Swifty: A VR controller providing dynamic haptic feedback through shifting weight and air resistance

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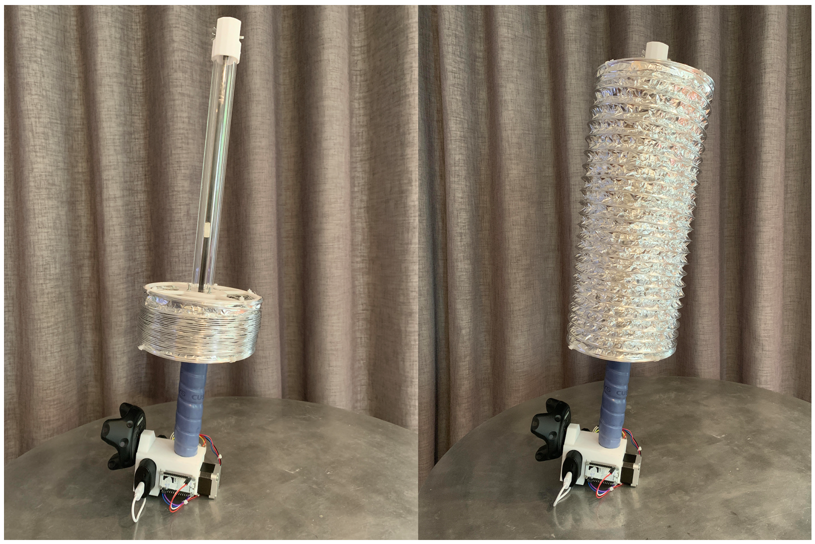

Figure 1: *Swifty* can change its air resistance and mass properties using a shifting weight and extendable bellows, it can be seen here representing a short sword (left) and a large long sword (right).

ABSTRACT

Standard virtual reality (VR) controllers lack the ability to convey realistic feedback as to a held objects weight, size or inertia. In this paper we present the concept and implementation of *Swifty*, a wireless VR controller that is able to provide dynamic haptic feedback based on its ability to change both its centre of mass and air resistance. It achieves this with an extendable outer bellows and a central movable weight. Our prototype is able to provide better haptic feedback when compared to standard VR controllers. *Swifty* provides an implementation that not only more closely matches the actual haptic properties of a held object but also increases the differences in haptic feedback between items in the same virtual environment (VE).

CCS CONCEPTS

• **Hardware** → **Haptic devices**; • **Human-centered computing** → **Virtual reality**; • **Computing methodologies** → **Perception**.

KEYWORDS

Haptic Shape Perception, Dynamic Passive Haptic Feedback, Virtual Reality, VR Props

1 INTRODUCTION

Virtual reality has progressed rapidly over the last few years, with immersive VR headsets such as the HTC Vive, Oculus Rift and PS VR available to the general consumer for home use. One aspect often overlooked is the design of the associated controllers and the feedback they provide. Controllers are the handheld input devices that allow the user to interact with the game world. They have simple triggers to close or open fingers and often provide simple vibrational feedback. Whether interacting with a heavy, light, big or small object the haptic experience of the user is identical. No matter how good the visual and audio simulation there will still be a divide in what is experienced in the virtual world and the feedback current controllers provide. The field of haptic feedback seeks to create devices that provide a sense of weight, texture and resistance within a virtual environment (VE) and more closely mimic real world interactions. Haptic devices are shown to create a greater sense of immersion for the player[2] which also has the benefit of better performance by the user, since they feel more comfortable within the virtual world and are able to approach challenges in a natural way[12]. This paper will look at the relatively new field of dynamic passive haptic props, introduced by Zenner and Kruger [13] in 2017. We will present *Swifty*, a low-cost and mechanically simple prototype that aims to combine dynamic weight and air resistance. The remainder of the paper will include a heuristic evaluation of *Swifty* and by comparing it to existing dynamic props show the potential viability of the design.

2 RELATED WORKS

This paper will mainly focus on passive haptics, and especially dynamic passive haptics. For a more general coverage refer to the taxonomy of Jeon & Choi[6]. Passive haptics is classified as feedback provided by an object's shape, texture and weight[1, 5, 12] and excludes active feedback generated by an artificial force-response. The application of haptics predates VR in the field of dynamic touch, first described in 1966[4]. It refers to the ability of people to perceive the weight and height of an object just by holding it, even if the object is not visible. Kingma et al.[7] explored this ability and proposed that the single most important factor in an object's perceived weight and height is the object's *static moment*, the mass times the distance between the point of rotation and the centre of mass.

More simply put, in a handheld object the further the object's center of mass is from the user's wrist the heavier and longer the object is perceived to be. This phenomenon is extremely useful in the design of VR props since a small prop can be perceived to be a different shape/weight by manipulating the prop's *static moment*.

Weighted props are not a new concept in VR. For instance, Fujinawa et al.[3] were able to build a *shape perception model*. This provided a "mapping from the mass properties of the controller to its perceived shape". Testing showed that users perceived an intended shape irrespective of the controller's actual appearance. For instance, a tennis racket prop was designed that was half the length of an actual racket but was still perceived as normal sized due to the prop's weight distribution. Weight is one of the ways that passive haptic feedback can be leveraged by props. Users can also receive passive tactile feedback which comes from an object's shape and texture. This was well documented by White[12], showing that both a solely tactile and a tactile weighted baseball bat prop led to greater immersion and performance in a simulated baseball game than traditional VR controllers. The tactile shape of a baseball bat handle caused almost 100% of users to adopt a traditional side-on batting stance, while only 58% of users did this with a standard VR controller. The added weight and tactile feedback also improved a user's hit/miss ratio and average distance per hit, with user's hitting 24% further. When the batting experience was made more realistic by including a haptic prop, the user experienced greater immersion and performed better.

While passive weighted props are effective at performance and immersion [12] their main issue lies in their lack of generality. A game with multiple objects requires multiple passive props. Zenner and Kruger [13] introduced an alternative with the concept of Dynamic Passive Haptic Feedback (DPHF), where a single shifting prop could take the place of multiple props. DPHF does not require any robotic arms or complex virtual warping but rather uses simple motors to alter the shape and weight properties of an object.

Zenner and Kruger have demonstrated two examples of DPHF props with *Shifty* [13] and *Drag:on* [14]. *Shifty* is a tracked lightweight rod with an internal lead filled weight. This weight can be moved up and down along a belt using a stepper motor. The shifting weight causes a change in the static moment of the object leading to a heavier or longer feel in the user's hands. In experiments conducted users reported a very strong feeling that the real world prop was actually getting longer and thicker despite there only being internal weight movement. It performed twice as well as a passive prop in terms of perceived realism and fun experienced by the user.

Drag:on is centred around using air resistance to provide different amounts of feedback. The device consists of a handle with two folding fans on either side. The fans can each open independently to create a variety of possible states, each one with a different amount of drag. When the prop is swung through the air the varying amounts of drag make the prop feel heavier and simulate resistance. Relying solely on air resistance means that when the prop is not being swung it provides very little feedback and by using fans, this also means that if the prop is swung parallel to the fan's orientation there is very little air resistance compared to swings perpendicular to the fans.

Other DPHF props include *Transcalibur* [10] and *ShapeSense* [8]. *Transcalibur* expands on *Shifty* and moves two weights separately, each being able to be placed anywhere in a quarter circle. This allows it to represent a variety of props with both symmetric and asymmetric weight distributions. *ShapeSense* attempts to combine dynamic air resistance and weight. The prop is made up of three shifting panels/sails that can move up and down a held handle. Each panel can also overlap reducing the overall air resistance of the prop. The prop can dynamically create different amounts of drag but also change its static moment by moving the panels further away from the user's hand. However, the flat panels still need to swung in the correct orientation in order to create drag.

The new field of DPHF has been proven to increase immersion and enjoyment of users, however as seen in the very different approaches in the four above props and Table 1, there is no agreed upon way to implement it. The most promising solution seems to be one that combines both dynamic air resistance and dynamic static moments.

Table 1: Current DPHF Props

Prop	Design	Limitations
Swifty	Single shifting weight inside a tube	Limited to single axis of movement, no change in resistance when swung
Drag:on	Expanding fans to vary air resistance	No air resistance if swung in wrong direction, no change in static moment
ShapeSense	Shifting panels that create varying levels of air resistance and weight distribution.	No air resistance if swung in wrong direction, overlapping panels can't create maximum air resistance and weight shift at the same time.
Transcalibur	Two shifting weights that can each be placed within a quarter circle	No change in resistance when swung

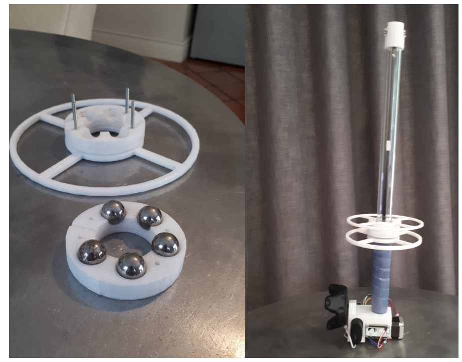

Figure 2: Left: The two halves of the outer ring Right: *Swifty* pictured without the bellows

3 DESIGN

Swifty is designed as a handheld VR proxy prop. It's primary design focus is to represent swords of different sizes and weights. The user holds *Swifty* in one hand and by shifting an internal weight, the prop is able to shift its center of mass and thereby change its static moment. As the weight moves this also expands/shrinks a surrounding bellows. This increases *Swifty's* surface area which leads to an increase in air resistance as the prop is swung. This combination of change in static moment and air resistance aims to cause different virtual objects to haptically feel different and perceived as heavier and longer, or lighter and shorter. Since the prop is designed to be swung while wearing a head-mounted display (HMD), the overall prop length cannot be too long in order to reduce the risk of hitting real world objects. The prop also needs to be completely wireless so it can be swung freely by the user.

4 CONSTRUCTION

The core of *Swifty* consists of a clear plexiglass pipe (diameter = 30mm, wall thickness = 5mm) capped on either end with 3D printed parts, leading to a total length of 61cm. An internal belt runs the length of the pipe and is fixed to a bearing at the top, and a NEMA-14 type stepper motor at the bottom. This is similar in approach to *Shifty*[13] and means that the belt is always kept taunt and is protected from any distortions when swung. A stepper motor was chosen as it allows a high degree of control over the movement of the weight. Additionally, while powered, stepper motors have a holding torque which is able to hold the weight in place when the prop is swung. The NEMA-14 represents a good middle ground between size and weight versus lifting power and holding torque. A 7mm groove runs down the majority of the length of the pipe which allows a bolt to connect the belt system with an outer ring. This outer ring contains five 15mm steel ball bearings, weighing a combined total of 133g. While the stepper motor is able to lift more than this, a heavier weight raises the chance of the ring overcoming the motor's holding torque when swung. These bearings not only act as the weight but also allow the ring to move up and down the pipe without much friction and stops the ring from rattling against the pipe. A weight could have been mounted within the pipe but due to the thin diameter it would have been spread across several centimeters. This would have reduced the effectiveness of shifting the weight, so the outer ring approach was chosen. The outer ring has four arms that connect to a thin outermost ring (15cm diameter). By choosing a circular design we eliminate the weakness seen in *ShapeSense* and *Drag:on* which only provided resistance if swung with the correct orientation. While a cylinder provides less air resistance than a flat panel we believe consistency and versatility are more important. This outermost ring serves as the mounting point for the prop's bellows system. The bellows is made from flexible aluminium ducting which can repeatedly expand and shrink using a coiled wire that acts like a slinky. This type of ducting was chosen as it is lightweight, inexpensive and readily available. The ducting is cable tied to the outermost moving ring and a similar stationary ring at the hilt which also doubles as the prop's cross-guard. When the stepper motor moves it raises/lowers the weighted ring which in turn expands/shrinks the bellows, it can do this over a range of 29.5cm.

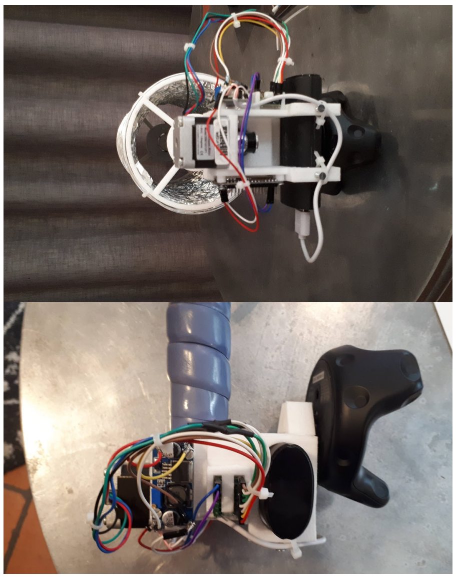

Figure 3: Closeup of pommel mount

5 ELECTRONICS

Swifty is controlled by a NodeMCU, which connects to a WiFi network using its inbuilt ESP8266. The NodeMCU was chosen since it has inbuilt WiFi and is much smaller and cheaper than an equivalent Arduino. The NodeMCU sends direction and step data to a A4988 stepper motor driver which controls the movement of the NEMA-14. Since advanced features such as micro-stepping were not needed the cheaper A4988 was chosen over more complex expensive drivers. The entire system is powered by a 6700mAh powerbank which is able to output 5V/2A. These kinds of powerbanks tend to be bigger and heavier than 5V/0.5A ones but allow the entire system to get adequate power from a single source and go several hours without a recharge. Power for the stepper motor goes through a buck converter to boost the 5V up the required 10V. When connected to WiFi a UDP connection is established between the Unity virtual environment and the NodeMCU. Messages can then be sent/received over this connection allowing the test environment to control the movement of the stepper motor. Using WiFi instead of Bluetooth means the target computer running the VE does not need Bluetooth and just needs to be connected to the same network. All of these components are screwed in place onto the 3D printed pommel with sits below the user's hand. On this mount is also place for an HTC Vive Tracker[1] which allows the prop to be tracked by the VR system. The tracker and powerbank and be easily unscrewed from the prop and charged when needed.

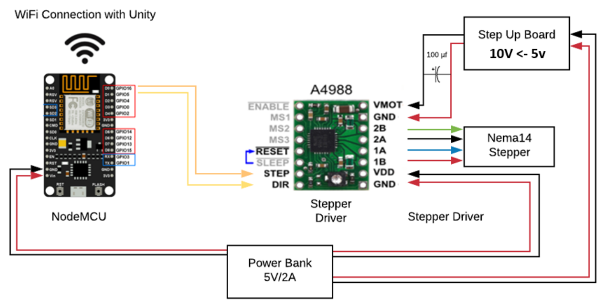

Figure 4: Swifty Circuit Diagram

6 VIRTUAL ENVIRONMENT

In order to test the effectiveness of *Swifty* a virtual food slicing game was created. This game can be played with a standard VR controller or *Swifty*. The game places the user in the middle of a medieval village which is an appropriate setting for the use of swords. The user starts off with a small one handed short sword but can switch to a large double-handed sword by reaching over their shoulder, which mimics drawing a sword from a back sheath. This is a useful way of weapon switching as it requires no button presses so can be done with *Swifty* or the controller in the same way. When the sword is placed behind the player's back it also leaves their field of view meaning no visual change animation is required and the change can be communicated with a simple unsheathing sound effect. If the player is using *Swifty* the prop grows/shrinks based on which sword has just been drawn. The swords are keyed to follow the position and orientation of whichever control device is currently being used. No hand or body avatar is displayed which means the prop can be held in the left, right or both hands and not have a visual conflict with what is shown in game. Once the game starts various food items are launched from two barrels and arc towards the player at a random height and speed. The user needs to slice the incoming food using their sword. This kind of game requires the user to judge the reach of their sword and correctly time swings. These are similar requirements to the baseball tests done by White[12] in which participants did better when given a haptic prop. This kind of test should allow us to determine whether *Swifty* is an effective haptic prop. If a food/sword collision is detected

[1] https://www.vive.com/eu/accessory/vive-tracker/

the food item is sliced in two along the cut line accompanied by a particle and sound effect. This is done dynamically and a new simple cut material mesh is drawn on either side of the exposed cut food. An alternative could be to create pre-made models for each cut segment that spawn when a collision is detected and allows for higher level of model detail. However this means that the fruit breaks along predetermined lines and does not match where the sword actually collided with the food. By dynamically splitting the food at run time, it allows the food to split exactly where the user would expect it to, which we believe is more immersive. To prevent users from just holding the sword in a single place, food will bounce off the sword rather than be sliced if the sword's velocity is too low and a 'thud' sound effect is played instead of the usual slice sound. If the sword is being swung fast enough to cut fruit, a trail will be rendered behind the sword and a 'swooshing' sound effect will play. Additionally whenever a collision is detected the stepper motor briefly steps up and down, while this does not move the weighted ring it does cause a slight vibration which is similar to the haptic feedback provided by standard controllers.

Figure 5: Left: Short sword slicing launched food Middle: Bird's-eye view of VE Right: Long Sword facing Medieval Village

7 HAPTIC EVALUATION AND TESTING

Due to the ongoing COVID-19 pandemic large scale user testing had to be abandoned in favour of a small scale heuristic evaluation similar to one laid out by Sutcliffe & Gault[11]. The prop was evaluated by 3 users experienced in both VR development and VR haptics, although this is a small number it has been proven that a high proportion of usability issues can be identified with only a few evaluators[9]. This paired with some physical measures of *Swifty's* performance provides an idea of the effectiveness of the prop.

Physical Measures

In this section we will look solely at various performance aspects of *Swifty*, comparisons with other existing DPHF props can be found in Section 8.

Swifty weighs in total 1025g with a shifting weight of 133g that allows for ≈13% of the prop's mass to shift along a 29.5cm range. In its smallest state the centre of mass sits 15.5cm from the bottom which lies in the centre of the grip. When extended the centre of mass shifts to 24cm from the bottom which places it above the cross guard, outside of the user's hand. This shift in centre of mass of 8.5cm allows *Swifty* to feel heavier and longer in the user's hand.

When compressed the bellows has a surface area of 660cm^2 which when extended becomes 1700cm^2. The frontal area of the cylindrical bellows, the area in contact with the air when swung, is approximately half the total surface area (330^2 - 850^2). This increase in frontal surface area of 520cm^2 causes an increase in air resistance. This change in air resistance allows *Swifty* to feel larger in the user's hand.

A round trip ping between the Unity VE and *Switfy* averages 32ms while a complete transition between the expanded and compressed states takes 3.2 seconds.

Figure 6: Left: Short sword in use Middle: Sword being swapped using back sheathe Right: Long Sword in use

Heuristic Evaluation

Evaluators each played the test game first with a standard controller and then with *Swifty*, in this way they were able to evaluate the test environment and the prop separately. This also allowed them to contrast the controller with *Swifty*. The evaluation was based on the heuristics and method laid out by Sutcliffe and Gault[11], however since evaluations of this nature usually only look for problems, it was adjusted to also be able to identify areas where *Swifty* is more effective than standard controllers. Notes and observations were taken during each evaluation, the evaluator was then interviewed about their experience and each observation was categorised and rated into Table 2. Problems encountered where further classified and rated into Table 3. The categories and rating scales are both taken directly from Sutcliffe and Gault.

Evaluators reported that *Swifty* created a highly immersive VE and it felt as if they were wielding an object of similar size to what was displayed virtually. There was noticeable difference between the long and short sword, and wielding them felt like different experiences. *Swifty* provided good tactile and kinesthetic feedback as well as some active feedback in the form of vibrations on colliding with food. The size of the hilt did cause some breaks in immersion as users wanted to sometimes hold the sword with two hands and would accidentally grab the pommel mount. In doing so they would sometimes touch the electronics or plastic, which did slightly break immersion. The biggest problem was the holding torque of the motors. If swung too hard the weighted ring would move up the shaft. This created an audible sound which was distracting and meant the prop could end up fully extended at the wrong time. Once evaluators were aware of this problem they were able to reduce the number of times this happened but in doing so were forced to constantly be mindful and could not react naturally.

8 DISCUSSION

By combining the positive effects found during the evaluation and comparing physical measures to existing successful DPHF props the overall effectiveness of *Swifty* can be assessed. A comparison between all 5 props can be found in Table 4. *Swifty* is about twice as heavy as existing props which does lead to a greater level of fatigue if swung for long periods of time. However this is more realistic as swinging an actual sword is very tiring, additionally *Swifty* is the only one of the props that is truly wireless. All the other props are connected via a wire to an external power source, which allows them to be so lightweight. We believe the ability to freely wield *Swifty* without having to worry about any wires is worth some additional weight. While the weight moved is very similar across the props, *Swifty* shifts a smaller percentage of it's total weight (≈13%). However, *Swifty* moves this weight across a further range leading to a comparable shift in centre of mass to *Shifty* (8.5cm vs 11cm). This expected result matches what was experienced by the evaluators who all reported that the object felt longer and heavier as it shifted its weight. Transition times are comparable across all props except *Drag:on*, which opens a fan rather than shift a weight.

It is difficult to compare air resistance across the props, although *Swifty* and ShapeSense have similar frontal surface areas they have very different shapes. A cylindrical bellows creates less drag than three flat panels, however the flat panel's drag does depend its orientation when swung. *Swifty's* ability to have a constant level of drag, no matter the orientation allows for a consistent user experience. The comparable **change** in surface areas between the two props does show that there will be a comparable difference between different props. This matches evaluators experiencing the long sword as not only heavier but also larger than the short sword. This change can be attributed to the change in air resistance. The results of the evaluation show that *Swifty* provided a realistic level of haptic feedback. Most of the problems identified do not have a major impact on the overall experience of the game. The major problem identified is the inability to quickly accelerate/decelerate the prop due to the inability to hold the weight with such a small stepper motor. This meant that users had to be consistently aware of how hard they were swinging their sword and were unable to be fully immersed in the VE.

9 LIMITATIONS AND FUTURE WORK

The experience of using *Swifty* was negatively impacted by the limited holding torque of the stepper motor. Not being able to freely swing the prop and the negative impact of a sudden unexpected weight shift meant that a user had to be constantly aware of how forcefully they were moving the prop. This problem is a result of the choice of stepper motor which only had a holding torque of 1 kg-cm. Upgrading to a larger more powerful stepper motor would have significantly increased the overall weight of the prop reducing the effectiveness of the shifting weight. Other solutions could be to use a non-backdrivable gear system that can only be operated by the stepper. Similar solutions were used in ShapeSense[8] and Transcalibur[10]. Another alternative solution would be some kind of locking mechanism controlled by the NodeMCU.

As discussed previously, *Swifty* is significantly heavier than previous DPHF props which somewhat limits its accessibility. A large contributor to the overall weight is the powerbank (135g). The need for a 5V/2A powerbanks meant that this was the lightest one available at the time. Swapping to an alternative power source or a lighter powerbank would decrease the overall weight and fatigue on the user as well as increase the effect of the shifting weight has it would make up a higher percentage of the overall weight.

The ducting material used deflects slightly when swung and makes a slightly audible sound. While this is not a problem if the user is wearing a headset with headphones, a more suitable material may be required.

Future implementations of *Swifty* could include a two-handed version which allows for a wider range of usage but the overall length of the prop should not be increased as that would increase the risk of hitting objects when swinging the prop. *Swifty* is already the longest of the current DPHF props and cannot be made much longer safely.

The lack of buttons on the prop also makes it difficult to add additional features. A future iteration would include buttons so *Swifty* can better perform standard controller task such as menu selection. Such solutions already exist in *Drag:on*[14] and *Shifty*[13].

While we were able to get a good idea of the effectiveness of *Swifty* this can be further investigated with a larger user experiment. Once it becomes safe to do so, an experiment with an improved version of *Swifty* with 30-40 participants should further show the viability of the prop and DPHF props in general.

Table 2: Haptic Feedback Comparisons

Heuristic	Benefits Observed	Problems Encountered
1. Natural Engagement	VE maintains a good degree of realism	Inability to impale the food onto the sword
2. Compatibility with the user's task	Swinging sword felt believable and realistic	No interaction between the sword and the ground.
3. Natural expression of action	Length of prop feels close to length of virtual item	Due to small hilt size, the user is unable to comfortably wield the sword in two hands. If swung too hard the weight moves so user has to limit power of swings.
4. Close coordination	Sword tracking and slicing was very responsive	Sword switching time was noticeable but not immersion breaking
5. Realistic Feedback	Noticeable difference between the two swords, size and weight of virtual swords was believable. The sword felt heavy in the hand and did cause some fatigue. Tactile feedback of sword grip was believable.	Contact with fruit vibration was noticeable but not entirely believable. Touching the plastic pommel mount or cross guard did not provide expected tactile feedback
6. Faithful viewpoints	VE was mostly believable	Slight tearing on sword model when swung at fast speed.
7. Navigation and orientation support	N/A	User stays within single area and play room limits handled by SteamVR room bounds
8. Clear entry and exit points	N/A	Not relevant for single area VE
9. Consistent departures	N/A	No major departures required
10. Support for learning	N/A	Not necessary for simple interactions
11 Clear turn-taking	N/A	Single user VE
12 Sense of presence	Very good level of immersion	Reduced only slightly by lack of hand or player avatar.

Table 3: Problem Classification

Feature	Problem Description	Problems Rating	Design Change
Graphics	Texture tearing	Slightly inconvenient	Faster Hardware
Presence	Unable to swing with too much force	Very Distracting	Use gearbox or add locking mechanism
Interaction	Unable to impale fruit as expected	Inconvenient	Add additional collision detection on point
Environmental features	N/A		
Controls	N/A		
Hardware	Touching electronics breaks immersion	Distracting	Design better electronics housing.

10 CONCLUSION

We presented *Swifty* a Dynamic Passive Haptic Feedback prop that implements the proven systems of weight and air resistance adjustment into a new design that combines the benefits of previous examples into a single wireless device. Despite the inability to do a large user experiment due to COVID-19, by comparing it to existing props as well as a heuristic evaluation we were able to show that *Swifty* is more immersive and enjoyable than a standard VR controller.

Table 4: *Swifty* vs Existing DPHF Props

	Swifty	***Shifty*[13]**	***Drag:on*[14]**	**ShapeSense**[8]	**Transcalibur**[10]
Transition Time	3.2s	2.8s	0.5s	12s	4s
Transition Range	29.5cm	24.5cm	N/A	18cm	21.5cm
Weight Moved	133g	127g	N/A	3x56g	2x72g
Total Weight	1025g	440g	598g	480g	400g
Surface Area	330 cm^2 -> 850cm^2	N/A	320cm^2 -> 2400cm^2	297cm^2 -> 891cm^2	N/A
Max Length	61cm	50.05cm	54cm	43cm	38cm

REFERENCES

[1] M. Azmandian, M. Hancock, H. Benko, E. Ofek, and A. D. Wilson. Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. In *Proceedings of the 2016 chi conference on human factors in computing systems*, pages 1968–1979, 2016.

[2] I. Choi, E. Ofek, H. Benko, M. Sinclair, and C. Holz. Claw: A multifunctional handheld haptic controller for grasping, touching, and triggering in virtual reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–13, 2018.

[3] E. Fujinawa, S. Yoshida, Y. Koyama, T. Narumi, T. Tanikawa, and M. Hirose. Computational design of hand-held vr controllers using haptic shape illusion. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, pages 1–10, 2017.

[4] J. J. Gibson. The senses considered as perceptual systems. 1966.

[5] S. Henderson and S. Feiner. Opportunistic tangible user interfaces for augmented reality. *IEEE Transactions on Visualization and Computer Graphics*, 16(1):4–16, 2009.

[6] S. Jeon and S. Choi. Haptic augmented reality: Taxonomy and an example of stiffness modulation. *Presence: Teleoperators and Virtual Environments*, 18(5):387–408, 2009.

[7] I. Kingma, R. Van De Langenberg, and P. J. Beek. Which mechanical invariants are associated with the perception of length and heaviness of a nonvisible handheld rod? testing the inertia tensor hypothesis. *Journal of Experimental Psychology: Human Perception and Performance*, 30(2):346, 2004.

[8] Y. Liu, T. Hashimoto, S. Yoshida, T. Narumi, T. Tanikawa, and M. Hirose. Shapesense: a 2d shape rendering vr device with moving surfaces that controls mass properties and air resistance. In *ACM SIGGRAPH 2019 Emerging Technologies*, pages 1–2. 2019.

[9] J. Nielsen. *Usability engineering*. Morgan Kaufmann, 1994.

[10] J. Shigeyama, T. Hashimoto, S. Yoshida, T. Narumi, T. Tanikawa, and M. Hirose. Transcalibur: A weight shifting virtual reality controller for 2d shape rendering based on computational perception model. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–11, 2019.

[11] A. Sutcliffe and B. Gault. Heuristic evaluation of virtual reality applications. *Interacting with computers*, 16(4):831–849, 2004.

[12] M. White, J. Gain, U. Vimont, and D. Lochner. The case for haptic props: Shape, weight and vibro-tactile feedback. In *Motion, Interaction and Games*, pages 1–10. 2019.

[13] A. Zenner and A. Krüger. Shifty: A weight-shifting dynamic passive haptic proxy to enhance object perception in virtual reality. *IEEE transactions on visualization and computer graphics*, 23(4):1285–1294, 2017.

[14] A. Zenner and A. Krüger. Drag: on: A virtual reality controller providing haptic feedback based on drag and weight shift. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–12, 2019.