

# FluidWalker: A Propeller-based On-leg Wearable System with Dynamic Haptic Feedback for Walking in Different Fluid Materials in VR

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## 1 INTRODUCTION

Providing kinesthetic feedback to the user's lower limb in virtual reality is a potential problem to be solved. In many early studies, researchers simulated the experience of the lower limbs when walking in different scenarios using grounded mechanical devices [4, 5]. Still, most of these hardware devices were bulky, difficult to install, and could only be used in specific environments. Recently, researchers have used techniques (e.g., vibrations [6], MR fluid [8], etc.) to simulate the user experience of interacting with virtual fluids. However, due to the limitations of the operating mechanism and hardware devices, this type of device also can only provide skin-based tactile feedback. It cannot generate large-scale force impacts to simulate the kinesthetic/haptic feedback generated during lower limb interaction.

In this paper, we introduce *FluidWalker*, a propeller-based wearable device that simulates the experience of walking through different fluids by adjusting the strength and direction of the wind force in real-time. By installing three pairs of ducted fans on the user's lower legs, force feedback is thus provided in a multi-direction to simulate both the vertical and horizontal forces generated on the lower limbs while moving through the virtual fluid. In addition, it can also simulate the dynamic forces during the interaction (e.g., changing force feedback when the foot is at different depths or when virtual fluid is sloshing and flowing). In contrast to existing devices that can only provide weak skin-based tactile feedback, this device can generate a strong thrust to produce corresponding kinesthetic/force feedback, thus simulating the forces (buoyancy and fluid resistance) induced by the lower limbs moving through different fluids and materials.

## 2 SYSTEM DESCRIPTION

In our first version of prototype, the system contains two wearable calf sleeves, one on each side of legs [3]. Each calf sleeve is equipped with two ducted fans that provide wind force in both upward and downward directions, thereby simulating the buoyancy and resistance feedback received by the lower limbs when the user interacts with the virtual fluid (Fig. 1). This approach effectively simulates the haptic feedback that occurs when the user moves through shallow

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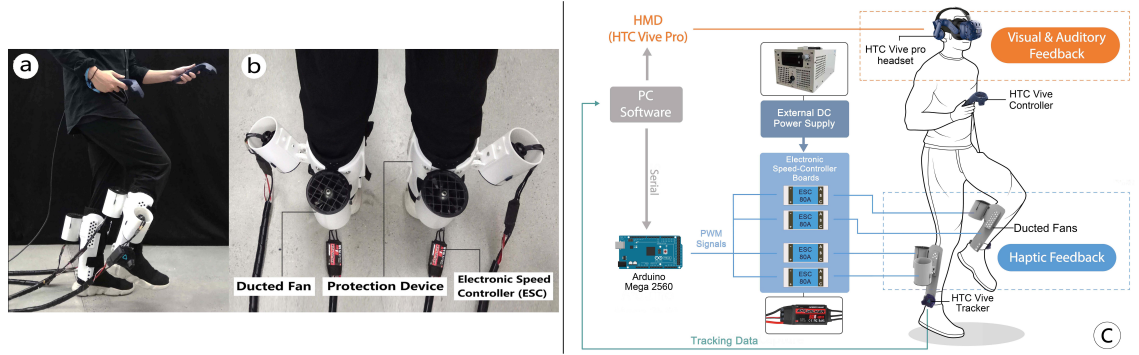


Fig. 1. (a) The device being worn on the VR user's legs; (b) The driven system of our original prototype (c) The system diagram of our design.

fluids, which can be commonly experienced in daily life. However, when the user interacts with a deeper fluid (e.g., moving in the swamp or quicksand that completely covers human knees), it can be difficult to simulate those kinds of more specific and complex scenarios with purely vertically haptic feedback.

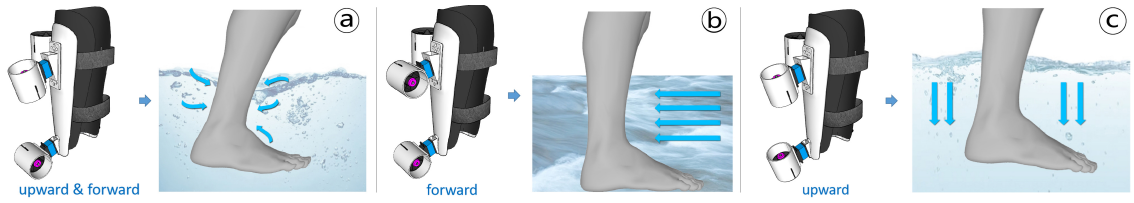


Fig. 2. The device can: (a) simulate turbulent flow of the fluid; (b) simulate the flow direction of the fluid; (c) simulate the weight of the fluid.

To solve this problem, we propose to provide multi-directional force feedback by assembling ducted fans with adjustable angles and force intensities on the calves to simulate the forces produced when the user walks into the deeper fluid. We design to install three ducted fans on each calf sleeve to provide powerful force feedback in vertical and horizontal directions. To effectively simulate the force feedback when walking through the fluid while considering the device's weight, we plan to use two types of high-power ducted fans (Model: EDF 70mm pro and Model: EDF 50mm). Each ducted fan includes a 12-blade propeller and a brushless motor. In our technical evaluation, the EDF 70mm pro ducted fan can generate up to 27N (2.7kg) of force at 70A drive current, while the EDF 50mm one can generate up to 8.5N (0.85kg) of force at 40A drive current. In addition, this system can provide low latency for airflow force generation (from 0 to 27N within 0.8 seconds). To improve the flexibility of the device, we install servo motors (Model: AX-12A) at each of the two ducted fan connections on the side of the calf sleeve to adjust the angle of the ducted fan in real-time. Regarding software, we use Unity 2019.1 to build the VR scenario. The corresponding sound effect would play when the participant entered and walked in a particular type of medium.

With the above setup, the system can dynamically change the strength and direction of the ducted fan to simulate different types of force (Fig. 2). More specifically, in the VR scene, the user can : 1) perceive the turbulent flow by sensing the dynamic change of force intensity and direction when stepping into the fluid (Fig. 2a); 2) feel the direction of the

flow direction by perceiving the direction of the force in the fluid (Fig. 2b); 3) perceive the weight of the fluid when lifting the leg in the fluid (Fig. 2c). This enhances the device's usability, allowing users to experience more detailed and richer haptic feedback and expands its application scenarios in VR.

To more efficiently control the force feedback generated by the device, we map the PWM signal generated by the system to the force generated by the fan through a computational model. We measure the force intensity by controlling the PWM signal from 0% to 100% duty cycle with an interval of 5% duty cycle and then build a linear regression model that is used to obtain the corresponding PWM value based on the desired force intensity. With the obtained linear regression model, we can simulate the buoyancy and drag forces of different fluid materials based on real-world fluid dynamics.

This study mainly focuses on the force feedback generated when the leg interacts with the fluid. So we use classical fluid dynamics to simplify the virtual fluid's force calculation rather than a more advanced fluid dynamics model, thus mapping the force intensity generated by the system more efficiently. This study mainly considers the combined forces of buoyancy, fluid resistance, and potential medium weight during the walking process. The main force  $\vec{F}_{horizontal}$  of the horizontal direction could be calculated using the drag equation shown in Eq. 3. Meanwhile, the joint force  $\vec{F}_{vertical}$  of the vertical direction could be defined as:

$$\vec{F}_{vertical} = \vec{F}_{drag} + \vec{F}_{buoyancy} + \alpha \vec{G}, \quad \alpha \in \{0, 1\} \quad (1)$$

In this equation,  $\vec{F}_{drag}$  represents the drag resistance (i.e., the resistant force) by the fluid and  $\vec{F}_{buoyancy}$  is the buoyancy of the fluid with upward direction. The buoyancy and the drag resistance could be calculated as Eq. 2 and Eq. 3 respectively:

$$\vec{F}_{buoyancy} = \rho V g \quad (2)$$

where  $\rho$  is the fluid density, and  $V$  is the volume of the displaced body of liquid;  $g$  represents the gravitational acceleration (9.8m<sup>2</sup>/s). In our case, we fix  $V$  as the average volume of adult human leg - 1300ml [2]. For most non-Newtonian fluid (e.g., mud and sand), we assume its buoyancy is 0 as it tends to be more solid under relative motion (e.g., human legs moving in mud).

$$\vec{F}_{drag} = \frac{1}{2} \rho C_d S v^2 \quad (3)$$

where the  $\rho$  is the density of the simulated fluid and  $S$  is the cross sectional area of the lower limb in the fluid,  $C_d$  is the drag coefficient, and  $v$  is the velocity of the lifting leg. In our case, we assumed that the leg-lifting velocity  $v = 0.3$  m/s while walking in place[7], and the approximating the leg as a quadratic prism with  $C_d = 2.0$ . The cross sectional area of the lower limb is about 0.026 m<sup>2</sup> [1]. Hence, the drag force is mainly dependent on the density of the fluid.

$\vec{G}$  is the weight of the medium on top of the foot. For the non-Newtonian fluid that tends to be solid in motion, the material may place a "solid" weight on the human foot. To this end, the parameter  $\alpha$  in Eq. 3 is set to 1 for this type of non-Newtonian fluid. Here we assume the instep area of the foot is 0.015 m<sup>2</sup> and the height of the leg part submerged in the medium is 0.08 m [1], for calculating the weight of the medium on the foot.  $\alpha$  will be set to 0 for Newtonian fluid, such as water and air.

### 3 USER STUDY

In the previous work, we conducted three user-perception studies to understand the capability of the system to generate distinguishable force stimuli. First we conducted the just-noticeable-difference (JND) experiment to investigate the threshold of the human perception of on-leg air-flow force feedback. The second perception study showed that users could distinguish generated force levels for simulating different walking mediums (i.e., dry ground, water, mud, and sand), with an average accuracy of 94.2%. And the VR user study showed that the system could significantly improve the users' sense of presence in VR. According to the results, we assume that extending the device in the methods mentioned above can enhance the user's interaction with the fluid, and improve the user's immersion in virtual reality. We will further test our hypothesis through experiments.

### 4 CONCLUSION

This paper presents the idea of *FluidWalker*, which can generate force feedback for walking in virtual fluids to enhance the VR experience. By controlling the angle and the force intensity of the ducted fans in real-time, this device can achieve a more detailed and rich simulation of the interaction with the virtual fluid.

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