2025 IEEE World Haptics Conference (WHC)
Suwon Convention Center, Suwon, Korea
July 8 ~ 11, 2025

Variable Stiffness Haptic Glove Based On Electrostatic Clutch

Hoi Yuen Tang[1], Seongjoo Byeon[1], Seunghui Huh[2], Yongjin Kim[1], Amy Kyungwon Han[1*]

I. Introduction

The rapid expansion of extended reality (XR) and metaverse applications demands more immersive and physically realistic haptic experiences [1]. Real-world objects exhibit varying levels of resistance and compliance, which are essential to replicate for authentic interaction in virtual environments. To achieve this, haptic devices must deliver variable stiffness feedback that accurately mimics the tactile qualities of real objects. While haptic feedback encompasses both cutaneous and kinesthetic components, we focus on the latter to provide variable stiffness kinesthetic feedback during virtual object grasping.

Many existing variable stiffness gloves rely on electric motors, resulting in bulky, heavy designs that limit comfort and mobility [2]. Although cable-driven and pneumatic-actuated gloves achieve high output force and displacement, their designs incorporate motors and rigid transmission components on the hand or wrist, increasing bulk and reducing portability and comfort [3], [4].

Electrostatic clutches offer a promising alternative with compact, lightweight, and flexible designs [4], [5]. However, using these clutches to fully block finger motion via static friction reduces interaction versatility in VR applications [5]. Recent research has introduced electrostatic sliding mechanisms to simulate stiffness sensations more realistically, yet this approach faces a critical limitation: the kinetic friction force decreases as the electrode overlap area reduces during grasping, which contrasts with real-world object interactions where gripping force increases as the object is squeezed [4]. Furthermore, placing clutch electrodes along the finger increases the risk of the mechanism buckling and restricts finger adduction and abduction [4].

To address these challenges, we present a compact variable stiffness mechanism for haptic gloves that integrates electrostatic clutches with elastic elements, offering two key advantages: 1) Precise and realistic stiffness feedback for gripping virtual objects of varying compliance; 2) Improved finger mobility and comfort by relocating the clutch assembly to the back of the palm, eliminating buckling concerns. Our design stacks four layers of electrostatic clutches, with the central two layers paired with elastic elements of differing stiffness. By selectively activating specific clutch pairs, the system achieves five discrete stiffness levels while decoupling force from displacement. A nitinol wire transmits force from the back-of-hand mechanism to the fingertip, preserving natural finger motion and enhancing user comfort.

*Research supported by the NAVER Digital Bio Innovation Research Fund, funded by NAVER Corporation (Grant No. [3720230030]) and the Nano & Material Technology Development Program through the National Research Foundation of Korea(NRF) funded by Ministry of Science and ICT(No.RS-2024-00411904, RS-2023-00208052)

[1]Hoi Yuen Tang, Seongjoo Byeon, Yongjin Kim and Amy Kyungwon Han are with the Department of Mechanical Engineering, Seoul National University, Seoul 08826, Korea (e-mail: amyhan@snu.ac.kr)

[2]Seunghui Huh is with the Department of Computer Science, Georgia Institute of Technology, Atlanta, GA 30332, USA

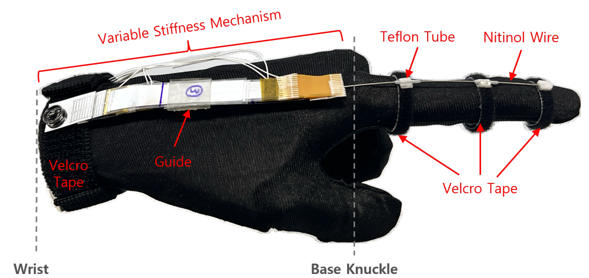

Fig. 1. Kinesthetic haptic glove integrated with the electrostatic clutch based variable stiffness mechanism.

II. Variable Stiffness Mechanism

A. Concept And Design Of Mechanism

Electrostatic clutches consist of two electrodes separated by a dielectric material that attract each other under an applied voltage. Assume that the model is the simplest form of electrostatic clutches based on Coulomb friction and electrostatic attraction.

$$F_f = \mu F_N = \mu \frac{\epsilon_0 \epsilon_r A E^2}{2} \tag{1}$$

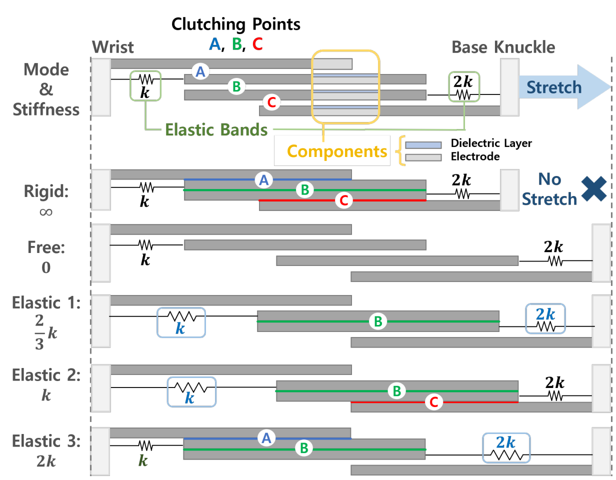

Fig. 2. Side view schematics of the variable stiffness mechanism capable of generating five different stiffness modes.

where μ is the static friction coefficient, ϵ_0 the vacuum permittivity, ϵ_r the relative permittivity, and A the overlapping electrode area.

The electrostatic clutches are integrated with elastic elements, as shown in Fig. 2. By selectively activating different clutch pairs, different elastic elements are engaged, resulting in variable stiffness of the mechanism. As the mechanism is pulled during a grasping motion, the elastic elements stretch, and the resulting resistive force increases nonlinearly with displacement, mimicking the behavior of real-world object gripping, where the perceived force grows as the object is squeezed more tightly.

Four clutch layers are stacked in parallel to activate different combinations of elastic elements, while the middle two layers are connected in series with elastic elements having spring constants of k and $2k$, respectively. To maximize the stiffness range, the elastic elements are designed with a two-fold difference in spring constant. Five distinct stiffness modes are achieved by activating specific clutch pairs (A, B, or C). Activating only the middle clutch pair (B) produces a stiffness of $\frac{2}{3}k$. Activating the two bottom pairs (B and C) yields a stiffness of k, while engaging the two upper pairs (A and B) results in a stiffness of $2k$. Engaging all three pairs (A, B, and C) places the mechanism in a rigid mode, where the effective spring constant approaches infinity.

B. Validation Of Mechanism

The haptic glove employs two elastic elements of differing stiffness, each with an initial length of 20 mm. As the springs do not fully conform to Hooke's law, each of them exhibits a non-linear stiffness profile. The stiffness of the weaker spring (k) was approximately 194 N/m at 50% strain, 337 N/m at 100%, and 235 N/m at 200%, while the stronger spring ($2k$) reaches 376 N/m, 663 N/m, and 485 N/m at the same respective elongations.

A 300 V 10 Hz alternating square waveform was applied to the electrodes with a 3 cm² contact area. The variable stiffness mechanism produces five modes, including three distinct force-displacement modes. In mode 1, where both springs are activated in series, the glove generates forces from 3 N to 6.8 N as displacement increases from 10 to 30 mm. Engaging the weaker spring (k) yields mode 2, producing 4.5 N to 8.5 N over the same range. Finally, activating a stronger spring ($2k$) produces mode 3, with forces rising from 7.5 N to 15 N between 10 mm and 30 mm of elongation (Fig. 3). In rigid mode, fully engaged electrodes can resist forces up to 20 N. As the user grasps objects with the hand, the haptic glove selectively activates each elastic mode, allowing smooth transitions between stiffness levels.

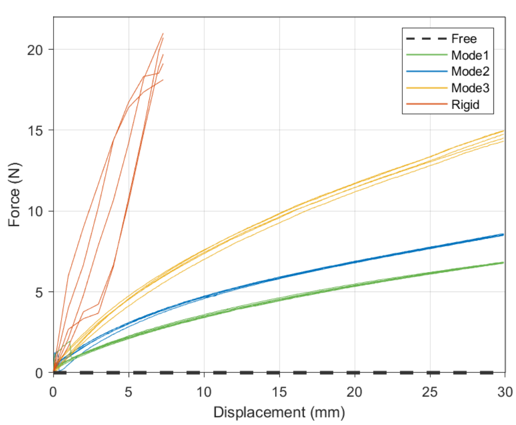

Fig. 3. Five stiffness modes generated by the variable stiffness mechanism. Each mode was tested 5 times.

Experimental force-displacement measurements validate that stiffness increases in all modes and that all three curves gradually smooth out as the elongation grows. These results demonstrate that the glove can produce a wide-ranging, continuous force feedback suitable for realistic grasp simulation. Future work will focus on optimizing the initial spring length and individual stiffness profiles to better match real-world object forces.

III. Kinesthetic Haptic Feedback Glove

Our approach miniaturized the system and relocated it to the back of the palm, thereby eliminating the wrinkle on the clutch and ensuring a greater degree of freedom of the finger without affecting the clutching area (Fig. 1).

The edges of the aluminum layer are etched to prevent arcing. The clutch is fabricated using 125 μm aluminum-coated PET film as the electrode, with a 14 μm layer of the dielectric layer P(VDF-TrFE-CTFE) directly deposited onto the metal surface. P(VDF-TrFE-CTFE) offers a high relative permittivity of approximately 45 and a friction coefficient around 0.75, enabling strong shear forces.

The variable stiffness mechanism measures 1.3 cm × 10 cm, with a thickness of 1 mm and mass 1.76 g, allowing easy dons and doff. A thin, stretchable fabric base maintains overall glove comfort and conforms to hand movements. A nitinol wire, sheathed in a Teflon tube for smooth, low-friction movement, transmits force from the mechanism to the fingertip. One end of the wire is connected to the moving clutches, while the other is attached to Velcro tape secured to the fingertip, enabling efficient transfer of the generated force. Flexible 3D-printed guides secure the alignment of the system. The system is anchored to the fingertip and wrist using Velcro tape, and the glove adapts to hands of varying sizes through adjustable Velcro straps.

References

[1] Zhu, Mengjia, et al. "Soft, wearable robotics and haptics: Technologies, trends, and emerging applications." *Proceedings of the IEEE* 110.2 (2022): 246-272.

[2] Tiboni, Monica, and Cinzia Amici. "Soft gloves: a review on recent developments in actuation, sensing, control and applications." *Actuators.* Vol. 11. No. 8. MDPI, 2022.

[3] Ceccarelli, Marco, Thibault Vaisson, and Matteo Russo. "Design of a Cable-Driven Finger Exoskeleton." *Designs* 9.2 (2025): 35.

[4] Hinchet, Ronan J., and Herbert Shea. "Glove-and sleeve-format variable-friction electrostatic clutches for kinesthetic haptics." *Advanced Intelligent Systems* 4.12 (2022): 2200174.

[5] Hinchet, Ronan, et al. "Dextres: Wearable haptic feedback for grasping in vr via a thin form-factor electrostatic brake." Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology. 2018.