QuadStretch: A Forearm-wearable Multi-dimensional Skin Stretch Display for Immersive VR Haptic Feedback

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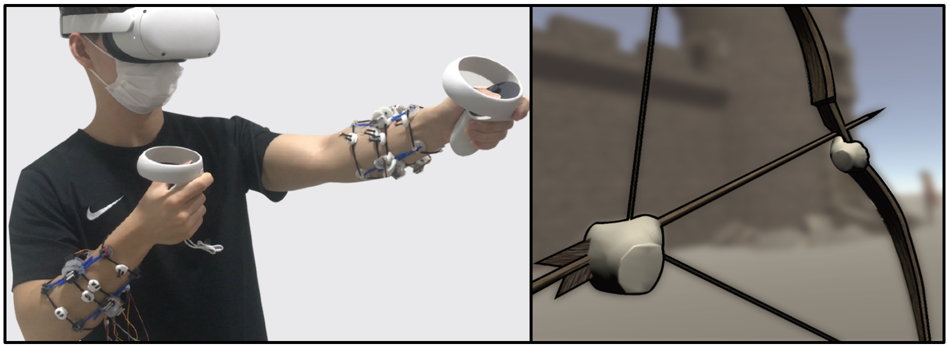

Figure 1: QuadStretch is a wearable skin stretch display that could deliver abundant haptic feedback for VR interaction.

ABSTRACT

This demonstration presents QuadStretch, a multidimensional skin stretch display that is worn on the forearm for VR interaction. QuadStretch realizes a light and flexible form factor without a large frame that grounds the device on the arm and provides rich haptic feedback through high expressive performance of stretch modality and various stimulation sites around the forearm. In the demonstration, the presenter lets participants experience six VR interaction scenarios with QuadStretch feedback: Boxing, Pistol, Archery, Slingshot, Wings, and Climbing. In each scenario, the user's actions are mapped to the skin stretch parameters and fed back, allowing users to experience QuadStretch's large output space that enables an immersive VR experience.

CCS CONCEPTS

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

KEYWORDS

Skin stretch display, Wearable haptic display, Virtual reality

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1 INTRODUCTION

Proper haptic feedback is essential for an immersive VR experience. Tactile wearable devices can effectively deliver haptic feedback while supporting the user's mobility, which is critical in recent wireless VR environments. In the HCI and haptics field, various tactile modalities such as vibration [1, 5, 10, 11], squeeze [7, 8], or pneumatic pressure [3] have been introduced for a wearable use. Among these modalities, a skin stretch is an expressive tactile feedback medium because even a single end-effector can control a large information space of stretch magnitude and direction. Also, it could deliver unobtrusive continuous feedback by simply sustaining the stretched state.

However, using skin stretch modality on a wearable device is challenging because the reaction force inevitably pushes the counterpart of the device backward when the tactor moves. This could hamper the user's stretch perception. In previous studies, a frame that is larger and heavier than the stretch tactor was used [2, 6, 9, 12–14] to minimize its movement. Installing a skin stretch device on narrow body sites still remains a problem.

For a small and light-weighted skin stretch device, we introduce an idea of counter-stretching, that is, moving a pair of tactors to the opposite directions. We implemented QuadStretch, a forearm-wearable multi-dimensional skin stretch device using a counter-stretching mechanism. Owing to its compact size, the QuadStretch device surrounds the user's forearm with eight skin stretch tactors and therefore delivers an abundant set of haptic feedback. In this Interactivity, we demonstrate the QuadStretch device to show its capability of expressing continuity, multi-dimensionality, and sufficient intensity through a sequence of six VR interaction scenarios.

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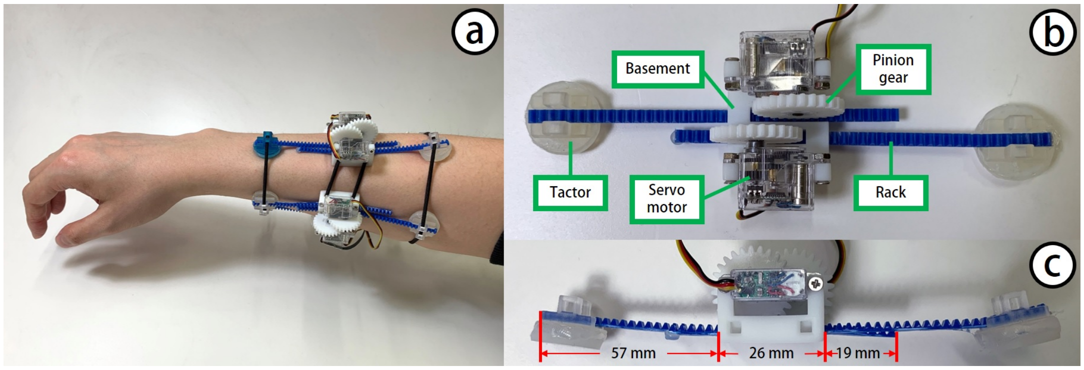

Figure 2: (a) The QuadStretch device. (b, c) A single stretch module of the QuadStretch.

2 QUADSTRETCH SYSTEM

The main goal when designing the QuadStretch was to provide abundant multi-dimensional haptic feedback by utilizing the skin stretch modality's wide expression space. Since the actions that can occur inside the VR environment are diverse, feedback for each action should be distinguishable and unique according to various physical properties such as position, speed, or intensity. To this end, we tried putting an additional output dimension of spatial placement by using multiple skin stretch tactors so that each tactor's expression space could be multiplied by their combination on different skin sites. Also, given that most of the VR actions are triggered by the hand controller, we decided to place the display on the forearm close to the hand.

Installing a large frame that is used in ordinary skin stretch displays on the forearm could be problematic. This kind of frame is rigid and heavy, so it restricts the user's movement. Also, the frame itself pressurizes the skin and makes the skin to be hard to be stretched, eventually obscuring the main skin stretch feedback (the need for clearance around the skin stretch tactor was explored previously in Gleeson et al. [4]'s work). We resolved this problem with the counter-stretching mechanism. Like the stretch module shown in Fig. 2(b), we symmetrically placed a pair of tactors so that their movement toward and away from each other could be successfully delivered without having to ground the display to the forearm with a large frame. Since motor basements are far apart from the tactors, we can secure the clear stretchable space around the tactor. Also, the rack gears for power transmission are built flexible, and therefore the whole display can be bent complying with the arm movement so that the users can naturally perform their action.

We placed the tactors around the forearm. We arranged four stretch modules and ensured a wide stretch range by making the stretch direction in line with the forearm's longitudinal axis. We built two QuadStretch devices for each arm to support VR interactions using both hands.

2.1 Implementation Detail

The device is shown in Fig. 2. One stretch module (Fig. 2(b,c)) consists of two tactors, two rack gears (KHK DR0.8-2000), two servo motors (HiTec HS-5035 HD), and a basement. The tactor is a silicone disc with a diameter of 20 mm and a thickness of 3 mm and is adhesively bonded to a 3D printed structure that connects it to the rack. The rack gear is 3 mm wide and 100 mm long. The pinion gear is 3D printed and has a reference diameter of 20 mm, a module of 0.8, and 28 teeth. The basement is also 3D printed and serves to fix the servo motor and create a track that makes the rack pass through. The four stretch modules were placed along the circumference of the forearm when worn, and connected and secured with elastic strings and cable clips. A total of 8 servo motors are connected to a driver (SunFounder, PCA9685 16-Channel 12-Bit PWM Servo Driver) and controlled by an Arduino board. The drive voltage of the servomotor was 6V. The Arduino is connected to the PC through serial communication and receives commands from the Unity VR application, which will be mentioned later.

2.2 Device Specification

One tactor can be moved by ±11mm around the neutral position, but we use only the range of ±8.5mm for the demonstration since the participants from the pilot study felt the full-range stimulus is excessive. The speed of each tactor is about 73 mm/s. The calculated maximum force of the tactor is about 0.8 kgf, considering the maximum torque on the servo motor's datasheet.

3 VR SCENARIO WALKTHROUGH

We implemented six VR interaction scenarios that can take full advantage of QuadStretch's characteristics. Each scenario consists of repeating a few simple movements and experiencing the corresponding skin stretch feedback. The visual overview of six scenarios is depicted in Fig. 3. The scenarios demonstrated at this CHI Interactivity are Boxing, Pistol, Archery, Slingshot, Wings, and Climbing. The scenarios were structured to highlight the QuadStretch's sufficient intensity (Boxing & Pistol), passive tension and spatial multidimensionality (Archery & Slingshot), or continuity in complex movements (Wings & Climbing), respectively. Implementation details and skin stretch feedback for each scenario are described in the following subsection.

The application was created with Unity Engine, and we used Oculus Quest 2 for presenting the VR scene. During the demonstration, the PC is connected with the Quest 2 through Oculus Link

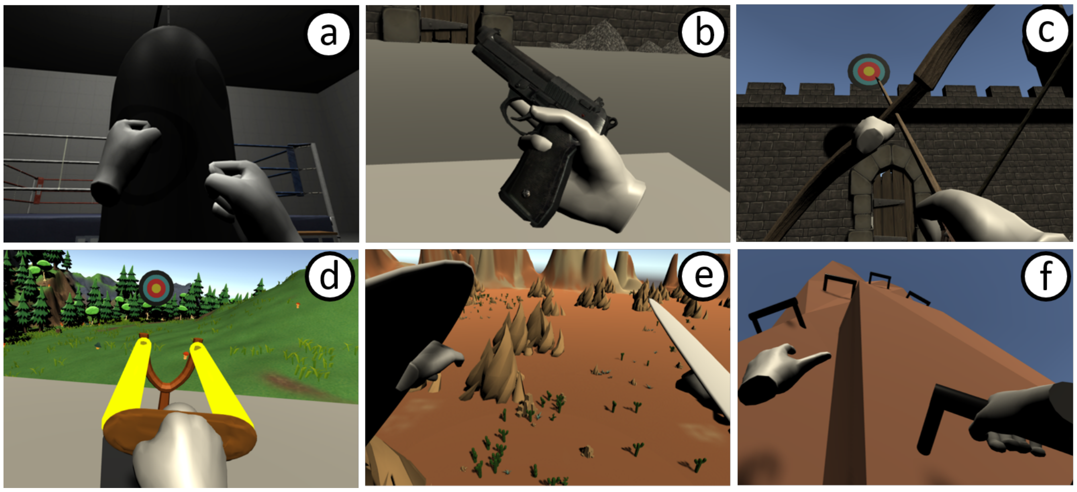

Figure 3: Overview of QuadStretch VR interaction scenarios. (a) Boxing, (b) Pistol, (c) Archery, (d) Slingshot, (e) Wings, (f) Climbing

so that it can control the QuadStretch device while running the application.

3.1 Interaction Scenarios

3.1.1 Boxing. In the Boxing scenario, the user can punch the sandbag and receive an impact through QuadStretch feedback. The user presses the grip button on the Oculus touch controller to transform the virtual hand model into a fist shape. When the user punches, the collision is detected and skin stretch feedback is generated according to the punch speed. Upon an impact, all four stretch modules of QuadStretch move, and in proportion to the punch speed, they contract up to the maximum travel distance of 8.5mm and then immediately relax. The stretch speed is at the maximum; depending on the stretch size, the feedback transfer is completed in up to 0.233 ms. This feedback feels like a short shock to the user, and the user can experience how the intensity of the stretch is variously adjusted according to the punch speed.

3.1.2 Pistol. When the user starts the Pistol scenario, two pistols are already held; one in each virtual hand model. The user can fire by pressing the trigger button of the controller. During firing, the bullet is fired head-on along with the pistol's percussion animation, and QuadStretch feedback is provided to express the recoil. As feedback, the four stretch modules simultaneously contract up to 8.5 mm and then immediately relax. This is equivalent to the maximum intensity feedback in the boxing scenario. The user can experience that the QuadStretch can be properly used for interactions that generate haptic feedback of strong intensity through this scenario.

3.1.3 Archery. In the Archery scenario, the user pulls the bow and shoots an arrow. When the scenario starts, a bow is attached to the model of the user's left hand. When the user brings their right hand close to the bow, the arrow is loaded, and the arrow model glows green to indicate that it can be grabbed. At this time, if the user presses the grip button of the right-hand controller, the arrow is hung on the string. When the user moves their right hand backwards as if pulling a bow in real life, the string of the bow is pulled, and QuadStretch also provides stretch feedback. When the grip button on the right-hand controller is released, an arrow is released according to the elasticity of the pulled string. When the bow is being pulled, all stretch modules in QuadStretch contract in proportion to the distance the arrow is pulled. Through this, the user can experience not only the feedback during the action of pulling the bow, but also the feedback caused by the bow tension in the stationary state.

3.1.4 Slingshot. In this scenario, the user holds the grounded slingshot by pressing the grip button on the right-hand controller to shoot the bullet. The elastic band connected from the support of the slingshot is stretched as much as it is pulled, and the elastic force of the string is expressed as QuadStretch feedback. The user can pull the string in any direction, so the direction of the elastic force is also reflected in the skin stretch feedback. When the grip button is released, a bullet is fired. Skin stretch feedback is mapped to the three-dimensional axis along which the elastic band is pulled. When the user pulls the rubber band toward their body, all four modules are contracted in proportion to the distance. When the rubber band is pulled to the right, the module on the ulnar side of the hand contracts, and the module on the radial side expands. Similarly, when the rubber band is pulled down, the module on the dorsal side contracts, and the module on the ventral side expands. Unique stretch feedback is created depending on the direction in which the rubber band is pulled. This allows the user to discern subtle displacement in the action while aiming at the target.

3.1.5 Wings. This scenario is based on a relatively surreal interaction. Wide wings are attached to the user's virtual hand in the VR scene, and the user can perform locomotion as if flying by flapping the wings. At this time, the moving speed is proportional to the flapping speed of the wing and the area perpendicular to the moving direction of the wing to represent air drag. Also, the air drag from each wing determines the QuadStretch feedback value of each arm. The magnitude of the stretch is proportional to the magnitude of the air drag, and when the wing moves in the ventral direction of the hand (flap down), the modules on the forearm's dorsal, ulnar, and radial side contract and the ventral module expands. Conversely, when the wing moves in the dorsal direction (flap up), the direction of the stretch is reversed. Through this, the user can understand the relationship between the flapping motion and the movement speed naturally by relating it to the stretch feedback.

3.1.6 Climbing. The Climbing scenario provides the user with the action of climbing a large boulder using their hands. There are handles on the boulder that the user can grab with the grip button on the controller. When the user holds the handle and moves the controller, the user's view moves in the opposite direction to the controller's moving direction, giving the effect of pulling up the body with the arm. The user continuously grabs the handle and moves up to reach the top of the boulder. In order to express the burden on the forearm at the moment of holding the handle with the hand, all modules of the QuadStretch of the corresponding arm momentarily expand by about 1 cm. Stretch feedback is determined according to the direction in which the arm is pulled and the distance from the handle to express the muscle burden from the pulling action. The distance between the HMD and the handle and the stretch size are inversely proportional, and when the vertical distance from the handle gets closer, the modules on the dorsal and ventral side of the forearm contract. When the horizontal distance to the handle gets closer, the ulnar or radial module contracts, depending on the direction. At the moment when the handle is released, the QuadStretch returns to its neutral state. The user can experience the feeling of muscle strain that occurs during the climbing activity through the feedback.

4 CONCLUSION

We demonstrated QuadStretch, a forearm-wearable multi-dimensional skin stretch display. We tried to improve the wearability of the skin stretch display by removing the need of the large and heavy frame that was commonly used to firmly fix the display to the body part in previous studies. Each stretch module in QuadStretch consists of a pair of tactors that move symmetrically. Through this counter-stretching mechanism, a clear stretch stimulus could be delivered to the user even if the actuator is loosely grounded to the body. Because the form factor is light and flexible, the user can naturally take various VR actions while wearing it. QuadStretch can express four degrees of freedom through four retractable/expandable stretch modules, and can provide feedback to each arm. We created and presented six VR interaction scenarios by taking advantage of the device's characteristics. Each scenario emphasizes QuadStretch's distinct stimulus intensity, spatial expression, and congruency for complex motions.

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