Glove- and Sleeve-Format Variable-Friction Electrostatic Clutches for Kinesthetic Haptics

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Clothing with integrated high-force actuators enables wearable haptics for immersive virtual reality (VR) and enables soft exoskeletons for rehabilitation or human augmentation. Electrostatic clutches (ESClutches) offer a very-low-energy solution to block motion and are mm thin. Challenges for ESClutches in wearables are 1) effective integration in clothing to accurately block body motion while ensuring comfort, 2) well-controlled sliding for variable stiffness rendering, and 3) adaptation to shoulder or hip joints. Here, the control of sliding friction of soft ESClutches is demonstrated, using materials that enable both integration in textile and efficient force transfer to the user. We present a 1.3 mm-thick soft glove with five ESClutches, providing up to 50 N of kinesthetic feedback per finger. A clutch in a thin haptic sleeve that controls elbow extension is reported. Eight cable-format ESClutches on a shoulder are shown, selectively blocking multiple degrees of freedom. VR tests demonstrate that the glove and the sleeve give the user the ability to rank the softness and weight of virtual objects. In a teleoperation scenario, the glove enables the user to remotely feel an object’s stiffness. The ESClutches and textile integration pave a path toward socially acceptable and comfortable kinesthetic haptics.

1. Introduction

Progress in headsets for virtual reality (VR) and augmented reality (AR) highlight the need for rich haptic feedback that goes beyond simple vibrotactile sensations. Wearables that give a realistic sense of the shape and hardness of virtual objects are key for immersive VR and for tactile internet. Kinesthetic haptic feedback can improve virtual dexterity and awareness to enhance interaction and immersion. This leads to applications in virtual training, immersive teleoperation, and enables faster design cycles by allowing more effective virtual prototyping. The hardware developed to deliver kinesthetic haptic feedback can also serve as a platform for rehabilitation systems.

Haptic garments are more socially accepted than rigid exoskeletons, as they are more discrete and look less like a machine. Haptic garments can be worn under other clothing or even be fashion statements. However, making clothing mechanically active with sufficient force to counter human muscles adds significant challenges compared with rigid exoskeletons, as the actuators need to be either both thin and compliant so as to feel like textile or are external to the clothing and linked by cables but are then more visible.

The performance and wearable of haptic garments strongly depend on the actuators and their integration, the latter being particularly challenging. Electric motors and cable systems offer excellent force and displacement, but are too bulky for direct integration in textiles, with the motors for instance worn in a small pack. Fluidic systems, especially in fiber format, enable haptic feedback, but speed is limited by fluidic impedance and integration and portability are limited by the need for a compressor, valves, and tubing. Thin actuators with high force density often come with tradeoffs. One option is electrostatic clutches (ESclutch), consisting of two sliding conductors separated by a thin dielectric. Applying a voltage between the electrodes generates an electrostatic force pulling them together, leading to friction. ESclutches can only block or hinder motion (i.e., they cannot generate displacement like a cable system), but can be sub-mm thick, textile based, block over 20 N cm$^{-2}$, and consume only a few mW cm$^{-2}$, as we reported in prior work. ESclutches on fingers enable enhanced interaction with virtual objects.

Here we address limitations of earlier work by reporting: 1) The ability to precisely control clutch sliding forces, rather than only fully blocking motion; 2) The analysis of materials (dielectric and substrate) to enable smooth voltage-controlled friction; 3) The comfortable yet effective integration of multiple clutches into a glove. This integration on complex shapes with small radius of curvature is essential for clutches to be useful in wearables for haptics or assistive garments; 4) The demonstration of both VR and teleoperation scenarios of the haptic glove in which the clutch’s unique variable sliding ability gives the realistic sensation that virtual objects have different stiffnesses, for instance, making a virtual sponge feel softer than a virtual brick.

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and 5) The integration of ES clutches beyond the hand, mounting them on the elbow in a sleeve format and on the shoulder in a fiber format to feel VR weight.

1.1. Types of Haptic Feedback

Haptic perception is typically classified into cutaneous and kinesthetic. Cutaneous sensation is related to the sense of touch, and is “skin deep,” stemming from the mechanoreceptors in the skin. Cutaneous feeling provides us with information about textures, local pressure, and vibration.[3,23,24] Kinesthetic sensation gives us awareness of the position and motion of joints and the force exerted on them. Kinesthetic sensations originate from sensors located in muscles, tendons and joints.[2,3] Kinesthetic feedback on hands is often discussed separately from feedback on other body parts because hands have particularly complex kinematics and are used for very fine manipulation tasks.[24–26]

One distinguishes grounded from ungrounded haptics. Few kinesthetic haptics devices are fully ungrounded, as forces need to be applied on joints or between body locations. Several types of grounding can be considered, depending on which relative motions are blocked. Body-ground feedback occurs for instance on the palm and on fingers when grasping a lightweight but solid object: motion at joints is blocked when the object prevents the fingers from closing. Table- or floor-ground kinesthetic feedback occurs when pushing against a virtual wall, desk, or steering wheel for example. Floor-ground haptics can provide higher realism for more scenarios, but cannot be delivered solely with an exoskeleton, as a mechanical link to the outside world is needed. Body mounted haptics are often addressed with a glove, sleeve, or jacket.[27]

1.2. Actuators for Kinesthetic Haptics

Kinesthetic feedback can be rendered by exerting force on limbs or fingers using electric motors or fluidic actuators.[3,28] The latter are more challenging to control quickly due to fluidic impedance of thin tubes and challenging to fully integrate because of the required pumps, compressors, valves, and tubes, despite recent progress.[15,18] Another approach is to prevent limb or finger motion using brakes or clutches.[29,30] Clutch mechanisms offer less function, but are usually simpler,[2,31–35] lighter, and consume far less energy than actuators that can generate strain. Numerous types of clutches exist.[31] Pneumatic vacuum jamming clutches can be soft and generate high blocking forces[16–19] but they have similar disadvantage than fluidic actuators. Electrically driven clutches can be easier to control, especially when many clutches are needed for systems with many degrees of freedom, such as a hand. Electromagnetic clutches have been widely used in robotics, but are not suited for wearables as they are rigid, bulky, and power hungry. Mechanical clutches can reduce power consumption, at the cost of reduced speed and added complexity and rigidity. ESclutches have been used on ankle exoskeletons[29] elbow,[10] and for hand kinesthetic feedback,[22] but to date only in off/on operation, and with basic integration in textile.

1.3. Challenges of ESclutches

ESclutches are promising actuators to generate wearable kinesthetic haptic feedback. We reported in earlier work flexible ESclutches that can block forces up to 21 N cm⁻²[21] weighing 30 mg cm⁻² and consuming only 1.2 mW cm⁻². Diller et al.[31] reported 2.4 N cm⁻², for 15 g and 3.2 mW of power, with reliable performance for over 3 million cycles. ESclutches are easily scalable in area.

Kinesthetic feedback garments based on ESclutches, like haptic gloves[21,22] and sleeves,[34,40] highlight ESclutch integration challenges. How to scale, place, guide, attach, and connect ESclutches on soft and curved garments?

To date, ESclutches have been used only as on/off devices for haptics. While variable friction may seem easy to achieve by tuning the applied voltage (as the electrostatic force between parallel plates scale with voltage squared), variable force control is challenging because of three highly nonlinear behaviors: at low voltage one has zipping pull-in (no force until pull-in occurs), at medium voltage one observes stick and slip sliding, and at high voltage the effective friction coefficient can change. Finally, after blocking high forces, it can take several seconds to disengage an ESclutch due to charge injection or surface forces.

Another difficulty is in the alignment, tensioning, and pull-back mechanisms of the ESclutches. Several approaches have been tested like partial hard guides[22] and soft springs.[21,29,30] None is fully satisfactory as they are complex, limit motion, or require frequent fine tuning. In addition, each body part integration is different and requires special care. Finally, user variability must be tackled.

1.4. Haptic Garment Challenges

There is a very big step from an effective soft actuator to an effective active garment. Developing effective wearable kinesthetic haptic feedback garment requires addressing both actuator performance and actuator integration challenges: 1) The actuators used must be strong enough to block motion, yet be thin enough to fit in a garment, and energy efficient enough to allow for untethered operation; 2) The system must be safe and must not force joints to any undesired position; 3) The actuators must deliver varying force levels and respond in tens of milliseconds; 4) As humans vary shape, size, and strength, both the actuators and the garment must be easily adapted to different users; 5) The actuators must block well-defined degrees of freedom without interfering with other motions. This requires both careful grounding (e.g., on fingertip, wrist, shoulder) and careful routing of the forces; 6) The integration of the actuators on the garment must be discreet and comfortable and not impede natural movements; 7) The garment should be easy to don and doff without external assistance.

Methods suited for hands (many degrees of freedom, very high curvature, low force, possible grounding at the wrist) may not be suitable for other joints such as hips (only 2° of freedom, but high forces and more challenging grounding). For some motions, it may not be feasible to use actuators in the garment and the actuators need to be external. However, for the outer side of hands and elbows, the actuators can be in a glove or sleeve.
1.5. Wearable Integration of ESclutches

To address actuator challenges, we modified our ESclutch structure\(^{[21,22]}\) to decrease response time and to allow for accurately controlled variable sliding. By adding a second thin insulating layer (Figure 1a) on top of the ESclutch (Figure 1b) to control the friction coefficient, we decouple friction and dielectric properties. Along with a careful choice of an ESclutch substrate to have the desired flexibility (enabling low-voltage zipping, yet limiting stick slip and stretch), makes for a much more accurate control of ESclutch motion, as well as shortens the detachment time when the voltage is removed.

![Figure 1](image1.png)

**Figure 1.** Overview of the ESclutch structure and several applications. a) Schematic diagram of an ESclutch. b) Photo of an ESclutch composed of a PET substrate and an electrode on the right, and an electrode insulated with a P(VDF-TrFE-CTFE) and a SMPU layer on top on the left. c) Illustration of the concept of placing ESclutches on fingers to block their movement and provide kinesthetic feedback. d) Photo of a kinesthetic haptic feedback glove and sleeve based on ESclutches, illustrating VR applications: to feel virtual objects, data, and weight. e) Demonstration of the use of the kinesthetic haptic feedback glove for teleoperation applications. The user feels the stiffness of what the robot arm is grasping.
Furthermore, we demonstrate position self-sensing of ESclutches using a simple resistor capacitor (RC) circuit model while consuming 1.8 mW cm\(^{-2}\).

We developed an integration method based on soft stretchable textile guides and flexible ESclutch substrates, providing an effective manner to embed multiple bare clutches (Figure 1c) in a haptic glove and sleeve (Figure 1d). The glove is thin (1.3 mm), lightweight (28 g) (Figure S1, Supporting Information), soft, and comfortable. The process of putting on the glove is quick (30 s). The modular approach makes it straightforward to adapt the glove to a broad range of hand shapes and sizes. The integrated ESclutches can block or brake fingers with a controllable force from 0.4 N up to 50 N at 300 V. The force can be turned off in under 100 ms when under a 5 N load. User tests shows that the glove can render variable stiffnesses in VR scenarios. Beyond VR applications, we show that this glove can also be used to distinguish the stiffness of real physical objects in teleoperation.

In this article, we address ESclutch actuator design, to enable variable friction with smooth sliding and to increase release speed. We report self-sensing capabilities of ESclutches. We then address integration challenges on hand (glove), sleeve, and shoulder and report user tests showing variable force kinesthetic feedback in VR and in robotic teleoperation.

2. ESclutch Characterization

In this article, we first address ESclutch actuator design, to enable variable friction with smooth sliding and to increase release speed. We report self-sensing capabilities of ESclutches. We then address integration challenges on hand (glove), sleeve, and shoulder and report user tests showing variable force kinesthetic feedback in VR and in robotic teleoperation.

2.1. ESclutch Principle

ESclutches consist of two partially overlapping flexible electrodes separated by a thin insulator and possibly an air gap (Figure 1a). When the voltage difference between the electrodes is zero, the electrodes are free to slide with very low friction. When the voltage between the electrodes is nonzero, an electrostatic force pulls them together, leading to friction between the electrodes, impeding or blocking their sliding motion.

The simplest model of ESclutch is based on electrostatic attraction and dry Coulomb friction. Considering perfect insulators (no Johnsen-Rahbek effect) and ideal parallel plate capacitors, the friction between the electrodes depends on the square of the applied electric field \(E\).

\[
F_{\text{friction}} = \mu \times \frac{1}{2} \epsilon_0 \varepsilon_r A E^2 \tag{1}
\]

where \(\mu\) is the friction coefficient, \(\epsilon_0\) the vacuum permittivity, \(\varepsilon_r\) the relative permittivity of the dielectric, and \(A\) the capacitor area. In practice it is difficult to accurately predict the friction force of soft ESclutches. The dielectric constant of high-permittivity insulators depends on the electric field and on frequency. Trapped charges and polarization change the electrostatic force. The static and dynamic friction coefficients depend on fabrication process, surfaces state, and wear. Friction forces also depend on force magnitude. Finally, Van der Waals interactions, stiction effects, and geometric confinement add to surface forces.

To reduce the voltage required to reach high blocking forces, insulators with high relative permittivity can be used, such as poly vinylidene fluoride, trifluoroethylene, and 1,1-chlorotrifuoro-ethylene (P(VDF-TrFE-CTFE)). This enabled high ESclutches forces of tens of N cm\(^{-2}\) at a few hundred volts. Luxprint, Mylar, and Kapton are also possible but less effective. Polyurethane (SPMU) makes a good sliding layer which is compatible with P(VDF-TrFe-CTFE). Wear-resistant coatings like polycarbonate or melamine formaldehyde resins could be interesting options. Springy plastics like polyethylene (PE) are well suited as the substrates for wearable clutches. Electrodes made of a thin Al coating are easy to source. Wear-resistant metal coatings with good adhesion such as chromium can increase durability. The ESclutches we report here are 1 cm wide to fit on fingers and we use an initial overlap length of 3 cm. Using square bipolar alternating current (AC) voltage rather than a DC voltage has been shown to increase the force and reduce the release time.

2.2. Effect of the Substrate on Minimum ESclutch Blocking Force

Our experimental characterization (Figure S2, Supporting Information) of ESclutches shows that the shear stress is proportional to the voltage (Figure 2a) above a threshold voltage, here of 50 V, which is related to electrostatic pull-in. ESclutch strips are not perfectly flat and not in full contact. When they engage, there is an initial zipping effect that pulls the electrodes together; this zipping propagates along the strips (Figure S3, Supporting Information). Electrostatic pull-in depends on the applied voltage, the gap between the electrodes, their shape, and importantly their bending stiffness. To minimize the pull-in voltage so as to be able to actuate ESclutches at the lowest voltage possible to generate low forces, we tuned the stiffness of the substrate (Figure 2b).

If the substrate is stiff like stainless steel, then several hundred volts are required to generate sufficient electrostatic attraction to deform the steel and reach a full contact (i.e., fully zip the entire overlapping area). If the substrate is very soft like pe textile, a few tens of volts will generate enough electrostatic attraction to bend the textile substrate and bring the strips in contact. However, for these very compliant substrates, zipping does not fully propagate all along the electrodes. Insufficient zipping creates an incomplete contact between strips and thus generates low friction. As a tradeoff, we found that 125 μm-thick poly (ethylene terephthalate) (PET) film substrate worked best to fully engage the ESclutch at lowest pull-in voltage of about 50 V when flat. The lower is the pull-in voltage, the lower is the minimal blocking force that the ESclutch can robustly generate. Engaging the ESclutch with a very low blocking force enables generating the low friction forces necessary to render the kinesthetic feedback corresponding to soft objects like a sponge or a pillow.
2.3. ESclutch Force–Displacement Profile

The ESclutch substrate plays a large role on the force–displacement properties of the clutch when under load. When a force is applied to the clutch, the substrate initially stretches, and then the clutch starts to slide, in a stick-slip mode. After each slip, the movement stops, the clutch fully re-engages, and the strips stretch and then slide again.

Figure 2c shows the sliding profile at a shear stress of 4 N cm$^{-2}$ for ESclutches made of three different substrates.
The stiffest substrate, steel shim,[22] generates smooth sliding curves with stick and slip oscillations of small amplitude and of short time period. There is initially a higher friction peak due to the static friction coefficient and then a lower sliding force due to the lower dynamic friction coefficient. The sliding force slowly decreases as we pull on the strips because the overlap surface decreases. Soft substrates like thin PE textile[21] generate a stick-slip profile with high amplitude and long-period oscillations. Friction peaks have a similar height. This friction is probably based on successive static friction peaks only. Oscillations amplitude and period increase with shear stress. Under high shear stresses, oscillations generate jolts that can be felt and degrade kinesthetic feedback feeling. Therefore, it is preferable to minimize stick and slip sliding using stiffer substrates. However, stiff substrates have higher pull-in voltages. We found that a 125 μm-thick PET substrate offers a good tradeoff, sliding reasonably smoothly with small stick and slip oscillations, while having a low pull-in voltage.

2.4. Release Time

The performance of the ESclutch strongly depends on the dielectric material. P(VDF-TrFE-CTFE) has a high relative permittivity and a friction coefficient of 0.75.[21] However, we found that P(VDF-TrFE-CTFE) can become temporarily tacky under shear stresses higher than several N/cm². This pressure sensitive tackiness can increase the release time of P(VDF-TrFE-CTFE)-based ESclutch under high shear stresses.

If a user pulls strongly on ESclutch when the voltage is turned off, release takes less than 15 ms.[21] However, if the user only exerts a low force on the ESclutch, it can take up to several seconds to completely release the ESclutch after the voltage is turned off. This can be a problem for VR applications that require responsiveness.

To minimize the release time, we cast a 500 nm-thick SMPU layer on the P(VDF-TrFE-CTFE) layer. This stack allows controlling the relative permittivity and the friction coefficient parameters separately. The thin bottom insulating layer (several μm-thick P(VDF-TrFE-CTFE)) has high permittivity to maximize the Maxwell stress in the ESclutch. The thin SMPU layer determines the friction coefficient (≈0.7) of the ESclutch. One can thus tune the slope of the shear stress versus voltage by changing the top thin coating. We chose SMPU because it has a friction coefficient similar to that of P(VDF-TrFE-CTFE), but shows far less tackiness under high shear stresses.

Figure 2d plots the release time of the SMPU-coated ESclutch after blocking 5 N for 1 min. Below 275 V, which corresponds to a shear stress of 17 N cm⁻², the ESclutch disengages in less than 65 ms. This takes into account all release steps: ESclutch capacitance, electric discharge, mechanical relaxation of the structure, and separation of the strips. 65 ms is fast enough for most VR applications.

We also used a Teflon AF (PTFE) coating to decrease the friction coefficient (down to 0.05–0.10) and therefore deliver very low shear stresses with good control. PTFE has a very low friction coefficient which significantly decreased the ESclutch blocking force to 1.7 N cm⁻² at 300 V.

2.5. ESclutch Capacitance Self-Sensing

The capacitance of the ESclutches depends on the electrodes overlap, that is, on the clutch motion. By measuring the capacitance of an ESclutch, it is possible to determine its overlap, hence, strain, as long as the clutches remain well aligned.

We determine the capacitance C by measuring the charging/discharging time constant \( t = RC \) when driving the clutch with a bipolar square wave, in series with a \( R = 1 \Omega \) resistance. By fitting the current versus time curve to an exponential function (Figure S4, Supporting Information), we can determine the value of the ESclutch capacitance at different actuation voltages. Since we typically drive the ESclutches with a 20 Hz square wave, we can update the ESclutch position every 25 ms. Figure 2e shows that the ESclutch capacitance depends linearly on ESclutch overlap for a given actuation voltage. The capacitance increases with the actuation voltage because of the increasing Maxwell stress and electorstric effect of P(VDF-TrFE-CTFE). We also observed a difference between the capacitance values extracted at 50 V and 100 V due to the pull-in phenomenon. The capacitance of the ESclutch enables determining the electrodes’ area overlap. The self-sensing accuracy of ESclutches depends on how well the strip alignment is kept during actuation, that is, on the integration method.

2.6. Power Consumption

The power consumption of an ESclutch is theoretically the product of the switching frequency and of the energy required to charge the capacitor:[21]

\[
P = \frac{1}{2} \times \frac{A \epsilon_0 \epsilon_f}{d} \times V^2 \times 2f
\]

where \( P \) is the power, \( d \) the insulator thickness, \( V \) the actuation voltage, and \( f \) the frequency. Considering a 1 cm² ESclutch with a 12.5 μm-thick P(VDF-TrFE-CTFE) of permittivity 45, actuated at 20 Hz, we calculated a power consumption of 2.55 mW at 200 V (Figure 2f). We experimentally measured a slightly lower consumption of 1.83 mW cm⁻². These power levels are extremely low given the high forces that are blocked, a key feature for untethered operation.

3. ESclutch Integration on Body

The effectiveness of an ESclutch at providing kinesthetic haptic feedback on the body depends very strongly on its integration in the haptic garment. Poor positioning with respect to a joint, loose anchoring, or slack will degrade the kinesthetic feedback. In addition, integration is a main element in user comfort and thus in adoption of a technology.[26,28] For these reasons, the principles that drove our design choices to make kinesthetic garments were the following: 1) It must provide effective kinesthetic feedback, on a well-defined joint or set of joints; 2) It must be light weight (e.g., <50 g for a glove) and thin (e.g., <2 mm); 3) It must be adaptable to different limb shapes and sizes; 4) It must not impede natural movements when off. Secondary but also
important considerations are as follows: 1) It should be quick and easy to put on and take off; 2) It should be comfortable and breathable.

Based on these goals, we designed two kinesthetic garments that fully integrate ESclutches: a glove that blocks finger bending and a sleeve that blocks elbow bending. Similar design solutions can be applied on other body parts that have comparable kinematics. For joints such as the shoulder where the upper arm motion with respect to the torso needs to be controlled, we use cable-format clutches attached externally to the clothing, as the force vectors are not readily compatible with routing through clothing.

3.1. Haptic Glove Design

The hand kinesthetic feedback system generally takes the form of a glove[48] onto which actuators or clutches are placed (hand dorsal). Other integrations strategies exist,[2] such as finger digit-based devices that integrate actuators between the fingers to control their spacing[49] or devices that control the movement of the fingers taking support on the palm.[50] The hand dorsal glove approach has the advantage of obstructing neither fingertips, nor the palm, which enables closing one’s hand to grasp real objects, which is important in AR. In addition, the glabrous skin on the fingertip and palm remain free for cutaneous feedback.

In light of these advantages, and because soft ESclutches can only block extension, we selected the hand dorsal integration approach with the ESclutches mounted on top of the fingers (Figure 3a) and thus controlling finger closing.

Jointed hand dorsal gloves use an articulated rigid exoskeleton powered by motors or pistons.[2,28] Jointless gloves use soft tendons (cables) with actuators on the back of the hand or on the forearm. Those gloves are small and flexible but require an additional rigid structure to fix, tension, and actuate the tendons. ESclutches, in the form of thin flat flexible tendons and the clenching element itself, offer unique integration possibilities that combine both advantages: the simplicity of control and the small light flexible form factor, without the need for extra rigid structures to fix, tension, and actuate.

Our haptic glove (Movie S1, Supporting Information) consists of three regions: in the central region, the two ESclutch strips (Figure 3b) overlap on the back of the hand (Figure 3c). A wrist band (Figure 3d) serves as the local mechanical anchor for the fixed ESclutch (i.e., mechanical grounding) and as an electrical connection hub. The moving ESclutch is attached to the fingertip with a textile loop (Figure 3e). We discuss below the design of these three glove parts.

Haptic gloves must be able to adapt to different hand shapes and sizes. We start with a very soft glove made of four-way stretchable nylon fabric. Each ESclutch’s strip is fabricated with multiple attachment holes so one can quickly adapt the strip to the finger’s length by simply using different attachment points. (Figure 3b). The strips overlap only on the back of the hand, as it is easier to engage the clutch on this flat surface than on fingers’ joints, where curvature can be high (Figure S5, Supporting Information), which would increase pull-in voltage as well as off-state friction. The strips attached to the fingers slide under the wrist strips located on the back of the hand. In this way, finger strips push against the wrist strips, which decreases pull-in voltage and facilitates zipping.

The mechanical guiding of the clutch is done using green stretchable textile channels glued on the nylon glove, covering the back of the hand and fingers (Figure 3c). The clutch slides in this textile channel, that gently compresses the clutches when worn (Figure S6, Supporting Information), ensuring the strips stay in mechanical contact and well aligned. This greatly facilitates the zipping of the strips and decreases the pull-in voltage to only a few tens of volts without generating much off-state friction. Finger abduction movement is permitted (Figure S5, Supporting Information) thanks to the flexibility of the glove and the ESclutches. Abduction is however not actively blocked. This could be done using two ESclutches per finger, one on each side. This would be especially useful on the thumb, which has more degrees of freedom than the fingers. We tilted the thumb ESclutch 30° outward[22] due to help cope with its more complex motion, with both flexion and abduction toward the palm. Similarly, we found that a small outward tilt (10° to 20°) is beneficial to block the pinky finger.

The glove design is the result of a tradeoff between the stiffness of the ESclutches and the stiffness of the textile guides. The ESclutches strips have a rounded tip (Figure 3b) and are free to slide inside the stretchable textile guides (Figure S6, Supporting Information). This simple design eases the fabrication and assembly of the haptic glove. However, it requires a precise control of the strips and guides stiffnesses to avoid wrinkling of the clutch (Figure S5, Supporting Information) when uncurling (extending) the fingers. The strips must be flexible enough to bend on fingers in the soft textile guides. However, the strips must be stiff enough to slide back in the guides when opening the hand, without a spring or tensioning system pulling them back. The textile guides must be soft enough to be comfortable and to conform to hand shape. However, they must be stiff enough to guide the strips backward without deforming on finger joints. To meet these conflicting requirements, we chose a soft polyester stretchable textile that includes 15% elastane and has a Young’s modulus of around 0.5 MPa. The textile guides were reinforced at their extremities to resist additional stresses at strips’ attachment points.

We use the wrist as the mechanical grounding point for the Glove ESclutches. One extremity of each clutch is attached to a fingertip and the other to the wrist. To be effective and accurate at blocking finger motion, the one extremity of the ESclutch must be firmly attached to a fixed point. Skin on the forearm is too compliant to be an effective ESclutch anchor. Even a few mm of motion due to skin stretch greatly reduces the VR effectiveness of the clutch. The wrist, that is, the carpal region taking support on the radius and ulna styloid process, was the most effective position to anchor the glove-format ESclutches. The wrist band must be tight, without being uncomfortable. We imposed a design constraint which is that the user must be able to don and tighten the wrist band without external help, to allow for unassisted operation. We used a heavy-duty Velcro loop onto which we affixed pressure button rivets to both mechanically attach the ESclutches (Figure 3d) and to make electrical contacts.

The glove fingertips, where the clutch strips are attached to the fingers, are made of nonstretchable thin textile rolled into cone shapes, which we fabricate in seven sizes to fit most users.
Figure 3. Haptic glove components. a) Schematic of the integration of the ESclutch strips, the “fixed” strip attached on the wrist, and the “moving” strip on the index finger. b) Photo of ESclutch strips. c) Haptic glove integrating the ESclutch strips into stretchable textile guides on top of the hand and fingers. d) P(VDF-TrFE-CTFE)-coated ESclutch strips are attached to a Velcro wrist band serving as a mechanical anchor to block finger bending. e) Conductive ESclutch strips are attached to fingertips using nonstretchable thin textile ribbon of different sizes. This serves as a fingertip fixation and provides passive tactile feedback.
Correct sizing is important because the fingertip attachments must fit well to effectively transmit the ESclutch blocking force. An alternative to multiple fingertips would be a continuously variable fastener mechanism. ESclutches were attached to glove fingertips using metal pressure buttons (Figure 3e). Like for the wrist band, the attachments could instead have been sewn directly on the glove but our modular integration method makes it much easier to adapt to the user’s hand size. Users could naturally grab and use real objects with dexterity. Users greatly appreciated the ability to manipulate real objects like a game controller, a pen, or a glass of water without needing to remove the glove. It is a plus in VR and a must for AR.

Cutaneous feedback at the fingertip is generated passively by taking advantage of the stress generated by engaged ESclutches. When pushing on a blocked ESclutch, stress increases in the ESclutch and at its anchors on wrist and fingertip. This stress compresses the fingertip and generates pressure on the fingertip. The harder the user grabs and compresses a VR object, the higher is the stress and higher is the passive cutaneous feedback. When pushing on a blocked ESclutch, stress increases in the ESclutch and at its anchors on wrist and fingertip. This stress compresses the fingertip and generates pressure on the fingertip. The harder the user grabs and compresses a VR object, the higher is the stress and higher is the passive cutaneous feedback. This passive tactile feedback is very simple and effective. Adding active cutaneous actuators on fingerprint, like piezovibrators or HAXEL actuators, could further enrich the tactile feedback experience.

3.2. Glove User Tests

To evaluate the performance of the kinesthetic glove, we performed user tests in two steps. First, the user performs a calibration process to find the ESclutch voltage that corresponds to the stiffness of our test objects (i.e., we find the voltages needed for each user to generate stiffness feelings corresponding to wool, PET, bottle, etc.). Second, the user sorts VR objects by stiffness order to evaluate the kinesthetic glove performance (Movie S2, Supporting Information).

The user-specific calibration of the kinesthetic glove is necessary for several reasons. First, hand shape and size vary, which slightly change the ESclutch position on the hand and hence their haptic performance: misalignment, twisting, or curvature impact the pull-in voltage, the zipping process, and the blocking force. Therefore, at a given voltage, the holding force of an ESclutch worn on the body is lower than the holding force of the same ESclutch when laid on a flat surface and held straight (Figure 2a). Second, hand sensitivity depends on morphology, age, and gender. Finally, kinesthetic sensations depend on musculature and occupation.

The calibration was performed using real objects as a reference. This enables users to rely as much as possible on their real-world experience to feel VR objects which accelerate user adaptation to the glove. We chose four objects (Figure 4a) to cover a wide range of different stiffnesses (Figure S7, Supporting Information): cotton swabs, a ball of wool, sponge, and a PET bottle. Users palpate these objects with their left hand and compare their perceived stiffness to the feedback provided by the glove worn on their right hand. If the users feel the real object is harder, we increase the glove voltage, and vice versa. The comparison was repeated 25 times (Figure 4b), starting with an initial voltage step of 25 V. At each iteration, the voltage step decreases by 10%. The average of the last five values gives a voltage that generates kinesthetic feedback very close to the kinesthetic feeling of the real object palpated.

Calibration was performed on 15 right-handed males with age from 26 to 33 years old. The calibration results converged to clearly distinguishable values for each user (Figure 4b). For all users (Figure 4c), the harder the object, the higher the voltage. We noticed two outliers during the calibration of the plastic bottle. After calibration, outliers were able to clearly feel and distinguish each object and to pass the VR test.

One noticeable difference between squeezing a real object and a virtual one using our glove is that the glove generates a constant blocking force, whereas a real object generates a force that increases the more it is compressed (Figure S7, Supporting Information). One solution to this would be to increase the glove voltage as users compress virtual objects. This would require more accurate objects modeling and finger tracking than we had.

After the calibration process, tests in a VR environment were performed (Figure 4d) to determine if users can rank VR objects by stiffness. The tests were performed on the same 15 users as for calibration. We designed a VR scenario with five cubes having five different stiffnesses, corresponding to five different voltages applied to the clutch when the user touches the cube (Figure 4e). Cube stiffnesses were assigned randomly before each test. Cubes had different colors for easy identification. The user could touch them but they did not deform or move under touch to avoid any visual hints. When the user releases the VR cube, the voltage is set to zero. User was not given training or adaption time before the VR tests. During the tests, the user was free to touch the cubes as long as they wanted. The users were asked to identify which cube corresponded to which stiffness, people sorting the cubes by stiffness order.

The confusion matrix of the VR tests (Figure 4f) shows that users identified the five different VR stiffnesses correctly over 93% of the time and over 97% for the three stiffer cases. A few users confused the two softest VR cubes.

The ability of the haptic glove to render small and high kinesthetic forces is limited by integration choices. First, to render very gentle kinesthetic feedbacks, we must very weakly block finger motion which implies not only a low force from the ESclutch, but also low friction sliding inside the textile guide. We chose to slightly compress ESclutch strips in the guide to ensure a very low pull-in voltage. However, this has the effect of slightly increasing the off-state friction between the strips, making it impossible to generate kinesthetic forces lower than this off-state friction. Second, to render very strong kinesthetic feedback, we must firmly block finger motion. This depends not only on the ESclutch force, but also on its anchor strength and slack. We did not try to render hard objects such as those made of glass, stone, or wood, because these objects are effectively incompressible by human hand: finger motion is fully blocked as soon as contact is made. Such high stiffnesses cannot be faithfully rendered when the ESclutch is mounted on a compliant glove, because even when the ESclutches are fully blocked, the glove can stretch slightly, leading to small motion of the finger. To minimize slack, we tighten as much as possible the wrist band. However, this is at the detriment of glove comfort. There is a tradeoff between the glove comfort and its ability to render strong kinesthetic feedbacks.
What we refer to as slack (i.e., a few mm of motion before the clutch engages due to skin elasticity or due to insufficiently tight wrist strap) limits performance in clutch-based systems. Active actuators like motors can pull on structures and remove the slack, whereas clutches are passive and can only block movement. One could, for example, actuate the glove preemptively before the user touches a VR object, to account for some slack. Increasing the glove voltages as the hand penetrates through VR objects would better render the rising compression feeling of objects. Motion prediction and user intention prediction would allow turning off the ESlutches as soon as user starts to open the hand to release a VR object. In our simpler setup, the clutch turns off only once the user has completely released the VR object. This is possible because ESlutches are flexible and the glove is soft enough that users can open their hand with small resistance, even if the glove is actuated. Such softness is a strong asset to convince people that the glove poses no safety risk.

**Figure 4.** Glove calibration and VR tests. a) Haptic glove user palpating real objects in the left hand and comparing the stiffness to the haptic glove worn on the right hand. The glove is actuated at different voltages. Users closed their eyes and wore sound-blocking earmuffs. b) Examples of voltage convergence curves to calibrate the glove to a user after palpating real objects. At each iteration, the user compares the object stiffness to the stiffness generated by the glove. If the glove feels harder, then its voltage is reduced, and vice versa. c) Results of the voltage calibration of the glove on 15 users. d) VR user wearing a VR headset, a hand pose sensor, and the haptic glove to touch and feel VR cubes. e) Screenshot of the VR view of a glove user touching VR cubes of different stiffnesses simulated using different glove actuation voltages. f) Results of the VR tests where users touched, identified, and sorted 5 VR cubes by their perceived stiffnesses. Users correctly identified the relative stiffness of the virtual cubes.
3.3. Teleoperation using the Glove

Beyond applications in VR, the haptic glove can be used to feel and distinguish real objects remotely for teleoperation (Figure 1e). We linked the glove, the VR setup, and the VR scenario (Figure S8, Supporting Information) to a robotic arm equipped with a two-fingered gripper and a force sensor (Figure S9 and Movie S3, Supporting Information). The controls and the feedback loops are the following: the Leapmotion finger tracking mounted on the Valve Index VR headset calculates the distance between thumb and index fingers on the right hand every 100 ms. The spacing information is transmitted to the robot gripper that moves the fingers accordingly. The force sensor installed in the gripper generates a readout voltage, proportional to the force, every 100 ms. After filtering, the measured force value is converted into a control voltage that is applied to the haptic glove to generate kinesthetic feedback proportional to the force measured.

Three objects of different stiffness were remotely manipulated: a plastic bottle, a sponge, and a cotton ball. We programmed three object positions in front of the robotic arm and objects were placed randomly at these positions by an operator. The user wears a VR headset so as not to see what the operator is doing. During the test, the robotic arm moves to one position and the operator notifies the user that the arm is in position, ready to grab an object. Then the user palpates in VR without seeing the object held by the robot and tries to identify the object. The test was repeated six times and the user correctly identified each time which real object the robot was grasping. This proof of concept shows that this kinesthetic feedback glove can bring new haptic functionalities to teleoperation such as object identification based on stiffness kinesthetic feedback. It could also be beneficial for improving dexterity in teleoperation.

3.4. Haptic Sleeve

Beyond providing kinesthetic haptic feedback to the hand, the clutch technology reported in this article can be scaled up and adapted to many joints on the body. As an example, we developed a kinesthetic sleeve based on ESclutches designed to block elbow bending. The elbow plays a major role in the perception of an object’s weight. To give a sense of mass to VR objects, we placed an ESclutch on the elbow to block its flexion.

The haptic sleeve (Movie S4, Supporting Information) is based on a soft PE sleeve onto which we integrated a 40 cm-long stretchable textile guide and we slid inside a 1 cm-wide 40 cm-long ESclutch (Figure 5a). The integration principle is the same as for the glove, but the clutch overlap is 2 times longer. The ESclutch passes over the middle of the elbow bone (Olecranon). It is anchored on one end at the wrist using a Velcro loop and a clip. The clip was added to strengthen the anchor and resist higher forces. The other extremity of the ESclutch was anchored above the bicep muscle with a Velcro strap and clip: this location does not hinder folding the elbow and is rather insensitive to the bulging of the bicep when it is contracted.

To account for the higher strength of human arms compared with fingers, the ESclutch strips’ overlap area was doubled from 3 to 6 cm². We chose to position the overlap of the ESclutch strips on the forearm (Figure 5b) because it engages more easily there (lower pull-in and higher force) than on the highly curved elbow joint. The ESclutch substrate were strengthened by doubling its thickness from 125 to 250 μm. This stiffens the ESclutch which becomes slightly harder to zip and more sensitive to bending and twisting. This can slightly decrease the blocking force. The thicker substrate also increases slightly the pull-in voltage and hence the minimum blocking force. However, this is not a problem in practice because the arm is much stronger and less sensitive than fingers. The ESclutch was connected to each clip using two pressure buttons to sustain higher forces while serving as an electrical connection.

The resulting haptic sleeve (Figure 5c) is soft and comfortable. It can be quickly donned and tightened by an unassisted user. The sleeve is thin 1.4 mm, light 38 g (Figure S1, Supporting Information) Velcro loops can be tightened to decrease slack and hence increase kinesthetic feedback.

To evaluate the haptic sleeve integration and the impact of slack, we attached a force sensor in series between the bicep clip and the ESclutch (Figure S10 and Movie S4, Supporting Information). Figure 6a plots force versus time, as the wearer bends and then straightens his arm. Starting with the ESclutch fully engaged on a straight arm, the force increases as the user folds his arm, slightly more slowly than predicted purely from geometry because of slack and tissue stretching. Once the full blocking force is reached, the ESclutch starts to slide. The sliding force is lower than for a flat ESclutch: at 200 V, a flat 6 cm² ESclutch can block 60 N, but over the elbow, it only blocks 10 N. A similar effect probably occurs in the glove. For the elbow, we attribute this difference to slight twisting and bending of the ESclutch when the user moves. We increased the voltage and reached a maximum blocking force of 20 N.

Like for the glove, we performed user-specific calibration of the voltage needed to obtain a given blocking force using the sleeve. We choose to calibrate and simulate VR weights between 1 and 1.5 kg. The calibration process uses a 1 kg weight attached to the wrist (Figure 6b). We followed a similar procedure to the glove calibration: first the haptic sleeve is disengaged and the user lifts a 1 kg weight by bending his elbow. Second, we remove the weight, engage the haptic sleeve at a given voltage, and ask the user to bend his arm. Third, we ask if user perceived a greater resistance with the haptic sleeve than with the 1 kg weight. If yes, then we decrease the sleeve voltage; otherwise, we increase it (Movie S5, Supporting Information). The comparison was repeated 25 times in the same conditions than for the glove (Figure 6c). Results converged toward a voltage of around 110 V, which generated a tangent blocking force of around 5 N only (Figure 6a), but users felt it as a normal force of 10 N (i.e., 1 kg). Depending on integration and on-body mounting, the kinesthetic sensation of a movement can be noticeably different from the force generated by the actuator.

Tests in a VR environment were devised to determine whether the kinesthetic sleeve is capable of simulating various VR weights and if users can distinguish them. The VR scenario consists of three identical-looking cubes (Figure 6d) having VR weight of 1, 1.25, and 1.5 kg. These VR weights were programmed by attributing a fixed voltage to the sleeve ESclutch equal to 1, 1.25, and...
1.5 times the 1 kg calibration voltage (Figure 6c), assuming linear weight/voltage scaling. VR weights were attributed randomly to the cubes test. There was no training and adaption time before the VR tests. During the tests, the user was free to take hold of the cubes and to lift them by bending his elbow to feel their VR weight (Movie S5, Supporting Information). The sleeve was engaged when a cube was grabbed and disengaged when released. There was no time limit and the user was asked to sort cubes by weight.

The confusion matrix result of the sleeve user tests (Figure 6d) shows users could distinguish the three different VR weights with high accuracy. Despite the limitations discussed earlier, the kinesthetic sleeve works well for VR weights between 1 and 1.5 kg if users bend their arm sufficiently to remove slack.

Users commented that the sleeve generates a kinesthetic feeling different from real weight but close enough to be associated with a kind of VR weight. This is because the sleeve blocks motion only when bending the arm and not when straightening the arm or moving the shoulder. In addition, the VR weight is only felt when moving. Finally, the blocking force is tangential to the arm and not vertical. This makes the kinesthetic feedback feel a bit different from a real weight but users adapted to it quickly.

The kinesthetic sleeve generated effective kinesthetic feedback that is complementary of the kinesthetic glove and enriched the user’s haptic experience.

3.5. Cable-Format Clutch

A main limitation of integrating ESclutches directly in garments is that it is not possible to use it on all locations on the body. For instance, the ESclutch works very well on the outside of the elbow to block arm bending, but not inside the elbow to block extension. Similarly, it would be effective in preventing bending of the knee from a straight-legged position, but not at preventing the knee from straightening. The shoulder has a similar but more complex issue.

Those locations require positioning ESclutches spanning distance, as shown in Figure 6e. This requires a self-contained ESclutch. We hence developed an alternative integration of ESclutch into long (12 cm) and thin (6 mm wide) elastic cables (Figure 6e) that block extension when engaged. To adapt our ESclutch, we decreased strip width to 5 mm and we doubled substrate thickness. The overlap was increased to 10 cm length to compensate for the narrower width. The strips were placed inside an elastic textile tube that serves as a guide for the strips.
Figure 6. Haptic sleeve on elbow, and cable-clutches on shoulder. a) Internal force blocked by the long ESclutch inside the haptic sleeve when bending the arm at the elbow. b) Calibration process: the user lifts a 1 kg weight with the right arm and then compares that sensation to what is provided by the haptic sleeve. c) Example of voltage convergence curves obtained when calibrating the sleeve to a user for 1 kg weight. At each iteration, the user compares the force needed to raise 1 kg with the blocking force generated by the sleeve. If the sleeve feels stronger, then its voltage is reduced, and vice versa. Box plot on the right shows the results of the voltage calibration on six users. d) Results of the VR tests where users lifted, identified, and sorted the 3 VR cubes based on their perceived weight. e) ESclutch integration into a 12 cm-long 6 mm-diameter cable with 10 cm × 5 mm of ESclutch overlap. Strips can block up to 20 kg at 300 V. f) Eight cable ESclutches integrated around the shoulder to block different arm movements.
The resulting cable EScutch is highly flexible and has similar performance than EScutch in the glove.

These cable clutches can be easily attached over the shoulder for example (Figure 6f). The cable format offers the advantages of being easier to attach, adjust, and move to different points on garments. To block arm movements (Figure S11, Supporting Information), we attached eight cable EScutches around the shoulder and distributed them to adapt the total blocking force in each direction to the strength of the shoulder in these directions. Because one can exert more force pulling down than up, we placed three cables on top of shoulder and only one under it. Then we place two cables front and back to block these motions. Cables spread on each side and can block combinations of motions.

4. Conclusion

Important haptic feedback factors include duration, intensity, accuracy and fidelity. The EScutches can block high forces during long periods, but intensity is limited by soft wearable integration which introduces some slack. Accuracy is similarly limited in comfortable wearables. Finally, fidelity can be tuned using calibration.

The improved electrostatic clutch presented in this article is capable of variable friction and fast release. We developed effective integration of EScutches in soft textiles to create novel garments for kinesthetic haptics. When integrated in a glove and in a sleeve, those active garments provide dynamic stiffness and sensation of weight in VR. Using both the on-textile clutches and in a sleeve, those active garments provide dynamic stiffness capabilities for kinesthetic haptics. When integrated in a glove and a Round Force-Sensitive Resistor FSR402 from Seeed Studio were used with control boards for the robotic teleoperation. Signal filtering and correction are essential at each step of the teleoperation loop. We tuned them experimentally to better feel the difference of stiffness between the objects tested. This included the hand tracking that was filtered to smooth motions, the control of the gripper motor to dump too strong grasps, the force sensor to linearize its sensitivity, and the haptic glove which was calibrated on user and whose sensitivity was amplified.

The experiments involving human subjects were performed with the full and informed consent of the volunteer. The tests on human volunteers were approved by the EPFL Human Research Ethics Committee, HREC No:047-2018, subprojects no:033-2020 and no:026-2021.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

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electrostatic clutch, haptic garment, kinesthetic feedback, soft exoskeleton, variable stiffness, wearable haptics, wearable robotics

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