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Original Article

Inducing unstable walking conditions through visual and auditory stimuli

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Abstract. [Purpose] Falls can significantly affect elderly individuals. However, most current methods used to detect and analyze high-risk conditions make use of simulated falling movements for data collection, which may not accurately represent actual falls. The present study aimed to induce natural falls using visual and auditory stimuli to create unstable walking conditions. [Participants and Methods] Two experiments were performed. The first experiment focused on inducing unstable walking using visual stimuli; whereas, the second experiment combined visual and auditory stimuli. To investigate the effects of stimuli on the induction of unstable walking, our results were compared with those of normal walking conditions. In addition, the two experimental conditions were compared to identify the most effective stimuli. [Results] Both experiments revealed a decrease in step length, an increase in step time and width, and an increase in the coefficient of variation of measurements, indicating an induced walking pattern with a higher risk of falls. Furthermore, combining visual and auditory stimuli caused deterioration of interlimb coordination, as observed through an increased phase coordination index, thus resulting in further instability during walking. [Conclusion] Visual and auditory stimuli induced unstable walking. In particular, the combination of visual and auditory stimuli with a 0.8-s rhythm increased instability.
Key words: Unstable walk, Visual stimuli, Auditory stimuli

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INTRODUCTION

Falls have a significant impact on a person's mobility and quality of life, particularly in older adults, and the severity of injuries tends to increase with increasing age. Numerous studies have proposed various fall detection systems[1)], many of which focus on detecting impact forces upon hitting the ground[2)] or activating safety devices based on changes in acceleration during a fall[3)]. However, these methods primarily aim to mitigate the severity of an injury after a fall has already occurred or to quickly notify third parties about a fall, rather than preventing the fall itself. To address this issue, it is essential to emphasize on the pre-fall condition to detect potential circumstances resulting into falls, thereby allowing third parties, such as physicians or caregivers, to take appropriate preventive measures. Our previous research involved the development of a system for detecting and classifying pre-fall conditions[4)], known as near-falls, using datasets such as SisFall[5)] and KFall[6)]. However, many previous studies, including ours, have the tendency to simulate falling movements or high-risk walking conditions in younger participants, potentially affecting the accuracy of the actual systems developed[7)].

To acquire actual falling movements, attaching sensors to the body or using continuous monitoring devices may be an effective means. However, a study involving 16 elderly participants who wore sensors for a six-month investigation detected

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only five instances of falls, indicating that creating a dataset through this method requires a substantial amount of time[8]. Additionally, the collection of data directly from older adults presents significant safety challenges. Therefore, it is necessary to develop alternative and more effective methods for data collection.

Previous research demonstrated that visual and auditory stimuli could improve the walking function of older adults and individuals with impaired mobility or underlying conditions[9]. These stimuli influence gait patterns, and studies on young adults reported a decline in walking function compared to normal walking[10]. Human balance integrates visual, vestibular, and proprioceptive information centrally, affecting both posture and gait. Therefore, it is believed that the presentation of visual stimuli affects central integration, influencing posture and gait. Additionally, when the uncertainty of visual information increases due to visual stimuli, auditory input becomes dominant, and individuals attempt to maintain their posture based on surrounding auditory information. Furthermore, while auditory stimuli alone have little effect[11], combining them with visual stimuli has been reported to promote the influence on posture and gait. Considering that the presentation of stimuli increases the uncertainty of both visual and auditory information[12], it is important to combine visual and auditory stimuli in inducing unstable gait.

In the present study, both visual and auditory stimuli were used to induce abnormal sensory integration and unstable walking that led to falls. We compared normal walking conditions with walking induced by visual stimuli alone and a combination of visual and auditory stimuli (referred to as audio-visual stimuli). In addition, walking induced by visual stimuli alone and walking under audio-visual stimuli were compared, aiming to identify the stimuli that could induce unstable walking more effectively.

PARTICIPANTS AND METHODS

In this study, we conducted two experiments: Experiment 1, in which participants were instructed to walk while being exposed to visual stimuli only; and Experiment 2, in which participants were instructed to walk while being exposed to audio-visual stimuli. For Experiment 1, the participants were 4 young healthy males and 2 young healthy females (age, 22.8 ± 0.3 years; body height, 1.63 ± 0.03 m; body weight, 57.3 ± 2.86 kg), while Experiment 2 involved 6 healthy young adult male participants (age, 23.3 ± 0.7 years; body height, 1.66 ± 0.03 m; body weight, 57.0 ± 3.00 kg). All experimental procedures were conducted in accordance with the Declaration of Helsinki. All experimental procedures were approved by the Ethics Committee for Human Research of Graduate School of Life Science and Systems Engineering, Kyushu Institute of Technology (approval number: 23-16). During the experiments, visual stimuli were presented using VR goggles (VR Box2.0, 8Ware) with a smartphone attached to the participants. Three types of visual stimuli were utilized: 1) vertical vibration (referred to as “Vibration”), 2) lateral waving motion (referred to as “Wave”), and 3) irregular movement in both vertical and lateral directions (referred to as “Irregular”). The selected visual stimuli simulated visual disturbances observed during dizziness or visual oscillations. Figure 1 illustrates the visual stimuli.

Wireless headphones (WH-CH710N B, Sony, Tokyo, Japan) were used for the generation of auditory stimuli. More specifically, four types of stimuli were presented using a pure tone of 440 Hz, as follows: 1) sound moving from left to right (referred to as “Left–Right”), 2) sound moving from front to back (referred to as “Front–Back”), 3) rhythm auditory stimulus with a 0.4-sec interval (referred to as “0.4 s”), and 4) rhythm auditory stimulus with a 0.8-sec interval (referred to as “0.8 s”). On the basis of past findings suggesting that left–right and front–back auditory stimuli can influence postural displacement[13], we hypothesized an impact on the participants’ self-motion perception during walking. In addition, rhythm auditory stimuli with a different tempo than normal walking were presented, which were inspired by previous studies reporting significant

Fig. 1. Imagery of visual stimuli.
From left to right: “vibration”, “wave”, and “irregular”.

changes in gait under altered walking speeds[14]. Consequently, participants were instructed to adjust their walking cycle according to the rhythm, inducing an altered walking state.

An optical motion capture system consisting of 10 infrared cameras (Flex13, Acuity, Tokyo, Japan) was used for data collection during walking. Infrared reflective markers (diameter: 12.7 mm, Novitech, Tokyo, Japan) were attached to four locations, namely heels and toes of both legs, and the motion was recorded at a sampling rate of 100 Hz.

To prevent accidental falls while walking, a cuddling robot (SH-YR21-0001, Sanyo Homes, Osaka, Japan) was used, as shown in Fig. 2, which was equipped with downward-facing accelerometers activating the actuators upon detection of vertical acceleration. In addition, brakes were applied depending on the speed, thereby mitigating the impact of a fall.

Our experimental procedure was as follows: In both experiments, participants walked a distance of 15 m. Measurements using the optical motion capture system were conducted between 5 and 10 m from the starting point.

In Experiment 1, participants performed normal walking at their own pace. After normal walking, three types of visual stimuli were randomly presented without prior notice. Each stimulus was measured in 10 trials. In Experiment 2, participants performed normal walking at their own pace and subsequently walked while being exposed to a combination of visual and auditory stimuli. Three visual stimuli, similar to those presented in Experiment 1, were used along with four auditory stimuli, resulting in a total of 12 combinations of audio-visual stimuli. Each combination was presented randomly, and four trials were made for each combination. An overview of the entire experimental process is illustrated in Fig. 3.

Measurements related to walking, including step length, step width, step time, and the coefficient of variation (CV) for each, were conducted using the optical motion capture system, focusing on data obtained from the heels and toes of both legs. The CV is known as an indicator of gait stability and is expressed as the ratio of the SD to the mean, with a larger value indicating less stability[15]. Additionally, the phase coordination index (PCI) was employed as an indicator of coordination

Fig. 2. Cuddling robot.

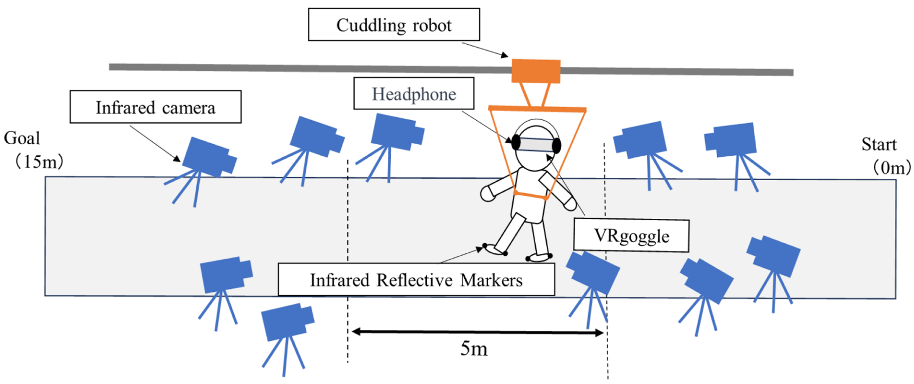

Fig. 3. Image of the experimental environment.

between the lower limbs. PCI evaluates the symmetry and variability of one step's symmetry, with higher values indicating greater instability in dynamic walking[16].

For Experiment 1, the average and SD of 10 trials were used as individual representative values, while for Experiment 2, the average and SD of 4 trials were employed for each participant.

Statistical analysis was performed by using the Mann–Whitney U test. All statistical analyses were performed using EZR (version 4.2.1)[17], with the significance level set at 5%.

RESULTS

Table 1 presents the walking parameters during normal walking and under three types of visual stimuli presented in Experiment 1, including measurements of step length, step time, and step width. Our results showed that the step length significantly decreased, whereas step time and step width were both significantly increased compared with normal walking. Additionally, the CV and PCI for each parameter was significantly increased compared with normal walking.

Table 2 displays the walking parameters during normal walking and when audio-visual stimuli were presented in Experiment 2. We found that the step length significantly decreased, as opposed to the step width that was significantly increased when visual and auditory stimuli were presented. Furthermore, CV and PCI for each parameter significantly increased compared with normal walking.

Tables 3–5 demonstrate a comparison of the results obtained from our two experiments, where the coefficients of variation for each gait parameter and PCI are compared. More specifically, Tables 3–5 compare the combination of each auditory stimulus with "vibration", "wave", and "irregular" stimuli, respectively.

For Table 3, the left–right sound images and rhythm auditory stimuli at 0.8 s were found to significantly increase the value of PCI. Also, rhythm auditory stimuli at 0.4s significantly decreased stride length CV and time per step CV. Table 4 indicates

Table 1. Measurement results of Experiment 1

Stimuli	Step length [mm]	Step time [s]	Step width [mm]	Step lengthCV [%]	Step timeCV [%]	Step widthCV [%]	PCI [%]
Normal walk	602.08 ± 62.03	0.57 ± 0.040	54.91 ± 36.50	3.42 ± 2.29	2.62 ± 1.02	50.94 ± 20.70	3.66 ± 1.83
Vibration	496.81 ± 68.96*	0.59 ± 0.050*	74.39 ± 51.08*	6.30 ± 2.94*	4.56 ± 2.10*	58.03 ± 16.22*	6.33 ± 3.05*
Wave	508.34 ± 84.53*	0.58 ± 0.079*	77.91 ± 60.16*	6.09 ± 3.59*	5.09 ± 4.88*	62.70 ± 16.85*	6.97 ± 3.01*
Irregular	529.92 ± 81.50*	0.60 ± 0.046*	69.90 ± 56.80*	5.62 ± 3.33*	4.03 ± 2.38*	63.92 ± 18.63*	5.26 ± 3.38*

*p<0.05. Mann–Whitney U test.
CV: coefficient of variation; PCI: phase coordination index.

Table 2. Measurement results of Experiment 2

Stimuli	Step length [mm]	Step time [s]	Step width [mm]	Step lengthCV [%]	Step timeCV [%]	Step widthCV [%]	PCI [%]
Normal walk	637.93 ± 32.16	0.58 ± 0.037	39.30 ± 26.93	3.96 ± 2.55	2.80 ± 1.09	57.65 ± 21.36	3.42 ± 2.29
Vibration	582.31 ± 90.25*	0.60 ± 0.061	73.15 ± 25.44*	5.16 ± 2.99*	4.14 ± 2.46*	60.74 ± 17.67	6.91 ± 4.13*
Wave	582.75 ± 64.01*	0.60 ± 0.092	72.01 ± 30.90*	5.72 ± 3.02*	4.31 ± 1.86*	60.78 ± 15.91	8.04 ± 3.50*
Irregular	601.89 ± 80.49*	0.60 ± 0.093	68.52 ± 31.13*	4.98 ± 2.87*	4.18 ± 3.63*	60.50 ± 17.77	6.46 ± 3.94*

*p<0.05. Mann–Whitney U test.
CV: coefficient of variation; PCI: phase coordination index.

Table 3. Comparison of visual and audio-visual stimuli ("Vibration")

Stimuli	Step lengthCV [%]	Step timeCV [%]	Step widthCV [%]	PCI [%]
Visual stimuli	6.30 ± 2.94	4.56 ± 2.10	58.03 ± 16.22	6.33 ± 3.05
Left-Right	4.53 ± 2.00	4.42 ± 2.91	65.42 ± 22.75	8.35 ± 5.16*
Front-Back	5.69 ± 4.92	3.19 ± 1.72	66.94 ± 20.51	6.16 ± 3.50
0.4 s	3.88 ± 1.27*	3.47 ± 2.67*	56.17 ± 15.57	6.63 ± 4.27
0.8 s	4.11 ± 3.05	4.55 ± 3.16	59.13 ± 15.98	8.96 ± 5.39*

*p<0.05. Mann–Whitney U test.
CV: coefficient of variation; PCI: phase coordination index.

Table 4. Comparison of visual and audio-visual stimuli ("Wave")

Stimuli	Step lengthCV [%]	Step timeCV [%]	Step widthCV [%]	PCI [%]
Visual stimuli	6.09 ± 3.59	5.09 ± 4.88	62.70 ± 16.85	6.97 ± 3.01
Left-Right	6.17 ± 3.52	3.82 ± 1.31	56.88 ± 11.13	7.62 ± 3.68
Front-Back	4.99 ± 2.23	3.39 ± 0.84	55.17 ± 19.49	6.87 ± 7.94
0.4 s	5.22 ± 1.41	4.32 ± 2.01	60.04 ± 13.49	7.94 ± 3.26
0.8 s	7.24 ± 3.38*	5.64 ± 1.50*	62.21 ± 14.42	11.14 ± 3.50*

*p<0.05. Mann–Whitney U test.
CV: coefficient of variation; PCI: phase coordination index.

Table 5. Comparison of visual and audio-visual stimuli ("Irregular")

Stimuli	Step lengthCV [%]	Step timeCV [%]	Step widthCV [%]	PCI [%]
Visual stimuli	5.62 ± 3.33	4.03 ± 2.38	62.70 ± 16.85	6.97 ± 3.01
Left-Right	4.31 ± 2.52	2.90 ± 1.73	54.48 ± 20.30	5.94 ± 4.39
Front-Back	3.95 ± 1.63	3.15 ± 1.44	60.23 ± 15.32	5.65 ± 2.61
0.4 s	4.16 ± 2.19	3.76 ± 2.18	55.45 ± 17.47	7.01 ± 3.58
0.8 s	6.06 ± 2.28	7.11 ± 7.05*	64.83 ± 16.30	9.47 ± 4.59*

*p<0.05. Mann–Whitney U test.
CV: coefficient of variation; PCI: phase coordination index.

a significant increase in the values of step length CV, step time CV, and PCI when presenting rhythm auditory stimuli at 0.8 s. Finally, as shown in Table 5, the presentation of rhythm auditory stimuli at 0.8s s resulted in a significant increase in step time CV and PCI.

DISCUSSION

The present study aimed to induce unstable walking using visual and audio-visual stimuli. Decreased step length, decreased walking speed, increased step width, increased CV in each parameter, and increased PCI are the main characteristics of high fall risk during unstable walking[18].

Table 1 exhibits a significant decrease in step length, increased step time and step width for all parameters during the presentation of a visual stimulus compared with normal walking. At the same time, CV and PCI significantly increased compared with normal walking.

Table 2 indicates that the introduction of audio-visual stimuli results in similar findings to those of Experiment 1, except for no significant difference in step time.

Our findings are consistent with the results of previous studies investigating the variability of walking due to visual stimuli[19]. The presentation of visual or audio-visual stimuli affected the integration of unstable sensations, inducing an unstable walking state. It is also believed that the induced unstable walking state leads individuals to attempt cautious walking out of fear of falling. This reaction is characterized by decreased step length, increased step time, and increased stride width. These characteristics are reported in individuals with an unstable walking state, suggesting that the stimuli in this experiment induced an unstable walking state[20]. In this experiment, both visual and audio-visual stimuli induced unstable walking. Tables 3–5 compare walking variations and PCI during the introduction of visual stimuli alone but also when combined with auditory stimuli. The combination of 0.8-s interval rhythm auditory stimuli led to a significant increase in PCI for all three visual stimuli, beyond the instability induced by visual stimuli alone. As indicated in Table 1, the presentation of visual stimuli induced unstable walking. In addition, the presentation of rhythm auditory stimuli with a 0.8-s interval resulted in a slower walking pace than the normal walking cycle. This cautious walking pattern necessitated the attention of all participants, leading to an increase in single-leg support time. The worsening of interlimb coordination during cautious walking likely contributed to the increased dynamic instability identified during walking. Previous studies demonstrated that a decrease in the walking speed of individuals beyond their comfortable pace results in increased PCI[21]. In situations where participants needed to focus during the walking process, an increase in PCI occurred, influencing the variability in the stance phase[22]. Therefore, it is reasonable to assume that a similar effect occurred with the 0.8-s auditory stimuli presented in this study.

The combination of vibration stimuli and 0.4-s interval rhythm auditory stimuli led to a significant decrease in the stride length CV and time per step CV compared with the induction of visual stimuli alone. This result suggests that by unconsciously considering visual stimuli and walking at a faster pace than usual, participants achieved a more stable walking pattern, reducing the need to allocate their attention to the surroundings, as opposed to the visual stimuli alone condition.

The limitations of the present study is the short measurement distance during the experiment. Walking took place for 15 m, but measurements were only taken for 5 m in between. It is thought that the effect was particularly apparent for the step width, and that the CV of the step distance was calculated to be larger because the number of steps was reduced. More detailed data could be obtained by increasing the number of sensors and extending the measurement distance. In addition include the small number of young adult participants in both experimental groups. Future studies should increase the number of participants and explore various types of visual and auditory stimuli, considering factors such as stimulus intensity, regularity, and combinations based on physiological responses. The current study considers a method of stimulus selection that combines eye tracking, postural sway measurement, and subjective evaluation surveys.

Furthermore, the use of devices that can simulate the physical activity of the elderly should be considered for future walking experiments to induce unstable walking that is more similar to a real environment. We believe that by creating movements similar to those performed by elderly people while presenting audio-visual stimuli, it would be possible to facilitate a walking condition with a higher risk of falling.

The goal of this research was to induce unstable walking in the elderly population. Through a detailed examination of stimulus selection and induced walking patterns, this study aimed to induce unstable walking with a high risk of falls.

In conclusion, this study attempted to induce unstable walking through visual and audio-visual stimuli. The results revealed that both types of stimuli could successfully induce unstable walking. Furthermore, the combination of 0.8-s interval rhythm auditory stimuli with visual stimuli deteriorated interlimb coordination, indicating increased instability during dynamic walking. Future research will delve into a more detailed examination of combinations of visual and auditory stimuli to further investigate the optimal induction of walking.

Conference presentation

Part of this research was presented at the 11th International Joint Symposium on Applied Engineering and Sciences (SAES2023).

Conflict of interest

There are no conflicts of interest to be disclosed in this study.

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