

# Layer Jammers in a Simulated Environment Soft Haptic (S.E.S.H.) Glove

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**Abstract**— The field of haptics is constantly seeking better wearable kinesthetic haptic devices. Devices that can render a wider range of impedances and transition from high transparency to high stiffnesses while also being compliant. Such kinesthetic haptic devices are desirable for VR/AR as well as telerobotic systems. We draw inspiration from the field of soft robotics and present a layer jamming based approach to wearable haptic devices. In this work, we explore vacuum-based layer jammers, characterize their jamming force versus key characteristics, and explore the design rules regulating their performance. We present a theoretical analysis, comparing the behavior of our layer jammers to results from classical beam theory, and we select one motif from which to build a demonstration device. We present a haptic glove consisting of layer jammers that provide kinesthetic haptic feedback. We demonstrate our proposed soft haptic glove through a Unity-based virtual environment, in which a user can grasp objects through our jamming glove which resists user motion.

**Keywords**—*haptics, layer jamming, transparency,*

## I. INTRODUCTION

Wearable kinesthetic haptic devices have been used in various human-robot interaction applications. Many kinesthetic haptic devices are attached to a fixed point in the environment (i.e. grounded) [1] to apply forces to a user. Recently, wearable devices have emerged that are attached only to a user (ungrounded) [2]. Ungrounded devices, such as haptic gloves, provide sensory feedback either to individual fingers or to the hand as a whole (gripping/vibrating) but cannot provide ground force resistance (e.g., simulating pushing against a wall) as they are not mounted to a grounding surface. These devices have found use in teleoperation [3] and medical rehabilitation [4]. Using haptic devices for virtual reality [5] is especially promising.

Within these haptic devices, the method of actuation has proven crucial to performance and effectiveness. An early haptic device, SPIDAR-MF [6] used DC Servo Motors, which can have safety risks, complex design or form factor, and low transparency (the ability to be deflected with low force when not actuated so the device appears “transparent” to a user). Other examples include magnetorheological fluid [7] and pneumatic pistons [8] which have controllable force but suffer from large system volume. Other approaches explore hydraulic artificial muscles [9] and dielectric elastomers [10] which offer creative approaches towards actuation, but drawbacks include electrical safety, high cost, and difficulty of fabrication. Another approach is using actively controlled brakes which can provide resistive loads in both grounded [11] and ungrounded devices [12], [13]. Typically, devices with passive actuators such as brakes have a high inertia and low transparency or need to use complex control methods to compensate for the non-linearities of the brake.



Fig. 1. A photograph of the S.E.S.H. glove with a detail diagram of a layer jammer.

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The emerging field of soft robotics presents potential options for actuation, braking, and sensing in wearable haptics. Soft robots can be built from intrinsically soft materials such as low-modulus elastomers [14] or from traditional materials in novel form factors to exhibit overall flexible behavior [15]. We utilize the former approach in this work (Fig. 1). This field gives us actuators that can provide resistive loads while also having a low reflected inertia. One compelling technology for haptics is jamming, in which a media of discrete components moves freely within an enclosed membrane, but “jams” in place when exposed to vacuum. Jamming media can be categorized into zero-, one-, and two-dimensional systems. *Zero-dimensional jammers* contain granular media (approximating zero dimensional points). When the enclosing membrane is pressed against an object, the grains freely displace, conforming to the shape of the object [16]. When vacuum is applied, the granular media is “jammed”, locking the object in its grasp until vacuum is released. *One-dimensional jammers* contain a bundle of flexible but inextensible fibers aligned lengthwise. The enclosed bundle of fibers is able to bend freely, wrapping around objects [17]. Vacuum jamming locks the fibers in place, yielding a high-modulus rod of the desired shape. *Two-dimensional jammers*, as developed in our 2017 work [18] and in Narang’s 2018 work [19], contain flexible sheets. In these systems, stacked layers of 2D sheets such as paper or fabric (Fig. 2A) are able to bend and slide relative to one another before they are jammed in place (Fig. 2B) upon exposure to vacuum.

In all of these systems, a low-modulus system deforms to a desired shape, then is jammed via exposure to vacuum, resulting in an increase in impedance. Jamming systems can be used in robotic grippers to cause force closure [16], in soft robots to vary modulus in actuators, and in wearable devices to simulate virtual environments [20]. There has been work with soft robotic gloves for virtual reality medical applications [21], and teleoperation [22]. Joint impendence with layer jamming has been investigated [20] but quantitative analysis of underlying variables governing performance has yet to be undertaken. We present a layer jammer, characterizing key variables and exploring the design rules governing their performance. We use this jammer in a demonstration of a Simulated Environment Soft Haptic (S.E.S.H.) glove. We believe that this work provides a foundation for robust predictive design to obtain desired performance in future VR/AR haptic devices.

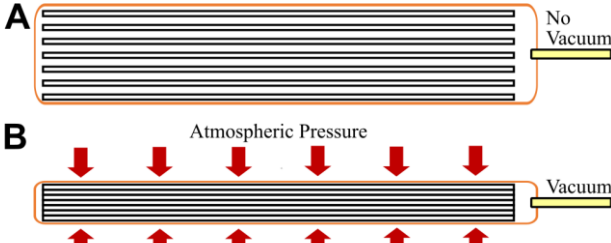


Fig. 2. A Diagram of the cross-section of jammer. A shows jammer vacuum is applied. B shows jammer after vacuum is applied.

There is a need in the wearable haptics community for a new method of force reflection, which allows the user to immerse themselves in a new reality without the use of complex, bulky, expensive brake systems.

We present a characterization of layer jammers and a design for a haptic feedback glove that can simulate environments as a demonstration of these jammers.

The key contributions of our work are as follows:

1. Systematic analysis of design rules governing layer jamming for haptics, relating these rules to first principles found in beam theory.
2. Characterization of the jammers for parameters: braking force, free space rendering transparency and effect of wear on braking force, and development of a system to measure these parameters.
3. Demonstration of a jammer design and fabrication method using readily available, low-cost components yielding a range of jammers with predictable performance.
4. Demonstration of a prototype haptic glove integrated with a virtual reality simulation.

## II. METHOD

The SESH glove consists of a modified work-glove, instrumented with five jammers and one bend sensor. The system uses an Arduino microcontroller to communicate with a Unity-based virtual environment. Layer jammers are a lightweight and low-cost way to achieve a soft brake, well suited for force reflection in haptic devices (Fig. 3). The jammer presented in this work can be fabricated of simple materials in under ten minutes at a cost of less than 20 cents. Printer paper was selected as it provides a high ratio of jammed to unjammed slipping force. Materials with higher friction (sand paper) retain friction force even when no vacuum is applied, reducing transparency. 1 mil PVC is selected as it shows little resistance to force. Both materials are inexpensive and readily available.

### A. Jammer Design

The following steps describe our fabrication method for our 40-sheet jammer, with sheets of 104 mm x 30 mm. Other configurations described in this work were fabricated using a similar procedure.

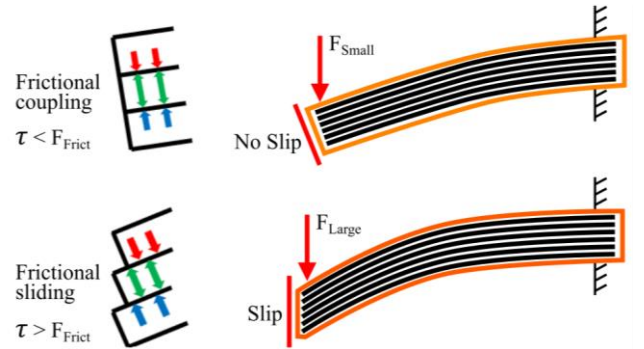


Fig. 3. A diagram showing the difference between frictional coupling and frictional sliding.

#### Assembly Procedure:

- Cut 40 sheets of 20 lb. printer paper (Boise Inc. Boise ID, USA) to 104 mm by 30 mm.
- Cut two sheets of PVC thermoplastic (1 mil shrink-wrap bag) large enough to enclose the sheets in step 1 (~115 mm x 40 mm) and place the paper sheets between the sized PVC sheets.
- With a film sealer (Yeler PFS-100, Runyii, China), seal the long edges and one short edge of the assembly from step b.
- Instrument the remaining open edge with 3 mm OD tubing. Seal the edge with a silicone gasket of Ecoflex 00-30 (Smooth-On, Macungie PA, USA). Sandwich the assembly between two layers of acrylic and screw together with M2 screws.

Without external pressure applied to the jammer, there is little friction between the sheets, thus they move freely relative to one another (Fig. 2A), allowing the jammer to bend with little resistance, similar to a 40-sheet magazine. When vacuum is applied to the jammer, the sheets are pressed against one another from outside atmospheric air pressure. The pressure creates a normal force between the sheets (Fig. 2B), making the jammer appear stiff under external load.

During jamming, external load causes little deformation of the stiff jammer (Fig. 3A) as the individual sheets resist slip due to frictional coupling ( $F < F_{slip}$ ) where  $F$  is as shown in Fig. 4, and  $F_{slip}$  is the force required to overcome friction, causing the pages to slip relative to one another. When the applied load is sufficiently large to overcome the frictional coupling ( $F = F_{slip}$ ), the sheets inside the jammer will slip (Fig. 3B) relative to one another. We call this transition the slipping point of a jammer. In this state, the layers slip to a new stiff state and will remain in that state until a new force causes frictional slip or until vacuum is released. Using classic Euler-Bernoulli beam theory from mechanics of materials, we explore the contributions that system parameters have on the slipping point, using variables as shown in Fig. 4:

$$\sigma_{slip} = m c / I \quad (1)$$

Where  $\sigma_{slip}$  is the point at which slip occurs, and  $c$  is the distance from the neutral axis. For a rectangular cross section:

$$c = h/2 \quad (2)$$

Moment at the base due to a force  $F$  is:

$$m = F \times L \quad (3)$$

And for a rectangular cross section, second moment of inertia is:

$$I = b h^3 / 12 \quad (4)$$

Combining Eq. (1), Eq. (2), Eq. (3), and Eq. (4)

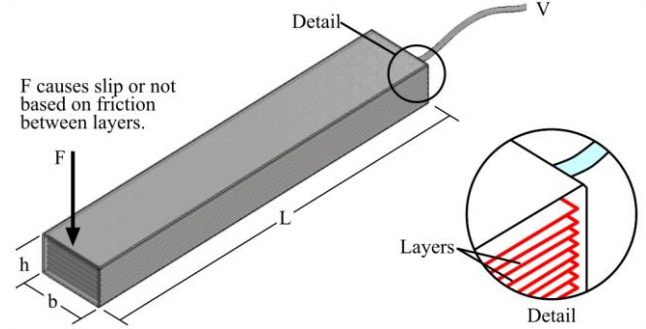


Fig. 4. Variables evaluated. Applying a force ( $F$ ), evaluate are the effects of varying height ( $h$ ), width ( $b$ ), distance from base to point of force application ( $L$ ), and vacuum applied ( $V$ ).

$$F_{slip} = \frac{\sigma_{slip} b h^2}{6L} \quad (5)$$

Where  $\sigma_{slip}$  is determined by the friction properties between layers, and vacuum applied.

#### B. Jammer Testing

To validate the correlation between our jammers and beam theory, we performed an experimental investigation using a testing assembly shown in Fig. 5. This assembly contained a vertical translation stage, (item 1 in Fig. 5), with a clamp to hold a jammer. This jammer (item 2 in Fig. 5) was translated onto a scale (item 4 in Fig. 5) which was used to measure  $F_{slip}$ .

**Test 1:** We evaluated jammers with sheet counts from 20 sheets to 50 sheets, each 104 mm by 30 mm, to evaluate the effect of sheet count (similar to  $h$  in eq. 5). We evaluated each jammer in its jammed state (vacuum applied) to

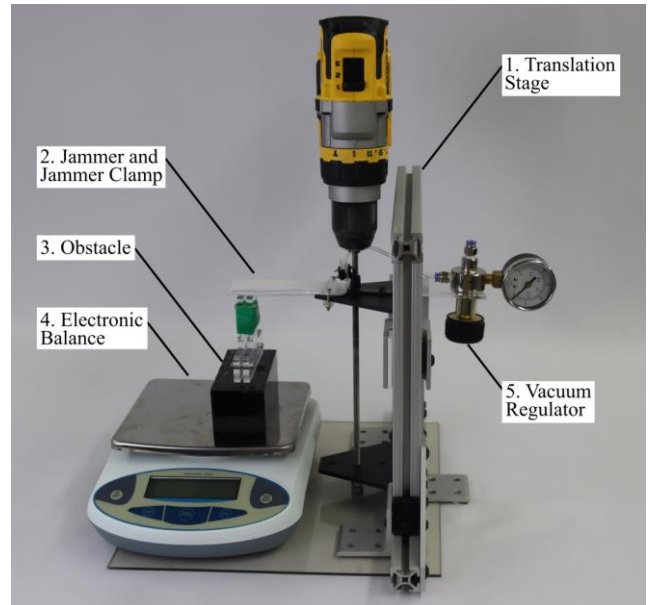


Fig. 5. A photograph of the testing assembly used to test jammer slip force. 1. Vertical Translation Stage to move jammer relative to stationary balance. 2. Jammer and jammer clamp mounted to Translation Stage. 3. Obstacle to control point of force application. 4. Electronic Balance to record force from jammer. 5. Vacuum Regulator to control jammer stiffness.

determine  $F_{slip}$ . In order to evaluate transparency (the reflected inertia when no vacuum is applied) we evaluated each actuator in a free (no vacuum state). We evaluated quantity three of each jammer using the following procedure:

*Test Procedure:*

- If the jammer is new, apply vacuum, apply force  $F$  until slip occurs. Release vacuum and repeat this procedure ten times as break-in cycles.
- With vacuum applied, lower the jammer onto the obstacle until slip. Record this value ( $F_{slip}$ ) from the scale.
- Raise the jammer. Release vacuum. Re-apply vacuum.
- Perform the lowering and raising procedure described above three times for each jammer in each configuration.

*Test 2:* We evaluated the effect of width ( $b$  in eq. 5) on slipping force of jammers. In this evaluation, we used jammers with 40 sheets, 104 mm by  $b$  mm, varying  $b$  from 20 mm to 45 mm. For each of these evaluations, we tested three jammers of each configuration and tested each three times using the procedure described above.

*Test 3:* We evaluated distance from the base of the jammer ( $L$  in Eq. 5) using jammers with 40 sheets of 154 mm by 30 mm. Rather than fabricate jammers of various lengths, we used the same configuration for each and varied the point of load application ( $L = 50$  mm, 100 mm, and 150 mm). This method was selected as we believe that it is likely that jammers will have loads applied in regions other than at the distal tip. We evaluated three jammers in each point of application and tested each three times using the procedure described above.

*Test 4:* To evaluate the effect that vacuum level has on slip force, (anticipated to be proportional to  $\sigma_{slip}$  in eq. 5), we evaluated three jammers, with 40 sheets of 104 mm by 30 mm, varying vacuum from -80 kPa to -20 kPa (gauge). We tested each using the test procedure described above.

*Test 5:* To test repeatability, we tested a jammer using the procedure described above for twenty cycles to find the relationship between cycle count and slip force. Jammer

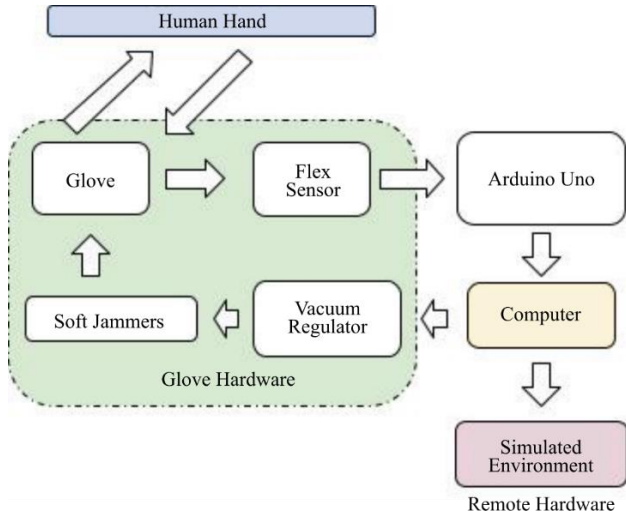


Fig. 6. Diagram showing the SESH glove system.

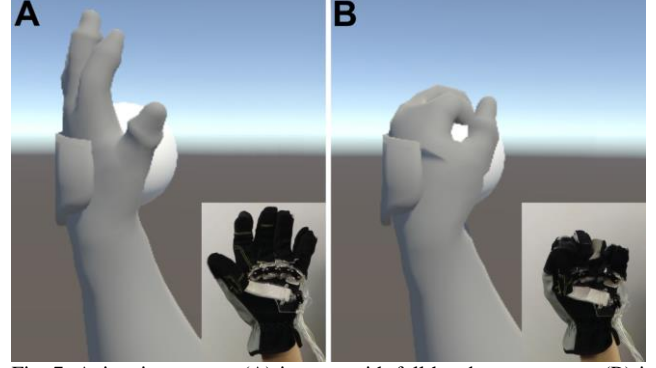


Fig. 7. Animation output. (A) is open with full hand transparency, (B) is closed grasp with jammers activated.

performance varied during the first eight cycles. Thus, we determined that ten “break in” cycles were required prior to use. This is the point at which a crease is formed in the individual sheets of the jammer, ensuring repeatable results.

### C. Glove Design

We developed a simulated environment soft haptics (S.E.S.H.) glove to demonstrate layer jammers' capabilities in a variety of applications. This glove was to take advantage of relationships discovered to allow a user to feel a computer-generated environment. We defined our design guidelines as shown in Table 1.

TABLE I. DESIGN RULES FOR JAMMERS

Table 1	Design Rules
Gesture Recognition	Sensing the motion of fingers
Transperency	Friction and interior force should be less than the user's detection threshold on force magnitude.
Force Refleciton	Apply resistant force on fingers sufficiently large to simulate stiff objects (4N)
Wearability	The method of mounting the glove to the user's hand

The SESH glove (Fig. 1) consisted of five jammers (each with 40 sheets of 30 mm x 104 mm) mounted to custom attachment hardware and sewn to a glove. The mounting hardware in the palm of the glove consisted of an acrylic plate which houses the jammer bases, allowing pivotal rotation for the thumb. This plate mounting style allows the jammers to act as cantilevers with jamming direction in the plane of actuation of each finger. A flex sensor (Adafruit, New York, NY. USA) is sewn to the dorsal surface of the glove's index finger to track finger flexion.

The flex sensor is connected to an Arduino Uno microcontroller, which is connected to custom software to interpret sensor data (Fig. 6). The software is connected to a vacuum regulator which applies vacuum on demand to emulate resistance in gripping. The glove uses palm-mounted layer-jammers connected to the vacuum regulator to reflect resistant force to simulate objects.

To simulate an environment, the SESH glove is connected to a computer program which allows the user to see the

simulated environment that they are feeling with the glove. To create this program, we used Unity 2024 game engine (Unity Technologies, San Francisco, CA. USA) to develop custom software which receives data from the integrated sensor on the glove and visualizes it to a hand model. As shown in Fig. 7, the animation shows the user navigating the environment that the glove is reproducing (See supplementary video).

#### D. Glove Testing

For evaluation, the S.E.S.H. glove was instrumented with a force transducer (Force Sensitive Resistor, Interlink Electronics, Camerillo, CA. USA) at the distal end of the

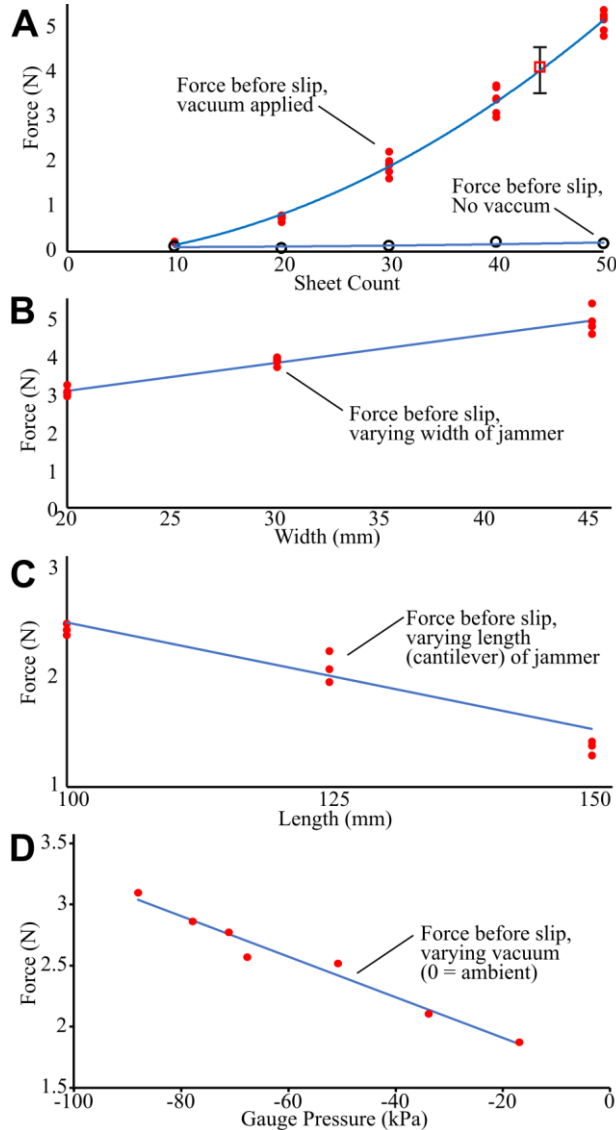


Fig. 8. Force response ( $F_{slip}$  eq. 5) of jammers. (a) Force vs number of layers inside jammer (sheet count) ( $\propto h$  eq. 5). All tests with 30 mm width, 104 mm length, -65 kPa vacuum. Glove test results square with range bar. (b) Force vs sheet width ( $b$  eq. 5). All tests with 40 sheets, 104 mm length, and -65 kPa vacuum. (c) Force vs actuator length ( $L$  in eq. 5). (d) Force vs vacuum (gauge pressure) ( $\propto \sigma$  eq. 5). All tests with 40 sheets, 30 mm width 104 mm length.

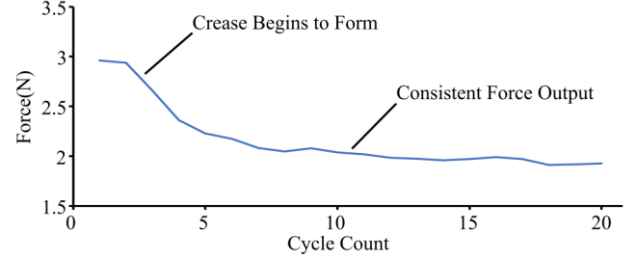


Fig. 9. Force output of a single jammer. After initial 8 break-in cycles, force is consistent. All tests at -65kPa (gauge).

index finger, between the glove and the wearer's finger. This allowed us to measure the force between the distal tip of the index finger and the jammer. Vacuum was applied to the jammer, the wearer flexed the index finger, and force required for slip was measured. This procedure was conducted twelve times.

### III. RESULTS

#### A. Analyzing Jammers

Using the processes described in Methods, results are presented (Fig. 8) showing the effects of varying parameters of jammers. The trend line for sheet count vs slip force (Fig. 8A) is second order. As  $F_{slip}$  is expected to increase with the square of thickness (eq. 5), correlating with beam theory. Unjammed slip force is also presented in Fig. 8A and does not rise above 0.2 N for any configuration tested. This yields a transparency ratio ( $F_{slip}$  for jammed/unjammed) from 2x for ten sheets for 28.4x for fifty sheets.

Initial cycle testing on new (never used) jammers had a higher slip force than those that had undergone numerous cycles. Our testing demonstrated that slip force decreased for eight cycles, then remained relatively constant (Fig. 9). Thus, we conducted ten "break in" cycles prior to experimenting with any jammers. During break in, a physical crease has been formed in the papers in the layer jammer.

#### B. Analyzing Glove

The force sensing resistor test yielded slip force of  $3.96 \text{ N} \pm 0.5 \text{ N}$ . With 44 sheets at 104 mm x 30 mm, This is within 3% of the 3.86 N predicted by the second order trendline and is highlighted in Fig. 8A with a red square and range bar.

### IV. DISCUSSION

We have presented a vacuum based layer-jammer as well as a layer jamming gripper for use in haptic devices. We characterized the jammers, analyzing the effect of design parameters (Sheet count, width, length, and vacuum gauge pressure) on overall slip force (max force that can be applied prior to jammer slipping). Using the resulting device, we presented a Simulated Environment Soft Haptic (S.E.S.H.) glove and used it in a Unity 2024 based virtual reality environment, simulating grabbing a ball. The jammers provided four Newtons of blocking force in the finger-sized configurations tested. When vacuum was released, force

dropped to near zero, for realistic transparency. Maximum slip force  $F_{slip}$  can be adjusted by varying the key parameters evaluated. This work enables future jammers to be designed with quantitative metrics known a-priori, varying parameters during the design stage to yield devices with desired performance characteristics. Future work will be needed to characterize other materials in jamming (using jamming layers of other materials such as fabric, polyimide or other plastics, or paper with different surface properties), and multi-dimensional actuation (for out-of-plane actuation). These jammers also have the potential to provide non discrete levels of stiffness by combining multiple jammers into one actuator and varying the pressure levels of vacuum. Further exploration of these jammers in this context will pave the way to make these jammers an attractive option for a soft haptic actuator. These jammers provide a low-cost, low-impedance actuator option for compliant and wearable haptic devices.

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