

Biomechanical Assessment of Walking in Simulated Low-Vision Conditions Using a Visual Aid Device [†]

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Abstract

Low vision is a major factor limiting mobility and increasing the risk of falls globally, with a significant impact on quality of life. The article presents the analysis of the effects of simulated visual dysfunctions—cataract and glaucoma—on the biomechanical parameters of gait and evaluates the effectiveness of a portable device based on ultrasonic sensors, called the Tridirectional Device. A sample of 25 clinically healthy subjects was evaluated in five experimental conditions, using a plantar pressure distribution analysis system (RSScan), the Tinetti scale and the center of pressure trajectory analysis. The results highlight changes in gait parameters under the conditions of use of the device, suggesting its potential as an accessible and non-invasive solution for supporting people with visual impairments.

Keywords: low-vision; visual aid; ultrasonic sensor

1. Introduction

Low vision is one of the most common causes of limiting mobility and independence globally. According to the World Health Organization, at least 2.2 billion people live with some form of visual impairment, of which the main causes of vision impairment are cataracts (94 million) and glaucoma (7.7 million) [1]. The impact of low vision on locomotion is well documented in the biomechanical literature. Low vision reduces postural stability and significantly increases the risk of falls and fractures [2]. Adults with visual impairments walk with a shorter stride length, reduced trunk flexion, and earlier plantar contact upon landing compared to people with normal vision [3]. In the specific case of glaucoma, balance and gait parameters are associated with the rate of falls, and the integrated visual field remains an independent predictor of them [4].

Traditional assistive devices—the white cane and guide dog—have significant limitations in detecting obstacles. No electronic assistive device available to date has seen widespread adoption, with the main obstacles being high cost, complexity of use, and difficulty in learning [5]. Technologies based on ultrasonic sensors represent a promising alternative: ultrasonic sensors offer high-precision non-contact detection in the range of 2–400 cm and are successfully integrated into wearable devices for people with visual impairments [6–8]. Systems that combine multiple ultrasonic sensors to cover multiple detection fields allow not only the detection but also the location of obstacles [9].

The Tridirectional Device, developed by the authors of this study [10], uses three strategically placed ultrasonic sensors: one at the torso level, fixed to the belt, and two at the lower-limb level, positioned above the knee. This configuration allows for the coverage



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of a three-directional detection field and the user to be warned by sound signals with variable frequency, proportional to the proximity of obstacles. Unlike existing solutions on the market, the device was designed with an emphasis on economic accessibility, ease of use and anthropometric customization for each user.

The present study evaluates, through standardized biomechanical methods—plantar pressure analysis (RSScan), Tinetti scale, and center of pressure trajectory analysis—the impact of cataract and glaucoma simulation on gait and highlights the improvements brought about by the use of the Tridirectional Device compared to unassisted gait.

2. Materials and Methods

2.1. The Sample of Subjects

The study included 25 adult subjects (13 males, 12 females) who were clinically healthy, with no history of locomotor, neurological, or vestibular disorders. Subjects with refractive errors participated with optical correction, such that visual acuity was 100% or corrected to normal. Demographic parameters of the group are presented in Table 1.

Table 1. Demographic and anthropometric characteristics of the studied sample.

Characteristics	Total Number (25 Participants)	Male (13 Participants)	Female (12 Participants)
Age	41.2	46.1	36.0
Weight	80.2	91.5	68.0
Height	171.7	177.8	165.1
Shoe size	40.2	42.2	38.00

The distribution by age group was as follows: 15 subjects under 40 years of age, 5 subjects between 40 and 60 years of age, and 5 subjects over 60 years of age. This distribution reflects an active population with representation also of the age group at high risk of falling.

2.2. Simulating Visual Dysfunctions

Cataract was simulated by using glasses with matte lenses, which reduce visual acuity and contrast sensitivity, reproducing the effects of lens opacification. Glaucoma was simulated by using glasses that limit the peripheral visual field, reproducing the specific pattern of visual field loss associated with this condition.

2.3. Experimental Protocol

Each subject walked a standardized path of approximately 3 m, of which 2 m were covered by the RSscan Footscan System plantar pressure distribution analysis platform. The path included a side panel of textile material, used as an obstacle, detectable by the Tridirectional Device. The tests were performed under five experimental conditions, applied in the same order for all subjects: 1. normal walking, without visual simulation or assistive device (reference condition); 2. walking with cataract simulation, without device; 3. walking with cataract simulation and use of the Tridirectional Device; 4. walking with glaucoma simulation, without device; 5. walking with glaucoma simulation and use of the Tridirectional Device.

The Tridirectional Device was also compared with other visual assistance solutions, under identical experimental conditions.

Before testing, subjects received instructions on how the device works and went through a familiarization phase with the generated sound signals. The device was individually adjusted, according to the methodology described in the article [10].

2.4. Measured Parameters

Step symmetry was assessed by recording the number of steps taken with the right and left foot in each experimental condition.

The Tinetti score (gait and balance assessment scale, gait subscale, maximum score 12) was applied by the same evaluator for all five experimental conditions. The score reflects the overall quality of gait: ≤ 6 points indicate high risk of falling, 7–9 points moderate risk and ≥ 10 points low risk.

The trajectory of the center of pressure (COP) was recorded with the RSScan platform (Footscan 7 Gait, 4096 sensors/m²). The mean and maximum deviation of the COP trajectory from the normal gait condition, used as a reference, was calculated.

3. Results

3.1. Symmetry of Steps

The analysis of the mean number of steps in the right and left lower limb, depending on gender and experimental condition, is presented in Table 2. In the normal walking condition, both genders presented similar values, with an average of 2.0 steps for the right lower limb, both in women and men. For the left lower limb, the values were 2.0 in women and 1.8 in men.

Table 2. Average number of steps on the right (RF) and left (LF) foot according to gender and simulated low vision condition.

Measurement Type	Female RF	Female LF	Male RF	Male LF
Normal gait	2.0	2.0	2.0	1.8
Cataract simulation	2.8	2.0	2.7	2.2
Cataract simulation + Tridirectional Device	2.8	2.3	2.7	1.9
Glaucoma simulation	2.8	2.3	2.3	2.0
Glaucoma simulation + Tridirectional Device	2.6	2.0	2.5	1.8

In the cataract simulation condition, the mean number of steps for the right lower limb increased from normal walking from 2.0 to 2.8 in women and from 2.0 to 2.7 in men. For the left lower limb, the mean number of steps remained constant in women (2.0), while in men it increased from 1.8 to 2.2.

When using the Tridirectional Device in the cataract condition, the average number of steps for the right lower limb remained at the same level compared to the simulation without assistance, respectively 2.8 in women and 2.7 in men. For the left lower limb, the average number of steps increased from 2.0 to 2.3 compared to normal walking in women, while in men it returned from 2.2 to 1.9, approaching the value of normal walking (1.8).

In the glaucoma simulation condition, the mean number of steps for the right lower limb increased from normal walking from 2.0 to 2.8 in women and from 2.0 to 2.3 in men. For the left lower limb, the mean number of steps increased from 2.0 to 2.3 in women and from 1.8 to 2.0 in men. When using the Tridirectional Device in the glaucoma condition, the mean number of steps for the right lower limb decreased from the unassisted simulation from 2.8 to 2.6 in women and increased from 2.3 to 2.5 in men—both values remaining higher than normal walking (2.0). For the left lower limb, the mean number of steps returned to normal walking values in both women (2.0) and men (1.8).

3.2. Tinetti Score

In the normal walking condition, without simulating the low vision state, both women and men obtained the maximum score of 12.0 points, which confirms a good state of locomotor function shown in Table 3.

Table 3. Mean Tinetti score by gender and simulated condition.

Measurement Type	Female	Male
Normal gait	12.0	12.0
Cataract simulation	5.3	6.1
Cataract simulation + Tridirectional Device	8.4	8.7
Glaucoma simulation	6.1	6.5
Glaucoma simulation + Tridirectional Device	8.9	9.1

In the cataract simulation, scores decreased significantly, reaching 5.3 points in women and 6.1 points in men, values indicating an increased risk of falling. The introduction of the Tridirectional Device led to a visible improvement: the score increased to 8.4 points in women and 8.7 points in men, which allowed the transition from the high-risk category to the moderate-risk category.

A similar pattern was observed in the glaucoma simulation. The initial scores (12 points) decreased to 6.1 points in women and 6.5 points in men, and the use of the device led to an increase to 8.9 and 9.1 points, respectively, keeping participants in the moderate-risk category of falling.

In both visual simulations, women obtained lower scores than men (5.3 versus 6.1 in the case of cataract and 6.1 versus 6.5 in the case of glaucoma), which suggests a higher sensitivity to the disturbances of the simulated pathologies. Even when using the Tridirectional Device, men recorded higher final values, but the differences were small: 0.3 points in the case of cataract (8.7 versus 8.4) and 0.2 points in the case of glaucoma (9.1 versus 8.9).

3.3. Trajectory of the Center of Pressure

The lateral deviation of the center of pressure was analyzed in comparison with the normal walking condition, used as a standard. In the normal walking condition, women showed a mean deviation of -0.40 mm (± 6.34 mm), and men 1.74 mm (± 4.75 mm).

When cataract simulation was performed, women recorded a mean lateral deviation of -2.12 mm (± 6.64 mm), compared to -0.40 mm (± 6.34 mm) in the normal walking condition, representing a shift of 1.72 mm to the left compared to the standard (normal walking without simulation). In men, the mean lateral deviation in the cataract condition was 1.08 mm (± 9.08 mm), compared to 1.74 mm (± 4.75 mm) in the normal walking condition, representing a reduction in the deviation to the right by 0.66 mm compared to normal walking. Therefore, cataract simulation caused a deviation of the COP trajectory to the left in women, while in men the trajectory approached the center of the trajectory in normal walking.

When using the Tridirectional Device in cataract simulation, women recorded a mean lateral deviation of -2.49 mm (± 5.69 mm), compared to -0.40 mm (± 6.34 mm) in the standard, representing a shift of 2.09 mm to the left from normal gait. In men, the mean lateral deviation with the active device was 0.09 mm (± 7.11 mm), compared to 1.74 mm (± 4.75 mm) in the standard, representing a reduction in deviation to the right by 1.65 mm from normal gait and a significant approximation to the trajectory of the simulated cataract condition without visual assistance (1.08 mm). In women, use of the device did not decrease the deviation from the simulated cataract condition without assistance, with the deviation remaining at similar values (-2.12 mm versus -2.49 mm), like the example in Figure 1.

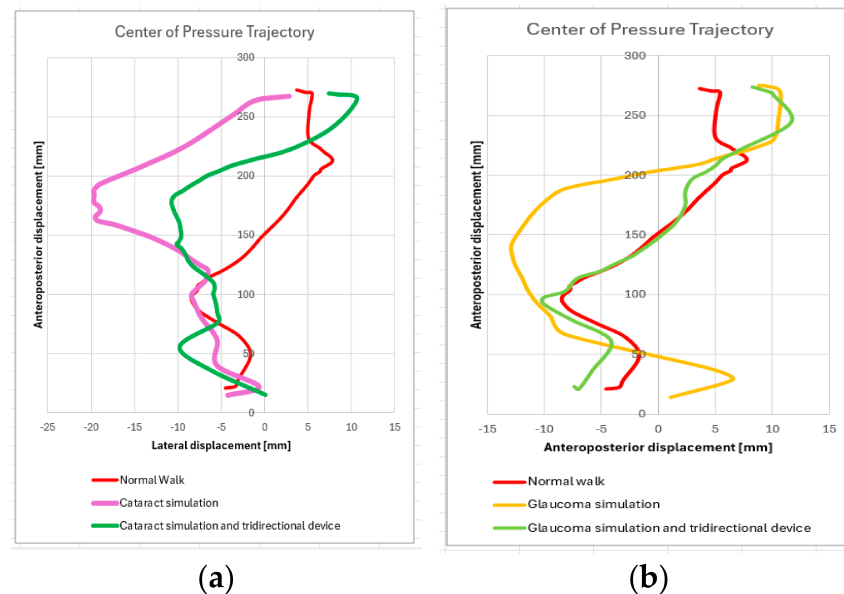


Figure 1. Center of pressure trajectory for a representative subject: (a) normal gait, cataract simulation, and cataract simulation with Tridirectional Device; (b) normal gait, glaucoma simulation, and glaucoma simulation with Tridirectional Device.

In the glaucoma simulation, women recorded a mean lateral deviation of -3.17 mm (± 6.03 mm), compared to -0.40 mm (± 6.34 mm) in the normal gait condition, representing a shift of 2.77 mm to the left from the standard. In men, the mean lateral deviation in the glaucoma condition was -2.94 mm (± 5.12 mm), compared to 1.74 mm (± 4.75 mm) in the normal gait, representing a shift of 4.68 mm to the left from the normal gait. Unlike the cataract simulation, in which the two genders showed different behaviors, in the glaucoma scenario both genders deviated in the same direction—to the left—from the normal gait, women by 2.77 mm and men by 4.68 mm.

When using the Tridirectional Device in the glaucoma simulation condition, women recorded a mean lateral deviation of -0.44 mm (± 5.58 mm), compared to -0.40 mm (± 6.34 mm) in the normal gait, representing an almost complete return to the values of the normal gait, with a difference of only 0.04 mm from the standard. In men, the mean lateral deviation with the active device was -3.49 mm (± 4.81 mm), compared to 1.74 mm (± 4.75 mm) in the standard, representing a deviation of 5.23 mm to the left from the normal gait. Therefore, in the glaucoma simulation, the Tridirectional Device brought the COP trajectory of women close to the standard values, while in men the lateral deviation was maintained and slightly increased compared to the glaucoma condition without assistance (-2.94 mm vs. -3.49 mm).

4. Conclusions

The present study evaluated the impact of simulated visual dysfunctions—cataract and glaucoma—on the biomechanical parameters of gait in a sample of 25 clinically healthy subjects and investigated the effectiveness of the Tridirectional Device with ultrasonic sensors in improving the identified disturbances.

Analysis of step symmetry revealed a deterioration in gait in both visual simulation scenarios compared to normal gait. In the normal gait condition, 22 of 25 subjects (88%) showed symmetrical gait. Cataract simulation reduced this percentage to 36% (9/25), and glaucoma simulation to 52% (13/25). Women showed a higher mean number of steps than men in all simulated scenarios, with the difference being most pronounced in the glaucoma scenario.

The Tinetti score confirmed a clear deterioration of gait quality under both visual simulation scenarios, with all 25 subjects scoring the maximum 12 points in normal gait. Cataract simulation reduced the mean score to 5.3 points in women and 6.1 points in men (high fall risk), while glaucoma simulation resulted in 6.1 points in women and 6.5 points in men. The use of the Tridirectional Device improved scores in all cases, eliminating the high-fall-risk category: in cataract, values increased to 8.4 points in women (+3.1) and 8.7 points in men (+2.6), and in glaucoma to 8.9 points in women (+2.8) and 9.1 points in men (+2.6).

Analysis of the lateral deviation of the center of pressure revealed that the cataract simulation caused a leftward deviation in women (−2.12 mm vs. −0.40 mm in the standard) and a slight reduction in the rightward deviation in men (1.08 mm vs. 1.74 mm in the standard). In the glaucoma scenario, both genders deviated to the left from normal gait, women by 2.77 mm and men by 4.68 mm. The use of the Tridirectional Device in the glaucoma scenario brought the COP trajectory of women close to the standard values (−0.44 mm vs. −0.40 mm in the standard), while in men the deviation remained at −3.49 mm.

The results of the study demonstrate that the Tridirectional Device improves the quality of walking under conditions of simulated visual dysfunction, with particularly clear results on the Tinetti score, where the high risk of falling was completely eliminated in both genders and in both scenarios. Future research directions include testing on larger groups, evaluating the effect of the training period with the device on biomechanical parameters, and testing on subjects with real visual pathologies.

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