Weighted Walking: Propeller-based On-leg Force Simulation of Walking in Fluid Materials in VR

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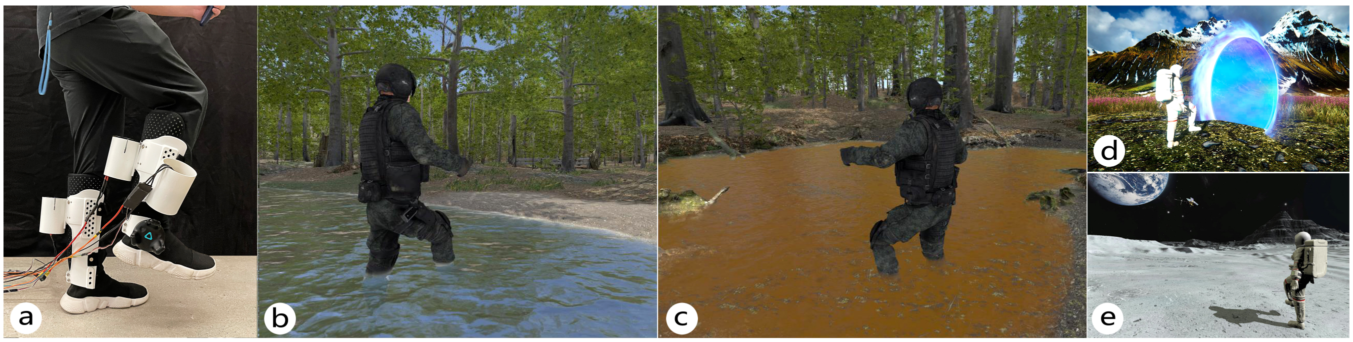

Figure 1: (a) a user wearing *Weight Walking* and walking in different fluids in VR; (b) & (c) examples of walking in the fluids with different viscosities (walk from water to air and from air to mud) in VR; (d) & (e) examples of walking in the virtual environments with different levels of gravity (teleport from the earth to the moon).

CCS CONCEPTS

• **Human-centered computing**; • **Virtual reality**; • **Haptic device**;

KEYWORDS

Haptic, leg, lower limb, force, fluid, virtual reality.

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1 INTRODUCTION

Deploying haptic and embodied feedback along with high-quality visual and audio contents in virtual reality (VR) can effectively improve users' experience and immersion. Many researchers investigated the hand-based haptic feedback devices to simulate the touch sensation in virtual reality [1, 3, 4]. On the other hand, the lower limbs, such as legs and foot, are another important body parts for us to explore experience the real world. For instance, we can feel different levels resistant force while walking on the ground, in the water, and in the mud or swamp. However, compared to hand-based haptics, there is less research on the haptic devices focusing on the low limbs for the VR application. The early works on locomotion interfaces in VR [5, 6] could simulate the walking experience in different solid surfaces with grounded setup, but most of their hardware are bulky to install. Later, to reduce the bulkiness of grounded system, researchers explored the installation of lightweight actuators, such as vibration motors [7], linear actuators [10], hydraulic pumps [9], in the shoes and on the soles to provide foot-based haptic feedback in VR. Recently, Gaiters [8], to provide skin-stretching feedback on the human calf by dragging the shear tactors with servo motors.

While it could be common for us to walk in different fluid mediums and experience different resistant force, there is no in-depth research in simulating such experience in VR, to our best knowledge. In this paper, we present *Weighted Walking*, a wearable device with a pair of ducted fans in opposite directions on the user's calf (Fig. 1a). By capturing the position and the velocity of the feet when the users are walking in place, the system can adjust the strength and the direction of the airflow in real time to simulate different types and levels of forces. The fans can generate powerful thrust to simulate the forces (buoyancy and fluid resistance) caused by the user's lower limbs when moving in different fluid and materials (e.g. water and mud in Fig. 1b & c). The device can also simulate the walking experience in different gravity conditions, such as walking in another planet (Fig. 1d & e).

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2 SYSTEM DESCRIPTION

Weighted Walking is a leg-based wearable haptic system which could provide buoyant and resistant force feedback on users' lower limbs while walking. The Weighted-Walking system contains two wearable calf sleeves, one on each side of legs. Each calf sleeve consists of two ducted fans (one for upward airflow and another

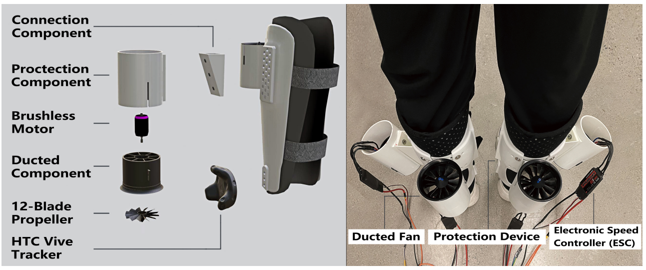

Figure 2: The system figure of Weight Walking. (a) the structural figure of Weight Walking (b) Weight Walking with the driven system

for downward), a lower-limb protection structure and a connection component (Fig. 2a & b). To simulate the force experienced by the user's lower limbs while walking in fluid, we use the high-power ducted fan (model: EDF 70mm pro) which includes a 12-blade propeller and a 2300KV brushless motor(ϕ28.4 × H87.7mm, Weight: 178g, Max Voltage: 25.2V, Max Current: 65A). In our technical evaluation, each ducted fan can generate the force up to 22.4N (2.24kg) with the driven current of 65A. Furthermore, our system demonstrates the low latency for the airflow force generation (from 0 to 22.4N within 1 second).

For the part of lower-limb protection, we use the 3D-printed PLA structure as our wearable base. The ducted fans are installed on the side and the back of the protection base structure. In addition, a sponge layer is placed inside the base to reduce the vibration and ensure the comfort of wearing. The control system includes the electronic speed-controller (ESC) boards (model: HOBBYWING SkyWalker, rated at 80A), and controlled by Arduino UNO using the Pulse-Width Modulation (PWM). An external DC power supply (24V, 80A) is used to drive the brushless motors. We use Unity (2019.1) to build the virtual reality application.

To smoothly control the force intensity generated by *Weighted Walking*, we implemented a computational model for mapping the fans-generated forces to the driven currents. Specifically, we measured the force levels/intensities by controlling the driven currents of the ESC board from 0 to 65A with the interval of 5A, and then built a linear-regression model for predicting the generated forces based on the currents.

With the aforementioned linear-regression model, we can simulate the buoyant and the resistance forces of different fluid materials based the real-world fluid dynamics. We mainly consider the joint force calculated by the buoyant and the resistant forces during the walking processing, to control two fans for the Weighted-Walking device on each leg respectively. The joint force $\vec{F}$ could be defined as:

$$\vec{F} = \vec{F}_{drag} + \vec{F}_{buoyancy} \tag{1}$$

In this equation, $\vec{F}_{drag}$ represents the drag resistance (i.e., resistant force) by the fluid and $\vec{F}_{buoyancy}$ is the buoyancy of the liquid; the direction depends on the leg movement. Both the buoyancy and drag resistance could be calculated as Eq. 2 and Eq. 3:

$$\vec{F}_{buoyancy} = \rho V g \tag{2}$$

where ρ is the fluid density, and V is the volume of the displaced body of liquid; g represents the gravitational acceleration. In our case, we fix V as the average leg volume of human - 13000ml [2].

$$\vec{F}_{drag} = 6\pi\eta r v \tag{3}$$

We estimated the drag resistance based on Stokes' law (Eq. 3). Here η is the viscosity of the fluid. r means the radius of the submerged calf in the fluid, and we estimate the radius of the calf as the radius of a sphere with the same cross-sectional area. v is the dynamic velocity of the leg movement which could be calculated from the real-time vive-tracker data.

In summary, it could be feasible to use *Weighted Walking* to simulate the perception of walking in different virtual fluid materials with different compositions and densities. We also simulate the experience of walking in different gravity conditions, as shown in Fig. 1-d&c. The on-leg force feedback in Weighted Walking can further improve the realistic sensations in VR.

3 ACKNOWLEDGMENTS

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