

Healable thermoplastic for kinesthetic feedback in wearable haptic devices

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ABSTRACT

The word “haptics” refers to technologies designed to stimulate the tactile and kinesthetic senses. Kinesthesia—the sense of motion—is triggered by imposing forces upon the joints, tendons, and muscles to recreate the geometry and stiffness of objects, as may be useful in physical therapy or virtual reality. Here, we introduce a form of kinesthetic feedback by manipulating the mechanical properties of spandex impregnated with a thermoplastic polymer. Heating or cooling this textile-thermoplastic composite just above or below its glass transition temperature (T_g) dramatically changes its mechanical properties (corresponding to a decrease in storage modulus from 36 MPa to 0.55 MPa). In the form of a glove, the composite can also be healed after inadvertent overextension in its stiffened state by heating it above its T_g . When fitted with thermoelectric devices for active heating and cooling, the flexible or stiffened state of a glove can be perceived by human subjects. As an example of a human-machine interface, the glove is used to control a robotic finger. When the robotic finger makes contact with a wall, a signal is sent to thermoelectric devices in the glove to cool (stiffen the finger) and thus provide kinesthetic feedback to the user.

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1. Introduction

Kinesthesia refers to the sense associated with moving parts of the body. This sense of self-awareness is enabled by mechanosensory neurons located in muscles, joints, and tendons [1]. A wearable device that manipulates the kinesthetic sense could have a number of applications in virtual and augmented reality, education, training, and physical therapy. For example, patients experiencing loss of sensation as a result of injury or stroke may require rehabilitation in the form of kinesthetic appliances [2,3]. Here, we introduce a wearable textile-thermoplastic composite in the form of a glove that exhibits changes in stiffness when actively cooled or heated. Changes in the mechanical properties of the material can be perceived by human subjects. This is the first demonstration of manipulation of the glass transition in polymers to produce kinesthetic feedback in a wearable device.

Many technologies known broadly as haptics have been developed to engage both the tactile and kinesthetic senses. Some approaches taken to engage the kinesthetic sense include the use of inertial forces produced by motors to impede a subject's motion [4]. Other devices provide kinesthetic feedback through pneumatic actuation [5–7], pulley systems [8], or magneto-rheological fluids [9]. The large pumps and motors required to drive traditional haptic devices can be obtrusive and suggest the need for a new class of sensory and kinesthetic devices which exploits the intrinsic properties of the materials from which the devices are made. One possible strategy to engage the kinesthetic sense that does not in principle require bulky ancillary equipment is the use of variable stiffness materials, which exhibit changes in mechanical properties as a result of a thermal transition. For example, Rich et al. described a conductive thermoplastic elastomer composed of a copolymer of poly(propylene) and poly(ethylene) containing a percolated network of carbon black particles [10]. This material was heated using resistive heating to initiate melting at 73 °C and a concomitant drop in stiffness as measured by a change in elastic modulus (10 MPa to 0.7 MPa) [10]. Composite foams made of eutectic mixture of tin,

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indium, and bismuth and a silicone elastomer have also been shown to undergo a large change in elastic modulus (3 MPa to 0.1 MPa) when the metallic component melted at 62 °C [11].

Shape-memory materials (e.g., metallic alloys [12] or polymers) [13,14] that switch from a deformed state to a predetermined geometry are another strategy to producing kinesthetic feedback, although these studies did not investigate the ability of human subjects to perceive the change in stiffness. Solazzi et al. show that shape-memory alloys composed of nickel and titanium can be used as actuators to provide tactile feedback through displacement of the skin, but such devices do not generate sensations in the joints and tendons [12]. These materials exhibit large changes in stiffness as well as changes in geometry when thermally activated, while remaining solid [15]. Another thermal transition—advantageous for a wearable device because it too does not involve wholesale melting of the material—is the glass transition of pure or plasticized polymers. This transition, marked by the temperature T_g , corresponds to a transformation of a polymeric material from a rigid, glassy state to a rubbery state in the solid phase [16] (which can be measured by a precipitous drop in storage modulus).

Variable stiffness materials have been developed for applications in the field of soft robotics [17,18], a sub-field of robotics concerned with compliant materials and actuators. When variable stiffness materials are combined with actuators, it is possible to change the shape of a robotic “limb” when heated while being able to support a load once cooled. In the context of a wearable device (Fig. 1), the T_g can be tuned to be close to the temperature of the skin: toggling the temperature just above or just below the T_g by a few degrees can trigger a transition between flexible and stiff while the change in temperature is small and, ideally, minimally perceptible. Affecting the rubbery vs. glassy state of a solid polymer can be treated as a passive form of actuation that provides tunable resistance to motion of a body part. A haptic device that interfaces with the kinesthetic sense would ideally exhibit short transition times between soft and stiff states, and not require bulky external equipment to operate as these devices may impede natural motion of the hand. In this paper, we explore whether it is possible to use the glass transition of a textile-thermoplastic composite material to interface with the kinesthetic sense of human subjects and characterize its thermomechanical properties to provide a foundation from which to design future materials.

2. Material selection

Polymethacrylates have a T_g that can be tuned by varying the length of the side chain (the longer the side chain, the lower the

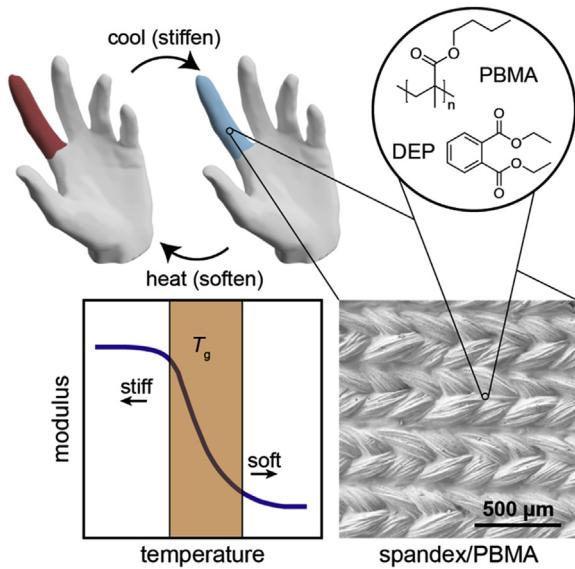


Fig. 1. Schematic drawing illustrating the use of variable stiffness material to produce kinesthetic feedback. Active heating and cooling of spandex/PBMA/DEP above and below the T_g causes a change in stiffness of warp-knit spandex infiltrated with PBMA/DEP, shown in the scanning electron microscope (SEM) image. Concept of tuning the T_g of PBMA to be near the temperature of the ambient environment (23 °C) or the skin (32 °C) generates large changes in stiffness with minimal changes in temperature.

T_g) and can be modified further (decreased) with the use of a plasticizer. We chose poly(butyl methacrylate) (PBMA) as the thermoplastic polymer and diethyl phthalate (DEP) as the plasticizer because this combination can be tuned to exhibit a T_g near the surface temperature of the skin. Solid PBMA is a rigid glassy polymer at room temperature and must be dissolved (e.g., in cyclohexane) or heated to high temperatures for it to be molded. To make this material compatible with wearable applications, 22 wt% PBMA and DEP were incorporated into warp-knit spandex, a polyether-polyurea copolymer. Knitted spandex textiles easily stretch, fit, and conform to the human body and are thus suitable substrates for wearable electronics [19,20]. Textiles made of functional materials are also amenable to scale-up manufacturing where traditional fabrics can be post-processed [21] or fibers made of functional materials can be incorporated during the weaving and knitting processes [22].

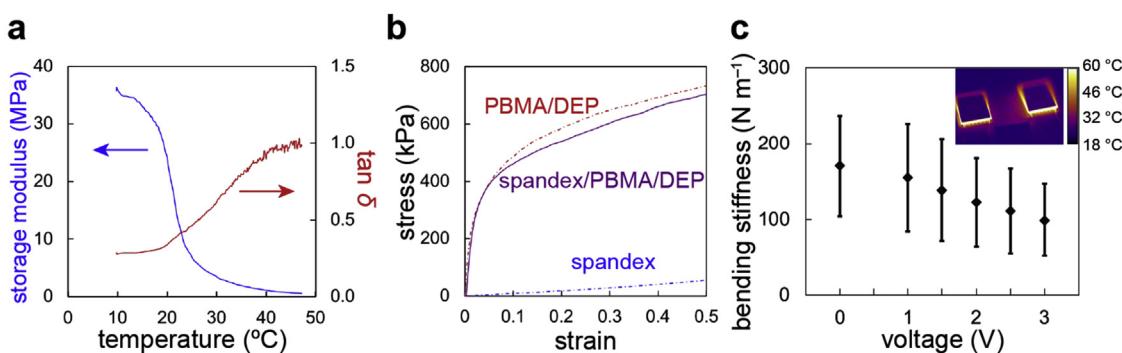


Fig. 2. Mechanical properties of spandex/PBMA/DEP composites. (a) Dynamic mechanical analysis of spandex/PBMA/DEP: blue line shows the variation in storage modulus and red line shows the variation in $\tan \delta$ (i.e., the ratio between loss modulus and storage modulus) as functions of temperature. (b) Tensile stress–strain curves comparing spandex (dotted blue line), pure PBMA/DEP (dotted red line), and the spandex/PBMA/DEP composite (solid purple line) at 10 mm min⁻¹. (c) Plot of bending stiffness in N m⁻¹ as a function of applied voltage across thermoelectric devices during active heating above room temperature. (c, Inset) Thermal image of the spandex/PBMA/DEP composite near skin temperature (32 °C) between two thermoelectric devices used to heat the sample (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

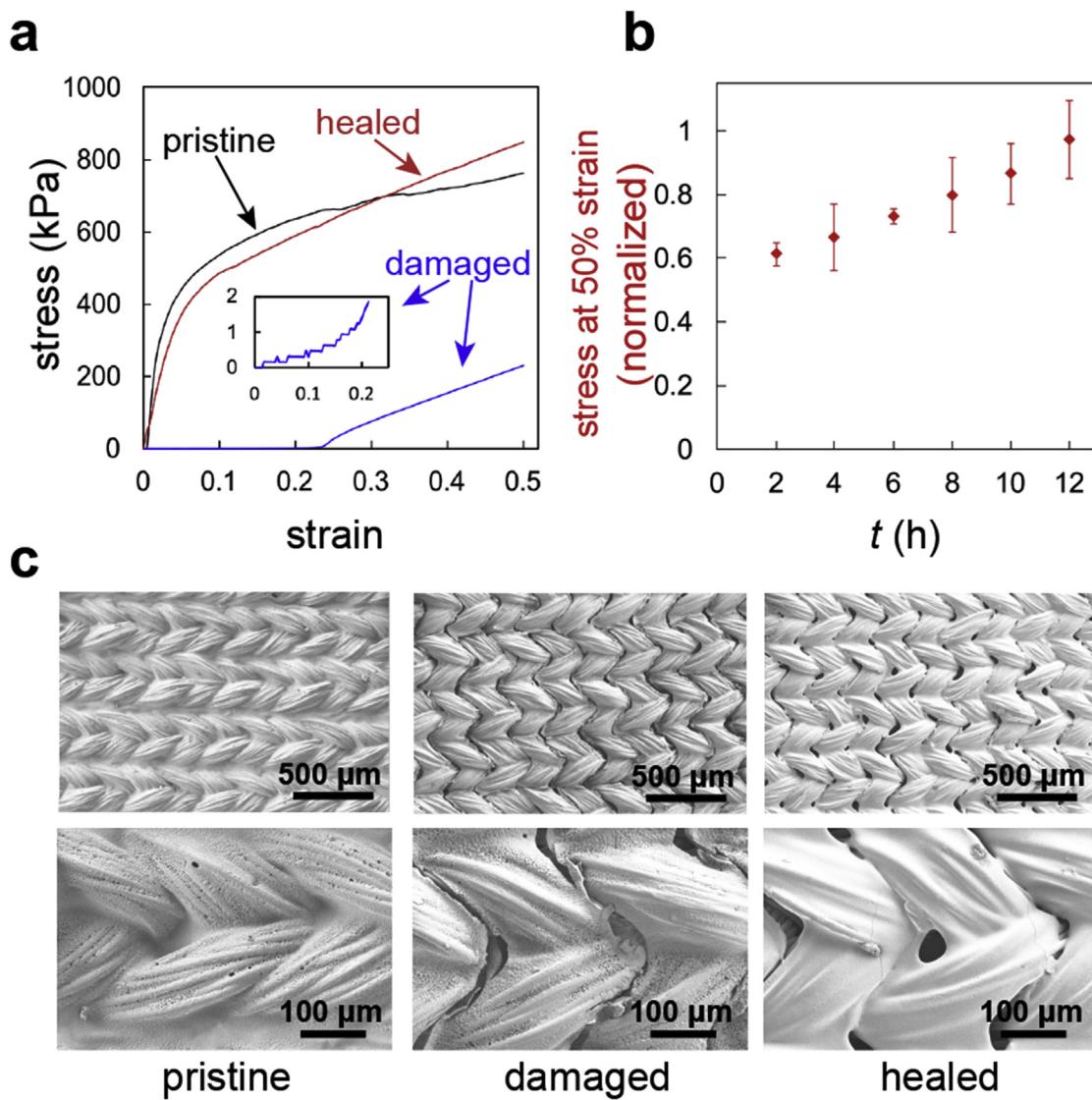


Fig. 3. Failure and healing of spandex/PBMA/DEP composites. (a) Stress–strain curves of (black) “pristine,” (blue) “damaged,” and (red) “healed” spandex/PBMA/DEP samples. (b) Normalized recovery of stress at 50% strain after heating at 90 °C for different amounts of time. (c) SEM images of “pristine,” “damaged,” and “healed” spandex/PBMA/DEP samples (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

3. Mechanical properties of spandex/PBMA/DEP composites

Given that the spandex/PBMA/DEP composite would be subjected to numerous mechanical stresses when worn as a kinesthetic device on the hand, we next sought to understand the mechanical properties. We began by performing dynamic mechanical analysis of spandex/PBMA/DEP composites to characterize the T_g as well as the range of stiffnesses that can be achieved in the range of temperatures used to heat and cool the composite. The spandex/PBMA/DEP exhibits a change of nearly two orders of magnitude in storage modulus (36 MPa to 0.55 MPa) over the tested temperature range (9.7 °C to 47 °C) (Fig. 2a). Based on previously reported specific heat capacities of PBMA (using differential scanning calorimetry), we estimated that it would require $\tilde{1}0\text{ mJ g}^{-1}$ to heat the composite from 20 °C to 35 °C [23]. We then performed stress–strain measurements on spandex/PBMA/DEP and solid PBMA/DEP. The spandex/PBMA/DEP composite ($E=14\text{ MPa}$) and PBMA/DEP ($E=18\text{ MPa}$) exhibited nearly identical mechanical behavior and showed elastic behavior at relatively small strains ($\varepsilon=1.5\text{--}1.6\%$) whereas knitted spandex ($E=99\text{ kPa}$) exhibited purely elastic behavior over the range of tested strains

($\varepsilon=0\text{--}50\%$ at 10 mm min^{-1}) (Fig. 2b). The materials used in this study became stiffer as the strain rate was increased; this behavior is typical of polymers [24] (Figure S1). Spandex/PBMA/DEP composites also showed anisotropic mechanical properties that depended on the orientation of the knit relative to the direction of applied strain (Figure S2). Uniaxial tensile tests (Fig. 2b) suggested that the stiffness of spandex/PBMA/DEP composites was due to the PBMA/DEP thermoplastic, which was in its glassy state at the temperature tested.

Although these tensile tests are useful in quantifying the mechanical properties of the spandex/PBMA/DEP composites, a more relevant metric in applications involving wearable devices is bending stiffness (N m^{-1}) because the material would undergo both tensile and compressive strain during a grasping motion when worn as a glove. Bending stiffness is a measure of the amount of force required to displace a material by a unit of length and it is a function of both the elastic modulus and geometry of the specimen. We performed a three-point bending test (Figure S3 for setup) to measure the stiffness of spandex/PBMA/DEP composites at small deflections (0.5 mm) and under different heating conditions. As expected, spandex/PBMA/DEP composites showed

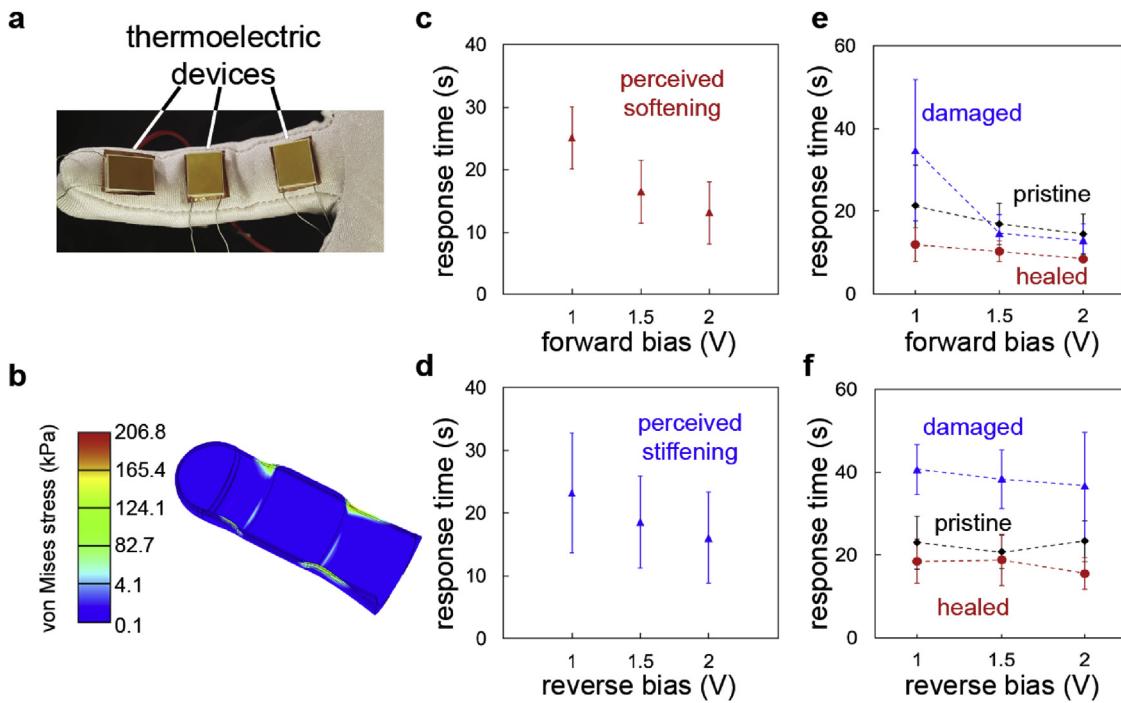


Fig. 4. Responses of human subjects to changes in stiffness of the glove. (a) Photograph of the kinesthetic glove fitted with thermoelectric devices. (b) Finite element analysis (FEA) of predicted stress concentration during bending of a finger of the glove. Response times of perceived (c) softening and (d) stiffening as a function of voltage applied to the thermoelectric devices ($n=2$ subjects, 30 samples per reported mean and s.d.). Comparison of perceived (e) softening and (f) stiffening times of the kinesthetic glove in “pristine” (black), “damaged” (blue), and “healed” (red) conditions (90°C for 17 h) ($n=1$ subject, 10 samples per reported mean and s.d.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

a steady decrease in bending stiffness as the voltage (and consequently the power, see **Figure S4**) applied to the thermoelectric devices was increased (heating) (Fig. 2c).

4. Healing properties of spandex/PBMA/DEP

Spandex/PBMA/DEP composites exhibited elastic behavior at low strain, followed by plastic deformation and fracture of the PBMA/DEP component at higher strains. To measure the change in mechanical properties of spandex/PBMA/DEP composites after overextension (which may occur during normal use as a wearable device), samples were fractured (100% strain) and again subjected to uniaxial tensile strain. One of the advantages of using the thermoplastic PBMA/DEP in providing resistance to motion (the basis of kinesthetic feedback) is that it can be reformed and healed when held at temperatures above T_g for a few hours (Fig. 3a). Mechanistically, spandex/PBMA/DEP composites have the ability to recover after being subjected to high tensile strain due to elastic recovery of the knitted spandex substrate and to heal at low strain due to the ability of PBMA/DEP to flow when heated (i.e., bridge cracks and fill residual void space). Healing of the spandex/PBMA/DEP composite can be repeated many times, since the process merely involves diffusion of polymer chains across fractured interfaces [25].

To measure the time-dependent healing properties of spandex/PBMA/DEP composites, samples were first stretched by 100% to fracture the PBMA/DEP component. The samples were then placed in an oven at 90°C (well above T_g) for different amounts of time to promote healing through the reflow of polymer chains across the fractured interface. These samples were strained again to measure mechanical properties (Fig. 3a) and to quantify the extent of recovery (Fig. 3b). Stress-strain curves of “healed” samples show significant recovery of the spandex/PBMA/DEP composite after 12 h at 90°C (Fig. 3a). The procedure for obtaining stress-strain

curves of “damaged” samples differed slightly from the procedure for “healed” samples in that the “damaged” samples were never removed from the grips of the tensile tester. The “damaged” samples were stretched to 100% (to damage them), returned to zero strain, and again stretched to 50% (to give the stress-strain curve shown in blue in Fig. 3a). Upon inspection of the stress-strain curves obtained for “damaged” samples, we originally attributed the low stress measured up to $\sim 20\%$ strain to slippage of samples from the grips. A tensile test with a sample marked at each end showed that the sample slipped minimally at the grips and suggested instead that the behavior was due to slack from plastic deformation and fracture of the PBMA/DEP component (**Video S1**). The stress at 50% strain for “healed” samples was normalized against the stress at 50% strain for “pristine” samples and plotted as a function of healing time (Fig. 3b). This parameter (stress at 50% strain) serves as a measure of the recovery of strength in the material and exhibits a linear dependence on healing time.

To describe qualitatively how spandex/PBMA/DEP composites healed, we performed scanning electron microscopy (SEM) on “pristine,” “damaged,” and “healed” samples. Fig. 3c shows PBMA/DEP evenly coats individual spandex fibers and fiber bundles in “pristine” samples, while “damaged” samples show a similar coating with crack formation perpendicular to the applied strain (100% strain). Both “pristine” and “damaged” samples exhibit holes we attribute to evaporation of solvent during preparation. The cracks formed in “damaged” samples of spandex/PBMA/DEP can be attributed to the mechanical failure of PBMA/DEP—as opposed to spandex, which undergoes elastic deformation even at large strain (Fig. 2b). Healing through the bridging of cracks as well as the filling of holes was apparent when comparing images of “damaged” and “healed” samples (Fig. 3c). We underscore that the composite was able to recover strength by heating only, without the application of external force.

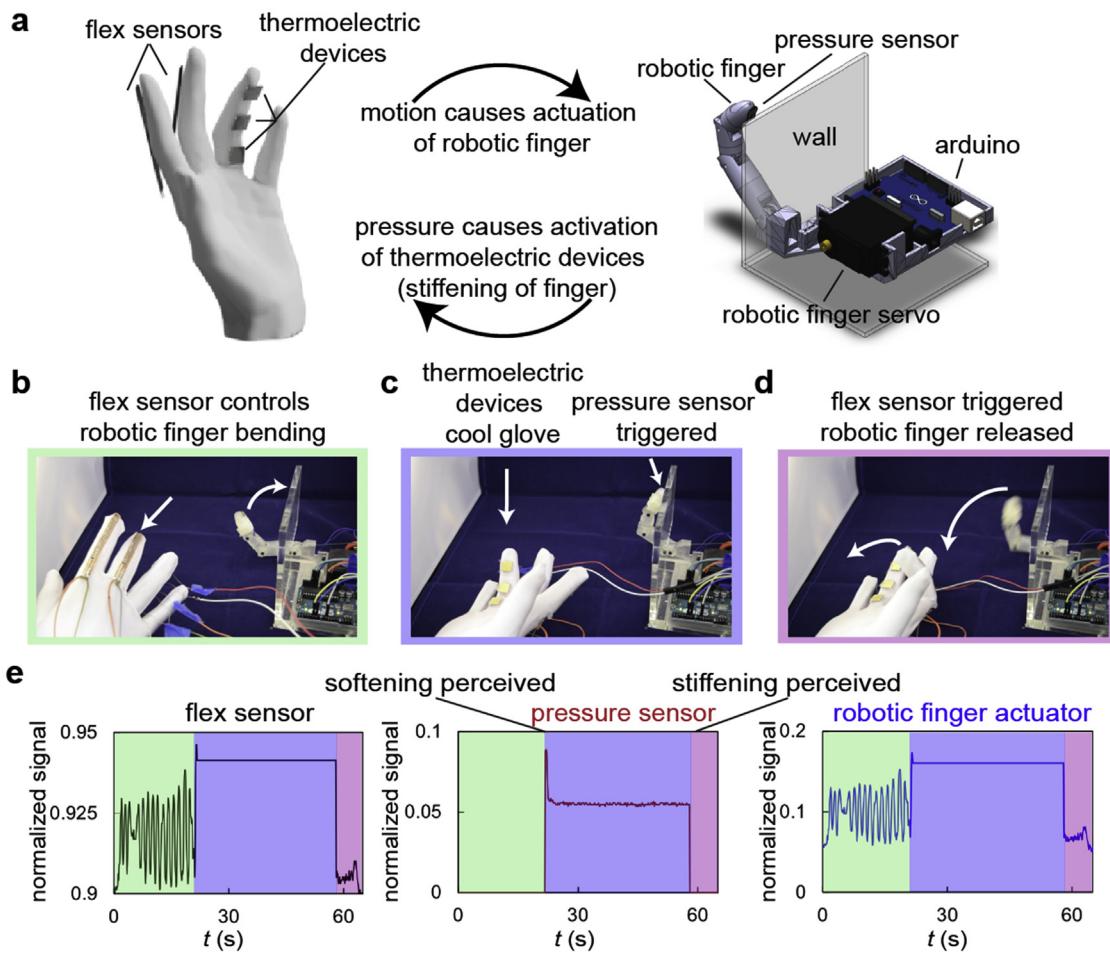


Fig. 5. Two-way communication of kinesthetic glove with robotic finger. (a) Schematic diagram. (b–d) Still images (corresponding to [Video S2](#)) of each stage of the demonstration; softening (green), stiffening (purple), and re-softening (pink). (e) Normalized sensor data of (left, black line) the flex sensor on the middle finger, (middle, red line) pressure sensor on the robot fingertip, and (right, blue line) the robotic actuator used to retract and extend the robotic finger in response to the flex sensor (middle finger). Signal processing was performed by using an analog-to-digital converter to discretize a range of analog signals (0–5 V) to a range of digital bits (0–1024 bits). Each reading was then normalized by the maximum bit value (1024) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

5. Human subject experiments

We fabricated a spandex/PBMA/DEP composite glove fitted with thermoelectric devices to deliver kinesthetic feedback to a human subject ([Fig. 4a](#)). To fabricate the device, we placed a spandex glove on a mannequin hand (wrapped in Teflon to prevent irreversible adhesion) and painted the bottom of the hand and fingers as well as the sides of each finger with a 0.1 g/mL solution of PBMA in cyclohexane containing 6 wt% DEP. The top side of the spandex glove was left unpainted to allow for elastic recovery (i.e., to bring the glove back to its original shape after bending). The glove was left to dry in ambient conditions for 24 h. Thermoelectric devices were fixed to the bottom side of a single finger between the joints using double-sided copper tape and sealed along the edges with clear silicone sealant (Loctite). Heating and cooling of the thermoelectric devices was determined by the direction of applied voltage across the thermoelectric devices (forward bias = heating, reverse bias = cooling). The direction of bias was controlled by an Arduino microcontroller, custom breadboard, and an external power source. Softening trials began at room temperature, while stiffening trials began at the end of softening trials when the glove was at an elevated temperature. Finite element analysis (FEA) of this material showed that stress concentrates around the finger joints, which highlights the importance

of coating the glove in these regions to maximize kinesthetic feedback ([Fig. 4b](#)).

To characterize how fast subjects respond to changes in material stiffness, two subjects were asked to continuously bend and unbend the finger inside the glove (fitted with thermoelectric devices) and to report when the glove felt softer or stiffer. Subjects reacted with shorter response times to changes in the stiffness of the material as the forward bias across the thermoelectric devices increased ([Fig. 4c](#)). Subjects showed a similar decrease in response time as the reverse bias increased when the glove transitioned from a compliant state to a rigid state ([Fig. 4d](#)). [Fig. 4c](#) and d show that there is wide variation in the response times of human subjects to the change in stiffness of spandex/PBMA/DEP. One possible explanation is that the large distance (3 mm) between the thermoelectric devices and the joints of the glove, i.e. where stress concentrates at the joints as observed in the FEA results of [Fig. 4b](#), combined with the low thermal conductivity of polymers, result in long switching times between soft and stiff states of the textile-thermoplastic composite. A similar experiment was performed to test the effects of plastic deformation of the kinesthetic glove on the ability of a subject to perceive a change in stiffness. One subject was asked to form a clenched fist to deform the glove past the elastic limit (to damage the PBMA/DEP component) and to repeat each response-time experiment ([Fig. 4e](#) and f). Damage of the glove had a pronounced

effect on perceived stiffening times where response times were ~20 s longer than the response times of the “pristine” glove (Fig. 4f). Fig. 4f also shows that when the experiment was repeated with a “healed” glove (glove placed in an oven at 90 °C for 17 h), the response times returned to the response times of the “pristine” glove.

6. Robotic finger demonstration

The glove was then equipped with flex sensors to control and receive kinesthetic feedback from a robotic finger. The robotic finger bent in response to flex sensors on the glove and contacted an acrylic wall when bent completely (Fig. 5a). When the robotic finger was in contact with the wall (measured by a pressure sensor on the robotic fingertip) the thermoelectric devices cooled (stiffened) the glove. Otherwise, the thermoelectric devices heated (softened) the glove. Three fingers of the glove were instrumented for different purposes. (1) The role of the middle finger was to control the bending motion of the robotic finger (Fig. 5b). (2) The role of the ring finger was to receive kinesthetic feedback induced by heating or cooling of the glove (Fig. 5c). (3) The role of the index finger was to signal the robotic finger to break contact with the wall once the subject had perceived that the glove had stiffened (Fig. 5d). For this demonstration, we used different fingers to control the motion of the robotic finger (middle finger) and to receive kinesthetic feedback (ring finger) because there was a risk that subjects would inadvertently overbend the finger used to control the robotic finger. Overbending would damage the composite material in its glassy state. In a realistic scenario, however, control of the robotic hand or virtual object would be combined with kinesthetic feedback in the same finger.

We began the first stage (softening) of the demonstration (Fig. 5b and e, green regions) by applying a forward bias to the thermoelectric devices to heat the kinesthetic glove. The subject was then asked to slightly bend and unbend both the ring and middle fingers cyclically (Fig. 5e, oscillatory signal arising from the flex sensor on the middle finger) until the subject perceived that the ring finger of the glove had softened. Once the subject perceived softening of the glove, the subject was asked to bend the middle finger until the robotic finger made contact with the wall. Contact of the robotic finger with the wall was registered by the pressure sensor at the tip of the robotic finger (Fig. 5e, signal peak of the pressure sensor). This contact automatically initiated the second stage (stiffening) of the demonstration (Fig. 5c and e, purple regions), where a reverse bias was applied across the thermoelectric devices to actively cool (stiffen) the glove. The subject was again asked to bend and unbend the ring finger (Fig. 5c and e, purple regions) until the subject perceived the glove had stiffened. During this stage, the robotic finger was programmed to ignore the bending motion of the flex sensor on the middle finger (marked by the absence of the oscillatory signal in the purple region of the flex sensor) to give the thermoelectric devices enough time to sufficiently cool the glove. Once the subject perceived the glove had stiffened, the subject was asked to bend the index finger. The signal of the flex sensor on the index finger caused the robotic finger to break contact with the wall (Fig. 5b and e, highlighted by the signal drop in pressure sensor signal). This break in contact triggered the third stage (re-softening) of the demonstration where a forward bias was applied to the thermoelectric devices to return the glove to a soft state (Fig. 5e, pink regions).

7. Conclusion

In summary, our work introduces a variable stiffness material and uses its glass transition to provide kinesthetic feedback in a wearable haptic device. While numerous technologies exist to

engage the kinesthetic sense and there are many materials whose stiffness can be tuned, these two concepts have not previously been combined. In addition to functioning as a wearable haptic device, this textile-thermoplastic composite can be healed in the same manner in which it provides kinesthetic feedback, through heating. While the switching times between states of low and high stiffness are currently quite long for practical use, we believe that they can be decreased by increasing the surface area at the interface of the composite and the thermoelectric devices. It may also be possible to increase the thermal conductivity of the thermoplastic component [26,27]. To increase the deformability of the entire device, we suggest that thermoelectric devices made of stretchable components would also prove valuable [28]. Some of the variation in response times and bending-stiffness samples can be attributed to the thermoelectric devices used to heat the textile-thermoplastic composite. Thermoelectric devices will continuously increase their temperature over time when held at a particular voltage. In future work, integrating the thermoelectric devices with a thermal sensor and proportional integral derivative (PID) controller would provide the capability of stabilizing the thermoelectric devices at a specified temperature. The field of soft materials may have a significant role in the development of wearable haptic technologies [29]. A similar recognition of the importance of soft materials is already underway in the fields of soft robotics [30] and stretchable electronics [31–33]. Beyond the production of haptic technologies, the science of soft materials may also help accelerate our understanding of the human tactile sense [34,35]. Making progress in these areas provide an exciting platform for interdisciplinary research involving chemistry, materials science, engineering, and cognitive science.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.sna.2019.01.032>.

References

- [1] J.C. Tuthill, E. Azim, *Curr. Biol.* 28 (2018) R194.
- [2] A.C. McConnell, M. Vallejo, R.C. Moioli, F.L. Brasil, N. Secciani, M.P. Nemitz, C.P. Riquart, D.W. Corne, P.A. Vargas, A.A. Stokes, *Front. Mech. Eng.* 3 (2017) 1.
- [3] L. Cappello, J.T. Meyer, K.C. Galloway, J.D. Peisner, R. Granberry, D.A. Wagner, S. Engelhardt, S. Paganoni, C.J. Walsh, *J. Neuron Eng. Rehabil.* 15 (2018) 59.
- [4] C. Pachierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, D. Prattichizzo, *IEEE Trans. Haptics* 10 (2017) 580.
- [5] Y.S. Narang, J.J. Vlassak, R.D. Howe, *Adv. Funct. Mater.* 28 (2018), 1707136.
- [6] S. Jadhav, V. Kannan, B. Kang, M.T. Tolley, J.P. Schulze, *IS&T International Symposium on Electronic Imaging*, 2017, pp. 19.
- [7] P. Polygerinos, Z. Wang, K.C. Galloway, R.J. Wood, C.J. Walsh, *Rob. Auton. Syst.* 73 (2015) 135.
- [8] B.H. In, B.B. Kang, M. Sin, K. Cho, *IEEE Robot. Autom. Mag.* (2015) 97.
- [9] R. Rizzo, A. Musolino, L.A. Jones, *IEEE Trans. Haptics* 11 (2018) 317.
- [10] S. Rich, S.H. Jang, Y.L. Park, C. Majidi, *Adv. Mater. Technol.* 2 (2017), 1700179.
- [11] I.M. Van Meerbeek, B.C. Mac Murray, J.W. Kim, S.S. Robinson, P.X. Zou, M.N. Silberstein, R.F. Shepherd, *Adv. Mater.* 28 (2016) 2801.
- [12] M. Solazzi, W.R. Provancher, A. Frisoli, M. Bergamasco, *IEEE World Haptics Conf.* (2011) 31.
- [13] S.M. Felton, K.P. Becker, D.M. Aukes, R.J. Wood, *Soft Matter* 9 (2013) 7688.
- [14] Y. Liu, B. Shaw, M.D. Dickey, J. Genzer, *Sci. Adv.* 3 (2017) 1.
- [15] J. Van Humbeeck, *Adv. Eng. Mater.* 3 (2001) 837.
- [16] G. Strobl, *The Physics of Polymers: Concepts for Understanding Their Structures and Behavior*, 2007.
- [17] T.P. Chenal, J.C. Case, J. Paik, R.K. Kramer, *IEEE Int. Conf. Intell. Robot. Syst.* (2014) 2827.
- [18] M.C. Yuen, R.A. Bilodeau, R.K. Kramer, *IEEE Robot. Autom. Lett.* 1 (2016) 708.
- [19] J.S. Heo, J. Eom, Y.-H. Kim, S.K. Park, *Small* 14 (2017) 1.
- [20] H. Jin, N. Matsuhisa, S. Lee, M. Abbas, T. Yokota, T. Someya, *Adv. Mater.* 29 (2017), 1605848.
- [21] L. Zhang, M. Fairbanks, T.L. Andrew, *Adv. Funct. Mater.* 27 (2017), 1700415.

- [22] Y. Zhao, A. Gumusenge, J. He, G. Qu, W.W. McNutt, Y. Long, H. Zhang, L. Huang, Y. Diao, J. Mei, *Adv. Funct. Mater.* 28 (2018), 1705584.
- [23] U. Gaur, S.F. Lau, B.B. Wunderlich, B. Wunderlich, *J. Phys. Chem. Ref. Data* 11 (1982) 1065.
- [24] J. Richeton, S. Ahzi, K.S. Vecchio, F.C. Jiang, R.R. Adharapurapu, *Int. J. Solids Struct.* 43 (2006) 2318.
- [25] Y.J. Tan, J. Wu, H. Li, B.C.K. Tee, *ACS Appl. Mater. Interfaces* 10 (2018) 15331.
- [26] S. Hong, H. Lee, J. Lee, J. Kwon, S. Han, Y.D. Suh, H. Cho, J. Shin, J. Yeo, S.H. Ko, *Adv. Mater.* 27 (2015) 4744.
- [27] M.D. Bartlett, N. Kazem, M.J. Powell-Palm, X. Huang, W. Sun, J.A. Malen, C. Majidi, *Proc. Natl. Acad. Sci.* 114 (2017) 2143.
- [28] B. Russ, A. Glaudell, J.J. Urban, M.L. Chabinyc, R.A. Segalman, *Nat. Rev. Mater.* 1 (2016) 16050.
- [29] M. Ying, A.P. Bonifas, N. Lu, Y. Su, R. Li, H. Cheng, A. Ameen, Y. Huang, J.A. Rogers, *Nanotechnology* 23 (2012), 344005.
- [30] P. Polygerinos, N. Correll, S.A. Morin, B. Mosadeghi, C.D. Onal, K. Petersen, M. Cianchetti, M.T. Tolley, R.F. Shepherd, *Adv. Eng. Mater.* 19 (2017), 1700016.
- [31] M.L. Hammock, A. Chortos, B.C.K. Tee, J.B.H. Tok, Z. Bao, *Adv. Mater.* 25 (2013) 5997.
- [32] J.H. Koo, D.C. Kim, H.J. Shim, T.H. Kim, D.H. Kim, *Adv. Funct. Mater.* 1801834 (2018) 1.
- [33] J. Wang, M.F. Lin, S. Park, P.S. Lee, *Mater. Today* 21 (2018) 508.
- [34] L. Skedung, M. Arvidsson, J.Y. Chung, C.M. Stafford, B. Berglund, M.W. Rutland, *Sci. Rep.* 3 (2013) 2617.
- [35] C.W. Carpenter, C. Dhong, N.B. Root, D. Rodriguez, E.E. Abdo, K. Skelii, M.A. Alkhadra, J. Ramírez, V.S. Ramachandran, D.J. Lipomi, *Mater. Horizons* 5 (2018) 70.

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