InvisiBow: Finger-Held Device for Bimanual Haptic Illusions during Virtual Archery

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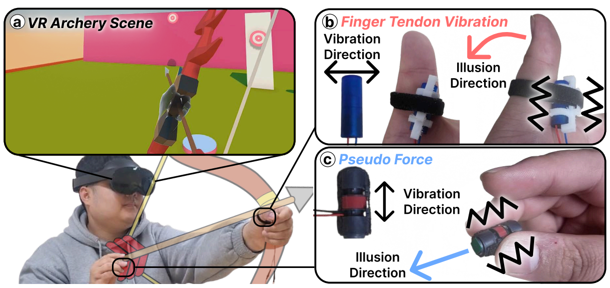

Figure 1: (a) InvisiBow uses two different vibration-based kinesthetic haptic illusions for realistic VR archery experience. (b) FTV simulates the virtual bow pushing against the thumb. (c) Pseudo force simulates bowstring tension.

Abstract

We present InvisiBow, a finger-held device that renders bimanual haptic feedback leveraging two haptic illusions, finger tendon vibration (FTV) and pseudo forces, for a VR archery experience. Each haptic illusion provides a different force sensation on the left and right hands to simulate the asymmetric forces during an archery experience. We evaluated the performance and results demonstrated a significant increase in realism and immersion for InvisiBow compared to controllers. Cross-illusion interactions revealed that amplifying asymmetric vibration intensity in the right hand heightened the perceived intensity of FTV on the left hand. These findings highlight the bimanual haptic design space and the potential of combining haptic illusions for creating realistic VR applications involving asymmetric hand actions.

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CCS Concepts

• **Human-centered computing → Haptic devices**; **Virtual reality**.

Keywords

virtual reality; bimanual haptics; finger tendon vibration; asymmetric vibration; haptic illusions

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1 Introduction

In daily life, we often interact with objects using both hands, making bimanual interaction a natural and important aspect of human experience. In the context of VR, providing bimanual haptic feedback enhances the realism and naturalness of interactions [29]. Additionally, incorporating haptic illusions in bimanual feedback has been shown to improve user experience and enable complex renderings with minimal hardware requirements [11, 15, 22, 24]. By exploring bimanual haptics, which has been comparatively under-researched, we aim to demonstrate how interaction effects between the two hands can enhance immersion, a concept supported by prior studies, such as Games Bond [22] and Pseudobend [15].

We present InvisiBow (Figure 1), a finger-held device that utilizes a bimanual system using two haptic illusions: finger tendon vibration (FTV), which causes illusory finger movement without physical movement [31], and pseudo forces, which employ asymmetric vibration to induce force sensations [9, 24]. We selected archery as our application because it naturally involves dynamic bimanual interactions with distinct forces.

Vibration on muscle spindle endings creates the illusion of muscle lengthening [13]. These vibrations on the arm [6], leg [14], or neck [28] create perceptions of movement or force [31]. In particular, by vibrating the tendons in the finger, FTV creates a feeling of finger extension or flexion without physically moving the fingers. This illusion has been used for hand rehabilitation [12, 20, 27]. In this paper, we use FTV on the thumb to simulate the force of the bow pulling back on the thumb.

Research on vibrotactile feedback has shown that vibrations coupled to user action induce aspects of force [10, 15, 16, 21, 32]. However, these methods are indirect and provide *force-like* experiences [26]. Another established method of inducing force sensations using vibration is with asymmetric vibrations. Asymmetric vibration, where a moving mass is unequally accelerated in two mutually opposite directions, has shown to induce a sensation of force, known as pseudo force [1, 3]. Research has explored different ways of rendering pseudo forces, ranging from changing vibration parameters [23, 30] to actuation motors [7], including voice coils [9], LRAs [19, 24], and DC motors [33].

While explored extensively alone, the integration of these two illusions has not been explored. Therefore, we focus on integrating them to a single interaction context of archery. Also, we evaluate its performance compared to only FTV, only pseudo force, and commercial controller-based vibrations for a bimanual VR application.

Our contributions are the following:

- A simple finger-held device, providing bimanual haptic feedback using FTV and pseudo force.
- Insights on combining two distinct haptic illusions for a bimanual application.
- An empirical evaluation comparing InvisiBow to commercial controllers, FTV and pseudo force illusions in isolation for a VR archery task.

2 InvisiBow

2.1 Design Approach

When holding a nocked bow, the archer feels the bow pulling on the thumb as the archer holds the bowstring. To match this sensation, we employed FTV on the left thumb. FTV on the dorsal side of the thumb creates a sensation of thumb flexion, while the opposite side creates a feeling of thumb extension. In this case, we use FTV to vibrate the palmar side of the thumb and create a sensation of thumb extension. To recreate the bowstring-pulling sensation, we rendered asymmetric vibration to generate pseudo forces on the right hand.

2.2 Hardware Implementation

We used an eccentric rotating mass (ERM) motor (VZ7AL2B169208T, Vybronics) for the vibration and placed it in a 3D-printed (TPU 95A) motor housing. We used a flexible housing material to dampen the vibration from spreading and tightened the housing on the finger using velcro straps. We placed the motor housing on the base of the palmar side of the proximal phalanx of the left thumb for the feeling of thumb extension. Using a motor driver (DRV8835, Texas Instrument), we vibrated the ERM at a constant 80 Hz to maintain the FTV illusion, resulting in a constant ±1 mm amplitude.

We rendered pseudo forces using an asymmetric vibration input waveform, which is derived from accelerating a mass unequally in two mutually opposite directions [1–3, 23]. Based on the research showing that LRAs can induce pseudo forces [19], we used a TacHammer Drake Low Frequency actuator[1] to convert input waveform to vibrations, see Figure 1c.

To render the asymmetric vibrations, we used the actuation pipeline from [24] which uses modified Haptic Servos [25]. Teensy 4.1 microcontroller with the PT8211 DAC shield converts the digital waveform to an analog signal. This analog signal is further amplified using a Visaton Amplifier (Visaton Amp 2.2). The output of the amplifier was supplied to the TacHammer to render the asymmetric vibrations. The amplifier gain was kept the same, and the amplitude change based on the pulling of the bow was controlled through the firmware. The frequency of the asymmetric vibration was 40 Hz, as it is shown to induce stronger pseudo forces [8, 23]. We added sandpaper on the actuator to minimize the slipping of the actuator between the fingers to improve the perception of pseudo forces [9].

2.3 Bimanual Haptic Rendering for Bow Shooting

For InvisiBow, we developed a VR archery scene (Figure 1a) using Unity 3D (2022.3.14f1). In our VR archery scene, the user grabs the bow with their left hand and nocks the bow with their right hand and shoots at 4 targets in the scene.

Drawing the Bow When the bow is in a ready state, the distance is set to zero with no vibrations. When the user's right hand pinches the virtual bowstring, the system enters the pulling state. When the user pulls their right hand back, vibration information is sent to the MCU via serial communication. To maintain the FTV illusion, we use a constant frequency for the FTV actuator, which activates it with a constant amplitude. However, for the right hand, we activated the pseudo force actuator with an amplitude proportionate to the bowstring pull distance.

Bowstring Tension To align with the user's action of pulling the bow, we used a simple force equation. Eq 1,

$$F = ax + b \tag{1}$$

We followed the parameters of flatbow from the work of Silviu [5], where F is the tension force, $a = 0.2837$, $b = 11.24$, and x is the distance of bowstring pulled from start point with a range of 0 $\sim$ 25 cm in virtual environment.

$$Intensity = (F - F_{\min}) \cdot (F_{\max} - F_{\min})^{-1} \tag{2}$$

where intensity is in the range of [0,1], $F_{\max}$ is the force of maximum distance (25 cm), and $F_{\min}$ is the minimum distance (0 cm). To evaluate our bimanual design, we compared InvisiBow with commercial controllers (Meta Quest Pro) as our baseline.

3 Study

We recruited 9 right-handed participants (4 male, 5 female; average age: 26.7, SD: 3.64) for virtual archery in VR. For *Controller*, participants held controllers in both hands with left vibration frequency of 80 Hz and right vibration of 40 Hz to match InvisiBow. For the other conditions, participants used our InvisiBow setup. During *FTV Only*, participants held the pseudo force actuator, but only the FTV motor vibrated when they nocked the bow. Likewise, for *PF Only*, participants had the FTV motor attached to their left thumb,

[1] TITAN Haptics DRAKE TacHammer (LF): https://titanhaptics.com/product/drake-haptic-actuator-kit-12-pack/; accessed January 30, 2025

but only the pseudo force actuator vibrated. We chose realism, immersion, and enjoyment to evaluate InvisiBow's performance. Participants answered the 5 criteria on a 7-point Likert scale from strongly disagree to strongly agree. 1 means they felt no realism, immersion,enjoyment, and force changes, and 7 means they felt them well.

4 Results

We conducted a Kruskal-Wallis test and post-hoc pairwise Mann-Whitney tests (Figure 2) with a significance level of $p = 0.05$ for each questionnaire categories.

For realism, Kruskal-Wallis test on participant answers yielded $H(3) = 8.69$ with $p = 0.029$. *InvisiBow*, *FTV Only*, and *PF Only* all had a significant difference with *Controller* with $p = 0.006$, $p = 0.033$, and $p = 0.032$ respectively. For immersion, Kruskal-Wallis test on participant answers yielded $H(3) = 9.21$ with $p = 0.021$. *InvisiBow* and *PF Only* had a significant difference with *Controller* with $p = 0.012$ and $p = 0.013$ respectively. For enjoyment, Kruskal-Wallis test on participant answers yielded $H(3) = 5.44$ with $p = 0.11$. Only *InvisiBow* had a significant difference with *Controller* with $p = 0.03$. These results show that our method, *InvisiBow* provided an enhanced VR experience compared to commercial controllers. We saw similar results for both realism and immersion when the illusions were compared in isolation with *Controller*. However, for enjoyment, only *InvisiBow* had a significant increase.

For the left hand, Kruskal-Wallis test on participant answers on perceived force change yielded $H(3) = 10.91$ with $p = 0.01$. *InvisiBow* had a significant increase in perceived force change compared to *Controller* with $p = 0.04$ and *PF Only* with $p = 0.007$. *FTV Only* had a significant increase from *PF Only* with $p = 0.017$. For the right hand, Kruskal-Wallis test on participant answers on perceived force change yielded $H(3) = 16.57$ with $p = 0.0006$. *InvisiBow* had a significant increase in perceived force change compared to *Controller* with $p = 0.029$ and *FTV Only* with $p = 0.0006$. *PF Only* had a significant increase from *FTV Only* with $p = 0.002$.

5 Discussion & Conclusion

Overall, the results from the evaluation show that *InvisiBow* was able to provide an immersive VR archery experience. Our finger-held interface showed significantly higher ratings in realism, immersion, and enjoyment (see Figure 2) compared to controllers. We found similar comments by participants who experienced an increase in the intensity of the vibration of FTV when the amplitude of the asymmetric vibration was increased, provided both actuators were activated. We speculate that this might be due to the phenomenon of tactile suppression [17]. The right actuator's amplitude increases, but the user movement suppresses this change, which makes the left hand's unsuppressed vibration become relatively more salient, similar to Sabnis et al. [24]. Another possibility is the bimanual coupling effect, where the illusion of movement caused by muscle vibration in one hand can influence the perception of the other hand [4, 22]. However, a formal investigation of this phenomenon is necessary to understand the interaction effects between two illusions on two different hands of the user.

Based on these findings, we summarize initial guidelines for bimanual haptic illusions. Utilizing different haptic illusions (e.g. FTV and pseudo-force) on each hand simultaneously creates a stronger and more immersive force sensation, while the interaction between distinct illusions enhances the overall realism and engagement. Designers should recognize where different forces can be applied to both hands simultaneously in their virtual environment to exploit this interaction effect. On the other hand, the increased perceived force from the interaction between the two illusions may exceed the intended force sensation, causing discomfort. Designers should be wary of this to avoid conflicting sensations, discomfort, or over-stimulation. Moreover, because the interaction of two illusions can produce nonlinear effects, user testing is essential while evaluating how different combinations and intensities of the illusions impact perception and comfort.

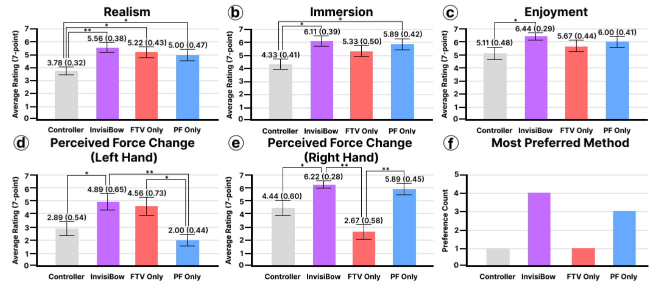

Figure 2: Average ratings of the 5 questionnaires and participants' most preferred method count. Numbers on top of the bar indicate the average, and numbers inside the parentheses are the standard error. * denotes p<0.05 and ** denotes p<0.01.

Our current setup shows lightweight, yet well-rendered pseudo force to the users. However, more studies regarding robust design considerations for various bimanual application are needed. In addition, an in-depth parametric investigation of our approach is also needed to improve InvisiBow. In our future work, we will explore the factors of separate rendering for each hand and integrated rendering. We will also add a calibration process for lets users select the appropriate range of intensity for appropriate interaction. We also plan to expand the application further, such as VR violin [18].

We demonstrated simulating the forces involved in pulling a virtual bow dynamically and observed how the illusions used together both performed better. We hope our approach contributes to advancements in the haptic illusion field and expands haptic interaction designs for richer, more immersive VR experiences.

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References

[1] Tomohiro Amemiya, Hideyuki Ando, and Taro Maeda. 2005. Phantom-DRAWN: direction guidance using rapid and asymmetric acceleration weighted by nonlinearity of perception. In *Proceedings of the 2005 international conference on Augmented tele-existence*. 201–208.

[2] Tomohiro Amemiya, Hideyuki Ando, and Taro Maeda. 2005. Virtual force display: Direction guidance using asymmetric acceleration via periodic translational motion. In *First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference*. IEEE, 619–622.

[3] Tomohiro Amemiya and Taro Maeda. 2009. Directional force sensation by asymmetric oscillation from a double-layer slider-crank mechanism. (2009).

[4] Monica Biggio, Ambra Bisio, Francesca Garbarini, and Marco Bove. 2021. Bimanual coupling effect during a proprioceptive stimulation. *Scientific Reports* 11, 1 (2021), 15015.

[5] Silviu Butnariu, Mihai Duguleană, Raffaello Brondi, Florin, Gîrbacia, Cristian-Cezar Postelnicu, and Marcello A. Carrozzino. 2018. An Interactive Haptic System for Experiencing Traditional Archery. *Acta Polytechnica Hungarica* (2018). https://api.semanticscholar.org/CorpusID:197643343

[6] Mantas Cibulskis, Difeng Yu, Erik Skjoldan Mortensen, Waseem Hassan, Mark Schram Christensen, and Joanna Bergström. 2025. Tendon Vibration for Creating Movement Illusions in Virtual Reality. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. 1–16.

[7] Heather Culbertson, Samuel B Schorr, and Allison M Okamura. 2018. Haptics: The present and future of artificial touch sensation. *Annual review of control, robotics, and autonomous systems* 1, 1 (2018), 385–409.

[8] Heather Culbertson, Julie M Walker, and Allison M Okamura. 2016. Modeling and design of asymmetric vibrations to induce ungrounded pulling sensation through asymmetric skin displacement. In *2016 IEEE Haptics Symposium (HAPTICS)*. IEEE, 27–33.

[9] Heather Culbertson, Julie M Walker, Michael Raitor, and Allison M Okamura. 2017. WAVES: a wearable asymmetric vibration excitation system for presenting three-dimensional translation and rotation cues. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 4972–4982.

[10] Yuran Ding, Nihar Sabnis, and Paul Strohmeier. 2024. Motionless Movement: Towards Vibrotactile Kinesthetic Displays. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–16.

[11] Eisuke Fujinawa, Shigeo Yoshida, Yuki Koyama, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2017. Computational design of hand-held VR controllers using haptic shape illusion. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology* (Gothenburg, Sweden) *(VRST '17)*. Association for Computing Machinery, New York, NY, USA, Article 28, 10 pages. doi:10.1145/3139131.3139160

[12] André Gay, Sebastien Parratte, Bruno Salazard, Didier Guinard, Thao Pham, Regis Legré, and Jean Pierre Roll. 2007. Proprioceptive feedback enhancement induced by vibratory stimulation in complex regional pain syndrome type I: an open comparative pilot study in 11 patients. *Joint Bone Spine* 74, 5 (2007), 461–466.

[13] Guy M Goodwin, D Ian McCloskey, and Peter BC Matthews. 1972. Proprioceptive illusions induced by muscle vibration: contribution by muscle spindles to perception? *Science* 175, 4028 (1972), 1382–1384.

[14] Vassilia Hatzitaki, Marousa Pavlou, and Adolfo M Bronstein. 2004. The integration of multiple proprioceptive information: effect of ankle tendon vibration on postural responses to platform tilt. *Experimental brain research* 154 (2004), 345–354.

[15] Seongkook Heo, Jaeyeon Lee, and Daniel Wigdor. 2019. PseudoBend: Producing haptic illusions of stretching, bending, and twisting using grain vibrations. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 803–813.

[16] Johan Kildal. 2010. 3d-press: haptic illusion of compliance when pressing on a rigid surface. In *International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction*. 1–8.

[17] Konstantina Kilteni and H Henrik Ehrsson. 2017. Sensorimotor predictions and tool use: Hand-held tools attenuate self-touch. *Cognition* 165 (2017), 1–9.

[18] Marius-George Onofrei, Federico Fontana, Silvin Willemsen, Stefania Serafin, et al. 2022. Bowing virtual strings with realistic haptic feedback. In *Proceedings of the 24th International Congress on Acoustics*, Vol. 7.

[19] Jun Rekimoto. 2014. Traxion: a tactile interaction device with virtual force sensation. In *ACM SIGGRAPH 2014 Emerging Technologies*. 1–1.

[20] Mike D Rinderknecht, Yeongmi Kim, Laura Santos-Carreras, Hannes Bleuler, and Roger Gassert. 2013. Combined tendon vibration and virtual reality for post-stroke hand rehabilitation. In *2013 World Haptics Conference (WHC)*. IEEE, 277–282.

[21] Joseph M Romano and Katherine J Kuchenbecker. 2011. Creating realistic virtual textures from contact acceleration data. *IEEE Transactions on haptics* 5, 2 (2011), 109–119.

[22] Neung Ryu, Hye-Young Jo, Michel Pahud, Mike Sinclair, and Andrea Bianchi. 2021. GamesBond: Bimanual Haptic Illusion of Physically Connected Objects for Immersive VR Using Grip Deformation. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 125, 10 pages. doi:10.1145/3411764.3445727

[23] Nihar Sabnis. 2021. Pseudo forces from asymmetric vibrations can provide movement guidance. (2021).

[24] Nihar Sabnis, Maelle Roche, Dennis Wittchen, Donald Degraen, and Paul Strohmeier. 2025. Motion-Coupled Asymmetric Vibration for Pseudo Force Rendering in Virtual Reality. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '25)*. Association for Computing Machinery, New York, NY, USA. doi:10.1145/3706598.3713358

[25] Nihar Sabnis, Dennis Wittchen, Courtney N Reed, Narjes Pourjafarian, Jürgen Steimle, and Paul Strohmeier. 2023. Haptic servos: Self-contained vibrotactile rendering system for creating or augmenting material experiences. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–17.

[26] Nihar Sabnis, Dennis Wittchen, Gabriela Vega, Courtney N. Reed, and Paul Strohmeier. 2023. Tactile Symbols with Continuous and Motion-Coupled Vibration: An Exploration of using Embodied Experiences for Hermeneutic Design. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 688, 19 pages. doi:10.1145/3544548.3581356

[27] Minoru Shinohara, Chet T Moritz, Michael A Pascoe, and Roger M Enoka. 2005. Prolonged muscle vibration increases stretch reflex amplitude, motor unit discharge rate, and force fluctuations in a hand muscle. *Journal of Applied Physiology* 99, 5 (2005), 1835–1842.

[28] Kun-Woo Song and Sang Ho Yoon. 2025. Neck Goes VRrr: Reducing Rotation-Induced Virtual Reality Sickness through Neck Muscle Vibrations. *IEEE Transactions on Visualization and Computer Graphics* (2025).

[29] Anthony Talvas, Maud Marchal, and Anatole Lécuyer. 2014. A Survey on Bimanual Haptic Interaction. *IEEE Transactions on Haptics* 7, 3 (2014), 285–300. doi:10.1109/TOH.2014.2314456

[30] Takeshi Tanabe, Hiroaki Yano, Hiroshi Endo, Shuichi Ino, and Hiroo Iwata. 2020. Pulling illusion based on the phase difference of the frequency components of asymmetric vibrations. *IEEE/ASME Transactions on Mechatronics* 26, 1 (2020), 203–213.

[31] Mitchell W Taylor, Janet L Taylor, and Tatjana Seizova-Cajic. 2017. Muscle vibration-induced illusions: review of contributing factors, taxonomy of illusions and user's guide. *Multisensory Research* 30, 1 (2017), 25–63.

[32] Dennis Wittchen, Valentin Martinez-Missir, Sina Mavali, Nihar Sabnis, Courtney N Reed, and Paul Strohmeier. 2023. Designing interactive shoes for tactile augmented reality. In *Proceedings of the Augmented Humans International Conference 2023*. 1–14.

[33] Vibol Yem, Ryuta Okazaki, and Hiroyuki Kajimoto. 2016. Vibrotactile and pseudo force presentation using motor rotational acceleration. In *2016 IEEE Haptics Symposium (HAPTICS)*. 47–51. doi:10.1109/HAPTICS.2016.7463154