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Published in:
Critical Reviews in Physical and Rehabilitation Medicine

DOI (link to publication from Publisher):
10.1615/critrevphysrehabilmed.2022043644

Publication date:
2022

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Pirscoveanu, C.-I., Hansen, J., Pedersen, M., & Madeleine, P. (2022). Overground Walking with a Passive Hip Exoskeleton during Obstacle Avoidance in Young Able-Bodied Adults: english. *Critical Reviews in Physical and Rehabilitation Medicine*, *34*(3), 1-13. Article 34. https://doi.org/10.1615/critrevphysrehabilmed.2022043644

Accepted for publication in Critical Reviews in Physical and Rehabilitation Medicine.
Cite as: Overground Walking with a Passive Hip Exoskeleton during Obstacle Avoidance in Young Able-Bodied Adult. Pirscoveanu, C-I., Hansen, J., Pedersen, M. & Madeleine, P., 2022, In: Critical Reviews in Physical and Rehabilitation Medicine. 34, 3, p. 1-13.

Overground walking with a passive hip exoskeleton during obstacle avoidance in young able-bodied adults

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Accepted for publication in Critical Reviews in Physical and Rehabilitation Medicine.
Cite as: Overground Walking with a Passive Hip Exoskeleton during Obstacle Avoidance in Young Able-Bodied Adult. Pirscoveanu, C-I., Hansen, J., Pedersen, M. & Madeleine, P., 2022, In: Critical Reviews in Physical and Rehabilitation Medicine. 34, 3, p. 1-13.

ABSTRACT: During everyday walking, we encounter challenges such as uneven terrain or curbs, all requiring adjustments to our gait patterns. These adjustments are made to circumvent the given obstacles and avoid falling or tripping. Exoskeletons have proven to assist walking by increasing walking speed and step length. However, most exoskeleton studies are traditionally carried out in a laboratory setting, which is an inaccurate depiction of everyday outdoor walking conditions. This study investigated the spatiotemporal gait parameters and hip kinematics during outdoor walking situations while wearing a passive-assistive hip exoskeleton (aLQ). Eleven healthy male participants walked on three 10-meters obstacle tracks at their self-selected walking speed with and without aLQ. The tracks were designed for the participants to 1) step up onto a sidewalk, 2) step over a pothole, and 3) walk without any obstacle (control situation). The cadence, gait velocity, step length, double stance time, and the 3D hip range of motion angles were extracted and compared for each track with and without aLQ. No significant changes were found for the spatiotemporal parameters with and without exoskeleton when navigating the obstacles. However, a significant decrease in the right hip internal rotation was observed when wearing the exoskeleton compared with without while stepping over (21%, p=0.05) and while walking with no obstacle (6%, p=0.04). These findings indicate that the gait of able-bodied adults was mostly unaffected during overground walking with a passive-assistive hip exoskeleton while navigating obstacles, proving that exoskeletons could be used safely in everyday situations.

KEYWORDS: Gait pattern, Kinematics, Outdoor Walking, Motor Control, Step up, Step over

I. INTRODUCTION

Locomotion is often challenged by everyday activities like navigating stairs, uneven terrain, or curbs [1]. Such challenges result in walking adjustments needed to circumvent the encountered obstacles and avoid falling or tripping. These adjustments could involve: stepping over something, changing the chosen path, or altering foot placement [2,3]. Paradoxically, avoiding these daily walking challenges can lead to reduced physical activity resulting in deterioration of quality of life and level of independence, and can increase the risk of falling.[2,4,5]. All these deteriorations contribute in turn to the development of cardiovascular diseases and musculoskeletal disorders [2,4,5]. Therefore, daily physical activity can enable the maintenance or even the increase of our physical function and thereby lower the risk of falling [4].

Changes in the spatiotemporal gait parameters like increasing walking cadence or velocity have been shown to improve walking capabilities and reduce the risk of falling [6]. Another way to improve gait is through the use of exoskeletons, which have been proven to reduce metabolic cost [7], increase gait velocity [8,9], and aid during obstacles avoidance [10]. Additionally, hip exoskeletons have been shown to cause kinematic adaptations often seen by increasing hip flexion [11]. All of which could lead to a reduced fall incidence [11]. However, all the retrieved studies have been performed in controlled laboratory settings and on even walking surfaces. Zhang et al. [10] proposed that future research should focus on navigating complex terrains with uneven walking surfaces. This suggestion is further reinforced by Park et al. [12], which stated that future research should focus on obstacle crossing and navigating uneven terrain, in more ecological conditions.

Sawicki et al. [7], has hypothesized that passive exoskeletons may not be suitable during diverse walking conditions, such as changes in pace or obstacle avoidance, because these devices are generally limited to one stereotyped form of gait at a fixed speed, e.g., even ground walking. However, more recently Feodoroff and Blumer [11] stated that passive exoskeletons could provide increased hip flexion which aids in successfully navigating daily activities, like for example stairs. Nonetheless, gait studies are traditionally carried out in a laboratory setting [13–16] and thus, considered as an inaccurate representation of everyday outdoor walking environments [17].

Fortunately, the advances in wearable sensors, like inertial measurement units (IMU), have made it possible to measure the spatiotemporal and kinematic parameters of walking *in situ* [18]. Moreover, IMUs can be used to assess adaptations during obstacle navigation [19]. However, an important factor when investigating fall risks is the safety of the participants. It is relatively easier to equip participants with a safety harness in a laboratory compared to outdoor conditions and young adults are less likely to sustain serious injuries when a fall occurs compared to the elderly [20]. Thus, it is safer to perform tests with the risk of falling or tripping in young asymptomatic participants and extrapolate the results to design proper rehabilitation protocols that minimize risks to fall-prone people.

To the best of our knowledge outdoor obstacle avoidance using passive exoskeletons is a mostly unexplored topic [10]. Therefore, the purpose of this study was to investigate spatiotemporal and hip kinematic parameters during commonly encountered walking situations while wearing a passive-assistive hip exoskeleton (aLQ). Such walking conditions will provide invaluable insights into a person's natural coping mechanisms when encountering a change in various walking situations. Cadence, gait velocity, step length, and double stance time will be used to describe the spatiotemporal gait parameters [18] and the 3D hip joint angles will describe the kinematics. It was hypothesized that young adults wearing a passive exoskeleton will increase cadence, gait velocity, and step length, and decrease double stance time during obstacle avoidance. Moreover, we also hypothesized increased range of motion (ROM) of the hip flexion angles when walking with a passive exoskeleton.

II. METHODS

A. Participants

Eleven healthy male participants, right foot dominant (age: 25.4 ± 3.0 years (mean ± standard deviation), height: 183.8 ± 5.6 cm, body mass 91.8 ± 13.3 kg) were recruited among university students. All participants reported no known history of musculoskeletal or other lower limb injuries within the past six months that could affect their natural gait patterns [21]. Additionally, shoulder, hip, knee, and ankle height; wrist, arm and elbow span, shoulder, and hip-width, as well as shoe length, were acquired. The measurements were used for kinematic calibration using Xsens MVN Analyze (Xsens Technologies BV, Enschede, Netherlands). All participants provided written informed consent as per the ethics committee of the North Denmark Region (LBK nr. 1083) guidelines and were in agreement with the Helsinki Declaration.

B. Experimental Design

The participants were asked to walk at their self-selected speed on three 10-meter outdoor tracks (Figure 1). Two of the three tracks included obstacles placed 3/4th of the way throughout the track. The following walking conditions were investigated:

- Stepping up ($Step_{up}$)
- Stepping over ($Step_{over}$)
- No obstacle (No_{obs})

The purpose of the environments was to emulate everyday walking conditions, such as stepping up onto a sidewalk, stepping over a pothole, and walking normally in a straight line where no obstacle was present (control situation). The walking surface area of the tracks was made of paving stones. The $Step_{up}$ and $Step_{over}$ obstacles were created utilizing additional similar paving stones (61cm in length, 80 cm in width, and 11 cm in height) to create platforms for the obstacles. The $Step_{up}$ obstacle was created by aligning four paving stones, whereas for the $Step_{over}$ obstacle a gap of 30 cm was created between the second and the third platform (Figure 1). The recordings were collected in a publicly available open area and in conformity to the current COVID-19 restrictions in Denmark.

[Figure 1 near here]

C. Protocol

To ensure natural walking, all recordings were made during overground walking at self-selected speed. Thel anthropometric measurements and applications of the equipment were performed by the same researcher. After the anthropometric measurements and the application of the Xsens MTw Awinda, a 4-minute familiarization period was performed followed by an Xsens calibration. The familiarization was performed to make sure that the equipment was securely mounted and not affecting the participants' gait. A cross-over design was used, where half of the participants started the recordings while wearing the exoskeleton (EXO) whilst the other half started with no exoskeleton (NoEXO). Five trials without any break were recorded for each walking condition ($Step_{up}$, $Step_{over,}$ and No_{obs}), thus resulting in 30 trials recorded per participant. A successful trial was considered a walk where the participant did not trip or step into the gap. The order of the obstacles was randomized. Participants had on their recreational shoes and were made familiar with the obstacles before recording. Each trial started and ended with the participant standing still at the start and endpoint of the track.

D. Data Acquisition

The kinematic measurements were recorded with Xsens MTw Awinda (Xsens Technologies BV, Enschede, Netherlands) at a sampling frequency of 100 Hz. Before data collection, the

Xsens N-pose and walk calibration was performed, followed by a 30- seconds walking period to warm up the Mocap engine. This calibration procedure was performed twice for each exoskeleton condition (EXO and NoEXO). The Xsens MTw Awinda lower limb configuration was used to capture walking data. The lower limb configuration consists of seven IMUs, i.e. micro-electro-mechanical-system-based accelerometers, magnetometers, tri-axial gyroscopes, and barometers [22]. The IMUs were attached to the left and right foot, shank, hip, and L5 using Velcro® straps. All the recordings were transferred from Xsens MTw Awinda to the Xsens MVN Analyze software (v. 2020.2) in real-time, which provides corrections for any orientation drift and improves the overall consistency of the IMU's position and orientation estimates [23].

The present study used the aLQ (Imasen Electrical Industrial Co., Ltd, Aichi, Japan) exoskeleton, a passive-assistive lower limb walking exoskeleton activated by a cam spring system designed and targeted at people with gait impairments [11].

E. Data Processing

No unsuccessful trials were recorded, therefore all collected trials were included in the data analysis. All recorded data were HD-reprocessed utilizing the Xsens MVN Analyze processing tool using the "single-level" function. Each trial was segmented to contain three steps for each walking condition from both limbs using the following segmentation sequence for the obstacle conditions:

- Start: the first frame at the point of heel strike before the obstacle
- End: the third toe-off after heel strike at the start (Figure 1).

Or for No_{obs}

- Start: the first frame at the point of heel strike of the middle three steps
- End: the first frame of the next step heel strike after the middle three steps

The kinematic data was then exported and processed using a MATLAB (R2021a, Mathworks, Natick, MA, USA) script provided by Xsens with custom modifications, where the double stance time was determined from the frames where both feet were in contact with the ground. This was achieved by using Xsens arrays of Boolean values, “0” depicting no ground contact and “1” representing ground contact. Step length was then calculated as the distance between the sensor location of both feet at the first frame of double stance time, using the distance formula from the rewritten Pythagorean theorem:

$$Step\ Length = \sqrt{((x_2 - x_1)^2 + ((y_2 - y_1)^2} \qquad \text{Eq. (1)}$$

where x_1, y_1, and x_2, y_2 are the x, y coordinates of the right and left foot, respectively. Cadence was extracted using local peak acceleration from the pelvis sensor and divided by the number of frames. Lastly, gait velocity was extracted from the pelvis sensor as the magnitude of the velocity’s anterior/posterior and medio/lateral components, averaged over time to complete the three steps per trial. The average of cadence, gait velocity, step length, and double stance time over the five trials was used for statistical analysis.

The hip joint angle was defined as the angle around the joint created by the pelvis and the thigh segments using the Euler rotation sequence ZXY, where Z-direction was defined as flexion (+) /extension (-), X-direction as abduction (+) /adduction (-) and Y-direction as internal (+)

/external (-) rotation [23]. The ROM angles for each direction (flexion/extension, abduction/adduction, and internal/external rotation) and each limb (left and right) were averaged over the five trials and used for statistical analysis.

F. Statistical Analysis

The data were imported into SPSS (v. 27.0; IBM® SPSS® Statistics, Chicago, IL, USA). Studentized residuals were used to determine outliers at ± 3 standard deviations. The normality of the data was assessed using a Shapiro-Wilks test and the pair variables that did not meet the assumptions were linearly scaled. Paired sample t-tests were used to compare the exoskeleton conditions (EXO and NoEXO) for each walking condition ($Step_{up}$, $Step_{over}$, and No_{obs}). A *p*-value of ≤0.05 was considered significant. The effect sizes were determined using the Cohen's d coefficient (*r*), where a value of 0.2, 0.5, and 0.8 was considered small, medium, and large, respectively [24]. The *r* values can be both positive and negative and indicate the level of the improvement.

III. RESULTS

A. Walking While Stepping up

No significant changes in walking speed, cadence step length, and double stance time were found between EXO and NoEXO when the participants were asked to $Step_{up}$ onto a sidewalk

(Table 1). Furthermore, no significant differences were discovered between EXO and NoEXO for the ROM of both the left and right hip joint angles (Table 2).

[Table 1 near here]

B. Walking While Stepping Over

No significant changes in walking speed, cadence, step length, and double stance time were found between EXO and NoEXO when the participants were asked to $Step_{over}$ a pothole (Table 1). Furthermore, no significant differences were discovered between EXO and NoEXO for the left hip ROM angle (Table 2). However, the ROM of the right hip joint angle showed a 21% significant decrease in internal rotation with a medium positive effect size when wearing the exoskeleton.

[Table 2 near here]

C. Walking Without Obstacles

No significant changes in walking speed, cadence step length, and double stance time were found between EXO and NoEXO when the participants were asked to walk without any obstacle on a straight path (Table 1). Furthermore, no significant differences were discovered between EXO and NoEXO for the ROM of the left hip joint angle (Table 2). However, similarly to $Step_{Over}$ the ROM for the right hip joint angle showed a 6% significant decrease in internal rotation with a medium negative effect size when wearing the exoskeleton.

IV. DISCUSSION

The present field study is the first of its kind to provide findings concerning obstacle navigating during overground walking at self-selected speed wearing or not a passive-assistive hip exoskeleton in an ecological valid setting. Contrary to what we hypothesized, there were no significant differences in the parameters describing the spatiotemporal characteristics of gait when comparing EXO to NoEXO for all obstacle conditions. This indicates that wearing the exoskeleton does not seem to hinder normal walking in daily walking activities among young able-bodied adults. Furthermore, our second hypothesis was not confirmed either as the range of motion of the right hip showed a 21% and 6% significantly decreased internal rotation during stepping over and while walking with no obstacle. All in all, the current findings revealed that gait remained mostly unaltered when young able-bodied adults navigate obstacles wearing a passive hip exoskeleton. Publishing these findings, although not significant, enabled us to evaluate the impact of the passive hip exoskeleton on gait patterns of able-bodied adults when confronted with unknown obstacles, before applying such devices on more at-risk populations. Therefore, the present results should be interpreted by how much the exoskeleton affected the natural walking pattern of the person wearing the device and not by the sole level of significance [25]. Thus, indicating that the device could be a “safe” clinical tool to be used during daily challenges and promote a more active healthy living for fall-prone individuals while exploring the outdoors.

A. Short-term Effects of Wearing an Exoskeleton on Gait Parameters

Passive hip exoskeletons usually use a spring system, which works in conjunction with the hip flexors/extensors muscles [26]. The stored energy in the spring during hip extension is then returned during hip flexion [11]. Sawicki et. al. [7] have suggested that rigid passive exoskeletons might be limited to one single type of locomotion, e.g., walking without the presence of any perturbations, due to the limited degrees of freedom it generally offers (e.g. assistance during hip flexion as in our study). Nonetheless, users of passive exoskeletons might struggle when facing acute change in conditions, e.g., obstacles as stepping around or over an obstacle may involve adaptations that may use a combination of flexion/extension, hip abduction/adduction and internal/external rotation. However, the findings of the present study do not indicate any gait impediments. Furthermore, Sawicki et al. [7] also allude that using malleable textile exoskeletons (often referred to as exosuits) might offer better assistance when having to face acute changes while walking as they could account for multiple degrees of freedom.

Gait improvement or deterioration can be assessed by measuring spatiotemporal parameters and kinematics [27]. There are generally two key components affecting gait velocity: changes in cadence or step length [4,14]. The present study showed no significant differences in gait velocity when wearing the aLQ, which contradicts the findings of Panizzolo et al. [8]. However, Panizzolo et al. [8] investigated healthy adults only walking with no obstacles on a treadmill while the current gait analysis was conducted in outdoor conditions. Likewise, we found no significant differences between walking with and without the exoskeleton for cadence, step length, and double stance time. This can mostly be explained by the fact that a low walking speed (< 5 km/h) does not influence the postural stability as the participants have more time to adjust to surface changes in the environment [10]. Huijben et al. [6] and Feodoroff and Blumer [11] have both reported an increase in gait velocity during treadmill walking underlining improvements in gait quality, especially among elderly adults. On contrary, no significant changes in velocity were seen among young able-bodied adults when wearing the exoskeleton.

In line with the lack of changes in gait spatiotemporal parameters, the hip joint angles were mostly not changed when wearing a passive exoskeleton in contradiction to our first hypothesis. However, the aLQ exoskeleton has been shown to significantly increase the hip joint range of movement when worn by the elderly [11]. Although the passive-assistive hip exoskeleton in this study was designed for aiding hip flexion [11], wearing the exoskeleton showed a significant decrease of the right hip internal rotation angle during stepping over and no obstacle walking, which partially confirms our second hypothesis. Such kinematic adjustment, present only for the right leg could be a consequence of walking at a 7% slower walking speed [28]. Furthermore, none of the participants reported any adverse events or discomfort while wearing the exoskeleton. All in all, the present findings suggest that wearing a passive exoskeleton during walking had no immediate beneficial nor detrimental effects on the gait pattern of young able-bodied participants. However, if the current findings should be combined with the study of Feodoroff and Blumer [11] which have investigated the effect of the same exoskeleton on neurologically impaired elderly, it could be inferred that using aLQ in more challenging conditions would not present adverse events. Nonetheless, a new protocol should be designed to confirm if the current protocol could be repeated and provide similar results using able-bodied elderly and even neurologically impaired elderly. Thus, deeming the aLQ a "safe device" that would not inhibit the natural gait pattern when more challenging walking conditions are present.

B. Immediate Effects of Obstacles on Gait Pattern in Outdoor Conditions

Outdoor conditions or uneven terrain have been suggested to alter gait patterns by actively increasing the step time and length to maximize stability, keeping the center of mass within the base of support [2,29]. In the present study, the two types of obstacles did not influence the investigated spatiotemporal parameters. Menant et al. [30] found that both young and elderly participants navigating an obstacle walked slower and with a decreased double stance time on uneven surfaces without changing their step length. Furthermore, it seems that using the tested exoskeleton during various walking situations, commonly encountered in our daily activity, did not have a negative impact on the extracted spatiotemporal gait parameters. Moreover, aLQ was previously shown to significantly improve gait, i.e., increased step length, among neurologic patients suggesting that wearing a passive exoskeleton could decrease risks of falling [11]. During no obstacle over ground walking, License et al [31] reported 170 ms of double stance time at a gait velocity of 0.78 m/s for able-bodied adults between 18 and 50 years old. The present study found lower double stance time values (78 ms) at a higher gait velocity (1.41 m/s). Furthermore, Hong et al [32] reported a double stance time near 95-100 ms (estimated from their graphical representation) at a gait velocity of 1.41 m/s for young adults. The difference in double stance time could be caused by the difference in measurement techniques or erroneous detection of the foot contact with the ground.

Moreover, even if there were no significant changes in hip flexion/ extension, we did see that the right hip internal rotation range of motion was significantly decreased, which could indicate postural adjustments that the participants are employing before encountering the obstacles. To the best of our knowledge, no other studies have assessed the effects of passive exoskeletons on spatiotemporal outcomes describing gait, i.e., cadence, velocity, step length, and double stance time combined with 3D hip joint angles during obstacle avoidance. The findings reveal that a hip exoskeleton does not increase apparent risks of falling or tripping in young able-bodied adults, when tested during obstacle avoidance. Therefore, we can infer that aLQ could provide aid to people suffering from walking impairments during navigating daily walking situations and increase their levels of physical activity by not altering their walking patterns during more challenging walking situation. Studies investigating the effects of such type of exoskeleton among people with walking impairments are needed.

C. Study Limitations

In this study, due to the specific time of the study, full COVID lock-down the only participants available were young healthy males. Therefore, the results are only applicable to young able-bodied males and cannot be extrapolated to females or the elderly as gait parameters change with age, e.g., velocity decreases with age [1]. Furthermore, the present study only investigated the immediate effects of wearing a passive-assistive hip exoskeleton, and future studies assessing the long-term effects are warranted. The Xsens MTw Awinda facilitates data collection on everyday outdoor walking. However, inertial sensors have tradeoffs in the form of lower repeatability and reproducibility [19], since IMUs are generally sensitive to electrical and magnetic noise [33]. Although the present study uses a relatively small sample size, the statistical power has been calculated to be 0.82 and should be adequate to detect significant differences between either obstacle or exoskeleton. However, the effect size varied largely between positive and negative improvements, as well as, from a very small to a medium effect size. Thus, our findings point towards non-detrimental effects of wearing the exoskeleton on gait spatiotemporal aspects among able-bodied healthy male adults.

Participants were allowed to get familiar with the obstacles before recording, which is a common practice in exercise sciences to obtain reliable recordings [8]. However, the familiarization procedure and the fact that the walking track was only 10 meters may have masked adaptations in gait patterns. For instance, tripping is often seen during the navigation of protruding unforeseen hazards [34] and may occur when a person is walking for a longer distance. Therefore, further studies where obstacle navigation could better emulate natural walking conditions are warranted and the findings of the present study should be considered preliminary. Moreover, only the following gait parameters were extracted: cadence, gait velocity, step length, double stance time, and the hip joint range of motion angles. Analyzing a parameter like the Lyapunov exponent would provide important information on the change in gait stability [35]. Furthermore, including information on the obstacle clearance height [2,8] could have also provided a better understanding of both the walking mechanism employed to overcome such a challenge and avoid tripping, as well as if the exoskeleton can actively aid during the challenge. The limitations of the present study and the study population does not allow meaningful clinical conclusions to be drawn and implemented in other populations.

V. CONCLUSION

In conclusion, our findings indicated that wearing a passive-assistive hip exoskeleton (i.e., aLQ) did not hinder the successful navigation of daily encountered obstacles among young able-bodied adults in outdoor conditions. There were no changes in cadence, gait velocity, step length, and double stance time as well as a slight change in the range of motion of the internal rotation of the right hip joint angle. These findings underlined that overground gait was mostly not altered during walking with a passive-assistive hip exoskeleton and navigating through everyday obstacles. Thus, the present study indicates that there were no apparent higher risks of falling or tripping in young able-bodied male adults. These findings indicate that this device could be the first steppingstone in designing and investigating larger clinical studies in various other at-risk populations. Further research is needed regarding the effect of wearing a passive-assistive hip exoskeleton and investigate the possible long-term changes in spatiotemporal parameters and changes occurring among young and elderly adults.

STATEMENT

This manuscript has not been published elsewhere and it has not been simultaneously submitted for publication elsewhere. All tables and figures are our original work, and no permissions are required.

ACKNOWLEDGEMENTS

The authors would like to thank Imasen for loaning out the aLQ exoskeletons. The study was funded by Imasen, Aalborg Municipality and Aalborg University.

CONFLICT OF INTEREST

Imasen loaned the exoskeletons but did not influence the analyses or the interpretation of the findings.

Accepted for publication in Critical Reviews in Physical and Rehabilitation Medicine.
Cite as: Overground Walking with a Passive Hip Exoskeleton during Obstacle Avoidance in Young Able-Bodied Adult. Pirscoveanu, C-I., Hansen, J., Pedersen, M. & Madeleine, P., 2022, In: Critical Reviews in Physical and Rehabilitation Medicine. 34, 3, p. 1-13.

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Table 1: Mean ± standard deviation for cadence (steps/s), double stance time (ms), step length (m), and velocity(m/s) while walking with an exoskeleton (EXO) and no exoskeleton (NoEXO) during stepping up ($Step_{up}$), stepping over ($Step_{over}$) and no obstacle (No_{obs}) with a level of significance ≤0.05 (*p*) and effect size (r) reported.

Variable	***Walk***	***Exo***	***NoExo***	***p***	***r***
Cadence (step/s)	$Step_{up}$	1.82 ± 0.26	1.93 ± 0.33	0.60	-0.16
	$Step_{over}$	2.20 ± 0.27	2.11 ± 0.18	0.25	0.37
	No_{obs}	2.17±0.22	2.09 ± 0.27	0.37	0.28
Double stance time (ms)	$Step_{up}$	0.08 ± 0.02	0.08 ± 0.01	0.86	0.05
	$Step_{over}$	0.08 ± 0.01	0.09 ± 0.01	0.19	0.37
	No_{obs}	0.07 ± 0.01	0.07 ± 0.01	1.00	0.00
Step length (m)	$Step_{up}$	0.72 ± 0.09	0.74 ± 0.07	0.20	-0.42
	$Step_{over}$	0.73 ± 0.04	0.73 ± 0.04	0.91	0.04
	No_{obs}	0.75 ± 0.09	0.75 ± 0.05	0.90	-0.04
Velocity (s)	$Step_{up}$	1.28 ± 0.12	1.28 ± 0.14	0.97	-0.01
	$Step_{over}$	1.37 ± 0.06	1.36 ± 0.07	0.22	0.40
	No_{obs}	1.39 ± 0.16	1.38 ± 0.14	0.74	0.10

Table 2: Mean ± standard deviation for left and right hip joint range of motion angles (°) while walking with an exoskeleton (EXO) and no exoskeleton (NoEXO) during stepping up ($Step_{up}$), stepping over ($Step_{over}$), and no obstacle (No_{obs}) with a level of significance ≤ 0.05 (p) and effect size (r) reported.

Range of motion	***Walk***	***EXO***	***NoEXO***	***p***	***r***
Left Hip (°) *Flexion/extension*	$Step_{up}$	38.3 ± 4.6	38.5 ± 4.5	0.72	-0.11
	$Step_{over}$	32.4 ± 3.5	32.6 ± 3.7	0.75	-0.10
	No_{obs}	35.1 ± 4.2	36.2 ± 3.6	0.75	-0.10
Abduction/adduction	$Step_{up}$	11.3 ± 3.3	11.8 ± 3.4	0.54	-0.19
	$Step_{over}$	8.2 ± 1.4	8.7 ± 2.6	0.47	-0.23
	No_{obs}	10.9 ± 3.0	10.5 ± 2.3	0.75	-0.10
Internal/external rotation	$Step_{up}$	11.3 ± 3.3	11.8 ± 3.4	0.54	-0.19
	$Step_{over}$	8.2 ± 1.4	8.7 ± 2.6	0.47	-0.23
	No_{obs}	9.0 ± 1.8	9.8 ± 2.1	0.47	-0.23
Right Hip (°) *Flexion/extension*	$Step_{up}$	40.7 ± 5.7	39.9 ± 6.2	0.23	0.38
	$Step_{over}$	32.8 ± 3.5	32.3 ± 3.7	0.41	0.26
	No_{obs}	36.0 ± 4.6	36.0 ± 0.9	0.41	0.25
Abduction/adduction	$Step_{up}$	9.9 ± 2.6	10.0 ± 2.4	0.41	0.26
	$Step_{over}$	9.9 ± 2.2	10.0 ± 1.5	0.10	0.55
	No_{obs}	9.9 ± 2.8	9.8 ± 3.2	0.87	-0.05
Internal/external rotation	$Step_{up}$	9.8 ± 2.1	9.8 ± 3.3	0.88	0.05
	$Step_{over}$	2.1 ± 3.8	1.7 ± 4.3	0.05*	0.67
	No_{obs}	8.4 ± 1.5	8.9 ± 2.0	0.04*	-0.72

* represents p-value ≤ 0.05

Figures Legends:

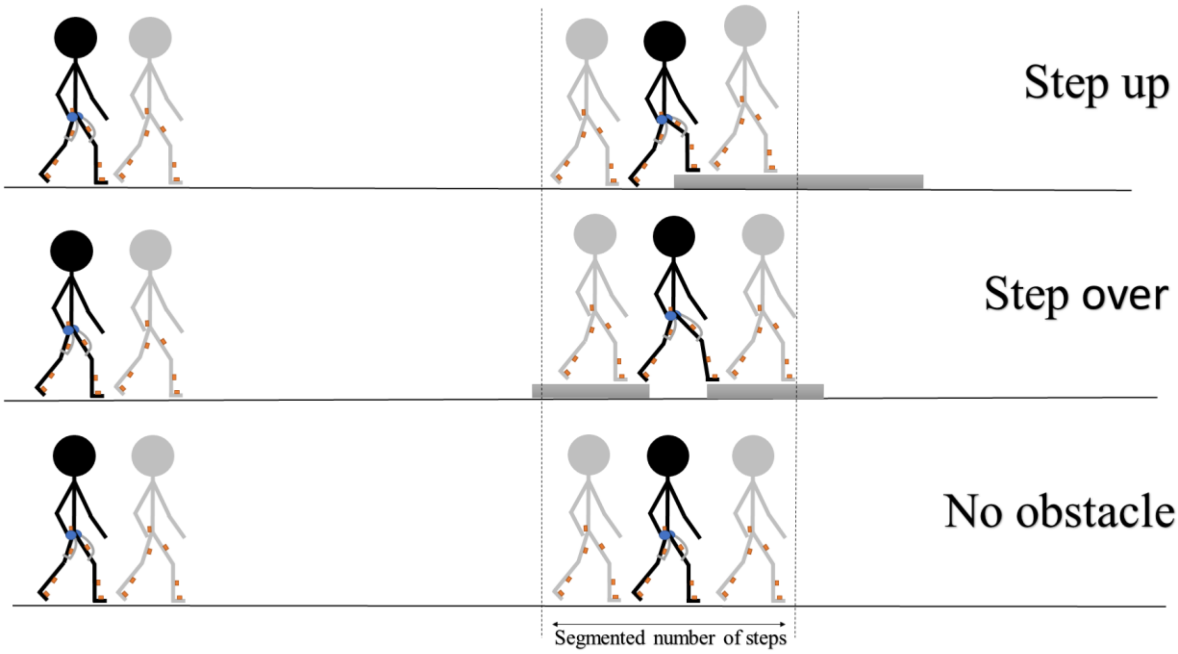

FIGURE 1: Illustration of the walking courses containing each obstacle from the top: stepping up, stepping over, and no obstacle. The stick figure illustrates a walking participant with the Xsens equipment (orange squares) with the exoskeleton (dark stick figure) and without the exoskeleton (gray stick figure). The segmented section of each walking trial is illustrated in the middle of the figure.