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両手インタラクションにおける疑似触覚バランスフィードバック

Pseudo-Haptic Balance Feedback for Two-Handed Interactions

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概要: 近年、VR 技術は視覚、また聴覚の没入感において大きく進展している一方で、両手操作における現実的な触覚提示は依然として困難である。本研究では、物理デバイスを用いず視覚・動作の手がかりのみで質量やバランスの知覚を誘発する疑似触覚手法を提案する。左右手の C/D 比の非対称操作や視覚的な傾き・遅延を導入し、仮想物体操作時にトルクや重心の偏りを知覚させる。心理物理学的実験を通じて本手法の有効性を検証し、コンシューマー向け VR への応用可能性を示す。

キーワード： 疑似触覚, 平衡感覚, 認知科学

1. Introduction

Virtual Reality (VR) technology has advanced significantly in recent years, offering highly immersive visual and auditory experiences that transport users into convincingly simulated environments [1]. The ability to create lifelike worlds through high-fidelity graphics and spatial audio has opened new possibilities in entertainment, education, healthcare, and other fields. These developments have greatly enhanced the sense of presence and user engagement in VR. Despite these improvements, a critical limitation remains in the realm of haptic feedback [2]. Most consumer-grade VR systems still lack realistic tactile responses, particularly in complex, two-handed interactions. This absence of touch feedback limits the sense of physicality when interacting with virtual objects, reducing the realism and effectiveness of many immersive applications.

Pseudo-haptic techniques have emerged as a promising alternative to traditional force feedback systems. By manipulating visual cues and motion dynamics, these techniques can create compelling illusions of physical properties such as weight, resistance, and balance. Without requiring expensive or bulky hardware, pseudo-haptics enable users to experience sensations typically associated with real-world touch.

This research explores the use of pseudo-haptic methods to simulate the perception of balance during two-handed interactions in VR. The objective is to investigate how asymmetries in visual or motion cues can evoke a sense of imbalance, thereby enriching the interaction without relying on actual haptic devices. This approach has the potential to expand the expressive capabilities of VR interfaces while maintaining simplicity and accessibility. Ultimately, the goal is to develop a system that enhances the realism, responsiveness, and intuitiveness of two-handed object manipulation in virtual environments. By focusing on balance perception through non-haptic means, this study contributes to the broader effort of bridging the gap between visual immersion and physical embodiment in VR, fostering more natural and engaging user experiences.

2. Related work

The challenge of rendering haptic sensations, especially of weight—in VR without physical force feedback has been approached through a range of pseudo-haptic techniques. These methods exploit sensorimotor discrepancies, particularly through visual and proprioceptive mismatches, to elicit convincing illusions of mass. Among these, manipulation of the control-display (C/D) ratio has emerged as a foundational technique [3].

2.1 Proprioceptive Manipulation with Weight

Dominjon et al. demonstrated that manipulating the translational C/D ratio could systematically alter perceived mass in virtual environments by coupling a foam ball with a PHANToM haptic device, thus modulating visual motion to influence weight perception [4]. Building on this, Samad et al. employed motion capture gloves and head-mounted displays (HMDs) to adjust visual hand displacement during lifting tasks, confirming the perceptual impact of C/D ratio manipulation. Notably, they proposed a mathematical model linking hand displacement to weight estimation and identified a perceptual sensitivity range: ± 10 cm of displacement yielded ± 5 g variation in perceived weight.

Focusing on vertical displacement to simulate gravitational load, Samad et al. retained stability along the horizontal and depth axes. Their use of psychometric functions within two-alternative forced-choice (2AFC) paradigms enabled quantitative modeling of perceived mass based on multisensory integration principles. The resulting framework—grounded in estimates of physical work and differential weighting of visual and proprioceptive inputs—facilitates precise visual tuning for pseudo-haptic weight simulation without the need for mechanical actuators.

2.2 Rotational Cues and Mass Distribution

While early work primarily addressed translational motion, recent studies have emphasized rotational kinematics in mass perception. Yu and Bowman proposed two strategies for simulating mass distribution: modifying the pivot point and scaling rotational speed based on virtual mass, with the latter showing greater accuracy in discrimination tasks [5]. Streit et al. [6] extended this by introducing rotational illusions through tracking offsets and visual spring metaphors. Rietzler's VR bowling game applied spring-like offsets between real and virtual hand positions, increasing user effort and perceived realism, though highlighting limitations in offset-based techniques. IIssartel et al. [7] proposed an alternative using six-degree-of-freedom spring constraints to combine translational and rotational feedback. This method enabled fine control over stiffness and inertia but required physical props, limiting applicability in fully virtual settings.

2.3 Multisenory Integration

Meta Research Lab proposed an idea that integrated pneumatic force feedback with visual C/D distortion, seeking to augment the perceptual realism of weight [8]. These multimodal systems offer higher fidelity but often come at the cost of reduced scalability and increased hardware complexity—barriers that visual-only techniques attempt to overcome. The perception of pseudo-haptics is often explained through multisensory integration models. The forced-fusion model suggests that the brain integrates visual and proprioceptive cues in weighted combinations to infer properties like mass. Leveraging this mechanism, researchers have demonstrated that visual distortions—when appropriately calibrated—can systematically alter perceived weight, offering a scalable approach to pseudo-haptic feedback in VR.

Prior work shows that both translational and rotational visual manipulations can induce convincing illusions of mass and balance. While early studies validated C/D ratio modulation, recent research has refined these effects through psychophysical modeling and the incorporation of rotational dynamics. Remaining challenges include perceptual calibration, long-term user adaptation, and managing interactions between multiple pseudo-haptic cues.

3. Pseudo-Haptic Feedback for Body Balance

3.1 Objective of the Research

The primary objective is to extend pseudo-haptic feedback to a two-handed scenario through visual cues to induce a sense of balance. We focus on simulating a balance beam held in both hands. As illustrated, we aim to measure changes in participants' sense of balance as the C/D ratio varies during the process of moving the balance beam between structures. In reality, a small ring is held by the participant, sized to fit comfortably in the palm of the hand. To investigate the relationship between the C/D ratio and perceived balance in the pseudo-haptic condition, we calculated the average rotation angle of the balance beam during the experiment. This metric served as an indicator of how the manipulated C/D ratio influenced users' hand movements and rotational stability.

To investigate the perception of balance and mass distribution in two-handed virtual interactions, we developed a set of pseudo-haptic techniques based on imbalance visual feedback. These techniques are designed to simulate imbalance without physical force-feedback devices.

3.2 Experimental Task

5 students participated in the experiment, including 2 males and 3 females. The average age of the participants was 24.6 years. Participants wore virtual reality headsets and held a ring-shaped object designed to fit comfortably in the palm of the hand. They were instructed to walk across a virtual high beam connecting two buildings while maintaining their balance. Experiment detail is shown in Figure 1. Each participant completed the task twice, once in each of two C/D ratio conditions:

1. **C/D = 0.3 (Stabilized Condition):** Visual rotation was dampened relative to physical input, simulating a more stable and less responsive beam.
2. **C/D = 1.0 (Unstable Condition):** Visual feedback matched real movement, replicating the natural instability of a real balance beam.

The stabilized (C/D = 0.3) condition was applied during the outward journey to the opposite building, while

図 1: Experience Design. A virtual balance beam in VR is set up between two tall buildings (top), and participants wear VR headsets and hold ring-shaped devices while walking on a simulated balance beam (bottom).

the unstable (C/D = 1.0) condition was applied on the return. After completing both trials, participants completed a five-item Likert scale questionnaire assessing their subjective sense of balance in each condition.

In each trial, participants completed the following steps:

1. Walked from one virtual building to the other along a narrow high beam.
2. Returned along the same beam using the identical route.
3. Focused on maintaining balance using only visual and proprioceptive feedback, as no physical force feedback was provided.
4. Completed a five-point Likert scale questionnaire to report their perceived sense of balance for each condition.

Dependent measures included subjective balance ratings (5-point Likert scale), , binary response accuracy in a forced-choice balance judgment task (C/D ratio = 0.3), and task completion time as an indicator of cognitive and motor effort. Additionally, raw kinematic data (balance wood average center offset) were recorded to correlate behavioral adaptation with perceived imbalance.

4. Result and Discussion

5 Scale Questionnaire asked participants questions about balance control based/not based on pseudo haptics we provided in VR. In addition, average rotation angle of the balance beam was also calculated.

4.1 Questionnaire Result

Participants completed a questionnaire evaluating their experience of balance, control, and immersion in a VR walking task with pseudo-haptic feedback. C/D ratio was reduced to 0.3 when walking to the building and set to 1.0 on the return path.

Due to the small sample size ($n = 5$), no statistical analysis was conducted, and all findings should be interpreted descriptively. Under the C/D = 0.3 condition, 3 out of 5 participants (60%) reported feeling “somewhat balanced,” and none selected “very unbalanced.” In comparison, under the C/D = 1.0 condition, 2 participants (40%) reported feeling “very unbalanced.” This may suggest a potential influence of the C/D ratio on perceived stability.

Responses regarding the object’s behavior were also distributed differently across conditions. In both C/D conditions, 2 participants (40%) indicated the object felt “somewhat balanced.” However, in the C/D = 1.0 condition, 2 participants (40%) reported that the object caused a strong sense of imbalance, a pattern not observed under the C/D = 0.3 condition.

Task difficulty responses varied across the scale, with each of the four categories—ranging from “very difficult” to “perfect control”—selected by at least one participant. This variation indicates a high degree of inter-individual variability. Additionally, 4 participants (80%) agreed that the imbalance felt physically realistic, and all participants (100%) reported a high sense of immersion. These descriptive trends suggest that the pseudo-haptic manipulation may influence perception and engagement, but further investigation with a larger sample is required to assess statistical reliability.

These trends suggest that pseudo-haptic manipulation via C/D ratio adjustment can effectively alter balance perception without disrupting immersion.

Due to the limited sample size, statistical analysis has not yet been conducted. Therefore, these results should be considered preliminary. Additionally, due to individual subjective judgments, including the degree of adaptation to VR and the level of awareness of one’s own balance, pseudo-tactile manipulation may have potential effects. However, further research with a larger participant group and appropriate statistical tests is needed to confirm these findings.

4.2 Rotation Angle Result

To quantify motor behavior under each condition, the average Euler angles (X, Y, Z) of the wood object were recorded per participant. These values represent the mean orientation of the object throughout the trial.

Under the C/D = 0.3 condition, the average rotations were more tightly clustered across participants, particularly in the Y (yaw) and Z (pitch) axes. The mean X-rotation was 278.2° (SD ≈ 2.7°), Y ranged from 138.7° to 239.1°, and Z from 107.9° to 190.7°. In contrast, under C/D = 1.0, the X-axis remained stable (M = 279.2°, SD ≈ 3.5°), but Y-axis values exhibited a wider spread (150.7° to 260.9°), suggesting increased variation in handling the object ' s orientation. Z-axis values showed a slightly broader distribution under C/D = 0.3, though the difference was marginal.

These differences imply that the stabilized C/D ratio led to more consistent rotational control, especially in the yaw axis. In contrast, the natural C/D condition resulted in greater compensatory movement and instability, aligning with participants ' reported difficulty in maintaining balance and control.

Both subjective and objective measures suggest that lowering the C/D ratio may help stabilize users ' perception and behavior during the task. Participants reported improved balance, reduced mismatch between expected and actual object response, and a strong sense of immersion. Rotation data showed less variation under the lower C/D condition, particularly along the yaw axis, indicating more consistent control.

However, individual differences such as balance ability, prior VR experience, or sensitivity to visual feedback may have influenced the results. Moreover, environmental factors and the simplicity of the task could have introduced uncontrolled variability. Further studies with more participants and controlled conditions are needed to verify these trends and draw broader conclusions.

5. Conclusion

This study investigated the use of pseudo-haptic feedback to simulate balance perception during two-handed object manipulation in a virtual environment. By modulating the C/D ratio, we explored how visual-proprioceptive mismatches could influence users' subjective sense of balance and their motor behavior. The results from both questionnaire responses and rotational tracking data suggest that reducing the C/D ratio led to more stable perceived balance and more consistent object control. Participants reported greater immersion and realism under the stabilized condition, and objective rotation measurements revealed lower variability in hand coordination.

While these findings offer initial insights into the potential of pseudo-haptic balance manipulation, further exploration is needed to understand its broader applicability. In future work, we plan to include a larger and more diverse participant group and examine a wider range of task conditions. This includes comparing performance with and without the virtual balance stick, as well as introducing varying degrees and types of visual imbalance. These extensions aim to clarify how pseudo-haptic cues influence balance perception under different scenarios and to refine the design of visual feedback for enhancing physical realism in VR interactions.

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