손의 굴곡과 신전을 이용한 양방향 힘 입력 가능성 탐구

Investigating the feasibility of force input using hand flexion and extension

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요약 가상 현실 (VR) 에서는 가상 물체의 위치, 방향, 크기 등 다양한 속성을 조작하며, 이같은 조작은 양방향의 컨트롤을 필요로 한다. 양방향 컨트롤이 가능한 조작 방식으로 인에어 (In-air) 제스처, 조이스틱, 터치패드 등의 등장성 (isotonic) 입력을 생각할 수 있으나 움직일 수 있는 공간의 한계, 제스처 인식의 한계 등의 한계점을 가진다. 본 논문에서는 이러한 점으로부터 자유로운 등척성 (isometric) 힘 기반 입력을 고려하되, 기존 입력장치에서 상대적으로 덜 연구된 손의 신전력 (extension, 펴는 힘) 과 함께 굴곡력 (flexion, 오므리는 힘) 을 양방향 힘 입력으로 사용하는 장치의 실현 가능성을 탐구한다. 첫 번째 단계로 엄지와 손가락 사이의 굴곡력 및 신전력을 감지하는 책상 고정형 프로토타입을 제작하였다. 이어서 각 방향의 힘이 낼 수 있는 최대 힘과 조작 성능에 기반하여 속도 제어와 위치 제어, 두 가지 제어 방식의 파라미터를 설정하였다. 각 방향의 힘과 제어 방식을 사용한 1-D 선택 실험 결과 굴곡력과 신전력은 컨트롤 방식에 관계없이 비슷한 성능을 보였으며, 속도 제어는 위치 제어에 비해 정확도 측면에서 50% 우수한 성능을 보였습니다. 본 연구 결과는 상대적으로 덜 사용되어 온 손의 신전력을 포함하는 양방향 힘 입력 성능이 충분히 우수하며, 사용자들이 양극성 조작에 굴곡력과 신전력을 직관적으로 사용할 수 있음을 보여준다.

Abstract While virtual reality (VR) offers diverse bipolar actions like translation, rotation and scaling. In-air gestures, joysticks, touchpads, and other isotonic inputs can be considered as bipolar actions, but they are limited by the space available for movement and gesture recognition. In this paper, we consider an isometric force based input that is free from these limitations, and explore the feasibility of a device that uses bi-directional force input along with flexion and extension, which is relatively under-researched in existing input devices. As a first step, we implemented a desk-fixed, hand-held prototype that senses flexion and extension forces between the thumb and fingers. Then, based on the maximum force that each directional force can produce and the manipulation performance, we set the parameters of two control methods: speed control and position control. The results of a 1-D selection task with different forces and control methods showed that flexion and extension forces performed similarly regardless of the control method, while speed control outperformed position control by 50% in terms of accuracy. The results of this study show that the performance of bi-directional force input, including the relatively underutilized hand extension force, is sufficiently superior, and that users can use flexion and extension forces intuitively for bipolar manipulation.

핵심어: Haptic Interface: 햅틱 인터페이스, Force Input: 힘 입력, Input Device: 입력 장치, Bidirectional Control: 양방향 제어, Hand Extension: 손 신전력

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1. Introduction

The thumb and fingers can move inward or outward. The inward finger movement is called flexion, and the outward finger movement is called extension. Flexion can produce a larger force than extension. For this reason, physical controls are often designed to utilize flexion rather than extension. Finger flexion is used to press a button, pull a trigger, grab handles, and squeeze a ball. There are few chances to use finger extension when interacting with an object. The consequence is that most of the finger actions are unipolar. For instance, a user can push a button but cannot usually pull a button. It seems that finger extension is under-utilized or explored. This observation led us to explore in this study the potential of bipolar actions enabled by combining finger flexion and extension. Bipolar actions are needed for controlling bipolar variables, and many variables in computer interfaces are bipolar. In VR applications, in particular, users often need to do diverse bidirectional manipulations in 3D space, e.g., moving an object back and forth, rotating it left and right, and scaling it up and down [1-4]. Therefore, we chose the VR environment in this study as a playground to explore the potential of bipolar actions. The first step in our exploration was to investigate the feasibility of bipolar force input. So, we designed a device using bipolar force, enabling users to utilize flexion and extension to do bidirectional inputs. Because bipolar actions in VR environments involve much switching between opposing controls in short periods, we used isometric inputs to enable users to reverse force input directions without slack rapidly.

A remaining important design option was the choice between position control and rate control [4-8]. The use of finger extension in an input device is not common. The use of extension and flexion in combination is even less common. Therefore, many questions need to be answered for the device's design using bipolar force: Can users use flexion and extension intuitively as opposite actions? Will rate control continue to be better than position control as it was for an isometric joystick? Our results showed that extensions performed similarly to flexion, though it has been less used and considered weak and less precise than flexion. In this paper, we report the results of a series of experiments that we conducted to answer these questions. In summary, the contribution of this paper is as follows:

- Exploration for the feasibility of extension force control and quantitative and qualitative comparisons with flexion force control

- Investigation for optimal design options for bipolar force device, the effect of two representative control methods was compared

- Demonstration of bipolar force in VR application scenarios and findings from user feedback

2. Experimental Hardware and Software

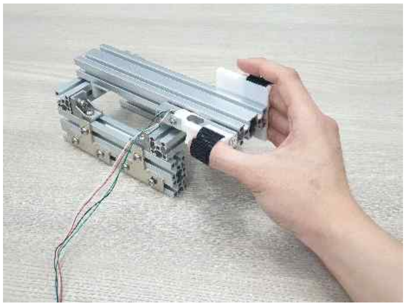

Fig. 1 Desk-fixed prototype used in the experiment

Fig. 1 shows the experimental device, which consists of a base, a sensor, and a hand grip. The hand grip is 3D printed and can accommodate fingers up to the second knuckle, except for the index finger, and is fastened with Velcro. To measure the user's flexion and extension forces, we attached a load cell under the thumb grip to measure forces in both directions.

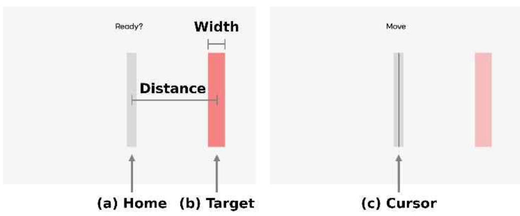

Fig. 2 Experimental Software

We conducted 1-dimensional visual selection experiment with two directional forces. Each trial starts with the Ready state, where the experiment software shows the home square and the target square. When ready, the participant presses the 'spacebar' on the keyboard using the non-dominant hand. The software changes into the Move state, where the cursor is presented at the home square's center, and the target square's opacity becomes 50 %. Participants move the cursor into the target square and end the trial by pressing the spacebar when the cursor is well located. When the participant hits the key, the target, cursor, and the home square disappear, and a new trial is presented after 2 seconds.

We calculated correctness (Accuracy) based on whether the cursor was in the target square when the participant submitted their answer. We measured the movement time (Task Completion Time) between two key inputs, the final positions of the cursor and the target square and the number of times participants passed the target square (Crossing).

3. Experiment

A tutorial session was organized to help participants understand and use the forces of flexion and extension. After that, we measured the participant's maximum force in thumb flexion and extension.

Participants were given a trial with a position and rate control, and both controls have the same task. We designed targets with 3 levels of width (30, 60, and 90 px) and 3 levels of distance (100, 300, and 500 px). The target width and distance were randomly presented by trial. We designed the farthest distance to correspond to 50 % of the maximum force for position control, as we found that accuracy dropped significantly at forces greater than 50 % of the maximum force in preliminary experiments.

The experiment was a within-subject design with four independent variables: the control method (Control), the target width (Width), the target distance (Distance), and the direction of force (Direction).

Two conditions were depending on the control methods: R (Rate control) and P (Position control). We counterbalanced the order of the condition. For each condition, there were 90 trials (3 target widths × 3 target distances × 2 directions × 5 repetitions).

4. Results

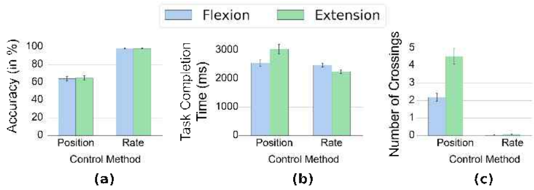

Fig. 3 (a), (b), and (c) are the average Accuracy, Task Completion Time, and number of Crossings of flexion and extension force task in position and rate control, respectively.

With a four-way (Direction × Control × Distance × Width) RM ANOVA, no significance was found between flexion and extension for Accuracy ($p > .05$) and Task Completion Time ($p > .05$). This validates the feasibility of moving away from traditional controls, primarily using flexion and extension with similar performance. The high number of Crossings in position control is due to the difficulty of maintaining an extension force rather than a flexion after arriving at the target square. As the distance increased and the target square width got smaller, all the metrics got worse. This is consistent with Fitts' law, which states that the more force a participant uses, the less precise they are.

All participants found the bi-directional force switching to be natural, and most found it easy to accept that the flexion and extension forces were mapped to the left and right. Some participants said it took a while to get used to it at first, and one said that the visual feedback helped them quickly identify and correct incorrect movements.

5. Discussion

5.1 Feasibility of Flexion and Extension

No significance was found between flexion and extension for Accuracy and Task Completion Time. This validates the feasibility of moving away from traditional controls, primarily using flexion and extension with similar performance. The high number of Crossings in position control is due to the difficulty of maintaining an extension force rather than a flexion after arriving at the target square. As the distance increased and the target square width got smaller, all the metrics got worse. This is consistent with Fitts' law, which states that the more force a participant uses, the less precise they are.

5.2 Switching Between Flexion and Extension

All participants found the bi-directional force switching to be natural, and most found it easy to accept that the flexion and extension forces were mapped to the left and right. Some participants said it took a while to get used to it at first, and one said that the visual feedback helped them quickly identify and correct incorrect movements.

6. Limitation and Future Work

We validated the feasibility of flexion and extension with similar performance, but there were some limitations. Force maintenance issues were mentioned as a reason for the low performance (Accuracy, Task Completion Time, Crossings) of position control. We expect that using clutching will reduce fatigue and improve accuracy. Also, high performance can be expected for fast and short position control tasks. About the shape of the device, some participants suggested a naturally curved surface or sphere shape rather than parallel thumbs and fingers for the stretching force.

As a next step, we plan to develop a hand-held VR controller based on the findings and investigate the usability of the bidirectional force input controller in a VR application scenarios which require bipolar controls to manipulate the object.

7. Conclusion

We validated the feasibility of extensional force control through quantitative and qualitative comparisons with flexion force control. An interesting finding was that Accuracy and Task Completion Time were not significantly affected by flexion and extension, regardless of control method. As a future work, we will conduct a user study through VR application scenarios to check the usability. We expect this paper will call more study on bidirectional force input and its applications.

References

[1] Doug Bowman, Ernst Kruijff, Joseph J. LaViola Jr, and Ivan P. Poupyrev. 3D User Interfaces: Theory and Practice. Munich, Germany: Addison-Wesley. 2004.

[2] Doug A. Bowman and Larry F. Hodges. An evaluation of techniques for grabbing and manipulating remote objects in immersive virtual environments. In Proceedings of the 1997 symposium on Interactive 3D graphics - SI3D '97. ACM Press, Providence, Rhode Island, United States, 35-ff. 1997.

[3] Ivan Poupyrev, Mark Billinghurst, Suzanne Weghorst, and Tadao Ichikawa. The go-go interaction technique: non-linear mapping for direct manipulation in VR. In Proceedings of the 9th annual ACM symposium on User interface software and technology (UIST '96). Association for Computing Machinery, New York, NY, USA, 79-80. 1996.

[4] Shumin Zhai. Human performance in six degree of freedom input control. Toronto, ON: University of Toronto. 1996.

[5] Sarah A. Douglas and Anant Kartik Mithal. The effect of reducing homing time on the speed of a finger-controlled isometric pointing device. In Proceedings of the SIGCHI conference on Human factors in computing systems celebrating interdependence - CHI '94. ACM Press, Boston, Massachusetts, United States, 411-416. 1994.

[6] Jacqui Fashimpaur, Amy Karlson, Tanya R. Jonker, Hrvoje Benko, and Aakar Gupta. Investigating Wrist Deflection Scrolling Techniques for Extended Reality. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23). Association for Computing Machinery, New York, NY, USA, 1-16. 2023.

[7] Herbert D. Jellinek and Stuart K. Card. Powermice and user performance. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '90). Association for Computing Machinery, New York, NY, USA, 213-220. 1990.

[8] I. Scott MacKenzie and Aleks Oniszczak. A comparison of three selection techniques for touchpads. In Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '98. ACM Press, Los Angeles, California, United States, 336-343. 1998.