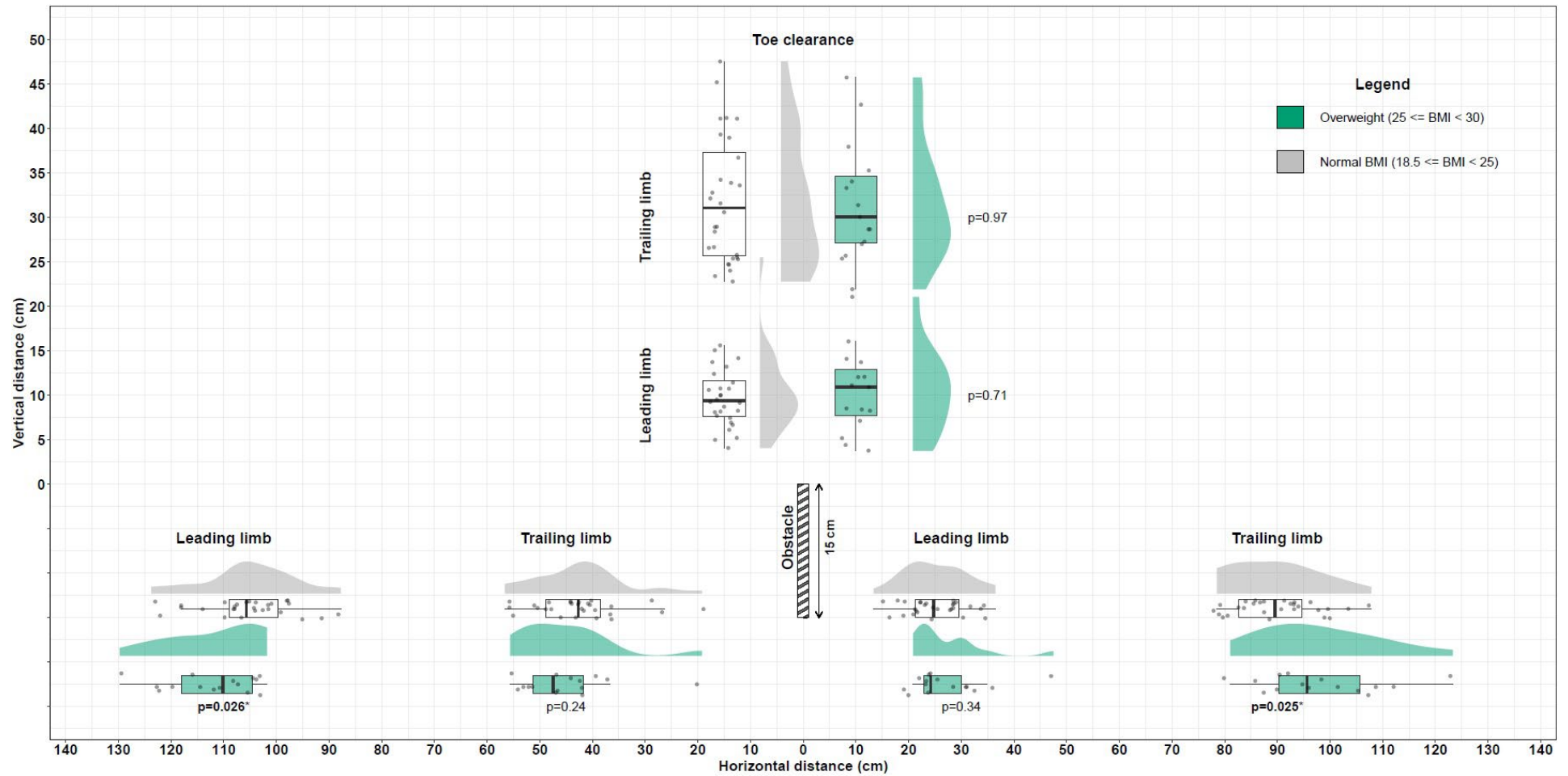


Figure 2. Raincloud plot of the distributions of obstacle clearance parameters measured. p : p -value of the Wilcoxon rank sum tests; * $p \leq 0.05$.

4. Discussion

The aim of this study was to compare spatial–temporal gait parameters, during an obstacle crossing task in normal-body-weight and overweight young adults. Therefore, this study makes a distinct contribution by specifically focusing on overweight individuals, a group often combined with or overshadowed by obesity research in the existing literature. Our hypothesis that overweight impacts gait behavior during obstacle crossing was partially confirmed as only leading foot horizontal distance prior to the obstacle and trailing foot horizontal distance after the obstacle were impacted, and no trips occurred. No changes were observed in the spatial–temporal parameters during both the approaching and crossing phase.

Compared to the individuals with normal body weight, overweight individuals significantly increased the leading foot placement distance prior to the obstacle and the trailing foot placement distance after the obstacle crossing. Considering that vertical clearance parameters are critical outcomes to assess the risk of tripping over an obstacle (e.g., [18,19,37–39]), our results suggest that overweight young male adults do not seem to have an increased risk of trips during the obstacle task compared to their normal-weight peers in those specific experimental conditions (crossing an expected 15 cm high obstacle at a self-selected speed).

This foot placement behavior observed in overweight young adults could represent an adaptive, effective and safe obstacle crossing behavior. Considering the vertical foot clearance as the safety margin in the obstacle crossing task, an unchanged clearance does not lead to a higher risk of tripping [39]. Moreover, no participants touched the obstacle during the experimental trials, suggesting that the behavior of overweight individuals is safe when avoiding obstacles. Potentially increasing horizontal distances is a behavior in overweight individuals to maintain dynamic balance (as no difference was observed in double-support time). It could be of interest for future studies to assess the foot trajectory while crossing the obstacle to identify potential differences between overweight and normal-body-weight participants regarding their strategies to maintain toe clearance [40] at different obstacle heights.

Our results revealed no significant group differences in the spatial–temporal gait parameters measured during the approaching and the crossing phase. In other words, both normal-body-weight and overweight young adults had a similar step velocity, length, width and duration and double-support time during the two steps before the obstacle and crossing step. Previous studies reported that step crossing velocity was reduced in obese individuals compared to normal-body-weight individuals. Moreover, the higher the BMI, the lower their velocity during obstacle crossing (reduction of 15.5%, 26.9% and 31.7% for overweight/Class I obesity, Class II obesity and Class III obesity, respectively [15]). In addition, the studies showed reductions in leading leg step length (14%), cadence (13.6%) and single-limb support (relative to a single gait cycle, 6.1%) in obese individuals compared to normal-body-weight individuals, while leading step width (37.4%) and double-limb support increased (relative to a single gait cycle, 24.5%) [13]. When looking at gait phases, Gill. 2019 [15] showed that the step crossing swing phase was reduced in all overweight/obesity classes compared to normal-body-weight individuals (9.7%, 11.4% and 12.7% for overweight/Class I obesity, Class II obesity and Class II obesity, respectively).

One may argue that the gait adaptations observed in obese individuals are caused by higher body mass [2]; hence, individuals with obesity need to increase their base of support for a greater amount of time relative to a single gait cycle [13] and reduce step velocity and length to successfully complete the gait task. A shorter single-limb support during the crossing phase might enhance the risk of tripping over the obstacle, to cross it “more quickly and with less assurance” [13] even if the step crossing speed was reduced. However, in the specific context of crossing a 15 cm high obstacle in laboratory settings, the results of our study showed that overweight individuals do not adopt a similar spatial–temporal gait behavior compared to those with Class I, Class II and Class III obesity. The functional and

balance impairments associated with being overweight are probably less deleterious than those associated with obesity [41,42].

Our study investigated overweight individuals, with lower body mass and BMI compared to obese individuals, and overweight individuals are able to adapt their gait behavior when crossing a 15 cm high obstacle at a self-selected pace, which simulates crossing a typical curb height in Brazil [43]. It is possible that the experimental obstacle crossing task was insufficiently demanding to reveal BMI-related changes in foot clearance parameters in overweight individuals due to their lower functional and balance impairments, as well as the likelihood that they perform this task very routinely. As previously mentioned, the obstacle height represents a typical curb height in Brazil [43]. Further studies should consider various task-related factors that have previously been shown to significantly impact foot clearance parameters. These obstacle crossing conditions that also resemble real-life situations could include crossing one or multiple obstacles [44,45] of different heights [39,44,46–48] at different walking speeds [49], under various lighting conditions [50,51], while wearing different footwear [46,52] or orthotic bracing [53], during single-task (obstacle crossing only) and dual-task conditions (obstacle crossing with concurrent cognitive or motor task) [54–58].

To the best of our knowledge, this is the first work that compared obstacle crossing during walking in normal-body-weight and overweight young adults. Also, this study is the first to assess BMI influence through obstacle clearance parameters, critical parameters of fall risk during obstacle crossing [16,17]. However, these changes do not seem to increase overweight individuals' risk of trips and falls when crossing an obstacle. The present findings per se may not reflect what was experienced by individuals with more excessive body weight, such as obese individuals ($\text{BMI} > 30.0 \text{ kg/m}^2$). It is furthermore probable that excess body weight would have a greater impact in older adults, as previously reported in other gait tasks [59,60].

The present findings indicate that overweight young male adults demonstrate adaptive gait adjustments during obstacle crossing without increasing their risk of tripping, suggesting stability is maintained under the specific conditions of this study (crossing a 15 cm high obstacle at a self-selected speed in a controlled laboratory setting). Indeed, even if overweight individuals placed their leading limb further prior to crossing the obstacle and their trailing limb further after crossing the obstacle, toe clearances remained unchanged compared to normal-body-weight individuals. The changes in horizontal clearance could be due to overweight individuals' willingness to ensure more space to cross the obstacle without reducing their vertical clearance. Additionally, the changes in foot placement without a change in vertical clearance imply a different foot motion over the obstacle. Overweight individuals might have a lower foot elevation during the beginning of the swing phase of the leading foot during the crossing step. Nevertheless, this interpretation remains speculative, and it would be of interest for future studies to investigate not only foot horizontal and vertical clearances relative to the obstacle but also the entire foot trajectory during the crossing steps, as was carried out in a recent study [39]. Finally, a relevant aspect that has not been addressed in this or previous studies is the investigation of muscle parameters. Obstacle crossing requires greater neuromuscular activation (e.g., increased knee flexor activation) compared to walking on flat ground [61], and obese individuals have reduced strength normalized by body mass compared to normal-weight individuals [62]. As a result, it seems essential for future studies to couple spatial–temporal and clearance data during obstacle crossing with muscular data in order to better interpret potential limitations in this population when performing this task. However, the limits stated above should caution readers not to draw conclusions too easily or to misinterpret the results.

To better understand whether and how excess body weight impacts obstacle crossing during walking, future studies are necessary to investigate different BMI, age and sex (as women exhibit different gait behavior on flat ground [63] and inclined walking [64]) groups of participants. Studying the influence of BMI on obstacle crossing behavior across various demographic groups would provide a more comprehensive understanding of how BMI

affects the functional capacities of these distinct demographic groups. Understanding the distinct gait adaptations in overweight individuals is essential for designing targeted interventions that support their balance and mobility as they transition across BMI categories, whether moving toward lower BMI ranges during weight loss programs or increasing within different obesity classes. These insights could guide the development of training programs aimed at improving balance and reducing fall risk in overweight populations. Such programs may include exercises focusing on dynamic balance, gait stability and obstacle negotiation under various real-world conditions, such as uneven surfaces or varying obstacle heights.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/s24237867/s1>, Figure S1: Box-plots of Clearance Parameters Across Normal Body Weight and Overweight Groups.

Author Contributions: Conceptualization, M.C., F.A.B. and N.V.; data curation: M.C., F.A.B., P.P. and N.V.; formal analysis: M.C., F.A.B., C.H., P.P. and N.V.; funding acquisition: F.A.B. and N.V.; project administration: F.A.B. and N.V.; supervision: F.A.B. and N.V.; visualization: P.P.; writing—original draft: M.C.; writing—review and editing: M.C., F.A.B., C.H., P.P. and N.V. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the French National Research Agency (ANR) in the framework of the Investissements d’avenir program (ANR-10-AIRT-05 and ANR-15-IDEX-02), the MIAI @ Grenoble Alpes (ANR-19-P3IA-0003), the São Paulo Research Foundation (FAPESP) (grant #18/18078-0), the National Council for Scientific and Technological Development (CNPq) and in part by the Brazilian CAPES—Finance Code 001.

Institutional Review Board Statement: This study was approved by the University Institution Review Board (authorization number: CAAE#99191318.0.0000.5398). The study and all methods were performed in accordance with the Declaration of Helsinki.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgments: This work is part of the Ph.D. thesis of the first author (M.C.) at Université Grenoble Alpes, France, and São Paulo State University, Bauru, Brazil. The sponsors were not involved in the review or approval of the manuscript for publication. This work also forms part of a broader translational and interdisciplinary research program, GaitAlps (NV).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. World Health Organization. *WHO Report*; World Health Organization: Geneva, Switzerland, 2021. Available online: <https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight> (accessed on 4 October 2022).
2. Teasdale, N.; Simoneau, M.; Corbeil, P.; Handrigan, G.; Tremblay, A.; Hue, O. Obesity Alters Balance and Movement Control. *Curr. Obes. Rep.* **2013**, *2*, 235–240. [[CrossRef](#)]
3. Capodaglio, P.; Gobbi, M.; Donno, L.; Fumagalli, A.; Buratto, C.; Galli, M.; Cimolin, V. Effect of Obesity on Knee and Ankle Biomechanics during Walking. *Sensors* **2021**, *21*, 7114. [[CrossRef](#)] [[PubMed](#)]
4. Adouni, M.; Alkhatib, F.; Hajji, R.; Faisal, T.R. Effects of overweight and obesity on lower limb walking characteristics from joint kinematics to muscle activations. *Gait Posture* **2024**, *113*, 337–344. [[CrossRef](#)] [[PubMed](#)]
5. Ferhi, H.; Maktouf, W. The impact of obesity on static and proactive balance and gait patterns in sarcopenic older adults: An analytical cross-sectional investigation. *PeerJ* **2023**, *11*, e16428. [[CrossRef](#)] [[PubMed](#)]
6. Kong, L.; Zhang, Z.; Bao, J.; Zhu, X.; Tan, Y.; Xia, X.; Zhang, Q.; Hao, Y. Influences of cognitive load on center of pressure trajectory of young male adults with excess weight during gait initiation. *Front. Bioeng. Biotechnol.* **2024**, *11*, 1297068. [[CrossRef](#)]
7. Maktouf, W.; Ferhi, H.; Boyas, S.; Beaune, B.; Chortane, S.G.; Portero, P.; Durand, S. The influence of obesity and fat distribution on ankle muscle coactivation during gait. *PLoS ONE* **2024**, *19*, e0294692. [[CrossRef](#)]
8. Shultz, S.P.; Kung, S.M.; Atack, A.C.; Buck, A.N.; Mahaffey, R. The impact of pediatric obesity on biomechanical differences across the gait cycle at three walking speeds. *Clin. Biomech.* **2024**, *114*, 106236. [[CrossRef](#)]

9. Molina-Garcia, P.; Migueles, J.H.; Cadenas-Sanchez, C.; Esteban-Cornejo, I.; Mora-Gonzalez, J.; Rodriguez-Ayllon, M.; Plaza-Florido, A.; Vanrenterghem, J.; Ortega, F.B. A systematic review on biomechanical characteristics of walking in children and adolescents with overweight/obesity: Possible implications for the development of musculoskeletal disorders. *Obesity Rev.* **2019**, *20*, 1033–1044. [[CrossRef](#)]
10. Steinberg, N.; Nemet, D.; Pantanowitz, M.; Eliakim, A. Gait Pattern, Impact to the Skeleton and Postural Balance in Overweight and Obese Children: A Review. *Sports* **2018**, *6*, 75. [[CrossRef](#)]
11. Scataglini, S.; Dellaert, L.; Meeuwssen, L.; Staeljanssens, E.; Truijien, S. The difference in gait pattern between adults with obesity and adults with a normal weight, assessed with 3D-4D gait analysis devices: A systematic review and meta-analysis. *Int. J. Obes.* **2024**, 1–13. [[CrossRef](#)]
12. Chardon, M.; Barbieri, F.A.; Penedo, T.; Santos, P.C.R.; Vuillerme, N. A Systematic Review of the Influence of Overweight and Obesity across the Lifespan on Obstacle Crossing during Walking. *Int. J. Environ. Res. Public Health* **2023**, *20*, 5931. [[CrossRef](#)] [[PubMed](#)]
13. Desrochers, P.C.; Kim, D.; Keegan, L.; Gill, V.S. Association between the Functional Gait Assessment and spatiotemporal gait parameters in individuals with obesity compared to normal weight controls: A proof-of-concept study. *J. Musculoskelet. Neuronal Interact.* **2021**, *21*, 335–342.
14. Silva, D.; Gabriel, R.; Helena, M.; Abrantes, J.; Faria, A. Foot Rollover Temporal Parameters During Walking Straight Ahead and Stepping Over Obstacles: Obese and Non-Obese Postmenopausal Women. *J. Aging Phys. Act.* **2017**, *26*, 227–234. [[CrossRef](#)] [[PubMed](#)]
15. Gill, S.V. Effects of obesity class on flat ground walking and obstacle negotiation. *J. Musculoskelet. Neuronal Interact.* **2019**, *19*, 448–454. [[PubMed](#)]
16. Galna, B.; Peters, A.; Murphy, A.T.; Morris, M.E. Obstacle crossing deficits in older adults: A systematic review. *Gait Posture* **2009**, *30*, 270–275. [[CrossRef](#)]
17. Guadagnin, E.C.; da Rocha, E.S.; Duysens, J.; Carpes, F.P. Does physical exercise improve obstacle negotiation in the elderly? A systematic review. *Arch. Gerontol. Geriatr.* **2016**, *64*, 138–145. [[CrossRef](#)]
18. Patla, A.; Rietdyk, S. Visual control of limb trajectory over obstacles during locomotion: Effect of obstacle height and width. *Gait Posture* **1993**, *1*, 45–60. [[CrossRef](#)]
19. Chou, L.S.; Draganich, L.F. Stepping over an obstacle increases the motions and moments of the joints of the trailing limb in young adults. *J. Biomech.* **1997**, *30*, 331–337. [[CrossRef](#)]
20. Chen, H.L.; Lu, T.W. Comparisons of the joint moments between leading and trailing limb in young adults when stepping over obstacles. *Gait Posture* **2006**, *23*, 69–77. [[CrossRef](#)]
21. Chou, L.S.; Draganich, L.F. Placing the trailing foot closer to an obstacle reduces flexion of the hip, knee, and ankle to increase the risk of tripping. *J. Biomech.* **1998**, *31*, 685–691. [[CrossRef](#)]
22. Silva, F.R.; Muniz, A.M.d.S.; Cerqueira, L.S.; Nadal, J. Biomechanical alterations of gait on overweight subjects. *Res. Biomed. Eng.* **2018**, *34*, 291–298. [[CrossRef](#)]
23. Defining Adult Overweight & Obesity | Overweight & Obesity | CDC. Available online: <https://www.cdc.gov/obesity/basics/adult-defining.html>. (accessed on 5 July 2023).
24. Barbieri, F.A.; Dos Santos, P.C.R.; Simieli, L.; Orcioli-Silva, D.; Van Dieën, J.H.; Obbi, L.T.B. Interactions of age and leg muscle fatigue on unobstructed walking and obstacle crossing. *Gait Posture* **2014**, *39*, 985–990. [[CrossRef](#)] [[PubMed](#)]
25. Santinelli, F.B.; Sebastião, E.; Simieli, L.; Antunes, B.M.; Vieira, L.H.P.; Kalron, A.; Barbieri, F.A. Is BDNF related to spatial-temporal gait parameters in people with multiple sclerosis? An observational study. *Mult Scler Relat Disord.* **2022**, *66*, 104064. [[CrossRef](#)] [[PubMed](#)]
26. Santinelli, F.B.; Sebastião, E.; Kuroda, M.H.; Moreno, V.C.; Pilon, J.; Vieira, L.H.P.; Barbieri, F.A. Cortical activity and gait parameter characteristics in people with multiple sclerosis during unobstructed gait and obstacle avoidance. *Gait Posture* **2021**, *86*, 226–232. [[CrossRef](#)]
27. Weir, C.B.; Jan, A. BMI Classification Percentile and Cut Off Points. In *StatPearls*; StatPearls Publishing: Treasure Island, FL, USA, 2022.
28. Ben Shachar, M.; Lüdecke, D.; Makowski, D. Effectsize: Estimation of Effect Size Indices and Standardized Parameters Aims of the Package. *J. Open Source Softw.* **2020**, *5*, 2815. [[CrossRef](#)]
29. Chardon, M.; Barbieri, F.A.; Petit, P.; Vuillerme, N. Reliability of Obstacle-Crossing Parameters during Overground Walking in Young Adults. *Sensors* **2024**, *24*, 3387. [[CrossRef](#)] [[PubMed](#)]
30. Hosp, S.; Csapo, R.; Heinrich, D.; Hasler, M.; Nachbauer, W. Does Kinesiology tape counter exercise-related impairments of balance in the elderly? *Gait Posture* **2018**, *62*, 167–172. [[CrossRef](#)]
31. Vitória, R.; Lirani-Silva, E.; Barbieri, F.A.; Raile, V.; Stella, F.; Gobbi, L.T.B. Influence of visual feedback sampling on obstacle crossing behavior in people with Parkinson’s disease. *Gait Posture* **2013**, *38*, 330–334. [[CrossRef](#)]
32. Vitória, R.; Lirani-Silva, E.; Baptista, A.M.; Barbieri, F.A.; Dos Santos, P.C.R.; Teixeira-Arroyo, C.; Gobbi, L.T.B. Disease severity affects obstacle crossing in people with Parkinson’s disease. *Gait Posture* **2014**, *40*, 266–269. [[CrossRef](#)]
33. Orcioli-Silva, D.; Barbieri, F.A.; Simieli, L.; Vitorio, R.; dos Santos, P.C.R.; Beretta, V.S.; Gobbi, L.T.B. Walking behavior over multiple obstacles in people with Parkinson’s disease. *Gait Posture* **2017**, *58*, 510–515. [[CrossRef](#)]

34. Santos PCR dos Barbieri, F.A.; Orcioli-Silva, D.; Beretta, V.S.; Hortobágyi, T.; Gobbi, L.T.B. Being physically active minimizes the effects of leg muscle fatigue on obstacle negotiation in people with Parkinson's disease. *J. Biomech.* **2021**, *124*, 110568.
35. Hedberg, P.; Nohlert, E.; Tegelberg, A. Effects of oral appliance treatment on inflammatory biomarkers in obstructive sleep apnea: A randomised controlled trial. *J. Sleep Res.* **2020**, *30*, e13253. [[CrossRef](#)] [[PubMed](#)]
36. Vargha, A.; Delaney, H. A Critique and Improvement of the "CL" Common Language Effect Size Statistics of McGraw and Wong. *J. Educ. Behav. Stat.* **2000**, *25*, 101–132.
37. Chen, H.C.; Ashton-Miller, J.A.; Alexander, N.B.; Schultz, A.B. Stepping over obstacles: Gait patterns of healthy young and old adults. *J. Gerontol.* **1991**, *46*, M196–M203. [[CrossRef](#)]
38. Heijnen, M.J.H.; Muir, B.C.; Rietdyk, S. Factors leading to obstacle contact during adaptive locomotion. *Exp. Brain Res.* **2012**, *223*, 219–231. [[CrossRef](#)]
39. Miura, Y.; Shinya, M. Foot clearance when crossing obstacles of different heights with the lead and trail limbs. *Gait Posture* **2021**, *88*, 155–160. [[CrossRef](#)]
40. Muir, B.C.; Haddad, J.M.; Heijnen, M.J.H.; Rietdyk, S. Proactive gait strategies to mitigate risk of obstacle contact are more prevalent with advancing age. *Gait Posture* **2015**, *41*, 233–239. [[CrossRef](#)]
41. Vincent, H.K.; Vincent, K.R.; Lamb, K.M. Obesity and mobility disability in the older adult. *Obes. Rev.* **2010**, *11*, 568–579. [[CrossRef](#)]
42. Hue, O.; Simoneau, M.; Marcotte, J.; Berrigan, F.; Doré, J.; Marceau, P.; Marceau, S.; Tremblay, A.; Teasdale, N. Body weight is a strong predictor of postural stability. *Gait Posture* **2007**, *26*, 32–38. [[CrossRef](#)]
43. Simieli, L.; Gobbi, L.T.B.; Orcioli-Silva, D.; Beretta, V.S.; Santos, P.C.R.; Baptista, A.M.; Barbieri, F.A. The variability of the steps preceding obstacle avoidance (approach phase) is dependent on the height of the obstacle in people with Parkinson's disease. *PLoS ONE.* **2017**, *12*, e0184134. [[CrossRef](#)]
44. Wang, Z.; Chien, J.H.; Siu, K.C. Stepping over multiple obstacles changes the pattern of foot integrated pressure of the leading and trailing legs. *J. Biomech.* **2020**, *98*, 109423. [[CrossRef](#)] [[PubMed](#)]
45. Chien, J.H.; Post, J.; Siu, K.C. Effects of Aging on the Obstacle Negotiation Strategy while Stepping over Multiple Obstacles. *Sci Rep.* **2018**, *8*, 8576. [[CrossRef](#)] [[PubMed](#)]
46. Chien, H.L.; Lu, T.W. Effects of shoe heel height on the end-point and joint kinematics of the locomotor system when crossing obstacles of different heights. *Ergonomics* **2017**, *60*, 410–420. [[CrossRef](#)] [[PubMed](#)]
47. Muir, B.C.; Haddad, J.M.; van Emmerik, R.E.A.; Rietdyk, S. Changes in the control of obstacle crossing in middle age become evident as gait task difficulty increases. *Gait Posture* **2019**, *70*, 254–259. [[CrossRef](#)] [[PubMed](#)]
48. Maidan, I.; Eyal, S.; Kurz, I.; Geffen, N.; Gazit, E.; Ravid, L.; Giladi, N.; Mirelman, A.; Hausdorff, J.M. Age-associated changes in obstacle negotiation strategies: Does size and timing matter? *Gait Posture* **2018**, *59*, 242–247. [[CrossRef](#)]
49. Raffegeau, T.E.; Brinkerhoff, S.A.; Kellaher, G.K.; Baudendistel, S.; Terza, M.J.; Roper, J.A.; Hass, C.J. Changes to margins of stability from walking to obstacle crossing in older adults while walking fast and with a dual-task. *Exp. Gerontol.* **2022**, *161*, 111710. [[CrossRef](#)]
50. Zhao, C.; Li, K.; Lu, J.; Li, Z. Risk of tripping, minimum foot clearance, and step length when crossing a barrier. *Int. J. Ind. Ergon.* **2021**, *83*, 103138. [[CrossRef](#)]
51. Li, K.W.; Chen, Y.; Li, N.; Duan, T.; Zou, F. Assessment of risk of tripping before and after crossing obstacles under dimmed lighting conditions. *Work* **2020**, *66*, 551–559. [[CrossRef](#)]
52. Ohtsu, H.; Togashi, R.; Hiramuki, M.; Yoshida, S.; Minamisawa, T.; Kanzaki, H. How does wearing slippers affect the movement strategy while crossing over an obstacle? *Gait Posture* **2021**, *86*, 17–21. [[CrossRef](#)]
53. Evangelopoulou, E.; Twiste, M.; Buckley, J.G. Restricting ankle motion via orthotic bracing reduces toe clearance when walking over obstacles. *Gait Posture* **2016**, *43*, 251–256. [[CrossRef](#)]
54. Lo, O.Y.; van Donkelaar, P.; Chou, L.S. Distracting visuospatial attention while approaching an obstacle reduces the toe-obstacle clearance. *Exp. Brain Res.* **2015**, *233*, 1137–1144. [[CrossRef](#)] [[PubMed](#)]
55. Chen, S.H.; Lo, O.Y.; Kay, T.; Chou, L.S. Concurrent phone texting alters crossing behavior and induces gait imbalance during obstacle crossing. *Gait Posture* **2018**, *62*, 422–425. [[CrossRef](#)] [[PubMed](#)]
56. Perry, C.J.; Kiriella, J.B.; Hawkins, K.M.; Shanahan, C.J.; Moore, A.E.; Gage, W.H. The effects of anterior load carriage on lower limb gait parameters during obstacle clearance. *Gait Posture* **2010**, *32*, 57–61. [[CrossRef](#)] [[PubMed](#)]
57. Jehu, D.A.; Saunders, D.; Richer, N.; Paquet, N.; Lajoie, Y. The influence of carrying an anterior load on attention demand and obstacle clearance before, during, and after obstacle crossing. *Exp. Brain Res.* **2019**, *237*, 3313–3319. [[CrossRef](#)] [[PubMed](#)]
58. Harley, C.; Wilkie, R.M.; Wann, J.P. Stepping over obstacles: Attention demands and aging. *Gait Posture* **2009**, *29*, 428–432. [[CrossRef](#)]
59. Ko, S.U.; Stenholm, S.; Ferrucci, L. Characteristic gait patterns in older adults with obesity—results from the Baltimore Longitudinal Study of Aging. *J. Biomech.* **2010**, *43*, 1104–1110. [[CrossRef](#)]
60. Law, N.H.; Li, J.X.; Law, N.Y.; Varin, D.; Lamontagne, M. Effects of body mass and sex on kinematics and kinetics of the lower extremity during stair ascent and descent in older adults. *Sports Med. Health Sci.* **2021**, *3*, 165–170. [[CrossRef](#)]
61. MacLellan, M.J.; McFadyen, B.J. Proximal lower limb muscle energetics and the adaptation of segment elevation angle phasing for obstacle avoidance. *Gait Posture* **2013**, *37*, 274–279. [[CrossRef](#)]

62. Hulens, M.; Vansant, G.; Lysens, R.; Claessens, A.L.; Muls, E.; Brumagne, S. Study of differences in peripheral muscle strength of lean versus obese women: An allometric approach. *Int. J. Obes. Relat. Metab. Disord.* **2001**, *25*, 676–681. [[CrossRef](#)]
63. Ko, S.; Tolea, M.I.; Hausdorff, J.M.; Ferrucci, L. Sex-specific differences in gait patterns of healthy older adults: Results from the Baltimore Longitudinal Study of Aging. *J. Biomech.* **2011**, *44*, 1974–1979. [[CrossRef](#)]
64. Chumanov, E.S.; Wall-Scheffler, C.; Heiderscheit, B.C. Gender differences in walking and running on level and inclined surfaces. *Clin. Biomech.* **2008**, *23*, 1260–1268. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

