Utilizing Liquid Transfer for Weight Simulation: Challenges and Future Directions

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ABSTRACT

Liquid mass transfer has emerged as a promising approach to induce weight perception in Virtual Reality (VR). This concept utilizes a tubing system to exchange a liquid between two or more units, to change their weight. As at least one of these units is attached to the user's body or controller, different weight sensations can be achieved. In this position paper, we provide an overview of related work in the area of liquid-based weight-changing devices, point at limitations of their approach and discuss future directions for their advancement.

KEYWORDS

virtual reality, haptic devices, weight perception, weight interfaces

1 INTRODUCTION AND BACKGROUND

Providing realistic haptic feedback is one of the key challenges to fostering the progress of VR technology. Therefore, researchers have shown an increased interest in the exploration of interfaces, that provide the sensation of the weight of physical objects [6]. Most notably, multiple research prototypes have been developed, that utilize liquid mass transfer to change the weight of handheld or body-worn devices. These devices contain liquid reservoirs and are connected to an external reservoir, from which liquid is drawn to facilitate the weight change. Unlike other methods, this approach allows the perception of real gravitational forces instead of simulating only aspects of the sensory information through which weight is perceived.

Niiyama et al. [8] developed a weight- and volume-changing device utilizing liquid metal transfer. The prototype featured a bidirectional pump that facilitated the transfer of Ga-In-Tin eutectic liquid. The flow rate was not specified. The weight range was 200 g in one application (a weight-changing block displaying different materials) and 162 g in another (a ball controlling a lever through weight change). Although this device was designed for such physical installations and teaching aids and not for VR applications, it introduced the concept of liquid mass transfer for weight rendering in human-computer interaction.

Cheng et al. [3] introduced GravityCup an approach to transfer the concept of liquid mass transfer to weight simulation in VR. However, due to the perceptible liquid inertia, they focused on the simulation of liquid containers, such as a cup of coffee or a watering can. The prototype incorporates a handheld water container and a water reservoir worn on the waist. Two water pumps enable the transfer of water between these two units, resulting in a weight range of 375 g for the handheld container (the total structure weight was 1.5 kg). However, to fill the handheld container, it takes the system 16.8 seconds which equals a flow rate of 19.62 g/s.

Similarly, Monteiro et al. [7] developed FluidWeight, which simulates a weight of up to 500g by pumping water from a body-worn container to a handheld device. The research focused on using low-cost materials, such as party balloons. Unlike GravityCup, FluidWeight's handheld device holds two separate water reservoirs to represent different centers of mass. This feature added significant complexity, with the system incorporating two stepper motor-driven syringes, two additional water pumps, and six water hoses between the handheld device and the body-worn device. The system achieved a flow rate of 66 g/s. In a VR demo, the system enabled users to experience different weights on the end of a fishing rod.

Wang et al. [9] presented VibroWeight, combining vibrotactile feedback with liquid-induced changes in the center of gravity and changes in absolute mass. A technical evaluation demonstrated absolute weight changes of up to 50g. The flow rate was not specified. The system utilizes water or Galinstan as the liquid medium and employs two 42 V-step motors, each moving a syringe. In a testbed virtual environment users could use the prototype to spray water or interact with stones or a sword.

Kalus et al. [5][4] developed PumpVR, which achieves a high flow rate of 150.8 g/s and absolute weight changes of up to 1 kg. It consists of two controllers, each containing a 500 g water bag, whose weight can be changed simultaneously or independently of each other. The system incorporates a high-performance bidirectional pump and four solenoid valves, that draw water from a flexible 1l tank. Due to this additional structure, the system was only evaluated in stationary experiences. In a VR game, players could use PumpVR to sense weight as they switched items of their inventory and used them to fight enemies. A second application demonstrated the ability of the system to simulate body weight.

Aiming to simulate weight across four body parts, Chen et al. [2] introduced GravityPack. It incorporates four water bags, that are, unlike previous prototypes, to be attached to the limbs. This enables the device to render absolute weight changes of up to 1.36 kg, distributed over four body parts. The total weight can be changed in approximately 40 seconds, with a flow rate between 39.2 g/s and 46.9 g/s. To meet the requirement of targeting multiple body parts, the structure employs over 1.3 liters of water, ten solenoid valves, and two water pumps. Consequently, the hardware, as well as the water tank are stationary and GravityPack therefore lacks mobility. The prototype was explored in a gamified VR application,

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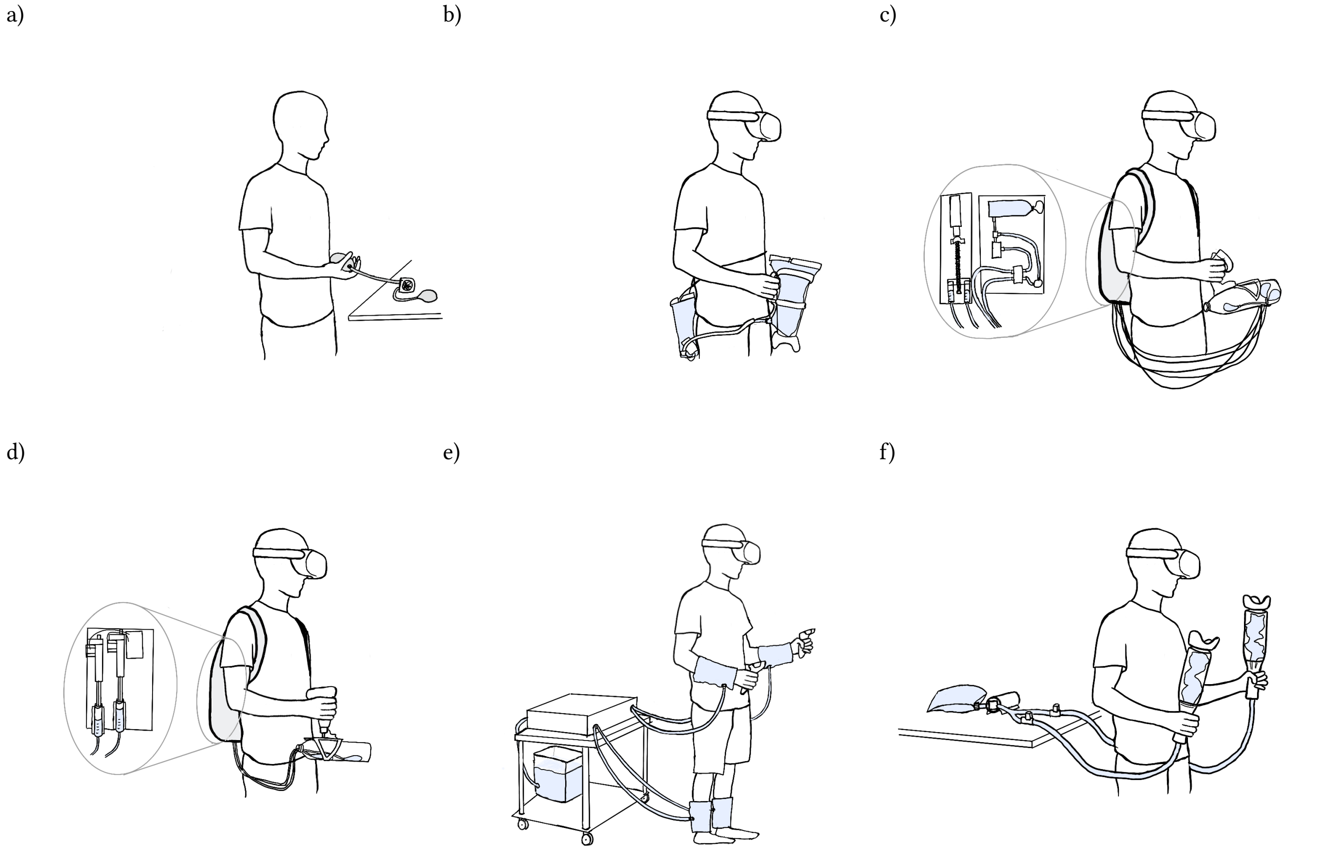

Figure 1: User perceiving weight through (a) the weight changing device of Niiyama et al. [8], (b) GravityCup [3], (c) Fluid-Weight [7]), (d) VibroWeight [9], (e) GravityPack [2], and (f) PumpVR [5] .

in which users watered carrots, pulled them from a bed, and fed them to rabbits.

Overall, research prototypes demonstrate various approaches to simulate weight in virtual reality through the transfer of liquids. Figure 1 illustrates the key characteristics of the presented systems. While some focus on a single body part, others aim for weight feedback on multiple body parts or different centers of mass at a single body part. Different electrical pumps, or step motors that move syringes are employed to facilitate the liquid transfer. The choice of the liquid medium varies between water, Ga-In-Tin eutectic, and Galinstan. Notably, some prototypes offer mobility, by making the hardware and liquid supply wearable in a backpack.

2 LIMITATIONS AND ROAD AHEAD

While the prototypes discussed in the previous section have made significant advancements in simulating weight through the transfer of liquids, several challenges remain to be addressed in order to achieve a truly immersive weight interface for virtual reality experiences. A comprehensive weight interface should meet multiple criteria to provide a truly immersive experience. Key objectives of the work discussed include:

(1) Render a wide range of weight
(2) Apply weight changes at high speed
(3) Allow mobile use
(4) Render weight at multiple body parts
(5) Allow the perception of different centers of mass

However, the prototypes presented in the related work section have focused on addressing two or three of the criteria but fall short in meeting the other criteria. This is demonstrated in Table 1. We considered weight ranges of 1 kg as wide [6] and flow rates of over 100 g/s as high and devices as fit for mobile use if demonstrated.

By examining the table, it becomes evident that while solutions exist to address individual objectives, they are unfit to satisfy all of the criteria simultaneously. Devices that focus on mobility aim to reduce the overall weight of the structure and therefore incorporate weak actuators and low-weight capacities. Devices, that demonstrate high-speed weight changes or heavy-weight rendering, in contrast, lack mobility. Additionally, none of the prototypes combine multiple limb targeting with multiple centers of mass.

Table 1: Features of Previous Liquid-Based Weight-changing Devices

	Weight changing device [8]	GravityCup [3]	FluidWeight [7]	VibroWeight [9]	GravityPack [2]	PumpVR [5]
Wide range					✓	✓
High speed						✓
Mobile		✓	✓	✓		
Multiple body parts					✓	✓
Multiple centers of mass			✓	✓		

Combining both features would further increase the weight of the structure, making comfortable mobile capabilities even less feasible. Hence, there is a clear trade-off between mobility and other essential features. To overcome this challenge, approaches need to be explored that prioritize lightweight and portable solutions without compromising on the other desired aspects.

Moreover, solutions that add complexity and thus weight to the system, hinder the goal of achieving a wide range of weights, as any weights lighter than the controller's empty weight cannot be perceived. This further highlights the need for alternative design considerations that do not add significant weight to the user's body.

Furthermore, alternative mechanisms to shift the center of mass need to be explored. Devices that incorporated changes in centers of weight typically employed multiple liquid bags within the same unit, allowing for independent targeting of each bag. Each reservoir is connected to the liquid supply individually, as a direct connection requires a solenoid valve and thus adds significant weight to the handheld device. As a result, shifting the center of gravity within a unit requires the emptying of one reservoir and the filling of another. This process can consume a significant amount of time, depending on the flow rate and complexity of the tubing system, which is a further limitation of the current approach to liquid-based weight change.

Future prototypes could attempt to separate the liquid supply and hardware from the user's body. A mechanism employing quick couplings might be explored, to ensure that the liquid reservoirs only have a tubing connection to the bulky components and the liquid supply when the weight is changed. Such an approach could reduce the overall weight burden and enable greater mobility. Moreover, future designs should consider incorporating hand-tracking, allowing the user to put the weight-changing device away for phases when no weight should be perceived. The weight of the device could then be changed externally before it gets picked up by the user again. This enables the user to discriminate between not holding anything and holding a weight that matches the controller's empty weight. This approach could involve Haptic Retargeting, a technique that exploits mismatches between the user's sensory channels to redirect the user during reaching movements [1]. By guiding the user to grab the device at a different location or at a different angle, distinct centers of mass could be perceived without the need to actuate a weight shift.

3 CONCLUSION

In conclusion, prototypes presented by related work have made promising advancements rendering a wide range of weight, applying weight changes at high speed, demonstrating mobile capabilities, targeting multiple body parts or shifting the center of mass. However to meet all of these criteria simultaneously, the current approach to liquid-based weight change needs to be rethought. By addressing these limitations via new design considerations, researchers can advance the field of weight interfaces for VR.

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