Gait Analysis under MR-simulated Low-Light Environment

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Abstract

This study presents a safe and easy-to-use gait evaluation framework for low-light environments. We simulate such environments by applying a low-light filter to the passthrough image of a mixed-reality (MR) device. Using this setup, we also introduce an MR-based 5-meter walk test that can place virtual obstacles and record the trajectories of the feet, hands, and head during walking. In the user study, we observed that walking speed and step length tended to increase in the MR-simulated low-light environment, which is consistent with previous reports on real low-light environments.

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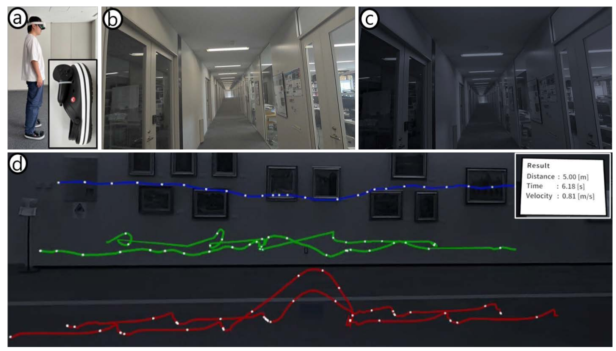

Figure 1: (a) A user wearing an HMD and shoes equipped with the controller. (b) MR-passthrough view. (c) Low-light view simulated with proposed method ($k = 0.08$). (d) Visualization of trajectories of head, hands, and feet during walking.

1 Introduction

Walking is a fundamental physical activity in daily life, and its evaluation and analysis are important in the rehabilitation of patients with various difficulties. The risk of falling increases in low-light environments with obstacles, which raises the demand for gait analysis in such conditions. However, gait analysis under low-light conditions is challenging due to the difficulties in ensuring safety and preparing a large dark room.

Virtual reality (VR) has been explored for rehabilitation and gait analysis because it can recreate immersive environments and provide consistent settings for repeated practice. Wang et al. [4] developed the VRGaitAnalytics system, which evaluates gait performance under visual, auditory, and cognitive loads. However, although VR-based rehabilitation has been widely studied, few attempts have been made to analyze gait under low-light environments.

To address this issue, this study proposes a safe and easy-to-use framework for gait analysis in low-light environments. We simulate low-light conditions using a mixed-reality (MR) technique. Specifically, we utilize a camera-passthrough head-mounted display (HMD) and apply a low-light filter considering blueshift effects to the passthrough view. Using this setup, we introduce an MR-based 5-m walk test that can record the trajectories of feet, hands, and head during the walk using MR devices and can provide virtual obstacles to observe object-avoidance behaviors. Since our method provides a virtual low-light environment only for the user, it enables detailed gait analysis using the MR-tracking function with safe assistance in a well-lit room.

2 Method

Our method consists of a camera-passthrough HMD, Meta Quest 3, and Touch Pro Controllers We attach the controllers to the shoes to capture foot motion while walking (Figure 1a). We simulate a low-light environment by applying a night-scene filter [3] to modify the RGB pixel color $\mathbf{c}$ of the passthrough view (Figures 1b and 1c) as, $\mathbf{c} = kV\mathbf{c}_{blue}$, where k is the empirically set gain coefficient (see below), V is the scotopic luminance [2] computed from the external camera image, and $\mathbf{c}_{blue}$ is a blueshift vector. Following [3], we compute $\mathbf{c}_{blue}$ by using a chromaticity of approximately $(0.03, 0.03)$ below the white point. We implemented this filtering using the passthrough-color lookup table of Meta Quest 3.

As an extension of the 5-m walk test commonly used in rehabilitation, we introduce the MR-based 5-m walk test. The user walks in the MR space between the start and end lines separated by 11 m. The 5 m walk is preceded and followed by 3 m of acceleration and deceleration sections, respectively. In addition, a virtual obstacle (about 23-cm-high box) can be placed in the MR environment to observe obstacle-avoidance behavior. After walking, our method

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Table 1: Luminance $[cd/m^2]$ measured under the four conditions. "Diff" shows the difference between white and gray.

	Bright	LowLight	MRPass	MRLowLight		
				k=0.01	0.005	0.001
white	132.767	0.027	47.872	1.240	0.626	0.250
gray	24.930	0.005	16.166	0.381	0.270	0.237
Diff	107.836	0.022	31.707	0.859	0.357	0.013

reports the walking speed and visualizes the trajectories of the head, hands, and feet (Figure 1d).

3 Evaluation of MR Low-Light Environment

To evaluate a virtual low-light environment and to determine the gain parameter k, we conducted a preliminary experiment. We measured the illuminance at the floor and the luminance from a sheet of paper placed on the floor in a windowless room under four conditions. In the *Bright* condition, half of the room's fluorescent lights were turned on. The *LowLight* condition used only a nightlight adjusted to produce a floor illuminance of approximately 0.1 lux. For the *MRPass* and *MRLowLight* conditions, we placed an HMD in front of the luminance meter under the same lighting as in the Bright condition, then measured the luminance of the paper as rendered on the HMD screen. In MRPass, we enabled the camera-passthrough of the HMD. In MRLowLight, we simulated the low-light environment with gain values: k = 0.01, 0.005, and 0.001. To address both unit-to-unit variation and noise, we averaged data taken from three different HMDs, with each measurement point repeated three times. For all conditions, we measured the luminance of two papers: white (Munsell N9.5) and gray (Munsell N5).

The floor illuminance was approximately 520 lux for the Bright, MRPass, and MRLowLight conditions and 0.1 lux for the LowLight condition. Table 1 summarizes the luminance for each condition. Comparing the Bright and MRPass conditions shows that, despite the same bright lighting, the passthrough image has lower luminance, which is likely due to the HMD's limited maximum brightness. Under LowLight conditions, the difference in luminance between the white and gray papers was approximately 0.022. Although the luminance in MR-LowLight with $k = 0.001$ was slightly greater than that in the LowLight conditions due to the HMD's black-level limitation, we found a similar difference (contrast) with this gain parameter. Consequently, we selected $k = 0.001$ for this study.

4 User Study

To evaluate the proposed MR-based gait analysis tool, we conducted a user study under six conditions: PassBright, PassBright-o, PassLowLight, PassLowLight-o, MRLowLight, and MRLowLight-o. PassBright used an HMD passthrough view of a bright room. PassLowLight used an HMD passthrough view of a low-light room. MRLowLight (the proposed method) used an MR-simulated low-light environment. The suffix "-o" indicates that a virtual obstacle was placed in the path. After brief practice in the PassBright condition, the participants performed a 5-m walking task twice in each condition with a 1-minute break between each condition. We varied the order of conditions among participants.

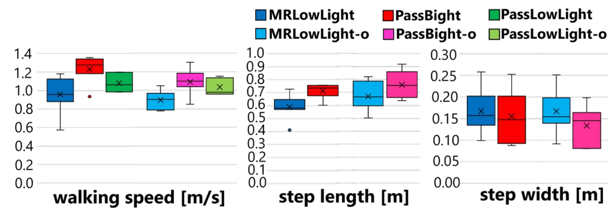

Figure 2: Gait analysis under the six conditions.

Seven engineering students participated in the user study. Figure 2 shows box plots of the walking speed, step length, and step width under each condition. The step length and step width were manually measured from the recorded trajectories. In the PassLowLight (-o) conditions, tracking failures prevented us from recording walking speed for two participants. Step length and step width were not measured in these conditions because the controllers' tracking function was unavailable in the low-light room.

Although we found no statistically significant differences in the repeated-measures ANOVA, several trends were observed. In the MRLowLight condition, the step length and walking speed tended to decrease compared with the PassBright condition. This suggests that participants walked carefully due to the limited visual information, which is consistent with previous findings in real low-light environment [1]. Similar trends were found for the MRLowLight-o and PassBright-o conditions. These results suggest that the proposed MR-simulated low-light environment can induce gait variation similar to that seen under real low-light conditions. In contrast, the PassLowLight condition produced little reduction in walking speed, which may be because that the floor illuminance was not sufficiently low (approximately 0.5 lux), making the floor more visible than under MRLowLight conditions (0.1 lux simulated). Further experiments with carefully controlled lighting remain as future work.

5 Conclusions

This study proposes simulating a low-light environment by filtering the passthrough image of an MR device. We also propose a 5-m walk test in the MR-simulated low-light environment. Future work will include evaluating the subjective perception of the MR-simulated low-light environments. In addition, we would like to conduct a larger scale user study to evaluate the feasibility of the walk test in the MR-simulated low-light environment in more detail.

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