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Differences of gait adaptability behavior between young and healthy older adults during a locomotor pointing task in virtual reality

Lisa Delbes¹, Nicolas Mascret¹, Cédric Goulon¹, Gilles Montagne^{1*}

¹Aix Marseille Univ, CNRS, ISM, Marseille, France

Corresponding author:

Gilles Montagne:

Aix-Marseille Université
Institut des Sciences du Mouvement
163 avenue de Luminy
F-13009 Marseille • France
Email address: gilles.montagne@univ-amu.fr

Lisa Delbès

Aix-Marseille Université
Institut des Sciences du Mouvement
163 avenue de Luminy
F-13009 Marseille • France
Email address: lisa.delbes@univ-amu.fr

Nicolas Mascret:

Aix-Marseille Université
Institut des Sciences du Mouvement
163 avenue de Luminy
F-13009 Marseille • France
Email address: nicolas.mascret@univ-amu.fr

Cédric Goulon:

Aix-Marseille Université
Institut des Sciences du Mouvement
163 avenue de Luminy
F-13009 Marseille • France
Email address: cedric.goulon@univ-amu.fr

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Research Highlights

Highlights

- Older adults initiated their gait adjustments earlier in comparison to young adults.
- Gait adaptability behavior depends on the current state of the agent-environment system.
- Virtual reality appears as a relevant tool to propose relevant training programs in older adults.

Abstract

Background

Gait adaptability training programs to prevent falls in healthy older adults can be proposed in virtual reality. The development of training programs requires the characterization of the target population.

Research question

Before proposing an innovative training program to develop gait adaptability behavior of healthy older adults in fully immersive virtual reality, we had to compare gait adaptability behavior between healthy older adults and young adults in virtual reality.

Methods

Twenty healthy older adults (with no fall history) and twenty young adults performed a goal-directed locomotion task in a totally secure virtual reality set-up. Gait adaptability behavior was investigated via a set of measures taking into account gait speed, pointing accuracy, and the evolution of the relationship between the participant and the environment through both inter-trial and trial-by-trial analyses. Mann-Whitney tests and linear regressions were performed to determine potential age differences.

Results

The results reveal some common and specific strategies in gait adaptability behavior between healthy older and young adults. In both populations, successive gait adjustments depend on the state of the agent-environment system. However, older adults walked more slowly than young adults ($p < .001$) with a greater coupling at the end of the target approach ($p = .003$).

Significance

In the context of fall prevention in healthy older adults, fully immersive VR appears as a relevant tool to propose relevant gait training programs to improve gait adjustments.

Keywords: fall prevention; virtual reality; gait adaptability behavior; age comparison

1. Introduction

Falls are a major societal issue, with one third of adults over the age of 65 falling at least once each year [1]. Falls occur mostly in cluttered environments when the required adaptive gait adjustments are imperfectly performed [2, 3]. In the context of falls in the elderly, many remedial gait interventions are proposed to prevent falls with older adults who have already experienced a fall [4]. These curative interventions are intended to develop gait adaptability behavior. Gait adaptability behavior refers to gait adjustments underlying the completion of goal-directed displacements in a more or less cluttered environment in order to avoid objects in the environment or, conversely, to intercept them [4-6]. According to the ecological approach to perception and action, the control mechanisms underlying these gait adjustments are based on a continuous visual control based on an information-movement coupling [7]. This tight coupling between information and movement has been very well described in goal-directed locomotion tasks in which the participants must adjust step lengths in order to position their foot on a target placed on the ground (e.g., [8, 9, 10]).

Gait adaptability behavior is affected by aging [11] and impaired gait adaptability is associated with a high risk of falling [6, 12]. Given the fact that older adults who have fallen once experience another fall within a year in 66 percent of cases [13] and that fall history is the strongest predictor of future falls in the elderly [14], approaches more centered on prevention of falls could be worth considering.

Virtual reality (VR) technologies appear as a relevant tool to propose gait adaptability training with a preventive approach [15, 16]. A recent study showed that the gait adaptability behavior of healthy older adults is the same whatever the environment (real vs. virtual) during a goal-directed locomotion task [17]. It seems clear that gait adaptability training programs

must also be proposed to healthy older adults with no fall history to avoid the first fall occurrence leading to repeated falls.

To develop these programs, a characterization of this specific population is necessary to detect if they have the same gait adaptability behavior as young adults. Characterizing the target population as precisely as possible will enable us to propose the most coherent training program content. Our long-term objective is to develop a training program designed to improve the gait adaptability of healthy older adults using fully immersive VR. For this reason, the present study compares the gait adaptability behavior of healthy older adults (with no fall history) and young adults in a goal-directed locomotion task performed in fully immersive VR. This comparison will allow us to characterize our specific population of older adults and determine potential population differences for developing our future gait training program.

To date, comparisons of gait adaptability behavior between young and healthy older adults in virtual environments have led to contradictory results. Janeh et al. [18] showed that older adults adopted the same gait adaptability behavior as young adults in terms of gait speed and step length. However, Osoba et al. [19] showed that older adults walked with shorter and slower strides compared to young adults. It is worth mentioning that the study of gait adaptability behavior in these two previous studies was limited to the analysis of gait parameters reflecting only the participants' behavior (i.e., without indicators of gait adjustments related to the environment). Gait adjustments, which allow participants to deal with environmental challenges, were imperfectly investigated. As in previous studies [9, 10, 17], gait adaptability behavior will be analyzed in the present study through a method which takes into account successive feet positions in relation to the target to be pointed [8].

To sum up, the present study will provide additional knowledge about gait adaptability behavior comparison (calling on new levels of gait analysis) between healthy older adults (with no fall history) and young adults during a goal-directed locomotion task in VR.

Secondly, the use of VR necessarily requires the study of acceptance of the VR device used to ensure that participants accept the technology, to avoid the risk that low acceptance will impact gait adaptability behavior. In accordance with the Technology Acceptance Model (TAM) [20, 21], it was shown that the intention to use VR technology is positively predicted by its perceived usefulness, its perceived ease of use, and perceived enjoyment [22]. In the context of fall prevention, studies showed that older adults accepted the VR technology before and after use [17, 23]. But no study, to our knowledge, has made the comparison between healthy older and young adults, which was a secondary aim of the present study.

2. Methods & Materials

Population

Twenty young adults (22.4 ± 2.8 years, 66.4 ± 8.9 kg, 176 ± 9 cm, 11 females and 9 males) and twenty healthy older adults (68.6 ± 3.4 years, 65.2 ± 10.1 kg, 174 ± 5 cm, 11 females and 9 males) volunteered to take part in the experiment. Participants should have never used an head-mounted device (HMD) before and never experienced a fall before. A Mann-Whitney test revealed that over-ground preferential gait speed (no VR) was similar between older and young adults ($p = .09$; 1.02 m/s (SD = 0.02 m/s) and 1.11 m/s (SD = 0.03 m/s, respectively). This lack of difference reveals that our older adult population has specific characteristics (i.e., active healthy older adults) which corresponds precisely to our research question on preventing the first fall occurrence. Participants had normal or corrected-to-normal vision and were included in the study if they were able to walk independently. These participants had no neurological, vestibular, cardiac, pulmonary, or orthopedic disorders. Participants had a Montreal Cognitive Assessment (MoCA) score between 26 and 30 [24]. The study was conducted in line with the

ethical guidelines of the national ethics committee (Ethical Committee for Research no. XXX, anonymous version of the article), as well as in compliance with the Declaration of Helsinki for human research and the international principles governing research on humans.

Procedure

Participants' feet positions were recorded in VR during a locomotor pointing task, which is paradigmatic to investigate the mechanisms underlying goal-directed locomotion [8-10, 17]. Participants had a familiarization period followed by an experimental phase consisting of two blocks of 10 pointing trials (to minimize cybersickness symptoms). Participants were instructed to place themselves in the starting area and to place their right foot tip as close as possible to the nearest edge of a flat target 5 cm long while walking at a normal pace and continuing to walk subsequently (Figure 1).

[FIGURE 1 NEAR HERE]

Set-up

Participants wore HTC Vive Pro[®] foot trackers on their feet which display two virtual foot avatars in the virtual environment (VE) and record their avatars' foot positions (in relation to the target) (Figure 2.A). A wireless HTC Vive Pro[®] HMD was used to display a VE which mimics the experimental room (Figure 2.D). The participants were equipped with a security system consisting of a safety harness connected to an in-ceiling rail by a safety rope and carabiner (Figure 2.B and 2.C).

[FIGURE 2 NEAR HERE]

Outcome variables

Gait parameters

Gait speed, step lengths, and toe-obstacle distances were computed from the feet positions, using MATLAB® (version R2017b, The MathWorks, Inc., USA). A step corresponded to two consecutive foot contacts (i.e., footfalls) of two different legs.

Gait speed

The average gait speed on the first five steps of each trial was computed. The standard deviation (within-subject inter-trial) of the gait speed was also calculated.

Pointing errors analysis

The absolute pointing error (APE) (i.e., the mean absolute value of the difference between the toe of the foot and the target at the last footfall) reflects the overall accuracy without considering the direction of the error.

The constant pointing error (CPE) (i.e., the signed mean difference between the toe of the foot and the target at the last footfall) reflects the direction of the pointing errors. It is negative when the toe was before the target (undershoot) and positive when the toe was after the target (overshoot).

Inter-trial analyses

Separately for each participant, during each foot-ground contact, the toe-obstacle distance was calculated for subsequent analyses. Two successive toe-obstacle distances made it possible to define a step length. The analysis then focused on the standard deviation (intra-subject and inter-trial) of both successive toe-obstacle distances (SD_{tod}) and successive step lengths (SD_{sl}).

Trial-by-trial analysis

An average pattern of step length was calculated from the mean step lengths of all 20 trials for each participant. Following Montagne et al.'s [8] method, a threshold of 4% is established on both sides of the average pattern of step length. For each participant and each trial, adjustments were identified by comparing each step length with the average pattern of step length. The amount of adjustments needed (AN) represents the difference between the current toe-obstacle distance and the average toe-obstacle distance for that footfall. The amount of adjustments produced (AP) represents the difference between the current step length and the average of the step length for that footfall. For each trial, the amount of AN at a given footfall and the amount of AP at the following step were computed for each footfall, as in previous studies in older adults [10, 17].

Acceptance of the VR-HMD

After the experimental phase, acceptance was assessed using self-reported questionnaires to quantify acceptance of the VR-HMD after use (Supplementary Materials 1) through four variables: perceived usefulness (PU), perceived ease of use (PEU), perceived

enjoyment (PE), and behavioral intention to use (BIU) [13]. Internal consistency was good for each variable, with McDonald's omegas ranging from .82 to .99.

Statistical analyses

The statistical software JASP (Version 0.14.1, 2021) was used to run statistical analyses. The statistical level of significance was set at $\alpha = .05$.

Between-group differences for gait speed, pointing accuracy, pattern of standard deviation of toe-obstacle distances and of step lengths (footfall by footfall), and acceptance were evaluated using Mann-Whitney tests. Wilcoxon tests were used, on footfalls two by two, to assess the onset of step adjustments. Nonparametric tests were used because the data did not follow a normal distribution. A linear regression was calculated to assess the relationship between the amount of adjustments needed and the amount of adjustments produced. Between-group differences on linear regression coefficients were evaluated using parametric T-tests.

3. Results

Gait parameters

Gait speed analysis

While the gait speed recorded in the tests carried out before the experiment (no VR) did not reveal any differences between the two populations, older adults walked more slowly than young adults in VR, at 0.97 m/s (SD = 0.06 m/s) and at 1.11 m/s (SD = 0.05 m/s), respectively ($p < .001$).

Pointing errors analysis

Older adults' absolute pointing errors were 2.78 cm (SD = 0.86 cm) and young adults' absolute pointing errors were 2.94 cm (SD = 0.98 cm). No difference was found between young and older adults ($p = .527$).

Older adults' constant pointing errors were -2.47 cm (SD = 0.98 cm) and young adults' constant pointing errors were -2.31 cm (SD = 1.44 cm). No difference was found between young and older adults ($p = .813$). Both young and older adults tended to place their feet before the target.

Inter-trial analyses

For both young and older adults, at the beginning of the target approach, the SD_{tod} was high (25.2 cm and 26.0 cm on average, respectively) and decreased through the approaches with an average value of 2.7 cm and 2.5 cm, respectively, at the last footfall whereas the SD_{sl} was low (3.5 cm and 3.7 cm on average, respectively) at the beginning of the target approach and increased through the approaches with an average value of 12.6 and 11.4 cm, respectively, at the last step.

No difference was found between the patterns of the SD_{tod} and the SD_{sl} between older and young adults (all $ps > .05$) computed over the target approach (Figure 3).

However, the onset of regulation (defined as the step rank for which an increase in step length variability is observed with reference to the previous step) for young adults was at

footfall -1 whereas the onset of regulation for older adults was at footfall -2. Older adults initiated their regulation one footfall earlier than young adults.

[FIGURE 3 NEAR HERE]

Trial-by-trial analysis

Linear regression analyses showed a significant linear relationship between the amount of AN and the amount of AP, only from footfall -4 to last footfall (footfall 0), with increasing slopes (β) and R^2 values for all footfalls, for young and older adults (**Table 1**).

Concerning slopes, the only difference between young and older adults was found at footfall -1 ($p = .003$) with a larger slope for older adults than for young adults.

[TABLE 1 NEAR HERE]

Acceptance of the VR-HMD

Young and older adults had a high perceived ease of use and perceived enjoyment (in comparison with the mean of the scale; all $ps < .001$). However, both young and older adults had moderate perceived usefulness and behavioral intention to use (in comparison with the mean of the scale). Both young and older adults considered the VR-HMD easy to use and enjoyable before use. Nevertheless, both of them considered the VR-HMD neither useful nor useless and they did not intend to use it, but they did not refuse it either. The detailed results of the VR-HMD acceptance are available in Supplementary Materials 2.

4. Discussion

Gait parameters

To the best of our knowledge, this is the first study examining age-related differences in gait adaptability behavior, during a goal-directed locomotion task performed in VR, with a combination of inter-trial and trial-by-trial analyses.

Gait speed analysis

In the present study, gait speeds were lower compared to those found in previous studies for both older and young adults. For older adults, Janeh et al. [18] found that healthy older adults walked on average at 1.09 m/s in VR. For young adults, Mohler et al. [25] found that they walked on average at 1.26 m/s in VR. This result can be explained by the experimental set-up with the safety harness connected to an in-ceiling rail by a lanyard which induces inertia during the first steps.

The difference in gait speed between older and young adults may be explained by age differences in gait speed as previously found in Osoba et al. [19]. By reducing their gait speed, older adults may adopt a “cautious” gait adaptability behavior to compensate for the decline of different body systems (e.g., balance and vestibular systems) with age [26].

Pointing errors analysis

Older and young adults produced the same low absolute pointing error. All participants were very accurate in the pointing task. These pointing errors were smaller than those recorded in a previous study conducted using VR in young adults which was 15 cm [27]. This difference may be explained by specific task constraints in the study by de Rugy et al. [27], with the disappearance of the target about one step before pointing.

Moreover, older and young adults had the same low constant pointing error reflecting pointing performances before the target (i.e., undershoot). These results showed that all participants tended to place their feet before the target as in the study by de Rugy et al. [27] with a constant pointing error of -2 cm. This result can be explained by the instructions given. The subsequent analyses will allow us to identify the gait adjustment strategies implemented by the participants in order to produce this level of accuracy.

Inter-trial analyses

Interestingly, the results revealed an increase in the mean standard deviation of step lengths combined with a decrease in the mean standard deviation of toe-obstacle distances at footfall -2 for older adults and at footfall -1 for young adults. On average, older adults initiated their regulation two steps before the target whereas young adults initiated their regulation one step before the target. Van Andel et al. [10] found no differences between older and young adults in the onset of regulation. This result can be explained by specific task constraints. In our study, participants had to perform a very accurate locomotor point task, which was more constraining in comparison with stepping onto a curb-like platform as in van Andel et al.'s study [10].

It is important to understand that the inter-trial analyses just allowed us to identify the average rank from which step length regulations are initiated. Only a trial-by-trial analysis can accurately describe the functional regulations implemented by the participants (cf. next section). Be that as it may, it is possible to affirm at this stage that, on average, older adults regulate earlier than young adults. The modulation of step lengths in the final steps to perform an optimal foot positioning tends to be increasingly accurate when approaching the target (e.g., [8, 28]). This pattern of compensatory variability underlines the need to correct the current foot position by changes in step length to perform accurate pointing in goal-directed locomotion tasks [10]. In our study, a different distribution of motor adjustments between young and older adults may explain the difference in the onset of regulation. An earlier initiation of adjustments allows a larger adjustment distribution on the last steps [9, 10]. Once again, the decline of some body systems with age, in particular the decrease of muscle strength and associated force production [29], induce differences in gait adaptability behavior. Changes in gait adaptability behavior reflect an adaptive and a compensatory mechanism to perform a “cautious” gait adaptability behavior [26].

Trial-by-trial analyses

The relationship between the amount of adjustments needed and the amount of adjustments produced gives supplementary information concerning the fact that gait adaptability behavior depends on the state of the agent-environment system. According to the ecological approach to perception and action, the agent and his/her environment are inseparable: the agent cannot be studied independently of the environment in which he/she moves [7]. The control of a goal-directed task based on a continuous information-movement coupling leads to successive gait adjustments depending on the state of the agent-environment

system [30]. The significant relationship between these two variables, from footfall -4 onwards with an increasing slope of the regression lines (β) for older and young adults, showed that the amount of adjustments produced at a given footfall moves closer and closer to the amount needed, during the target approach, to succeed in the task. In other words, the current difference of toe-obstacle distance at a given footfall was gradually rectified by a step length modulation leading up to the following footfall. For this reason, as in previous studies, the linearity of the relationship increased progressively from footfall -4 to footfall 0 and the slope was almost equal to 1 at footfall 0 [10, 17].

For both older and young adults, the successive adjustments produced, within a trial, depend on the current state of the agent-environment system. Step length adjustments were produced gradually but the slope difference at footfall -1 reveals age group differences (i.e., a larger slope for older adults) as previously shown in van Andel et al. [10]. Therefore, the distribution of step length modulation needed while approaching the target was spread over Therefore, the distribution of step length modulation needed while approaching the target was spread over a larger number of steps in older adults. This result can be interpreted as an adaptation of gait depending on gait capacities as explained in the inter-trial analyses.

Acceptance of the VR-HMD

We found that both older and young adults had a high perceived ease of use and perceived enjoyment. However, we found that they considered the VR-HMD neither useful nor useless and did not intend to use the VR-HMD, but they did not refuse it either. As shown in Delbes et al. [17], these neutral attitudes toward the VR-HMD may be explained by the presentation of the VR-HMD in a fall prevention context whereas the pointing task performed in the study was not effectively useful for preventing fall occurrence, which was not in fact its

objective. Finally, high levels of perceived ease of use and perceived enjoyment highlighted the user-friendly and hedonic perception of the participants during VR experience as previously found by Manis and Choi [22].

To sum up, the comparison of gait adaptability behavior between healthy older adults (with no fall history) and young adults in a goal-directed locomotion task highlighted specificities in terms of gait adjustment strategies. Although the gait adaptability behavior of healthy older adults is based on the state of the agent-environment system as with young adults, our results showed that older and young adults have different action abilities on the perceptual-motor mechanisms underlying motor control in goal-directed tasks [31]. Training program implementation must take these specificities into account: the participation of healthy older adults in a VR training program should optimize the circular relationships between information and movement. Gait adaptability behavior should be investigated by considering gait adjustments in relation to environmental constraints as recommended in the context of fall prevention in older adults [32].

In this context, fully immersive VR appears as a relevant tool to propose relevant gait training programs for healthy older adults. The content of the VR training sessions can lead to a high level of enjoyment (i.e., engagement increase) in controlled task conditions (i.e., consistency with action capabilities) [33]. However, some precautions need to be considered to enhance gait adaptability improvements in VR gait training programs. Firstly, the ecological validity of gait training must be ensured by the use of a VR device. Some VR devices allow a high level of immersion and non-constrained locomotion which should optimize the ecological validity of proposed virtual tasks [17]. In addition, motor learning principles (variability of practice, the amount of practice, individualization, and feedback

supplementation) should be implemented to optimize gait adaptability improvements [34]. Moreover, the investigation of potential gait adaptability behavior improvement should be investigated through levels of analyses which allow one to study the evolution of the state of the agent-environment system [10]. Nevertheless, knowledge of the mechanisms underlying gait adaptability behavior alone is not sufficient to conclude the relevance of a VR gait training program [23]. The effectiveness of a training program is also established by taking psychological determinants into account. For this reason, the study of the acceptance of the VR device used is necessary in future VR gait training program implementation.

5. Conclusion

This study showed that the gait adaptability behavior of both healthy older and young adults depends on the current state of the agent-environment system during a goal-directed locomotion task in VR. But our results highlighted that gait adjustment strategies reflect differences in action capacities between older and young adults. Future development of gait training programs in VR with healthy older adults must take into account the age differences in gait adaptability behavior found in this study. Thus, the content of the training sessions will be consistent with their action capabilities (i.e., challenges of the environment) leading to gait adjustment improvements. The study of the effectiveness of a training program must be based on investigation of gait adaptability behavior (in terms of perceptual-motor control) and of expectations about the program (in terms of acceptability). Future VR training program implementation should be based on older adults' specificities (from locomotor and psychological perspectives), the guarantee of ecological validity, and respect for motor learning principles.

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Table

Table 1: Slopes (β), R^2 values, p-values of β values, and p-value of β values comparison of linear relationship between the amount of adjustment needed at a certain footfall and the amount of adjustment produced in the following footfall for older adults and young. * $p < .05$

		Older adults	Young	P-value of β values comparison
Footfall -4	β	0.05	0.04	.310
	R^2	0.26	0.11	
	p-value of β values	< .01	< .01	
Footfall -3	β	0.09	0.07	.570
	R^2	0.42	0.28	
	p-value of β values	< .01	< .01	
Footfall -2	β	0.22	0.16	.075
	R^2	0.67	0.53	
	p-value of β values	< .01	< .01	
Footfall -1	β	0.46	0.36	.003*
	R^2	0.86	0.84	
	p-value of β values	< .01	< .01	
Footfall 0	β	0.92	0.89	0.223
	R^2	0.96	0.97	
	p-value of β values	< .01	< .01	

Figure captions

Figure 1: For each trial, participants were instructed to place their right foot tip as close as possible to the lower extremity of the target while walking at a normal pace and continuing to walk subsequently. To avoid locomotor regularities and prevent any calibration of the distance being covered, the position of the target was manipulated unbeknownst to the participants (3 different target positions: 0 ± 20 cm).

Figure 2: Test equipment. (A) A wireless HTC Vive Pro[®] was used to display (D) the virtual environment mimicking the experimental room. Two HTC Vive Pro[®] 2.0 trackers were used to record the positions of the feet and display virtual 3D shoes in the VR. The security system is composed of (C) a safety harness connected to (B) an in-ceiling rail by a safety rope and carabiner.

Figure 3: Patterns of the standard deviation of toe-obstacle distances and of step lengths as functions of footfall number. Data of older adults in red and of young adults in blue. Vertical lines mark the onset of step adjustments for older adults at footfall -2 (in red) and for young adults at footfall -1 (in blue). Footfall 0 is the pointing footfall. SDtod: standard deviation of toe-obstacle distances; SDsl: standard deviation of step lengths.

Figures

Figure 1

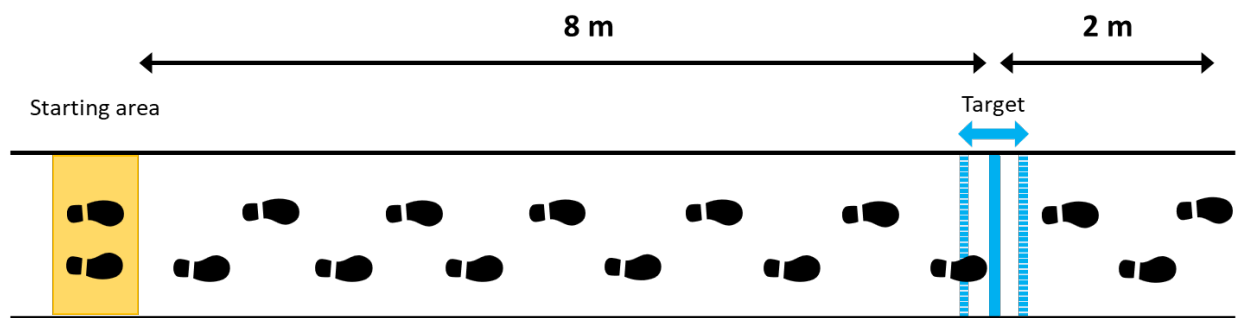


Figure 2

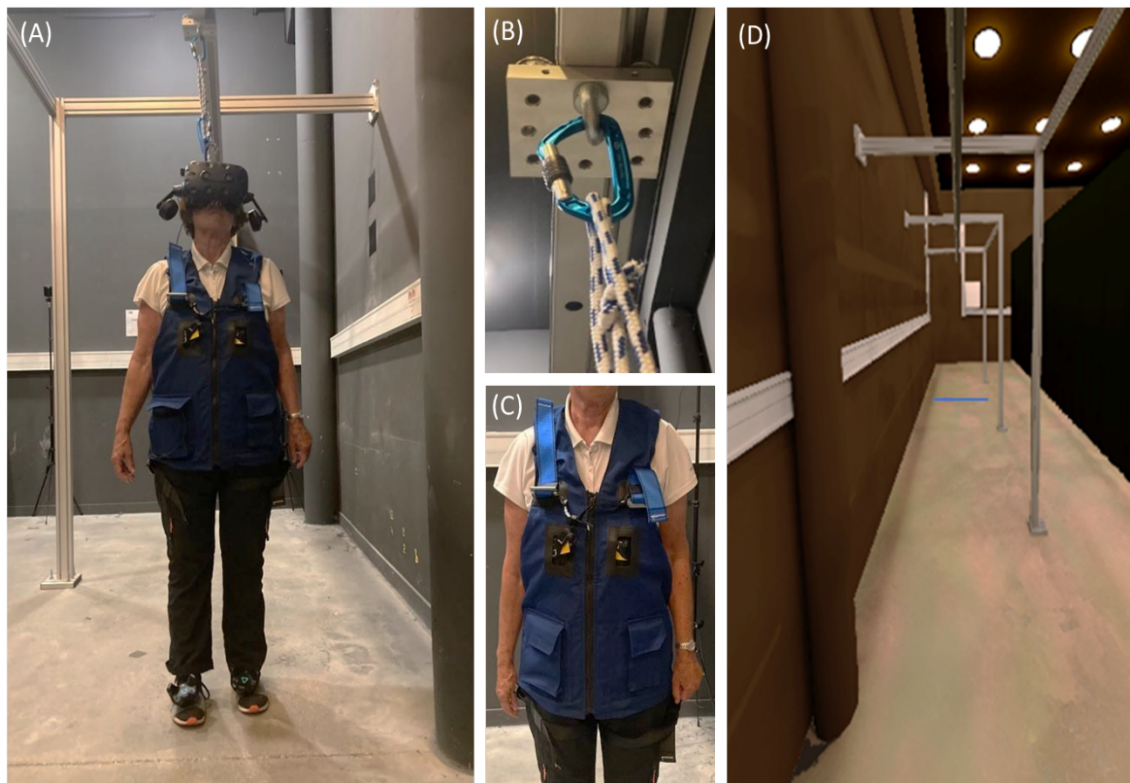


Figure 3

