PropelWalker: A Leg-based Wearable System with Propeller-based Force Feedback for Walking in Fluids in VR

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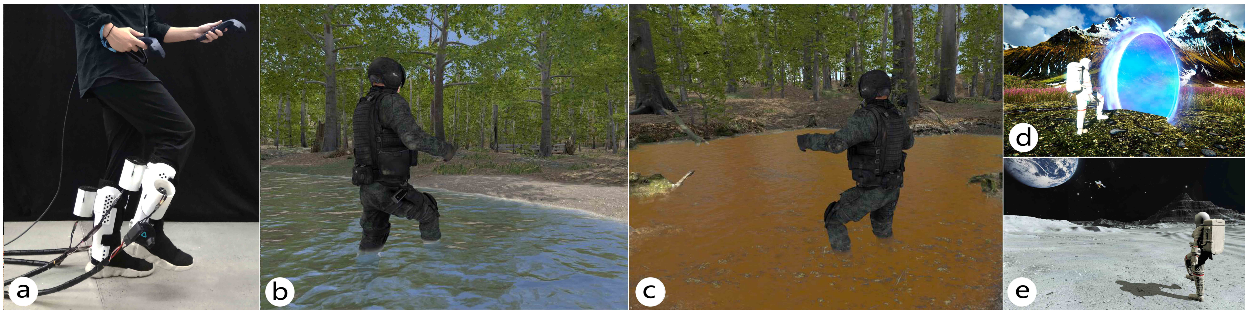

Fig. 1: (a) *PropelWalker* being worn on the VR user's legs; (b) & (c) Examples of walking in the different virtual fluids (walk from water to dry ground and from dry ground to mud) in VR; (d) & (e) Examples of walking in the virtual environments with different levels of gravity (teleport from the earth to the moon).

Abstract—
There have been increasing focus on haptic interfaces for virtual reality (VR), to support high-quality touch experience. However, it is still challenging to haptically simulate the real-world walking experience in different fluid mediums. To tackle this problem, we present *PropelWalker*, a pair of calf-worn haptic devices for simulating the buoyancy and the resistant force when the human's lower limbs are interacting with different fluids and materials in VR. By using four ducted fans, two installed on each calf, the system can control the strength and the direction of the airflow in real time to provide different levels of forces. Our technical evaluation shows that *PropelWalker* can generate the vertical forces up to 27N in two directions (i.e., upward and downward) within 0.85 seconds. Furthermore, the system can stably maintain the generated force with minor turbulence. We further conducted three user-perception studies to understand the capability of *PropelWalker* on generating distinguishable force stimuli. Firstly, we conducted the just-noticeable-difference (JND) experiments to investigate the threshold of the human perception of on-leg air-flow force feedback. Our second perception study showed that users could distinguish four *PropelWalker*-generated force levels for simulating different walking mediums (i.e., dry ground, water, mud, and sand), with the average accuracy of 94.2%. Lastly, our VR user study showed that *PropelWalker* could significantly improve the users' sense of presence in VR.

Index Terms—Virtual Reality, haptic, propeller, fluid.

1 Introduction

Haptic and embodied feedback in virtual reality (VR) can improve users' experience and immersion [4, 5]. One purpose of providing haptic feedback in VR is to simulate the real-world touching experience. Many researchers studied the hand-based haptic devices to simulate the touch or the weight sensation in VR [6,11,17,23,44,47,50,54,59,61]. Besides the hands and the other upper body parts, the lower limbs of human body, such as legs and feet, are another important body parts for us to explore the real world [52,57]. For instance, we can feel different types and levels of forces while walking on the solid ground, in the water, in the sand, and in the mud or swamp. It is more viscous or resistant to walk in the mud than on the dry and solid ground. Walking in water would feel more floating/buoyant, and it is more difficult to balance while walking in the fluid medium than on the ground. However, compared to hand-based haptics, there is less research on the haptic experience for the low limbs in VR.

The early works on VR locomotion interfaces [35, 39] could simulate the walking experience in different solid surfaces with the grounded mechanical setup, but these hardware are mostly bulky and difficult to install. Later, researchers explored the installation of light-weight actuators, such as vibration motors [43, 46], linear actuators [58], hydraulic pumps [57], in the shoes and on the soles to provide foot-based haptic feedback in VR. Recently, researchers [24] proposed a largescale walkable actuated pin array to simulate different ground setups in VR. Some other studies [48, 51] used vibrotactile feedback to simulate the forces generated when people step on different textured grounds. Researchers also proposed to use the magnetorheological fluid to simulate the deformation of different materials (especially liquid) when stepping into the mediums [57], and achieved a better result than using vibration. Though these existing works could provide the tactile feedback on the feet, they primarily focused on the tactile feedback on the skin surface other than a large-scale of kinesthetic/force feedback.It is still challenging to use these systems to generate corresponding force impact that may be experienced by human while walking in the liquid. When we are walking in different medium in real world, the legs, another equally important part besides the soles and the feet, is also undertaking the large-scale force feedback (e.g., the resistant and the buoyant forces) during the walking experience in different fluids. It could be common in real world for us to walk in different fluid mediums and experience different resistant/buoyant forces, but there is a lack of in-depth research in simulating such experience on legs in VR.

In this paper, we present *PropelWalker*, a wearable device with a pair of ducted fans in opposite directions on the user's calf (Fig. 1a). In the current prototype, we focused on the technique of walking in place (WIP) [49] as the locomotion approach in VR, due to its convenience, inexpensiveness, and safe nature [12]. Under the WIP locomotion technique, the user mainly performs the leg-lifting actions in the same

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physical location [37]. Research [36] showed that WIP can achieved a natural walking experience similar to the actual spatial walking in VR while reducing the requirement of a large physical space. By capturing the position and direction of the feet when the users are performing WIP, the system can adjust the strength and the direction of the airflow in real time to simulate different directions 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 mediums (e.g. water and mud in Fig. 1b & c). The device can also simulate the walking experience in different gravity conditions, such as walking on another planet (Fig. 1d & e). Our technical experiments showed that the *PropelWalker* system generates the vertical forces up to 27N in two directions (i.e., upward and downward) within 0.85 seconds, and it can stably maintain the generated force. With *PropelWalker*, we investigated three main hypotheses: H1) the system could generate a range of on-leg force feedback that are distinguishable fore users; H2) Users could identify different virtual fluid based on the *PropelWalker*-generated force feedback; H3) Users would rate their sense of presence in VR significantly higher with the proper-controlled force feedback from *PropelWalker*, compared to the uncontrolled *PropelWalker* force feedback and the condition without *PropelWalker*. We first conducted a set of user-perception studies to evaluate the just-notifiable difference (JND) of the forces generated by *PropelWalker*. For the purpose of simulating the on-leg force feedback of walking in fluid, we first generated the forces of walking four different types of mediums: on the dry ground, in the water, sand, and mud. Our user study showed that users could distinguish these four on-leg force feedback in the average accuracy of 94.2%. Lastly, we showed that walking with *PropelWalker* in VR received significantly higher user ratings in terms of presence.

This paper presents the following contributions:

- We designed and implemented the *PropelWalker* prototype to simulate the forces (buoyancy and fluid resistance) generated by the user's lower limbs moving in different fluids in VR.
- We conducted the technical evaluation on the capabilities and limitations of the *PropelWalker* device on generating different levels and directions of on-leg force through air-flow control.
- We conducted the user-perception studies to investigate the user's ability to discern the levels of forces generated by *PropelWalker*.
- We conducted the user study to evaluate how *PropelWalker* may improve the immersion and the presence in VR.

2 Related Work

2.1 Lower-limb Haptics

We observed more research attention focusing on the upper limbs than the lower limbs for simulating real-world haptic experiences in VR. However, a few researchers have started studying the application of on-leg/foot haptic feedback for other contexts [10], such as information notification, sports, rehabilitation, and so on. Homma et al. [18] introduced a 4-DOF leg-rehabilitation system using a low-effort parallel wire mechanism focusing on rehabilitation of limbs in elder people, thus assisting them to perform multiple-DOF motion exercises. Banala et al. [3] proposed Active Leg Exoskeleton (ALEX) which could apply the force-field controller to provide the appropriate force on the user's foot to assist the patients with walking disabilities in gait rehabilitation. Luo et al. [33] developed a wearable brace-like device consisting of a force transducer and an active angle sensor to measure and detect the lower-limb motion data of users, thus facilitating the rehabilitation for the total-knee-arthroplasty (TKA) patients.

Researchers have also studied the on-leg/foot haptic feedback for VR applications. As one early work, Iwata et al. [22] developed Gait Master, a device using two on-foot mechanical platforms to allow users to naturally walk in different virtual terrain while maintaining their physical positions. Kim et al. [27] used a cable-driven system with four-wire ropes to simulate the reduced gravity experienced on the moon or Mars. HapticWalker [42] used two programmable mechanical foot platforms with permanent foot contact, to simulate walking on the flat or rugged ground. Recently, Je et al. developed Elevate [24], a dynamic and walkable pin-array floor installation on which users can experience the shape of the virtual terrain. Freiwald et al. [13] proposed Walking by Cycling, a locomotion interface to provide lower-limb haptic feedback for the seated situation in VR by mapping the cycling biomechanics of the user's legs to the walking motion in VR. Although these methods can simulate the kinaesthetic forces of walking in the real world and improve users' sense of presence in VR, their devices are bulky and need to be grounded. Turchet et al. [51] developed an audio-tactile synthesis engine and a pair of shoes with the vibrotactile actuators to provide users with a sense of touch and hearing when walking on solid surfaces. However, the intensity the vibrotactile actuators can provide was limited. Level-Ups [41] is a pair of foot-worn motorized stilts that allow users to experience walking up and down steps in VR. Snow Walking [58] is a boot-shaped wearable device that provides the feeling of walking on snow in VR. Realwalk [45, 57] used the in-shoe magnetorheological fluid (MR fluid) to generate the tactile feedback for users' feet while stepping on different virtual grounds. Compared with the vibrotactile feedback, MR fluid can better simulate the ground deformation and the texture sensations on the foot. For the on-calf haptic feedback, Wang et al. developed Gaiters [52], a pair of skin-stretching devices worn on the users' calves, to provide the dragging forces on legs in VR. Wang et al. developed GroundFlow [53], a water-recirculation system that provides multiple water-flows feedback on the floor in VR. While these existing works on on-foot/leg haptics in VR partially studied the feasibility of providing the force feedback for the experience of walking in different ground textures, there is no in-depth investigation and solution on simulating the large-scale force feedback (e.g. the buoyant and the resistant forces) induced by walking in different types of fluid mediums (e.g., water, sand, and mud).

2.2 Propeller-based Force Feedback

Researchers have explored using the propeller thrust to provide flexible and powerful haptic feedback through strong airflow. HapticDrone [1] is a drone-based device that can provide ungrounded haptic feedback. The device can offer safe and encounter-type force feedback in one direction and generate 1.53N upward and 2.97N downward force. Abtahi et al. [2] proposed to use the quadcopters as the agents/proxies of virtual objects to provide dynamic touch sensation in VR. Besides flying drones, researchers also investigated the direct usage of propeller-generated airflow for haptic feedback in VR. Ranasinghe et al. developed Ambiotherm [38], which contains a pair of miniature fans installed on the VR headset to provide the wind sensation for different weather conditions in VR. AlteredWind [20, 21] is a multi-sensory wind display that uses the fan-generated wind stimulation to simulate the change of wind direction in VR. Ke et al. introduced Embodied Weather [26], a set of multi-sensory VR devices with high-powered fans, which can simulate the embodied feedback in extreme weather such as typhoon and rain.

Researchers also experimented to install the propellers on handheld devices to offer hand-based force feedback. LevioPole [40] showed a rod-shaped handheld device, which is composed of two rotor units with four propellers, and demonstrated the capability of mid-air haptic feedback for full-body interaction in VR. Heo et al. developed Thor's Hammer [17], an ungrounded handheld haptic device which used motors and propellers to generate powerful air thrust for 3-DOF force feedback on users' hands. Similarly, Aero-plane [23] proposed a handheld controller with force feedback based on the propeller thrust. Odin's Helmet [19] installed four propellers on the head and simulated the force encountered on the head in real life through the generated push-pull force.

Inspired by these works on propeller-based haptic feedback, we developed *PropelWalker*, a pair of calf-worn propeller devices, to provide the force feedback encountered by the lower limbs while walking in different fluid mediums in VR. We argue the need for a new solution for fluid-based on-leg force feedback rather than adopting the existing propeller-based systems for two main reasons: 1) According to the reported results of the existing propeller-based force systems (e.g., WindBlaster: 1.5N; Thor's Hammer: 4N; Aero-plane: 7.1N), it would be difficult to directly use these existing hardware solutions for relatively large fluid-based forces; 2) To our knowledge, they didn't specifically focus on fluid-based force generation.

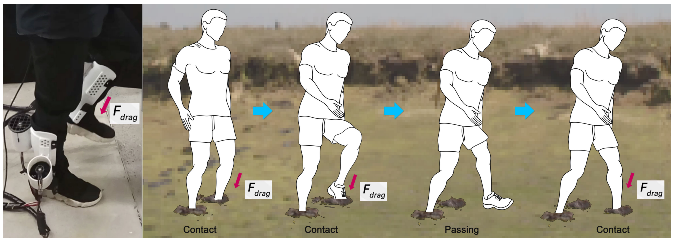

Fig. 2: Common walking process in fluids. The left part shows the situation in the real world and the right part shows the virtual-world situation.

3 Walking in Fluid

In this work, we mainly focused on the lower-limb force feedback experienced while walking in shallow fluids which usually immerse the calves. Before designing the *PropelWalker* prototype, we investigated the common postures that might be adopted while humans walking in different fluids.

3.1 Walking Postures

To understand how people may walk in fluid in real life, we conducted an informal analysis on the relevant online videos of people walking in different shallow fluids, with the search keywords of "walking in mud", "walking in swamp", "walking in desert", and "walking in water". Looking into more than 20 videos, we summarized the common walking postures in fluid as shown in Fig. 2. Specifically, while making a step in fluid, one usually first pulls one of his/her leg out from the fluid, then make the forward motion by swinging the leg in the air, and lastly step back into the fluid. Therefore, he/she would mainly experience the upward buoyant force, and the downward gravity and dragging forces, in the vertical direction. Meanwhile, As shown in table 3, the horizontal resistant forces while moving the leg in the air were weak (0.016N). In addition, there could be low or no acceleration in the horizontal direction, so the air resistance could be almost negligible. As one first attempt of providing the on-leg force feedback of walking in the fluid in VR, at the current stage we focused on the locomotion technique of WIP without any external locomotion equipment (e.g., treadmill), due to its convenience, inexpensiveness, and safe nature [12]. WIP mainly involves the vertical leg movements. Therefore, we designed the hardware prototype of *PropelWalker* to provide the on-leg force feedback on the vertical direction.

3.2 Fluid-based Force Calculation

While walking in the fluid in real world, our legs usually undertake the resistant force whose direction would be always opposite to the direction of the leg movement. Meanwhile, there is also the buoyant force for the leg part that is immersed in the fluid. For our experiments, we mainly consider the joint force combining the buoyant, the resistant forces, and potentially the weight of the medium, during the walking processing, to control two fans for the *PropelWalker* device on each leg respectively. The joint force $\vec{F}$ could be defined as:

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

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.

While the fluid-based forces could be modeled by advanced fluid dynamic models [7, 32], we, with the main focus of on-leg force generation, simplified the force calculation of virtual fluid using the classic fluid-dynamic model whose physical properties remain stable during the movement. To this end, the buoyancy and the drag resistance could be calculated as Eq. 2 and Eq. 3 respectively:

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

where ρ is the fluid density, and V is the volume of the displaced body of liquid; g represents the gravitational acceleration (9.8m^2/s). In our case, we fix V as the average volume of adult human leg - 1300ml [9]. 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).

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

where the ρ 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 performing WIP [56], and the approximating the leg as a quadratic prism with $C_d = 2.0$ [28]. The cross sectional area of the lower limb is about 0.026 m^2 [8]. 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 α in Eq. 1 is set to 1 for this type of non-Newtonian fluid. Here we assume the instep area of the foot is 0.015 m^2 and the height of the leg part submerged in the medium is 0.08 m [8], for calculating the weight of the medium on the foot. α will be set to 0 for Newtonian fluid, such as water and air.

4 Design of *PropelWalker*

Considering the aforementioned analysis of walking in fluid in real life, we designed *PropelWalker* to generate upward and downward airflow, for simulating the buoyant and the resistant force feedback on users' lower limbs while walking.

4.1 Hardware Implementation

The system contains a pair of calf sleeves, one to be worn on each side of the legs. Each calf sleeve consists of two ducted fans (one for upward airflow and another for downward), a lower-limb protection structure, and the connection structure (Fig. 3a & b). To simulate the force experienced by the user's lower limbs while walking in different fluids, we use the high-power ducted fan (Model No.: FMS 70mm pro V2, Weight: 255g) which includes a 12-blade propeller and a brushless motor (Model No.: 3060-KV1900, Max Voltage: 24.5V, Max Current: 70A).

As it may cause significant delays when switching the airflow direction in one fan to provide bidirectional thrust, we use two ducted fans for two opposite airflow directions respectively. With this setup, we aim to reduce the system delay for switching the force direction. In our technical evaluation, each ducted fan can generate the force up to 27N with the driven current of 70A. Furthermore, our system demonstrates the low latency for changing the airflow force strength (from 0N to 27N in about 0.85 seconds).

For the 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. In addition, a sponge layer is placed inside the base to reduce the vibration and ensure the comfort of wearing. The weight of the wearable structure including the fan is about 1.2kg. The external control system includes the electronic speed-controller (ESC) boards (Model: HOBBYWING SkyWalker, current rated at 80A), and is controlled by Arduino using Pulse-Width Modulation (PWM). An external DC power supply (24.5V80A) is used to drive the brushless motors.

4.2 Software Implementation

The VR application and the device-control mechanism were implemented in Unity3D 2019.1.0f2 with C#. We use the HTC Vive tracker to obtain the position and the orientation of the user's calf in real-time and send the data to the computer simultaneously. When the computer receives the data, the software controls the HTC Vive Pro HMD and the device through Arduino to provide visual and haptic feedback. Fig. 3c illustrates the system diagram of *PropelWalker*.

5 Pilot study : Fan-Angle Determination

One straightforward way of fan installation is pointing the fan perpendicularly to the ground which could provide the strongest airflow in the vertical direction. However, the strong wind may directly blow

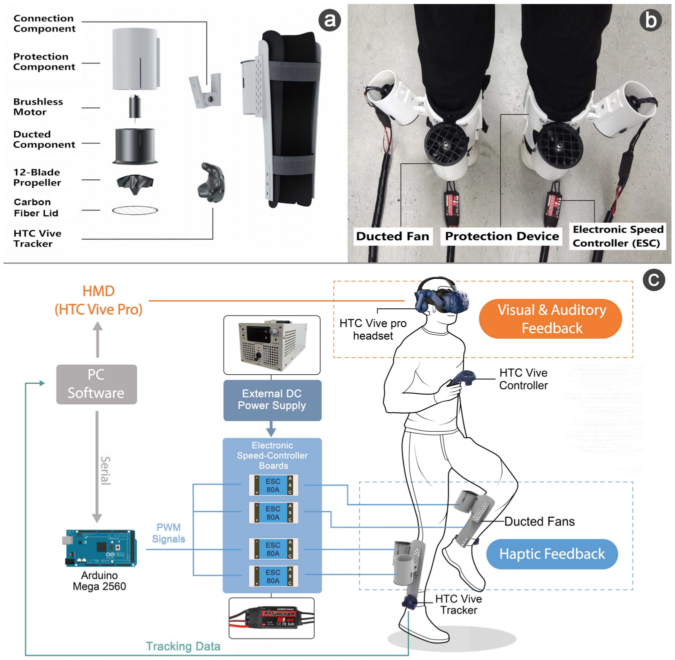

Fig. 3: The system figure of *PropelWalker*. (a) The structural figure of *PropelWalker*, (b) *PropelWalker* worn on the user's calves, (c) The system diagram of *PropelWalker*.

towards the user's upper body (especially the limbs), which may affect the user's walking actions and experience. While the wind interference may be reduced by tilting the fans, this may reduce the range of the force levels that can be generated by the system. To study how the airflow may impact the user experience, we first conducted a preliminary test with three persons (the co-authors), independently testing the fans mounted on the protection base's side and back (which create upward and downward airflow, respectively). The results showed that while the upward airflow had a strong impact on their bodies, the downward wind could be tolerable. We therefore applied the 0° mounting angle for the ducted fans on the back of the protection base, to generate the downward airflow. For the ducted fans mounted on the side of the protection base, we conducted a pilot user study to investigate the generated force levels and the user experience of WIP under different fan directions, to determine the optimal hardware setup.

5.1 Participants

We recruited six participants, aging 23-33 years old (Mean: 26.5, SD: 2.88). During the experiment, users needed to put the *PropelWalker* devices on both of their legs, experience the wind force generated under different fan angles while performing WIP for 2 minutes, and rate their experiences (e.g., perceived force, comfort, etc.) in a 7-point Likert scale.

5.2 Apparatus

For the pilot study, we designed a 3D-printed fan-mounting structure with the joint for angle adjustment, and connected it to the wearable calf-protection shell (Fig. 4). By rotating and fastening the joint, we can fix the fan at any angle between 0 to 90°. In our prior test, we found that when the included angle between the fan and the calf shell exceeds 50°, the airflow barely affects the user's upper limbs. Therefore, we chose the range of 0-50° and an interval of 10°, resulting in six fan angles (i.e., 0°, 10°, 20°, 30°, 40°, and 50°) for our pilot experiments. Each angle was repeated five times, resulting 6 angles $\times$ 5 repetitions = 30 trials for each participants. These trials were presented to the participants in a random order.

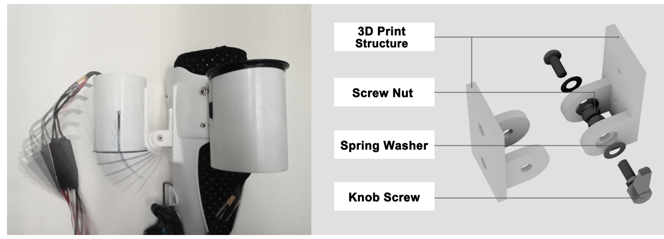

Fig. 4: 3D-printed fan-mounting structure. The left part shows the installed fan with different angles and the right part represents the assemble schema of the fan-mounting structure.

5.3 Results

Fig. 5 showed the descriptive results of the pilot study. Friedman Test showed that the angle of propeller significantly affected the comfort level of user ($\chi^2(5) = 25.83$, $p < 0.0001$), the user preference ($\chi^2(5) = 24.72$, $p < 0.0005$), and the force intensity provided by the propeller ($\chi^2(5) = 27.51$, $p < 0.0001$). Post-hoc pairwise Wilcoxon Signed Ranks Test showed that the angles of 20° and 30° yielded significantly higher ratings in terms of comfort level and user preference than other degrees ($p < 0.05$), and there was no significant difference between 20° and 30° for the rated comfort.

In addition, the perceived force intensities decreased along with the increasing of the angle of the ducted fans. The results showed that there was no significant difference between 10° and 20°, 20° and 30°, and 40° and 50°, while there were significant differences between other pairs of angles ($p < 0.05$), for the perceived force intensities. While experiencing our device under different angles of the ducted fan, some participants commented: "When the fan angle is below 10°, I can feel a strong wind hitting my upper limbs, especially my arms". Another participant said, "When the angle of the ducted fan exceeds 30°, I can feel the force on both sides of my calves pushing my legs inward". Therefore, we chose a 20° angle as the final angle setting for the ducted fans on both sides of the calves. It enables our device to balance the trade-off between the generated force level and the user's comfort.

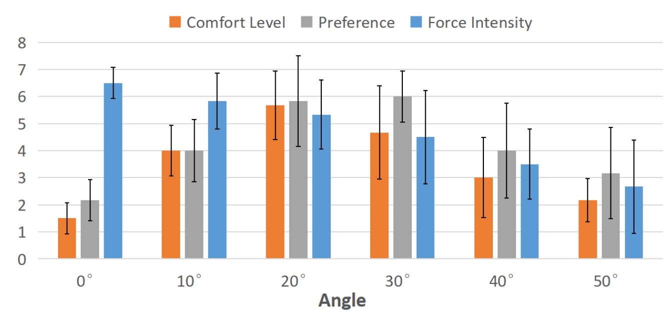

Fig. 5: Questionnaire responses on the pilot study (the error bar represents 95% confidence intervals of the results).

6 Technical Evaluation

While the performance of the ducted fan is generally described in its datasheet, it is still unclear how it may perform technically in the setup of *PropelWalker*. Specifically, the range of the generated force, the mapping between the controlled signal and the generated force, the responsiveness, the noise level, and the power consumption need to be evaluated under the chosen fan-angle settings (i.e., 0° and 20°).

6.1 Evaluation Setup

For the technical evaluation of the system, we built up an electronic weighing scale to customize a measurement system. as shown in Fig. 6. The weighing scale can measure the maximum force of 40 kg and a minimum accuracy of 1g. It collected the data through a resistance-strain

PWM Duty Cycle	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
Mean (N)	0.00	0.75	1.91	3.22	4.59	5.95	7.39	8.63	9.98	11.16	12.30	13.39	14.38	15.54	16.92	18.68	20.61	22.67	24.78	26.83	27.03
SD (N)	0.000	0.007	0.018	0.033	0.054	0.017	0.014	0.019	0.012	0.013	0.020	0.032	0.018	0.060	0.042	0.043	0.033	0.063	0.069	0.113	0.109
Max (N)	0.00	0.76	1.95	3.31	4.74	6.00	7.41	8.67	10.00	11.18	12.33	13.48	14.42	15.64	16.98	18.75	20.74	22.74	24.87	26.96	27.09
Min (N)	0.00	0.74	1.88	3.20	4.52	5.94	7.34	8.58	9.96	11.13	12.25	13.34	14.35	15.43	16.83	18.59	20.52	22.47	24.60	26.57	26.97

Table 1: The Mean, SD, Max and Min values of the target force at the angle setting of 0°.

PWM Duty Cycle	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
Mean (N)	0.00	0.69	1.84	2.96	4.22	5.48	6.77	8.00	9.15	10.30	11.35	12.35	13.31	14.23	15.63	17.18	18.91	20.92	22.94	24.92	25.19
SD (N)	0.000	0.006	0.012	0.020	0.036	0.012	0.011	0.017	0.013	0.026	0.023	0.014	0.031	0.032	0.035	0.081	0.046	0.055	0.072	0.065	0.061
Max (N)	0.00	0.71	1.87	3.03	4.36	5.52	6.79	8.04	9.17	10.35	11.39	12.38	13.35	14.28	15.7	17.27	19	21	23.06	25.12	25.26
Min (N)	0.00	0.67	1.82	2.94	4.2	5.47	6.75	7.97	9.12	10.25	11.31	12.32	13.24	14.16	15.55	16.98	18.83	20.8	22.8	24.83	24.99

Table 2: The Mean, SD, Max and Min values of the target force at the angle setting of 20°.

pressure sensor (CZL 601) connected through an Analog-to-Digital Converter (HX711) placed on an aluminum alloy bracket, and then transmitted the data to the Arduino and a LCD1602 display for data recording. We developed an experimental program with C# to control the generated force level through the PWM by Arduino UNO.

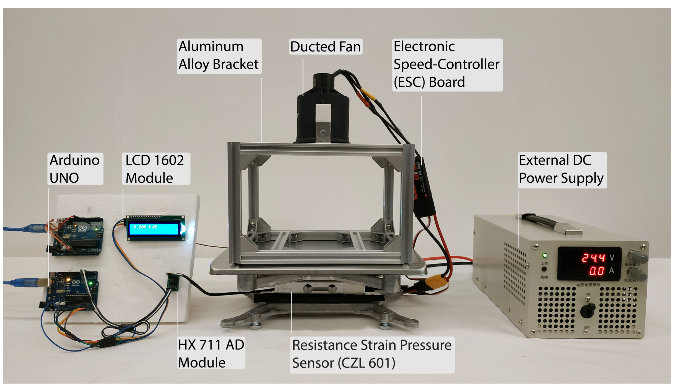

Fig. 6: Measurement setup built with aluminum alloy bracket and resistance strain pressure sensor.

6.2 Generated Force

To evaluate the accuracy and the steadiness of force generation, we controlled the Arduino UNO through a desktop PC to send the input signals with the PWM from 0% to 100% duty cycle, with an interval of 5% duty cycle to the electronic speed controller (ESC). We maintained each force output for 5 seconds, and recorded 21 measurements from the pressure sensor. Results showed that at the angle setting of 0° (Table 1), the average force could be up to 12.30N in 50% duty cycle and 27.03N in 100% duty cycle. At the angle of 20°(Table 2), the ducted fan could generate an average force level of 11.35N in 50% duty cycle and 25.19N in 100% duty cycle, from a total still status.

6.3 Response Time

While walking in VR, the user may leave one kind of fluid and enter another, such as getting out of the water and stepping on the dry land or entering the water from the dry land. This requires the force-generation system to respond fast enough to provide real-time on-leg force feedback. We calculated the activation and the deactivation time of the device, as defined in Fig. 7a. Fig. 7b shows the measured response time for the 21 PWM input, resulting in an average activation time of 666ms (SD = 71ms) and 1106ms (SD = 112ms) for the deactivation. This indicates an acceptable responding speed [34] of our system. Besides, the acceleration/deceleration time increased with the increase of the force. For the input of full PWM cycle, it takes 844ms to reach the target force from 0, and 1267ms to reduce the force back to 0, while it is 644ms for activation and 827ms for deactivation with the input of 5% PWM duty cycle.

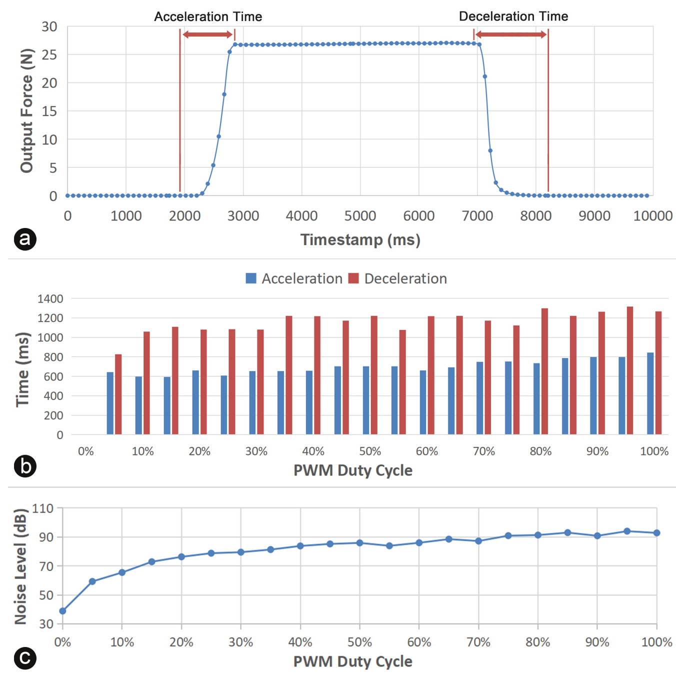

Fig. 7: (a) Measured output force (N) by step inputs with response time (ms), (b) Activation and deactivation time (ms) with increasingly duty cycle of the PWM signal (0%-100%), (c) Measured noise level (dB) with increasingly duty cycle of the PWM signal (0%-100%).

6.4 Stability

To study the stability of the force generation in our system, we measured the fluctuation of the force output by examining the maximum value (Max), the minimum value (Min), and the standard deviation (SD) for the 21 sensor measurements under each PWM signal. The results are shown in Table 1. It can be observed that the average upper bound of the output fluctuation was 0.80%, and 0.64% for the lower bound, indicating the stable output across 21 force values.

6.5 Power Consumption

The power consumption of the propeller mainly depended on the generated force level. The stronger the generated force is, the more power the system consumes. For instance, the system needs the power of 14.6W to generate a 0.75N force, 575.8W for 12.30N, and 1715W for 27.03N. Due to the weight of the device itself, it is necessary to constantly generate an upward force to compensate the device weight, to simulate the walking experience on the dry land without any resistant or buoyancy force. This means the device needs to constantly switch on, and consume at least 24.4V 0.6A (i.e., 14.6W) to generate an upward force of 0.75N on each leg. To this end, we used two external DC power supplies rated at about 2000W (24.5V80A) to provide enough endurance.

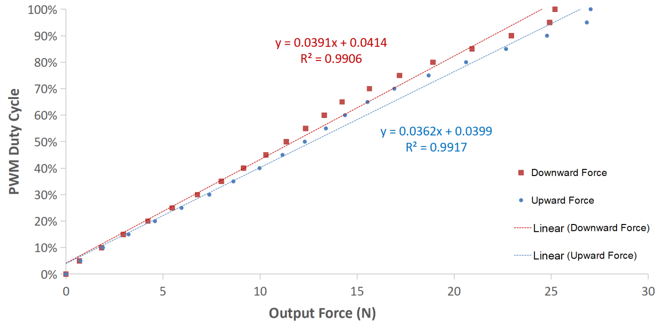

Fig. 8: The mappings between the input PWM duty cycles and the output force levels at the fan angles of 0° and 20°.

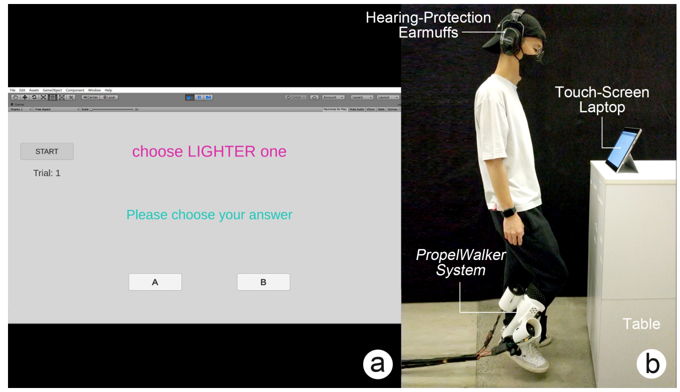

Fig. 9: (a) The experimental interface for the JND evaluation, (b) Setup of the JND study environment.

6.6 Operating Noise

We also measured the level of noise generated by the propeller. We placed a sound-level meter at a distance of 1.5 meters from the propeller, to simulate the approximated distance between the propeller and the user's ear when the device is activated. The measurement was carried out in a lab environment that is usually used for VR user study. The ambient noise level in the lab was 38.9dB. We activated the constant force during the measurement by sending the PWM signal and recorded the sound level once it's stable. As shown in Fig. 7c, the ambient noise increased as the PWM value (the intensity of the applied force) increased. The ambient noise level was 59.3dB, 85.9dB, and 92.8dB for the PWM duty cycle of 5%, 50%, and 100% respectively.

6.7 Force Control

To smoothly control the force intensity generated by *PropelWalker*, we implemented a computational model for mapping the fans-generated forces to the PWM signals (Fig. 8). Specifically, we measured the force levels at the angle settings of 0° and 20°, by controlling the input PWM signals from 0% to 100% duty cycle with the interval of 5% duty cycle in Arduino UNO. We then built the linear-regression models correspondingly, as shown in Equation 1 & 2, to reflect the mappings between the desired force output and the PWM signal.

(1) 0° fan-angle:

$$y = 0.0362x + 0.0399 \tag{4}$$

(2) 20° fan-angle:

$$y = 0.0391x + 0.0414 \tag{5}$$

where x represents the desired force levels (0-27N) and y is the corresponding duty cycle of the PWM signals (0%-100%). The correlation coefficient is 0.9917 for 0° and 0.9906 for 20°.

While our system can achieve a relatively short period for force generation, the fan-activation/deactivation time may still affect the user experience in certain contexts that require high-speed force controlling. To this end, we adopted the real-time control mechanism by constantly turning on both the upward and the downward fans. For the force output in a specific direction, the system will mainly control the corresponding fan to achieve the desired level, while maintaining the other fan spinning with the PWM signal of 4% duty cycle which generates the theoretical force value of 0N. This could avoid activating/deactivating the fan from/to a total still status while the force output in the opposite direction is needed, to reduce the response time of our system.

In summary, our technical experiments showed that the *PropelWalker* system can generate a wide range of force levels with a short latency, and stably maintain the generated force level. With the linear-regression model, we can accurately generate the desired force level. These demonstrated the feasibility of using *PropelWalker* to simulate the on-leg force perception in VR. In the following experiments, we will further evaluate the user perception towards the force generated by the system, and the effectiveness of using the system for simulating the force feedback of walking in different virtual fluid materials in VR.

7 User-Perception Experiment 1: Just-Noticeable-Difference Evaluation

To measure the users' perception of the varying force levels generated by the *PropelWalker* system, we performed a study of Just-Noticeable Differences (JND) [25]. The aim of this experiment is to investigate the humans' discrimination thresholds of force generated by *PropelWalker*. To our best knowledge, there is no literature describing the human perception on the propeller-based on-leg force feedback in different levels and directions. In the following sections, we referred to the absolute forces perceived by users as the "force stimuli" generated from our system.

7.1 Participants

We recruited 12 participants (4 females) from a local university, with an average age of 28.5 years (SD=1.07). Based on their self report, all these participants are right-handed, have healthy calves, and can normally perceive the force feedback. None of them had prior experience in psychophysical perception experiments.

7.2 Apparatus

Fig. 9b shows the setup of the research environment, including the *PropelWalker* system and a 12" touch-screen laptop placed on the table. The participant wore the device on his/her right calf and touched on the screen for selecting the perceived intensity. We assumed that the ability of weight perception of human's two legs (i.e., left and right) were identical, so we chose the right leg which is the dominant-leg for most people and also easy for performing actions. We also provided a pair of hearing-protection earmuffs with built-in earphones that play a constant white noise to avoid auditory bias.

7.3 Stimuli

According to the range of the force levels that could be generated by our system, we selected four force stimuli: F1=-15N, F2=0, F3=+15N, F4=+30N, as our reference stimuli applied on the participants' lower limbs, and measured the JND values respectively. The "-" and "+" signs indicate the upward and the downward force directions, respectively. The net weight of one *PropelWalker* device is about 1.2kg that produces a downward force of 12N on users' lower limbs. To counteract the device weight and achieve the force stimuli of zero, the device would generate the upward airflow to generate the force of -12N corresponding to the stimuli F2=0. The maximum upward force that can be generated by one *PropelWalker* device is -15N, combining the upward airflow-based force of -27N and the force induced by the device weight of +12N. Such upward forces may result in the illusion of feeling less body weight than usual, while the downward forces would yield the feeling of being dragged or having heavy steps. According to the system capabilities of *PropelWalker*, and considering that the resistant forces are more commonly experienced than the driving forces in daily leg/foot-based activities (e.g., walking and running in different mediums), we chose two levels of downward force (+15N and +30N) and one level of upward force (-15N) as the reference stimuli for the JND experiments. In our experiments, we tested the JND values from 0 N to -15 N (denoted as Interval-A), -15 N to 0 N (Interval-B), +15 N to 0 N (Interval-C), 0 N to +15 N (Interval-D), +30 N to +15 N (Interval-E), and +15 N to +30 N (Interval-F) respectively, with a total of 6 discrimination intervals.

During the experiment, the participants were asked to wear the *PropelWalker* device on their right calf, and stand in front of the table with the touch-screen laptop. Each force stimuli was activated and maintained for 5 seconds. After the generated force reached a stable stage, the participants were instructed to raise their right legs to experience the force intensity.

7.4 Experiment Design

We adopted a within-subject factorial design in this experiment, in which the independent variable was the interval. We used a two-alternative forced-choice (2AFC) paradigm [15] to estimate the minimum force levels of detectable/noticeable weight sensation change, which is the just-noticeable differences (JNDs) between two stimuli. For each interval setting, it consisted of about 40-50 blocks, and each block was composed of two trials, one with the reference force (S) and the other with the test force (S±ΔS). The reference force strength S was set to -15N, 0N, +15N and +30N, respectively. For the test force S±ΔS, ΔS represents the difference of the interval between the reference and the test force. It means that the test force was either heavier or lighter than the reference one by ΔS. These two forces were presented in a random manner in each block, with each force lasting for 5 seconds. In each trial, the participants were asked to lift their legs to perceive the presented force level. Then they needed to choose which force level was heavier/lighter. According to the 2AFC paradigm, it is compulsory for the participants to choose one or the other to be heavier/lighter, without the option of the two force levels being equal.

We adopted the process of one-up two-down staircase procedure for each interval, to determine the value of ΔS (i.e., JND), which tracks a level of 70.7% correct responses [30, 31]. Using the one-up two-down staircase procedure, a sequence of two correct responses decreases the level of the signal after the last change in signal level, while a sequence of one incorrect response or a sequence of one correct response followed by an incorrect response leads to an increase in the level of the signal [29]. This experimental protocol has been adopted by the previous psychophysical experiments [52, 60]. The force magnitudes of reference trials S were the force values we mentioned above. The value of tested force S±ΔS was initially set to a value that is significantly different from the value of reference force S. Following the previous research, we set this initial step size ΔS as 1N, where the step size (ΔS) increased by 1N after each incorrect response and decreased by 1N after two consecutive correct responses. A change in the force intensity from decreasing to increasing or vice versa was recorded as one reversal. After first three reversals, the step size was set to 0.2N (20% of the initial step size). The experiment of each force interval would end after 9 complete reversals, and the average value of the last 6 reversals was used as the estimated JND value for the particular force interval. The experiment ended after the participants finished all 6 intervals, the order of different experimental intervals was counter-balanced by the Latin square.

7.5 Procedure

Upon the arrival of the participant, we first introduced the process and the precautions of the experiment to the participant, and helped them to wear the *PropelWalker*. Then we invited the participant to stand in front of the table where the touch-screen laptop was placed and asked them to put on the earphones and the noise-canceling earmuffs. The earphones played the constant white noise to block the noise generated by the motors.

Before the formal start of the experiment, we conducted a practice session to ensure that the participant was familiar with the process. During the practice session, the participant could try the force comparison as much as possible until he/she reported him/herself to be familiar with the experimental procedure. As one interval session began, the system started to count down for 5 seconds, and then the screen displayed the words "Force A starts!". At the same time, the device activated and maintained the corresponding force stimulus for 5 seconds. The participant was instructed to perform a foot-lifting action to perceive the on-leg force intensity when the force output was in the steady status. After 5 seconds of force presentation, the device was turned off and the system started to count down for 5 seconds. Then the screen displayed "Force B starts" and the second force stimulus was activated and maintained for 5 seconds. When two trials in each block were finished, two options appeared on the screen (Fig. 9a), and the participant needed to tap the screen to choose which stimulus was lighter/heavier depending on the interval condition. That is, the participant needed to choose the lighter stimulus for the increasing interval, and choose the heavier one for the decreasing interval. There was a 10-second break between each block. After 10 blocks, the participant could take a compulsory one-minute break to avoid over-fatigue.

In general, each participant performed approximately 40 to 50 blocks in each interval, where it took about 20-25 minutes. Each participant would take a compulsory five-minute break between two intervals. To this end, it took about 2.5-3 hours for each participant to complete the experiment.

7.6 Results

Fig. 10a illustrates the distribution of the JND values of each interval condition. The results showed that the measured JND values varying across different interval conditions. In general, the JND values increased with the increase of the force magnitude in both directions of force changing. Furthermore, these four reference force levels and their corresponding ranges of JND values do not overlap with each other, as shown in Fig. 10b. This indicated that our device could generate a range of force feedback that are potentially distinguishable for the users. Taking the interval condition as the independent factor, we ran a repeated-measured ANOVA on the recorded JND data, and found that the interval condition played a statistically significant effect upon these JND values ($F_{(5,55)} = 36.357$, $p < 0.0005$, $\eta_p^2 = 0.768$). Post-hoc pairwise comparison showed the significant differences on the JND values between all the pairs of Interval-A/Interval-F and other references ($p < 0.05$). In addition, we also found that there was a significant difference between Interval-B and Interval-D ($p = 0.012$), and Interval-C and Interval-D ($p = 0.047$), while there was no significant difference between Interval-B and Interval-C ($p = 0.266$), Interval-C and Interval-E ($p = 0.526$), and Interval-D and Interval-E ($p = 0.123$). This suggested that the participants tended to be more sensitive to the force change generated from the force references with small absolute values in both the increasing and the decreasing directions.

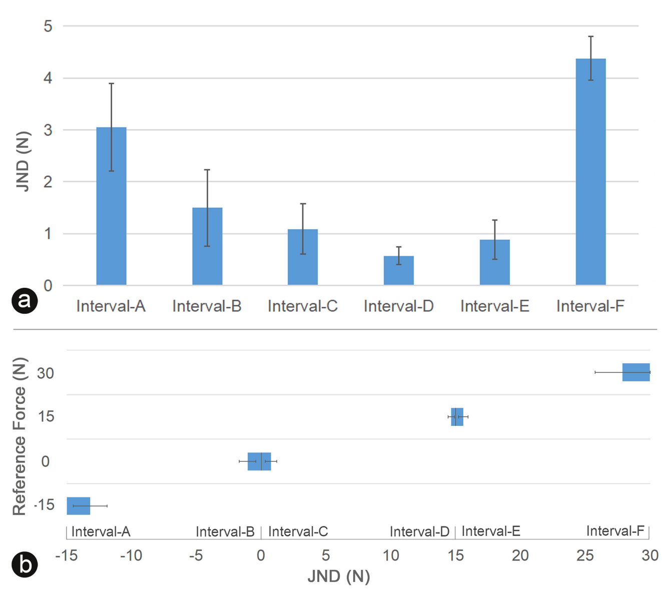

Fig. 10: (a) Mean values and 95% confidence intervals of the JND values, (b) The ranges of the reference force levels with the JND values.

8 User-Perception Experiment 2: Fluid Material Simulation

For the purpose of on-leg force-based fluid simulation, we conducted the second user-perception experiment on the users' ability of identifying different fluid materials according to the forces generated by *PropelWalker*.

8.1 Participants

We recruited 12 participants (3 females), with an average age of 27.4 years old (SD = 2.87). All these participants did not attend the previous experiments. They are all right-handed, have healthy calves, and can normally perceive force feedback.

8.2 Apparatus

We adopted the experimental hardware setup similar to the JND experiment (Fig. 11b). Additionally, we developed an experimental interface using Unity3D 2019.1.0f2 (Fig. 11a) for recording the participants' responses on material identification. During the experiment, participants needed to lift their legs to perceive the intensity of the force stimulus, and tap the tablet's screen to select the fluid-medium option (such as air, water, sand, and mud) that matched the on-leg force stimulus.

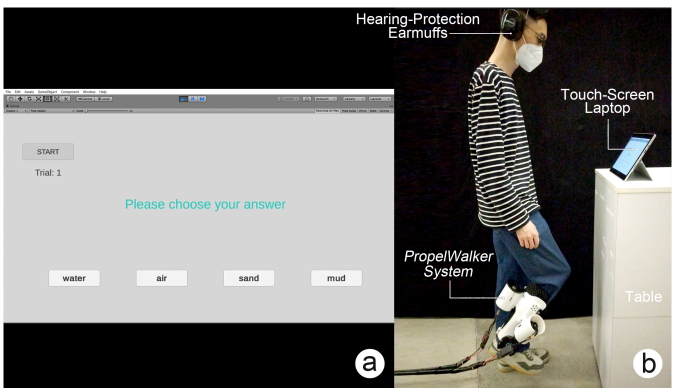

Fig. 11: (a) The experimental interface for the material simulation study, (b) Setup of the material simulation study environment.

8.3 Stimuli: Force Generation for Different Materials

According to the JND values resulted in the first user-perception experiment and the system capability of *PropelWalker*, we chose four types of materials that we may commonly walk-in in real world for this experiment. That is, Water, Air/Dry Land, Sand and Mud, including Newtonian fluid (e.g., Water and Air/Dry Land) and Non-Newtonian fluid (e.g., Sand and Mud). The densities [1] of different materials and the values of the buoyancy, the drag resistance, the potential weight, the joint forces, and the generated forces for these 4 material stimuli were shown in Table 3.

Material	Density (kg/m^3)	$\vec{F}_{buoyancy}$ (N)	$\vec{F}_{drag}$ (N)	$\alpha\vec{G}$ (N)	Joint force (N)	Generated force (N)
Water	1000	-12.70	+2.34	0	-10.36	-22.86
Air	1.225	-0.016	+0.016	0	0	-12.50
Sand	1442	0	+3.37	+16.96	+20.33	+8.33
Mud	1840	0	+4.30	+21.60	+25.90	+13.90

Table 3: The physical properties of different materials and the generated forces for *PropelWalker* considering the net weight of the device (1.25kg or 12.5N). "-" indicates the upward force direction for the weightless experience, and "+" indicates the downward force direction for the overweight experience.

8.4 Experiment Design

We adopted a within-subject experiment design. The independent variable was the type of the material, and we measured two main dependent variables, including the accuracy of material identification, and the trial-completion time. We also recorded the participants' ratings on the NASA-TLX questionnaire [16] to reflect the workload of material identification in the experiment.

The participant stood in front of the table and perceived the force stimuli by performing the action of WIP. The force stimuli lasted for 5 seconds. There was a 5-second break between two force stimuli to avoid the impact of the previous stimulus. Each type of material was repeated for five times, and all the stimuli appeared in a random order. In general, each participant completed 4 types of materials * 5 repetitions = 20 trials. Each trial took about 10 seconds including the break, and the total experiment lasted for about 15-20 minutes.

8.5 Procedure

Upon the arrival of the participant, the experimenter helped the participant to put on the *PropelWalker* devices on both legs and the noise-canceling devices, and introduced the experiment procedure which consists of two training blocks and one testing block. In the first training block, the participant could freely experience the force stimuli of four materials as much as possible until he/she reported that he/she was familiar with them. By tapping the corresponding button of four different materials (water, air, sand, and mud) on the tablet screen, the participant was able to activate the haptic stimuli by him/herself. After the first training block, the participant practiced identifying four random material stimuli without data recording. In between the second training block and the testing block, the devices were turned off, and the participant took off the devices for 5 minutes.

After the break, the experimenter helped the participant put on the devices again, and started the testing block. There were no visual or auditory cues when stimuli were presented. The participant was instructed to walk in place when the stimulus was presented, and provide his/her choice after the end of the stimulus as fast as possible, then click the Next button to confirm and complete the current trial. The task of material identification required the participant to physically feel the on-leg forces and mentally recognise the material type. Therefore, after finishing all the trials, the participant was asked to fill the NASA-TLX questionnaire [16] to rate his/her perceived workload in a 7-point Likert scale.

8.6 Results

Overall, the participants achieved an average accuracy of 94.2% for material identification. Table 4 shows the confusion matrix of the material-identification task. The repeated-measures ANOVA showed that there were no statistical differences for accuracy across the force intensities of four different mediums (Water: 93.33%, Air: 95.0%, Sand: 90.0%, Mud: 98.33%). The trial-completion time was obtained by measuring the time from the end of the force stimulus to the moment that participant confirmed his/her answer. The average trial-completion time of four different mediums were: Water (Mean = 2.6s, SD = 1.60), Air (Mean = 2.2s, SD = 1.13), Sand (Mean = 2.4s, SD = 1.43), and Mud (Mean = 2.2s, SD = 0.84). The repeated measures ANOVA showed that there was no significant difference between the completion time for different types of mediums.

	Water	Air	Sand	Mud
Water	93.33%	6.67%	0	0
Air	5.0%	95.0%	0	0
Sand	0	0	90.0%	10.0%
Mud	0	0	1.67%	98.33%

Table 4: Confusion matrix for material identification.

The NASA-TLX questionnaire results showed that the material-identification task based on the *PropelWalker*-generated force yielded low user ratings on the mental demand (Mean=1.92, SD=1.165), the physical demand (Mean=3.50, SD=1.977), the temporal demand (Mean=1.42, SD=0.669), the effort (Mean=3.50, SD=1.679), the frustration (Mean=1.50, SD=1.000) for the participants. In addition, the rating was relatively high in terms of the performance (Mean=6.00, SD=0.853).

[1] https://www.engineeringtoolbox.com/dirt-mud-densities-d_1727.html
[1] https://civiljungle.com/density-of-cement-sand-and-aggregate/

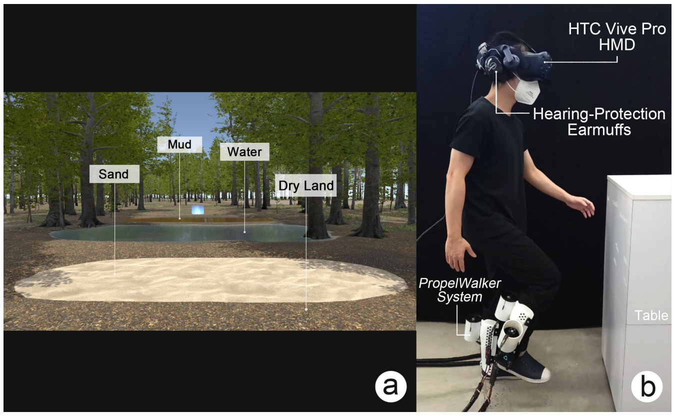

Fig. 12: (a) The virtual scene for the user experience evaluation, (b) Setup of the user experience study environment.

9 User-Perception Experiment 3: User Experience with *PropelWalker* in VR

With the experiments validating the effectiveness of the on-leg force feedback generated in *PropelWalker*, we further conducted the third user experiment to investigate how *PropelWalker* could affect users' sense of presence in immersive VR.

9.1 Participants

We recruited 12 participants for this experiment, with an average age of 27.1 years (SD= 3.06). All these participants are right-handed, and did not attend the previous experiments. Among them, 2 people self-reported that they had no VR experience before.

9.2 Apparatus

We developed a VR application using Unity3D (2019.1.0f2) (Fig. 12a). The participant needed to reach the highlighted destination in the virtual world, through the technique of WIP. The application used a HTC Vive Pro HMD, a pair of HTC Vive handheld controllers, a pair of HTC Vive trackers attached on the user's legs for tracking the walk-in-place action, and the *PropelWalker* system, as shown in Fig. 12b. When the users perform walking in place by raising their legs, the HTC Vive tracker records the user's leg movement state and maps it to the virtual motion of the avatar in the VR scene, thus enabling exploration in an infinitely large virtual environment. The corresponding sound effect would play when the participant entered and walked in a particular type of medium. There were three operating modes used in the experiment: 1) using the bare legs without *PropelWalker* (denoted as BareLeg), 2) wearing *PropelWalker* with corresponding haptic feedback (denoted as PW_C), and 3) wearing *PropelWalker* with randomly generated haptic feedback (denoted as PW_R). The purpose of testing the PropelWalker with random force levels (PW_R) is to investigate the necessity of providing the force feedback that matches with the virtual fluid.

9.3 Task and Procedure

Each session included one participant and one experimenter. The experimenter first introduced the experiment procedure, and helped the participants to put on the VR headset and the *PropelWalker* devices. The experimenter then taught the participant how to perform the walk-in-place action and navigate in the virtual world. The participant then went through three testing sub-sessions of VR interaction representing three aforementioned operating modes. In each sub-session, the participant was instructed to walk towards the highlighted destination in the virtual world. He/she would step into different mediums, such as dry land, sand, water, and mud. At the end of each sub-session, the participant was asked to fill out the presence questionnaire [55] with selected haptic-related questions, in a 7-point Likert scale (1: strongly disagree - 7: strongly agree). The questionnaire also included open-ended questions for reflecting out the participants' thoughts and suggestions for the device. The visual and auditory feedback was the same across the three modes, and the three modes were presented in a Latin-square-based counterbalanced order.

9.4 Results

The subjective ratings under these three conditions are descriptively shown in Fig. 13. Taking the operation mode as the independent factor and the participants' ratings as the dependent variables, we analyzed the results using the Friedman test followed by the post-hoc pairwise comparison using the Wilcoxon signed-rank test. The results showed that the type of operation mode significantly affected the perceived naturalness of the interaction ($\chi^2(2)$ =14.04, $p < 0.001$), consistency of VR and real world ($\chi^2(2)$ = 19.45, $p < 0.0001$), attraction of interaction ($\chi^2(2)$ = 11.69, $p < 0.005$), experience involvement ($\chi^2(2)$ = 15.32, $p < 0.0005$), ease of material identification through interaction ($\chi^2(2)$ = 18.53, $p < 0.0001$), sensory engagement ($\chi^2(2)$ = 16.39, $p < 0.0005$), consistency of the multi-sensory information in VR ($\chi^2(2)$ = 15.49, $p < 0.0005$). Post-hoc Wilcoxon signed-rank test revealed that PW_C outperformed the other two conditions in most of the items except for the noise interference, and the walking/interaction capabilities. There was no significant difference between PW_R and BareLeg in all the items. Table 5 shows the detailed average scores and pairwise comparisons for each questionnaire item. Specifically, the non-statistically-significant difference between BareLeg and PW_C (p = 0.417), BareLeg and PW_R (p = 0.13) to the question on the capabilities of walking and interacting in the VR environment indicated that the setting of *PropelWalker* did not affect users' movement and interaction in VR.

We also asked participants to rate the effect of noise interference and provide verbal feedback. The results showed that the operation mode significantly affected the rating of the noise interference ($\chi^2(2)$ = 8.72, $p < 0.05$). Post-hoc analysis revealed that BareLeg was significantly lower rated than PW_C ($p < 0.05$) and PW_R ($p < 0.05$). There was no significant difference between PW_C and PW_R (p=0.317) for the noise interference. P11 said, "I could hear the faint sound of the fan when the force intensity was high, but it didn't distract me or detract from my immersion in VR."

9.5 Qualitative Feedback

At the end of the experiment, we interviewed the participants to obtain their feedback on our system. Compared with the condition with only vision and auditory sense, the conditions involving haptic feedback improve the sense of realism and immersion in the virtual environment. When we asked the participants which condition they preferred, almost all the participants indicated that they preferred the condition with the on-leg haptic feedback which matched other senses, except one participant (P11) who preferred the BareLeg condition. P11 said, "I think the high-quality virtual environment and the vivid sound already made me feel good. The immersion is definitely stronger in the conditions involving haptic feedback, but it is more comfortable for me to walk without haptic feedback." Six participants stated that the overall experience felt natural as the sound was matched to the visual content, and the corresponding haptic feedback further improved their VR experiences. P8 commented that the auditory feedback of stepping and walking in the fluid actually helped reducing the noise generated by the fans.

Regarding the haptic feedback, several participants reported that it was very interesting to walk in different mediums with force feedback on their legs. P3 stated, "Switching between different force feedback was very smooth, and the change of force feedback generated by different mediums was also obvious." P5 said, "When interacting with different mediums with their corresponding forces, I feel very realistic. It was easier to distinguish the mediums through the physical interaction." Five participants reported that they were impressed with the scene of interaction with the mud, and "it feels like walking in the real mud." P2 stated, "When walking in the mud, I felt that my feet became heavy and hard to move, and I felt that my feet were stuck in the mud, and it was very real." P11 said, "When I stepped into the water, I could feel it's bouncy, and it makes me feel it's kind of floating." P7 and P9 stated that while the overall sense of presence was improved, the experiences in the mud and the sand were more realistic than those in the water and on the dry land.

We also asked participants to comment on the possible improvements and provide their suggestions. P8 said: "I feel that the sand is not as realistic as the mud, which may be caused by the different walking styles

Questionnaire Item	BareLeg	PW_C	PW_R	Pairwise Comparison
How natural did your interactions with the virtual environment seem?	3.75 (0.98)	6.17 (0.53)	3.17 (0.81)	PW_C > PW_R, PW_C > BareLeg, PW_R ∼ BareLeg
How much did your haptic experiences in the virtual environment seem consistent with your real world experiences?	2.58 (0.99)	6.17 (0.46)	2.83 (0.75)	PW_C > PW_R, PW_C > BareLeg, PW_R ∼ BareLeg
How compelling was your sense of moving around inside the virtual environment?	3.92 (1)	6.25 (0.48)	4.75 (1.05)	PW_C > PW_R, PW_C > BareLeg, PW_R ∼ BareLeg
How involved were you in the virtual environment experience?	3.83 (1.11)	6.42 (0.43)	3.92 (0.79)	PW_C > PW_R, PW_C > BareLeg, PW_R ∼ BareLeg
How easy was it to identify those fluid materials through physical interaction, like stepping on dry land or into water, sand, and mud?	2.67 (1.06)	6.50 (0.43)	3.00 (0.98)	PW_C > PW_R, PW_C > BareLeg, PW_R ∼ BareLeg
How completely were your senses engaged in this experience?	3.67 (1.06)	6.42 (0.51)	4.42 (1.03)	PW_C > PW_R, PW_C > BareLeg, PW_R ∼ BareLeg
Was the information provided through different senses in the virtual environment (e.g., vision, hearing, touch) consistent?	2.67 (1.16)	6.33 (0.49)	2.75 (0.9)	PW_C > PW_R, PW_C > BareLeg, PW_R ∼ BareLeg
How well could you move and interact in the virtual environment?	5.75 (0.61)	6.00 (0.39)	5.08 (0.83)	PW_C ∼ PW_R, PW_C ∼ BareLeg, PW_R ∼ BareLeg
Did the noise distract your attention?	1.58 (0.74)	2.50 (0.92)	2.58 (0.99)	PW_C ∼ PW_R, PW_C > BareLeg, PW_R > BareLeg

Table 5: Average questionnaire responses in Study 3. The numbers within the brackets are the 95% Confidence Interval for Mean. The $>$ in the "Pairwise Comparison" indicates the significant different with $p < 0.05$, and the $\sim$ indicates non-significant difference.

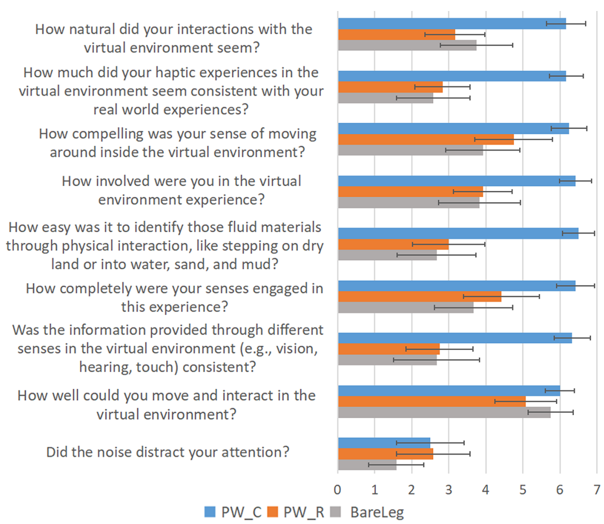

Fig. 13: Questionnaire responses on the user experience.

used in daily life and experiments." P3 said, "As soon as I step into the water, I could feel the upward buoyancy, but I didn't encounter any resistance when I walked forward." P12 stated, "When I walked on the land and the water in VR, the wind bouncing off the ground had influenced the experience a little bit." P9 suggested, "If user can feel different levels of force feedback according to the depth of stepping, it may be more realistic.". P1 stated, "I could clearly experience the buoyancy and the drag resistance, then I want more detailed haptic sensation, such as the pressure on the skin surface or the roughness of the ground."

10 Discussion

Our first user-perception experiment resulted in a set of non-overlapping JND values, suggesteding the *PropelWalker* system could generate a range of on-leg force feedback that can be potentially distinguishable for the users (H1). The JND values could further describe the resolution of human lower-limb perception for the propeller-based haptic feedback, and they could indicate the granularity for designing such types of on-leg haptic system for walking-medium simulation.

Our second user-perception experiment examined and verified our second hypothesis (H2) that based on the *PropelWalker*-generated force values for fluid simulation, users could identified different virtual fluid. Using our device, users can effectively distinguish four different fluids (air, water, mud, and sand), with the accuracy averaging over 90%. During the experiments, users commented that it was easier to distinguish air and water from mud and sand. This is echoed by the 100% accuracy of distinguishing these two groups of materials. That is, there was no water/air being identified as sand/mud, and vice versa, as shown in Table 4. On the other hand, it was sometimes easy to confuse air with water or mud with sand, which could be due to the same airflow directions.

In the VR-experience study (i.e. the third user epxeriments), we evaluated how three different feedback conditions affected the users' ratings of the sense of presence in VR. The results showed that the condition with the *PropelWalker*-generated forces matching the virtual fluids (i.e. PW_C), the users rated the sense of presence significantly higher than the other two conditions, validating our H3. Consistent with the previous research, providing the force feedback corresponding to the visual and the auditory contents was significantly more preferred by the users than vision/audio-only, indicating that multisensory integration is an important factor in eliciting ownership and embodiment in VR [14].

During the third user experiments, we collected a few possible use cases of *PropelWalker*. The straight-forward application is for gaming and sports. Some participants also suggested using *PropelWalker* to improve the VR experience/illusion in different planets (Fig. 1d & e), as they could feel being weightless and overweight with the device. While the actual gravity in another planet could be largely different from the earth, we see this user-suggested scenario mainly as an illusion rather than an exact simulation of gravity. Secondly, the participants mentioned that haptic sensation rendering might be applied to rehabilitation training to help users with lower-limb injuries. Another potential application is to provide alternative haptic feedback for the users with disability in their upper limbs to enhance their exploration in VR.

11 Limitation and Future Work

We also identified a few limitations in our current system. Firstly, noise is one potential issue affecting the user experience of *PropelWalker*. While the ducted fans used in our system could generate strong enough airflow and achieve a wide range of force feedback, they usually generate a large amount of noise especially for the strong force level generation. Although we can reduce the noise by using noise-canceling headphones and white noise and minimize its influence on the user experience, it is still challenging to eliminate all the noise due to the equipment limitations. In the future, it may be possible to consider using higher-level active noise-reduction devices or special sound-insulation materials to solve the noise problem, further enhancing the user experience. Besides, safety may also be a concern. In the current version, we installed a carbon fiber shield on the top of the ducted fan to prevent external objects from contacting the propeller blades. However, it is still difficult to avoid small items (e.g., debris) entering the fans. To this end, we conducted experiments in a clean lab environment to ensure no small item around.

Secondly, our technical experiments showed that it took a certain amount of time for the fan to start spinning from the total-still status, and this charging/delay time increased along with the strength of the force feedback. Currently, we simulated the force by turning on the upward and the downward fans simultaneously, thus generating the joint force of both fans. The real-time speed adjustment of the equipment did not cause a noticeable delay according to our user studies. In addition, applying the upward and the downward forces simultaneously allows the equipment as a whole to be in the same operating state. While we did not observe the major issue of the system delay on the user experience in our studies, in some scenes that require high-response feedback (e.g., quickly jumping out of and falling back into the water), the delay may place a negative impact on the user experience. The important future work includes investigating the user experience with *PropelWalker* in the VR scenario that requires high-speed on-leg force control, and designing complementary feedback techniques (e.g., visual illusion, and user-action prediction) to minimize the potential negative effect.

Thirdly, the current *PropelWalker* device mainly renders the sensation of weight and force in the vertical direction. As commented by some participants in the third experiment, it did not take into account the horizontal resistant force while walking in the fluid. Additionally, the current *PropelWalker* system mainly focuses on the kinesthetic force feedback on the calf, rather than the tactile feedback on the skin that could be generated by the liquid texture. In the future work, we plan to integrate other types of feedback mechanisms, such as vibration, pressure, and temperature, into the calf sleeves, to achieve more comprehensive haptic feedback on the lower limbs.

Another limitation of the current version of *PropelWalker* is the mobility and power consumption. Although our equipment can be used without large grounding structure and does not affect the walking experience very much, the system may still occupy certain level of physical space due to the usage of the external power supply. While the high-capacity battery could be used to power up our system, it may not be able to support the device for a long time. This could be potentially solved with the emerging development of power electronics, such as new types of battery and wireless power. In some VR scenarios where the strength of on-leg force feedback is low (e.g., shallow water, loose sand, snow, etc.), we could reduce the power output and adopt the portable/wireless power solution.

12 Conclusion

In this paper, we present *PropelWalker*, a propeller-based lower-limb haptic device that can simulate the vertical force perception of walking in different virtual fluid materials. We first conducted the pilot study to determine the optimal hardware setup. Our technical evaluation showed that the device could generate continuous and highly accurate force feedback ranging from 0 to 27N. Two user-perception studies were conducted to characterize how users could perceive force simulating fluid materials. The results showed that users could perceive high-resolution force feedback, and the *PropelWalker* system could effectively support them to identify different fluid materials (e.g., water, air, sand, and mud). Finally, the VR user study showed that the on-leg force feedback provided by *PropelWalker* significantly improved the immersion and the sense of presence in the VR environment. With *PropelWalker*, we hope to enrich the design space and the interaction paradigm of the propeller-based haptic device for VR.

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