Supporting Information

All-Fabric Wearable Electroadhesive Clutch

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Clutch Holding Force Derivation

An electric field $\mathbf{E} = E_i \mathbf{e}_i$ is created between the plates of a parallel plate capacitor when a potential difference Φ is applied across its electrodes. Charges flow across the plates until the voltage drop across the capacitor approximately equals Φ (see Figure S1). The electric field induces Maxwell stress σ with tensor components that can be expressed as:

$$\sigma_{ij} = \kappa \epsilon_0 \left(E_i E_j - \frac{1}{2} \delta_{ij} E^2 \right) \tag{1}$$

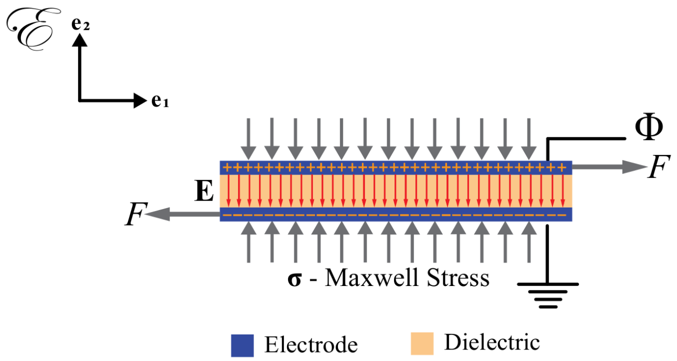

Figure S1: Voltage Φ applied across a parallel plate capacitor gives rise to charge separation between the electrodes. In the Euclidean space $\mathcal{E}$, the generated electric field $\mathbf{E}$ induces the Maxwell Stress tensor $\sigma = \sigma_{ij}\mathbf{e}_i \otimes \mathbf{e}_j$ that increases shear resistance to the applied load F.

Here the indices $i, j \in \{1, 2, 3\}$ are subject to Einstein summation convention. Since the electric field is directed normal to the electrode plane, we have $E_1 = 0$, $E_2 = 0$, and $E_3 = \Phi/x$, where x is the dielectric thickness or the separation between the parallel plates. Assuming the edge effects of the electric field to be negligible, and for a given capacitance $C = A\kappa\epsilon_0/x$, the component of the stress tensor normal to the electrode plane is given by:

$$\sigma_{33} = \frac{1}{2}\kappa\epsilon_0 \left(\frac{\Phi}{x}\right)^2 \tag{2}$$

while the remaining components are zero. For n engaged clutch plate pairs, the frictional force F in the electrode plane that acts opposite to the direction of loading is

$$F = \mu n A \sigma_{33} = \frac{1}{2}\mu\kappa\epsilon_0 n A \left(\frac{\Phi}{x}\right)^2 \tag{3}$$

where μ is the coefficient of static friction between dielectric surfaces.

Capacitor Charging and Discharging

In the H-bridge shown in Figure S2, the two branches, B1 and B2, are RC circuits each consisting of the capacitive load, two transistors, and a measurement resistor: B1 (S1-R-C-S4) and B2 (S2-C-R-S3). Here, the transistors S1, S2, S3, and S4 are identical. Initially, S3 and S4 are closed and S1 and S2 are open. When a 5 V digital signal is sent from the Arduino microcontroller pin D9 to close S1 (and open S3), a high voltage Φ is applied across B1 and current begins to flow through it. Once the voltage is applied, the probes of a digital oscilloscope measure the voltage drop Φ_R across the resistor R, which decays exponentially as a function of time t. The voltage drop Φ_C across the capacitor is obtained by taking the difference between the applied and measured voltages:

$$\Phi_C = \Phi - \Phi_R = \Phi\left(1 - e^{-t/\tau}\right) \tag{4}$$

H Bridge Schematic

Signal	S1	S2	S3	S4	Result
D09 - OFF D11 - OFF	0	0	1	1	Capacitor Deactivated
D09 - ON D11 - OFF	1	0	0	1	Capacitor Activated
D09 - OFF D11 - ON	0	1	1	0	Capacitor Activated
D09 - ON D11 - ON	1	1	0	0	Capacitor Deactivated

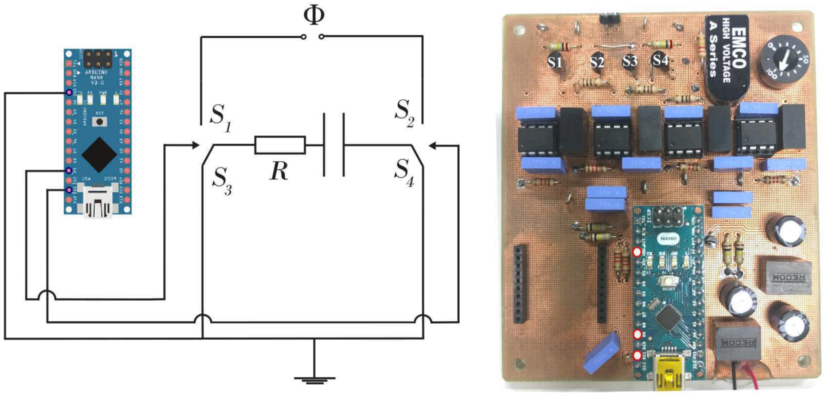

Figure S2: Capacitor charging and discharging is carried out with the aid of a customized H-bridge. The table provides the schematic of the H-bridge operation with regard to clutch activation. The H-bridge consists of two branches, B1 (S1-R-C-S4) and B2 (S2-C-R-S3), each comprised of the capacitor, a measurement resistor and two transistors. The transistors are activated by a 5 V signal sent from the Arduino Nano microcontroller. By default, S3 and S4 are closed.

where $\tau = RC$ is the time constant. The charging time t_c is calculated as the time required for $\Phi_C = 0.993$ Φ, which corresponds to $t \approx 5\tau$. The capacitor charging power P_c is dependent on the amount of current flow regulated by R.

$$P_c = \sum_i \left(\frac{\Phi_C(t_i)^2}{R} \right) \tag{5}$$

where i refers to the time index of voltage measurement. Power consumption is computed between t_0 when the voltage is applied and t_c when the capacitor is charged. Capacitor discharge can be instigated in two ways, either shorting the circuit or reversing the polarity of applied voltage for a specific period of time.

Short Circuiting

Capacitor discharge by short circuiting takes place by grounding the two ends of the branch B1 i.e., closing S3 and opening S1 by ceasing the D9 digital signal. The current flow through the circuit reverses and the voltage drop across the capacitor, Φ_C decreases exponentially.

$$\Phi_C = \Phi e^{-t/\tau} \tag{6}$$

Voltage Polarity Reversal

To decrease the discharge time of the charged capacitor, branch B1 is opened and branch B2 is closed simultaneously. Branch B1 is opened by closing S3 and opening S1 i.e., D9 stops sending the 5 V signal. Branch B2 is closed when D11 sends a 5 V digital signal, closing S2 and opening S4. Due to the reversal in voltage polarity, the voltage drop across the resistor increases to 2Φ as soon as B2 is closed. Thereafter, the resistor voltage begins to decay

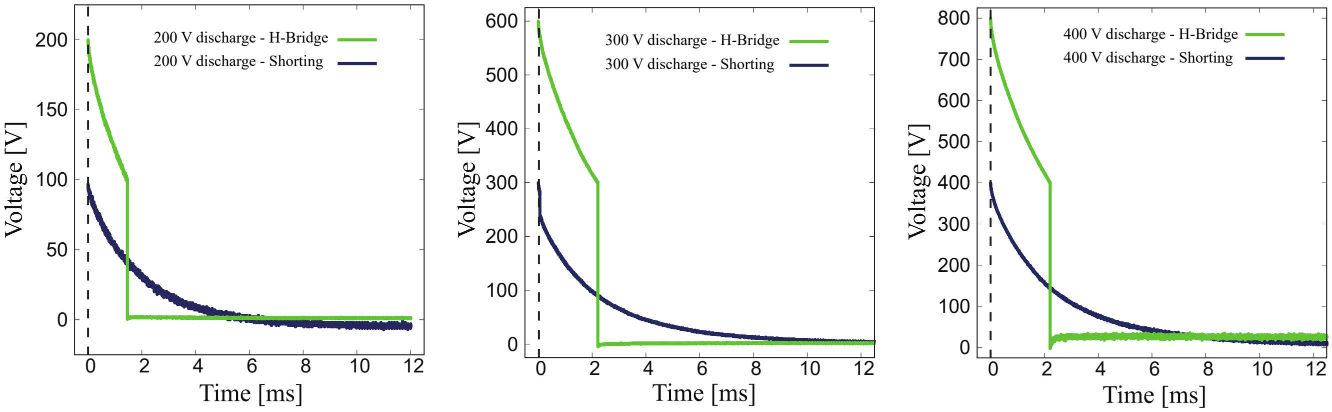

Figure S3: Clutch plate discharge characteristics observed measuring the voltage drop across the measurement resistor placed in series with the capacitor. The discharge characteristics are plotted for cases where the clutch was initially engaged at 100 V, 300 V, and 400 V, both by short circuiting and by reversing the voltage polarity using an H-bridge.

exponentially. The voltage drop across the capacitor Φ_C also decreases exponentially.

$$\Phi_C = \Phi e^{-t/\tau} - \Phi = \Phi \left(e^{-t/\tau} - 1 \right) \tag{7}$$

To discharge the capacitor, it is important that the branch B2 is short-circuited when the voltage drop across the resistor equals Φ i.e., the voltage drop across the capacitor is zero. The duration that Branch B2 is kept closed corresponds to the time required to charge the capacitor when a voltage Φ is applied. Branch B2 is short-circuited by ceasing the digital signal from D11, closing S3 and opening S2.

As shown in Figure S3, the time required to discharge the capacitor is smaller when the voltage polarity is reversed compared to when the circuit is shorted.

The discharge time t_d is calculated as time required for $\Phi_C = 0.07\ \Phi$. For both cases, the power consumption during discharge is calculated using the following expression:

$$P_d = \sum_i \left(\frac{\Phi_C(t_i)^2}{R} \right) \tag{8}$$

Here the power consumption is computed from t_n when the branch B1 is opened until t_d when the capacitor is discharged.

Scaling Law

Apart from the voltage Φ across the electrodes, the behaviour of the haptic device is governed by the amount by which the device is stretched. As shown in Figure S6, the length of the unconstrained knitted fabric and dielectric overlap in the reference (rest) configuration $\mathcal{B}_0'$ are ℓ_0 and L_0, respectively. When the module is stretched, the extensible knitted fabric length becomes ℓ and dielectric overlap length reduces to L. The width W of the clutch plate remains invariant in the deformation mapping $\chi_0 : \mathcal{B}_0' \to \mathcal{B}_0$. The current configuration $\mathcal{B}$ refers to the case

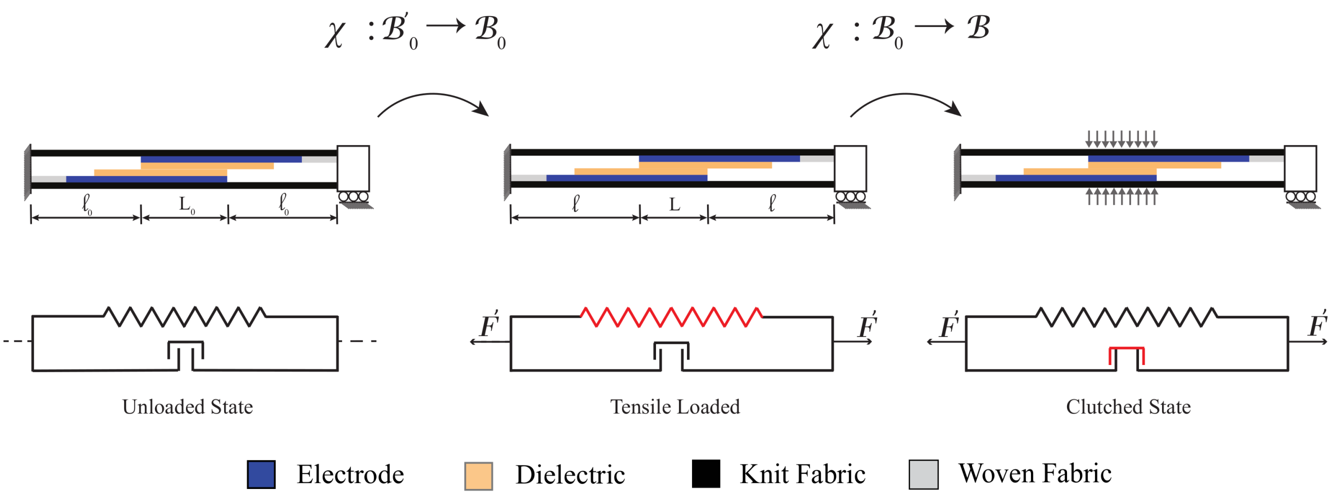

Figure S4: Haptic device kinematics - in the reference configuration $\mathcal{B}'_0$, the device is unloaded. When the device is subjected to a tensile load F', the device stretches like a spring and the area of dielectric overlap reduces. In the current configuration $\mathcal{B}_0$, voltage is applied and the clutch is engaged.

when voltage is applied and the clutch is engaged. We re-write Equation (3) in terms of the width W and the length L of dielectric overlap between the electrodes:

$$F = \frac{1}{2}\mu k W L \left(\frac{\Phi}{x}\right)^2 \tag{9}$$

From Equation (9), it is evident that F is related to the stretch $\lambda = \ell/\ell_0$ due to the reduction in overlap length. The length of the knitted fabric that is constrained by the woven fabric and the textile electrode remains invariant since they are inextensible i.e., $L = L_0 - (\ell - \ell_0)$. We define the dimensionless quantity $\zeta = L/L_0$ that can also be expressed as:

$$\zeta = 1 - (\lambda - 1)\frac{\ell_0}{L_0} \quad \forall \quad \lambda \,\epsilon\, \{1, \lambda_{max}\} \tag{10}$$

Here, λ_{max} is the maximum extensibility of the knitted fabric. Equation (9) and Equation (10) allow us to express the voltage in terms of prescribed quantities, provided that the stretch λ is known:

$$\Phi = \sqrt{\frac{x^2 F}{k \zeta W L_0}} \tag{11}$$

From Equation (3), we know that the maximum holding force of the clutch is dependent on both the overlap area, WL and the voltage applied, Φ. However, only the latter quantity can be controlled. Therefore, the applied voltage needs to account for the changing module length. This could be enabled by using a reliable stretch sensor that can determine the total device length for a changing electrical quantity such as capacitance or resistance. Denoting the total device length as $L_t = L + 2\ell$, we can obtain an expression for the stretch λ from Equation (10) in terms of given or measured parameters:

$$\lambda = \left(\frac{L_t - L_0}{\ell_0} \right) - 1 \tag{12}$$

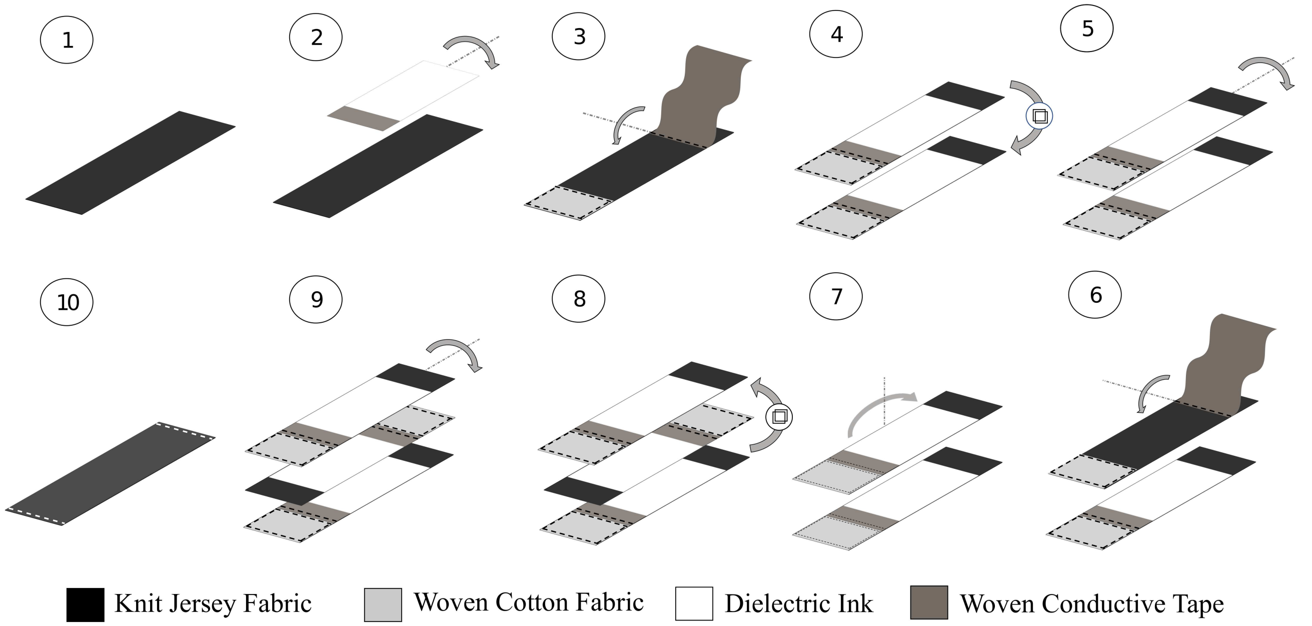

Figure S5: Fabrication process to develop the haptic device with two clutch pairs. (1) The substrate knitted fabric is laser cut into rectangular pieces. (2) Copper plated polyester fabric electrodes are coated with a dielectric ink using a thin film applicator. (3) The posterior surface of the electrode is stitched onto the knitted fabric substrate along the end of the coated surface. The electrode is folded to cover the stitched seam and the coated surface is aligned in parallel with the knitted substrate. (4) The uncoated portion of the coated electrode face is stitched onto the substrate. A rectangular woven fabric is stitched onto the substrate surface extending from the uncoated portion of the electrode to the substrate edge. The entire sample is replicated. (5) The first sample is rotated about the longitudinal axis and the unstitched surface of the knitted fabric is used as a substrate. (6) Steps (3) and (4) are repeated, with the exception that the sample is not replicated. (7) The first sample is rotated about the vertical axis until the unstitched portions of the knitted substrates in both samples are at opposite ends. (8) The second sample is replicated. (9) The third sample is rotated about its longitudinal axis until the dielectric surfaces of the first and third samples are in planar contact. (10) Finally, the three samples are stitched along the wider edges. To develop the haptic device with multiple clutch pairs, steps (2)-(4) are repeated.

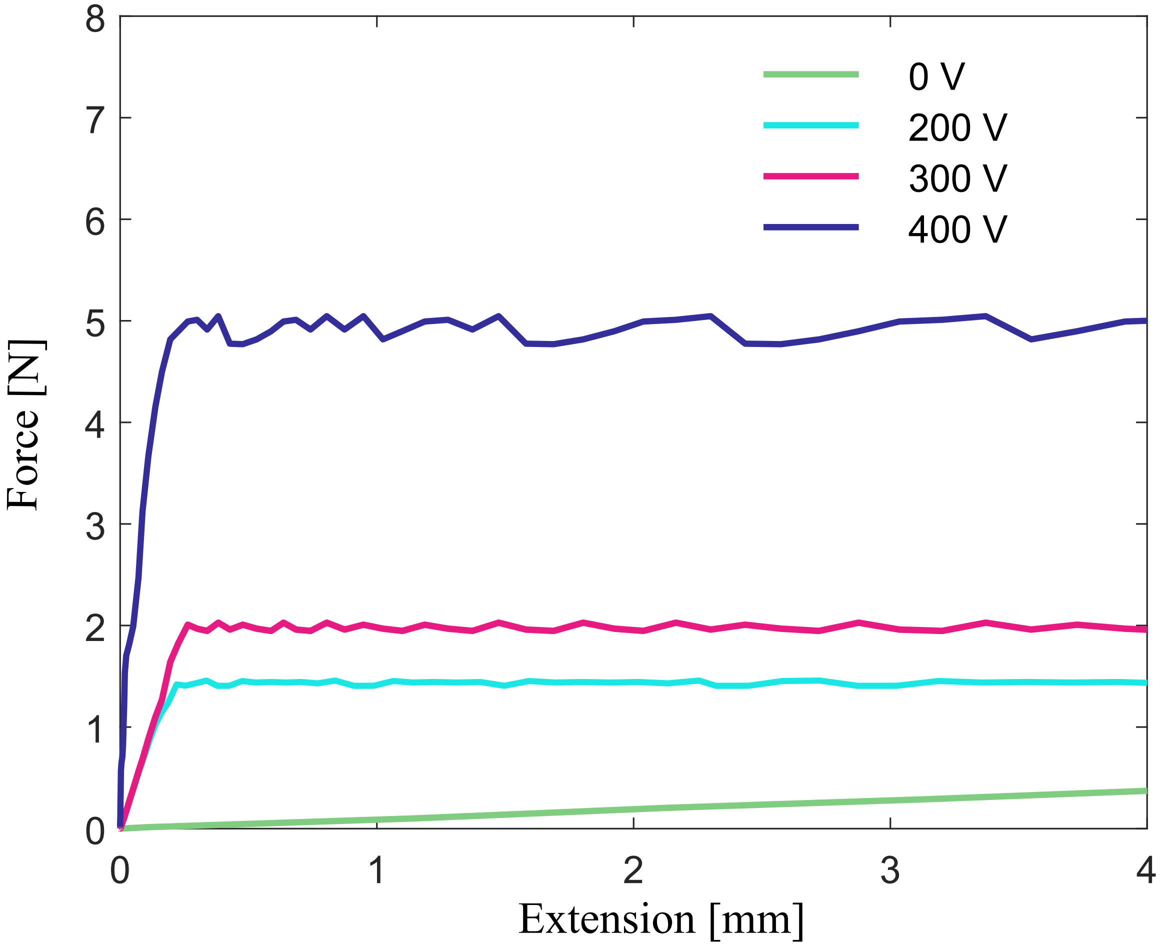

Figure S6: Holding force measurements for a pair of clutch plates with a dielectric overlap area of 50 × 60 mm^2 when the device is operated at 0 V, 200 V, 300 V, and 400 V and loaded at 10 mm/s. As one can observe from the plots, the clutch plates are fully engaged when the device undergoes an extension that is negligible in value compared to the dimensions of the device.