Texergy: Textile-based Harvesting, Storing, and Releasing of Mechanical Energy for Passive On-Body Actuation

Yu Jiang
Saarland University, Saarland Informatics Campus
Saarbrücken, Saarland, Germany
yjiang@cs.uni-saarland.de

Alice C. Haynes
Interaction Design
KTH Royal Institute of Technology
Stockholm, Sweden
ahaynes@kth.se

Jürgen Steimle
Saarland University, Saarland Informatics Campus
Saarbrücken, Saarland, Germany
steimle@cs.uni-saarland.de

Figure 1: *Texergy* enables more interactive and programmable passive on-body actuation by "powering" the actuation with mechanical energy that is harvested from innate user actions, stored on the body, and later released on demand. For example, this shape-changing costume is powered implicitly by dance moves to actuate a dramatic visual effect that amplifies the performance. (a) *Texergy* mechanisms are made with textile-based materials and a digital fabrication process, enabling seamless integration into the clothing and customization.

ABSTRACT

Humans instinctively manipulate and "actuate" their clothing, for instance, to adapt to the environment or to modify aesthetics. However, such manual actuation remains inflexible and directly tied to user action. We introduce *Texergy*, a textile-based technical framework that decouples user input and actuated output to make passive on-body actuation interactive and programmable. *Texergy* achieves this by harvesting energy from user interactions with a set of input modules, storing it mechanically on the body in elastic materials, later releasing the energy on demand, and finally connecting to output end-effectors that realize the actuation. We present a fabrication approach based on almost entirely textile materials using laser-cutting and simple manual assembly to enable integration into clothing and easy prototyping. We report the results of technical experiments and provide a design tool to support customizing the actuation's force and distance, type of harvesting, and deployment of *Texergy* mechanisms. We practically demonstrate the capabilities of *Texergy* with four applications, including a quick-release belt, a passive exosuit with dynamic assistance, a haptic feedback top powered by implicit user actions in VR, and a dance-driven shape-changing costume.

CCS CONCEPTS

• **Human-centered computing → Interaction devices**; • **Hardware → Emerging interfaces**.

KEYWORDS

Fabrication; actuation; energy harvesting; wearables.

ACM Reference Format:
Yu Jiang, Alice C. Haynes, and Jürgen Steimle. 2025. *Texergy*: Textile-based Harvesting, Storing, and Releasing of Mechanical Energy for Passive On-Body Actuation . In *The 38th Annual ACM Symposium on User Interface Software and Technology (UIST '25), September 28-October 1, 2025, Busan, Republic of Korea.* ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3746059.3747738

UIST '25, September 28-October 1, 2025, Busan, Republic of Korea

ACM ISBN 979-8-4007-2037-6/2025/09.
https://doi.org/10.1145/3746059.3747738

1 INTRODUCTION

Throughout history, humans have been instinctively manipulating and "actuating" their clothing. For instance, people roll up or down their sleeves to regulate temperature or swing their skirts for aesthetics. These manual and passive manipulations on clothing have become innate to the body and deeply integrated into everyday life. Despite this, the outputs of such passive actuation are directly tied to user input and limited - they often only occur where the user acts and are confined by the force applied. Advancements in e-textiles have opened up new actuation possibilities by mounting computer-controlled actuators on the clothing, such as shape memory alloys [25] and pneumatic [32] and linear [9] actuators for haptic feedback, motion assistance, and personal aesthetics, etc. These actuators offer the ability to create on-body actuation at any time, location, and scale. Despite their flexibility, integrating the entire end-to-end systems of these electronics-based actuators, including batteries, electronics, and other materials for practical mobile uses, presents a challenge. This integration often compromises wearability and disrupts the soft, flexible nature of the textiles. Furthermore, while efforts have been made to create adhesive-less smart textiles with sewn-in electronics, these deeply embedded components remain hard to recycle and unsustainable.

Therefore, we explore exploiting the rich passive actions people already do on clothing but for more flexible and interactive actuation of on-body outputs, pushing towards **passive and programmable on-body actuation that is powered solely by user actions**. To this end, we present *Texergy*, a textile-based technical framework that harvests energy from user movements and mechanically stores it on the body such that the energy can be later released by a small action to produce a user-defined output. By storing some energy beforehand, *Texergy* decouples user input and the output, enabling designers to control *when* and *how much* output is triggered by *what user action.* We take inspiration from existing rigid mechanical frameworks for energy harvest, store, and release [14, 27] but contribute a novel textile-based solution that can be integrated into clothing and offers a highly wearable form factor. This unlocks the body as a new site for passive actuation, enabling outputs that can happen intimately on the body, occur during physical activity, and can be simply worn as part of clothing.

Texergy presents an end-to-end solution for textile-based passive and programmable on-body actuation based on a harvest–store–release–actuation pipeline (Figure 1). A wide range of user interactions, including both body movements and clothing manipulations, can be harvested or used to release the stored energy. We identify three fundamental movements from common user interactions and provide string-based input modules that can effectively obtain displacement and energy from the movements. To store energy on the body unobtrusively, we routed elastic cords, which are slim, soft, and easy to parameterize, along the seams of the clothes. The core to *Texergy* are energy control mechanisms that can store the energy from one-time or repetitive user actions in the elastic cord and later release it for actuation. The released energy can then be redirected around the body and attached to different end-effectors to actuate on-body outputs. We demonstrate four example string-driven output modules that can create on-body shape change, visual display, and tactile and kinesthetic haptic feedback.

We contribute a novel fabrication approach for the core mechanism based on almost entirely textile materials using laser-cutting and simple manual assembly. Taking inspiration from clothing elements like bra hooks and pleats, we design soft analogs of gears and ratchets to create functional mechanisms that can effectively store and release energy. The chosen soft materials enable the entire end-to-end system to be integrated directly into clothing to create highly wearable and sustainable actuation systems; the digital fabrication process, along with a dedicated design tool, makes *Texergy* systems easy to prototype and customize. We empirically iterated the design parameters with the materials for robustness and durability of *Texergy*. The design tool modifies the parametric design file for laser-cutting based on designer-defined force, displacement, and type of harvesting.

A series of technical evaluations were carried out to validate *Texergy*. We characterize the energy stored in elastic cords, the efficiency of harvesting and releasing energy when deploying *Texergy* on curved body surfaces, and the forces required to trigger the release. To demonstrate the practical feasibility of *Texergy* and its versatile potential, we implemented four example applications. These include a quick-release belt, a passive exosuit with dynamic user-triggered assistance for effective training, a haptic feedback top powered by implicit user actions in VR, and a dance-driven shape-changing costume that creates dramatic visual effects with dance moves.

To summarize, we make the following contributions:

(1) *Texergy*, an end-to-end solution for textile-based energy harvesting and releasing for passive but interactive on-body actuation.
(2) A fabrication method based on laser cutting and simple manual assembly to enable programming and easy prototyping of *Texergy*.
(3) A design tool and a series of technical evaluations to support customization.
(4) Four implemented example applications that demonstrate the practical feasibility of our technique.

2 RELATED WORK

2.1 Interactive Clothing

As computing devices are getting lighter, smaller, and more flexible, interactive devices that process user input and produce outputs have evolved to take on more wearable form factors. Textiles have attracted a rising interest in becoming wearable interactive devices. They are soft and innate to our human body and thus can potentially be “seamlessly woven” [45] into our everyday lives to support interactivity without additional devices. We as humans are also accustomed to body movements and clothing manipulations (e.g., rolling up sleeves) when wearing an attire. This rich space of comfortable, socially acceptable, and sometimes implicit actions serves as natural user input to versatile interactions on the clothing.

Some works focused on guiding such user actions into intent-based user input by transforming traditional UI elements and affordances on digital screens to textile counterparts [29], such as sliders [33] and icons [37] that can be recognized by touch to enable eyes-free interactions. Many works contribute approaches to sensing user actions on clothing. These include detecting body gestures [49], touch [1], conductive objects [10], pressure and deformation [16, 28], and natural clothing manipulations such as pinching [19] and sleeve deformations [34]. Other than physical actions, detecting physiological signals such as sweat [51], ECG [39], and the ambient environment [47] with textile sensors have also been demonstrated. A series of works also explored mounting electronics onto the clothing but with miniaturized and textile-specific form factors [17, 23] to support more versatile interactions.

With the existing interactive clothing predominantly enabled through synthetic materials and electronics, washability and sustainability are major concerns. To tackle this, efforts have been made to make interactive clothing washable [35] or enable destructive fabrication processes through disassembling [46] such that the textiles and the integrated functional elements can be recycled and reused. We contribute a different approach to more sustainable interactive clothing by taking advantage of the rich user actions people do with the clothing to enable textile-based passive interactions. Instead of only sensing user actions and then triggering a corresponding output through actuators, we want to harvest and use these user actions in a controlled way to directly actuate an output on the body. Through this, we aim to power the entire interaction loop with only passive user actions to create electronics-free and sustainable interactive clothing.

2.2 Actuating textiles

The clothing we wear is in itself a rich source of output channels - their textures rub against our skin to offer tactile experiences and their appearances reflect one's personal aesthetics. This has motivated on-body outputs that can be actuated to further enhance the expressivity of the clothing by adding onto or changing its existing visuotactile properties.

One popular approach is by actuating thin and flexible wire-based shape memory alloys (SMAs) that can be integrated into the textile structure. SMAs have been used to create folding-based [7, 25, 31] or compression-based [13] shape changes, change the fabric's stiffness [3], and create squeezing-like feedback [21, 40]. Other actuators based on joule heating have also been shown, including thermoplastic threads [9] and liquid crystal elastomers [8] for shape change, and thermochromic threads for creating color changes [5, 6]. Fluidic and pneumatic actuators that enable small-scale locomotion [22], haptic feedback [20], and wearable robotics [32] have been demonstrated.

These actuators, however, are usually power-intensive and some come with bulky actuators (e.g., pumps for pneumatic systems) or safety concerns (e.g., overheating in heating-based textiles), making the entire end-to-end system not mobile and inappropriate for wearable contexts. To strip the heavy and bulky power sources and actuators, some works have worked on passive actuators that do not need electricity and can be integrated directly into clothing. A series of passive actuators that can be triggered by the body or surrounding environment are able to create gradual on-body outputs, including sweat-actuated shape and fluorescence change [44], temperature-responsive porosity change [48], and sunlight-triggered shape change [50]. Some outputs can simply be user-triggered on demand through actions such as pulling a tendon to trigger shape changes [2], finger presses to change textiles' surface topology [18], or stretching elastic fabrics in exosuits to assist human movements [24, 41]. By using materials that are triggered naturally by stress, such as mechanoluminescent composites, researchers have also created on-body user motion displays that are actuated by the user's implicit movements [15]. One major drawback of these passive actuation systems is that the actuated output happens only when and where the user performs the action. We thus aim to decouple the user input and the actuated output to make on-body passive actuation programmable and interactive. Specifically, we store the energy from the user and only release it later on demand. This allows the system to control how, when, and where to release this energy to actuate a controlled output on the body. In this paper, we present an end-to-end passive actuation system that allows designers to program on-body actuation.

2.3 Mechanical Energy Systems for Actuation

Mechanical energy systems are systems that store energy mechanically with physical components such as springs, flywheels, and compressed air, and later release the stored energy in a controlled manner when needed. These systems have become ubiquitous in our everyday lives, such as wind-up toys and bicycles. While these mechanical energy systems usually come as part of a mass-produced product that is designed for specific functionality, there are also research works that make such energy systems customizable so users can more flexibly design their own mechanical energy devices. To help with customization, these works often use digital fabrication approaches and offer modular building blocks or design tools. Some examples include controllable kinetic motions from 3D printed plastic modules [14], self-sustaining pneumatic actuation for shape change powered by renewable energy [27], assistive robotics powered by foot strike [38], and morphing devices triggered by environmental degradations [26]. Orthogonal to these mechanical systems are energy harvesting approaches that convert mechanical energy to electricity to power electronics [12]. While such methods have been adopted to power sensors and small electronics, powering actuators, which are much more energy-intensive [4, 42], remains challenging due to the low power output and inefficient energy conversion.

These mechanical energy systems thus have the benefits of being electronics-free, energy-efficient, more sustainable than traditional batteries, and capable of actuating output motions. However, the existing commercial or research-oriented systems are not suitable for wearable contexts as they are primarily composed of rigid plastic or metal parts. We thus want to explore a mechanical energy system that optimizes wearability and can be used to create controlled output on the body without electronics. We approach this by presenting a fabric-based mechanical energy system that is soft, flexible, and can be directly integrated into our everyday clothing. We provide a streamlined fabrication process and design tool that allows users to easily customize and fabricate their own systems for programmable on-body actuation.

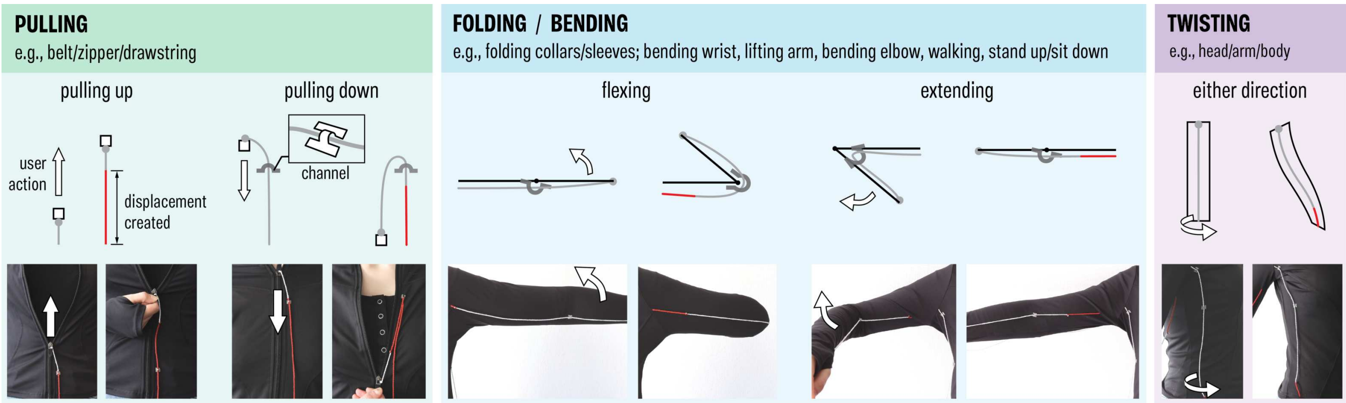


Figure 2: Three fundamental movements that can be used for harvesting and releasing the energy are identified from common clothing manipulations and body movements. We provide input modules and implemented examples for obtaining displacement from the movements.

3 *TEXERGY*

We present an end-to-end solution for passive on-body actuation based on the proposed pipeline in Figure 1. We take inspiration from existing energy harvesting works and contribute a solution for body-oriented and fabric-based contexts, enabling programmable actuation to blend seamlessly into our everyday activities and attire. The system harvests mechanical energy from **user interactions**, which can also be later used to trigger the release of the energy. The energy can then be **stored** in textile-based elastic materials that are soft in nature and can be comfortably worn. The core to *Texergy* are textile-based **energy control mechanisms** that connect to the elastic materials and orchestrate the user interactions to effectively store and release the harvested energy in a slim and flexible form factor. When the energy is released by user interaction, a displacement is created at the control mechanism. Finally, with **actuation end-effectors** that connect the displacement to existing on-body output systems, the system can passively "power" the actuation. The benefits of *Texergy* are that it (1) uses the energy from the body directly on the body for actuation, (2) does it in a programmable way such that the designer can control when and how much energy is harvested/released by what user interaction, and (3) can be fabricated easily with textile-based materials, which we will show in Section 4, to support integration. In this section, we dive into the crucial components that enable this pipeline.

3.1 User interactions

To effectively leverage user interactions for harvesting or releasing energy, they need to be transformed into displacement with acting force at a certain position. To achieve this, we contribute generic string-based input modules that can be placed at different body locations to generate displacement from specific user interactions. From most common biomechanical body movements that people do and clothing manipulations that people perform on the clothing surface, we identified three fundamental actions: pulling, folding/bending, and twisting. In Figure 2, we list example interactions that involve these fundamental actions, present input modules for these actions and show implemented examples. For pulling and folding, obtaining the displacement from both directions of motion are shown. We use arrows to show the user actions and color-coded white and red strings to visualize the created displacement. To flexibly route the strings around the body and secure their paths, we create fabric-based channels (Figure 2, left) at fixed clothing locations through which the string can pass. These channels are made by sewing the two ends of H-shaped fabric pieces close enough to create channels of around 2 mm diameter.

Pulling is a common clothing manipulation that can be done on belts, zippers, drawstrings, etc., as shown in Figure 2 left. To obtain the displacement from a pulling action, the string can directly be connected to the pulled element (e.g., the zipper) if the user is pulling along the same direction; to harvest pulling in the other direction, the string can be redirected by going through a channel and reverting the direction.

Folding part of a clothing or bending a body part is also frequently done on the body (Figure 2, middle). Collars, sleeves, and even edges of a skirt can be folded. Bending can take place at many different body parts at varying scales, including the wrist, arm, leg, torso, etc. We present modules for harvesting both directions of folding/bending. For flexing an originally flat body part or piece of fabric at a joint, the string is attached to one end and is routed along the outer convex side of the fold, which gets elongated when folding. Similarly, routing the string along the inner concave side of the fold creates a displacement during extending. To ensure the string stays on the correct side for very thin folding planes like the arm shown in the example, the channels can be placed at the joint to secure the string's path.

Lastly, twisting is a fundamental body movement that can be performed at the head, arm, body, etc., as shown in Figure 2 right. For twisting motions, the string is fixed at one end and creates a displacement on the other end when the body part is twisted, as shown by the user twisting the torso in the example.

The specific user interactions will create displacement and force at varying scales, from around 30 cm when pulling the zipper of a jacket to only 2 cm when twisting the forearm. Larger-scale user interactions can accumulate energy more effectively, whereas

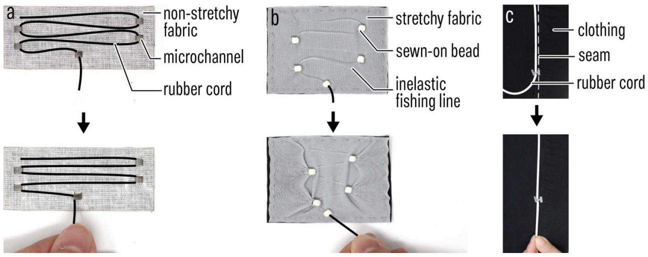


Figure 3: Some of the storing strategies we experimented, including (a) routing elastic cord in a zigzag manner and (b) routing inelastic cord on stretchy fabric. We finally opted for (c) linearly routing elastic cord along clothing seams for ease of deployment and parameterization.

smaller-scale interactions can be exploited for effortless and easy release of energy. The given examples are not exhaustive and can be further expanded since the clothing elements are very specific to the clothing design, and the human body has over 200 degrees of freedom. The user interactions that drive *Texergy* thus can vary across individuals and contexts, enabling highly customized interaction for harvesting and releasing the energy.

3.2 Storing energy in textiles

To effectively store the mechanical energy, soft elastic materials that can be easily deployed onto different body parts are needed. There is a great variety of elastic textiles in the form of both 1D strings and 2D fabrics that store mechanical energy when stretched. We empirically experimented with various materials as well as layouts and show interesting ones in Figure 3 to offer options in different design contexts.

(a) We tried routing elastic rubber cords in a zig-zag manner on a fabric patch which can then be sewn onto the clothing. This allows hosting a lot of elastic material in a very small area, making it space-efficient and capable of generating very large displacement on the body for actuation. However, redirecting the rubber cord multiple times through the channels adds a lot of friction, and characterizing the energy in the cord becomes overly complex. The underlying patch also has to be deployed on non-stretchy areas on the clothing. (b) We also tried using 2D textiles to store energy by sewing plastic beads onto a stretchy fabric and routing inelastic fishing lines through the beads. When the fishing line is pulled, the beads stretch the underlying fabric to store energy. This is beneficial when the clothing on which *Texergy* is deployed already has a stretchy area, which then can directly be used for harvesting the energy without using additional materials. However, the force that can be generated by stretching a small piece of fabric is limited, and additional sewing effort is also required.

In order to make *Texergy* programmable and easy to deploy, we finally chose to linearly route elastic rubber cords like shown in Figure 3 c. The cord's 1D form factor allows us to flexibly route it around the body and integrate it into the clothing as stretchable "seams". The transparent rubber cord can be either worn outside the clothing or inside loose clothes and can be routed with the channels. To wear the rubber cord inside tight clothing, one can route the cord inside a Bowden tube, which can be sewn onto the inside seams of clothing. The rubber cord stretches globally without redirection and, therefore, makes it easier to characterize its force and displacement behavior to make *Texergy* programmable. A stress-strain characterization of the rubber cord is shown in Section 5.1. The rubber cord also has good elasticity and can be stretched to more than 200% of its original length. It can therefore be reliably used to provide significant displacement for actuation.

3.3 Energy control mechanism

The harvested energy then needs to be stored and later released by another user action to generate user-defined actuation. Mechanisms for this purpose have been realized in rigid form factors, such as pull-back toy cars and automatic umbrellas, but a soft version that fit wearable contexts is yet to be shown. We thus contribute textile-based and deformable energy control mechanisms with soft latches that keep the elastic material stretched to store the energy and can later be opened to release the energy. To enable harvesting different types of user interactions, we present a basic control mechanism that stores the energy from *one-time* user actions and an extended mechanism that can accumulate energy from *repetitive* user actions.

3.3.1 Harvesting one-time movements. Figure 4 shows the basic control mechanism that is soft and almost entirely textile-based with only one very small (3 mm in height and width, 5 mm in length) 3D-printed piece. As shown in the schematics (a), we create a soft textile-based latch with (1) a hoop, (2) a compliant hook with a higher left edge, enabling it to travel rightward under the hoop but is stopped by the hoop when moving leftward (i.e., engaging the latch), and (3) a pleat connected to the hoop that is folded when the hook is engaged but can be unfolded to remove the hook (i.e., releasing the latch). We then lay out the energy control mechanism

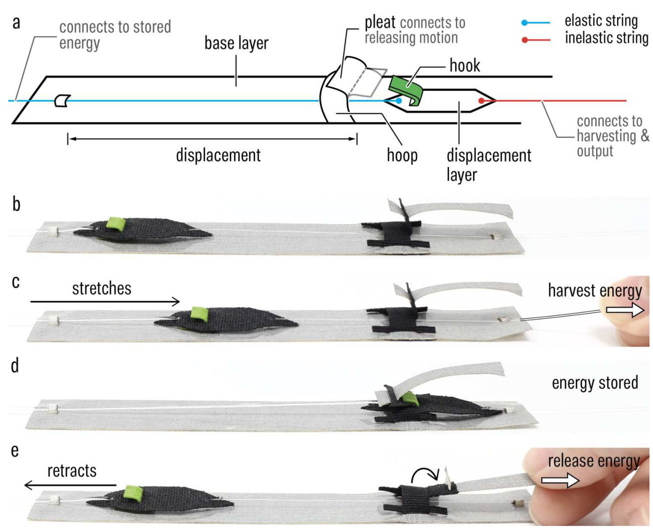


Figure 4: (a) The schematics of the control mechanism. (b) The fabricated prototype. The mechanism (c) harvests the energy from user interactions with an elastic cord and (d) stores it by keeping the cord stretched. (e) The energy can be later released by another action to actuate the output.

based on this soft latch. The hoop and the connected pleat sit on the fixed base layer. The hook is mounted on a moving displacement layer and connect to the elastic rubber cord on the left and the harvesting and output string on the right.

Figures 4 b-e show the working prototype. (b-c) When the harvesting string is pulled by a user action, the rubber cord stretches and moves the hook. (d) When the desired displacement is harvested, the hook travels past the hoop and is stopped. This keeps the rubber cord stretched and stores the energy. (e) Later, the pleat on the hoop is pulled to unfold and remove the engaged hook. The hook then retracts to its original position to release the stored energy in the rubber cord for actuation.

With only one soft latch, the basic control architecture allows harvesting one-time motion.

3.3.2 Harvesting repetitive movements. We expand the versatility and functionality of *Texergy* by extending the basic control mechanism for one-time harvesting motion to be able to harvest repetitive movements. This enables *Texergy* to be applied to a wider range of application scenarios, including harvesting energy from smaller, fine-grained repetitive motions (e.g., wrist bends and arm twists) and accumulating more energy over time for actuation. We achieve this by adding more latches to allow multi-step energy storage, and a repetitive harvesting mechanism to allow harvesting the same user interaction multiple times in an accumulative manner.

Figure 5 shows the repetitive harvesting control mechanism. As shown in the schematics (a), the added hoops allow the hook to make multiple stops when charging. The releasing strip is adapted to connect all pleats to allow instant release of energy. On the right, we add a second retractable hook that connects to the base with elastic strings and can be moved repetitively by the same harvesting interaction. Each interaction moves the retractable hook to pull the upper displacement layer to store one step of energy. After each interaction, the retractable hook returns to its housing and is ready for the next repeating harvesting motion.

Figure 5 b-g show the working prototype. (b-d) The harvesting user interaction moves the retractable hook, which then pulls the displacement layer and the main hook to stretch the rubber cord. (e) After one harvesting motion, the main hook is stopped at the first hoop to store one step of energy. Meanwhile the retractable hook returns to the housing. (f) After four steps of harvesting with repeated user interactions, the energy is completely charged. (g) Pulling the releasing strip unfolds all the pleats such that the main hook can retract to the left to release the stored energy.

The detailed design, fabrication, and customization of the control mechanisms are detailed later in Section 4.

Both mechanisms are 18 mm in width, and the lengths scale with the total displacement required by the design. For repetitive harvesting mechanisms, the one-step displacement is determined by designer-defined total displacement and the number of steps (e.g., the mechanism shown in Figure 5 has 4 steps of 2.5 cm one-step displacement to achieve 10 cm in total). The maximum number of steps that can be accommodated for a fixed total displacement is constrained by the length of the hoop, which should be smaller than one-step displacement to avoid overlapping hoops.

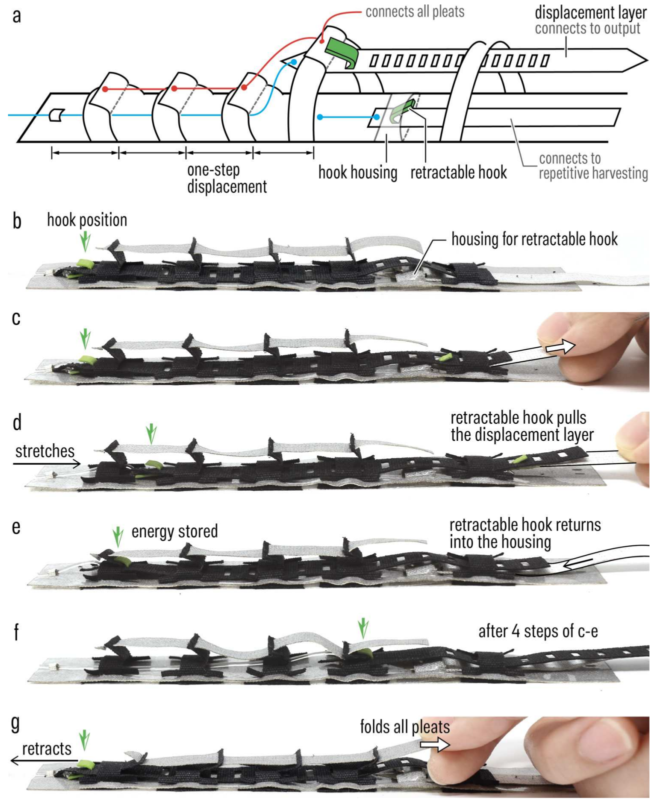


Figure 5: (a-b) The schematics and implemented prototype of the extended mechanism that allows harvesting energy from repetitive user interactions. (c-d) The user pulls a retractable hook, which then moves the displacement layer to accumulate one step of energy. (e) The retractable hook returns to its original position after the user interaction and is ready for the next harvesting movement. (f) After four harvesting steps, the energy is fully charged. (g) We adapt the releasing mechanism to multi-step harvesting by using a tendon structure to connect the pleats.

The mechanisms are fabricated with deformable, textile-based materials and can be deployed flexibly on curved surfaces on the body. To avoid the base layer crumpling due to the tension, it needs to be anchored (e.g., by sewing) to the underneath clothing, which is ideally low-stretch and tightly worn. This can be achieved with form-fitting garments common in sports, performance, and medical apparel, or even with everyday items like tight jeans. For looser clothing, a stiffer base layer can be used at the cost of compromising flexibility. The efficiency of harvesting and releasing energy decreases on more curved surfaces and higher number of harvesting steps, with a more detailed evaluation shown in Section 5.2.

3.4 Actuation end-effectors

The displacement and force created when the stored energy is released can then be used to actuate on-body outputs. The default output created by *Texergy* is a string being displaced. Here, we demonstrate a variety of actuation end-effectors that can be coupled with the output string to extend to a diverse set of on-body output types. When deployed, the end-effectors need to be securely anchored to the body (e.g., by fixating onto the clothing) to deliver effective outputs.

Figure 6 shows the four implemented end-effector examples. The displacement and force needed to actuate the specific output are indicated for reference. To start with, string-based actuators can trigger tendon-driven shape-changing outputs (Figure 6, top left). We route the actuation string in a zig-zag manner on a skirt which, when pulled, could change the style of the skirt for personal expression, aesthetics, changing environment, etc. The visual display of the clothing (Figure 6, down left) can also be changed. This can be done by overlapping two layers and cutting out areas on the top layer selectively such that when the string pulls the underlying display layer with visual patterns, the display can be seen from the cutouts. With this sliding actuation mechanism, one can either hide or reveal a display (e.g., our rose example) or show an animated/changing visual effect using an underlying layer with multiple visual patterns.

We also contribute two simple methods that use strings to create haptic feedback on the body. These can include tactile feedback (Figure 6, top right) as well as kinesthetic ones (Figure 6, down right). Tactile haptic feedback employs strings to act on the skin or clothing surface. For example, we directly route the output string around the arm to deliver squeezing sensations when the string is pulled. Our tests showed that a 2 N output force was able to create a strong squeezing feedback on the arm. Kinesthetic feedback can be created by routing the output string along body joints on the kinematic chain. When the string is tightened, the movement of the joint along the routing is constrained and the user feels resistive force. We show an example of a finger-worn device that resists the index finger's bending when the string is pulled. Our tests show that 1N of output force could create strong resistive haptic feedback.

While the demonstrated actuation end-effectors already show the versatility of the on-body outputs that *Texergy* is compatible with, the list is far from complete. As we focus on contributing a passive actuation system, the simple and generic form factor of *Texergy*'s output string can be extended to adapt to many existing on-body output designs with specific end-effectors.

Figure 6: Example string-based output end-effectors that enable creating a shape change, a display, and tactile and kinesthetic haptic feedback.

4 FABRICATION AND DESIGN

We present a fabrication approach that makes *Texergy* easy to fabricate and customizable. Here, we detail the material choices, our fabrication method using laser-cutting and the iterated design parameters, and a dedicated design tool that allows programming of *Texergy* systems.

4.1 Material choices

We experimented with different elastic cord and textile options to determine the materials for *Texergy*. We use thin rubber cords with high elasticity and low surface friction for all elastic strings in the system - 1 mm diameter cords are routed for storing energy and 0.4 mm diameter cords that take a small force to stretch (1 N to extend a 5 cm cord to 10 cm) connect the harvesting strip to the base layer for harvesting repetitive movements. Standard inelastic fishing lines or other non-stretchy textile strips can be used to connect the input modules and the actuation mechanism to the core control mechanism.

The textiles used in *Texergy* need to be non-stretchy to avoid losing mechanical energy to the stretch, and non-fray and laser-cut-safe to comply with our fabrication method. On top of these requirements, textiles with lower friction reduce the energy lost in friction and allow the layers to move smoothly on the surface to achieve more efficient energy harvesting and release. We empirically tested a range of fabrics available in a local fabric store and chose two fabrics of different softness (Figure 7 top). A heavier and

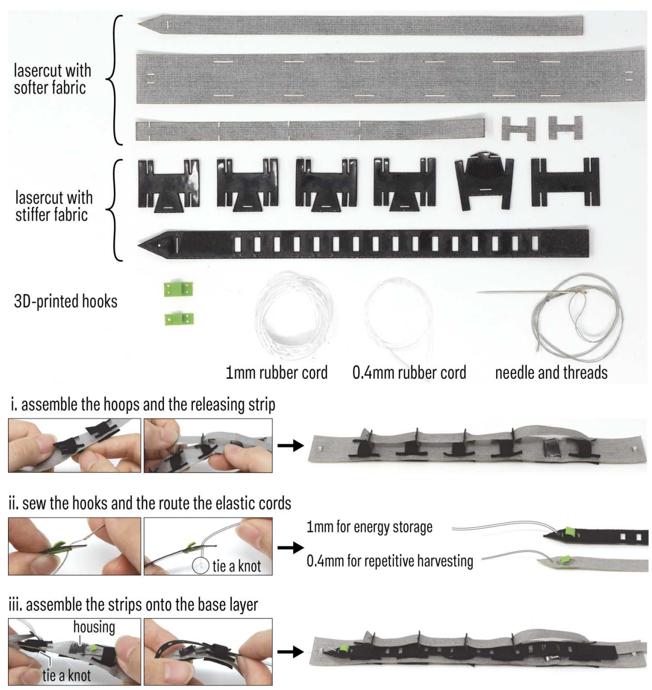


Figure 7: The materials required to create a repetitive harvesting control architecture (top) and the assembly process (i-iii).

thicker dry waxed organic cotton[1] of 227 g/m^2 is used to make the hoops and the displacement layer which requires more stiffness - the hoops need to maintain the shape for the underlying layer to pass through and the displacement strip should avoid buckling up to move along the surface smoothly. For all other parts of the system, a thinner and lighter coated cotton[2] of 180 g/m^2 is used to make the entire system softer and conform to the body better during wear. We further taped the textiles with standard transparent acrylic tape to make the textile surfaces glossier to reduce friction.

4.2 Fabrication

We provide a novel fabrication process that leverages laser cutting and simple manual assembly to create textile structures for ease of prototyping *Texergy*. The *Texergy* mechanism is mostly based on layers with different dimensions (e.g., base layer, hoops, releasing strips) that should be connected at the correct position for the system to be functional. This could be done by sewing the layers together at the connecting points, but the sewing process is time-consuming and requires expertise considering the amount of sewing and the precision needed. We thus adopted a novel laser cutting and simple manual assembling procedure. Figure 7 top shows the laser-cut pieces used for creating the core mechanism. We used a repetitive harvesting architecture as an example, which include all pieces needed for the one-time harvesting mechanisms.

For parts that need to stay fixed and securely connect with each other, including the base layer, the hoops, the hook housing, and the releasing strip, we create slot and tab joints for connection, which can be lasercut and simply assembled without sewing. The assembly process is shown in Figure 7 i. As shown in Figure 7 top, we lasercut H-shaped hoop pieces (in black) with wide tabs on both ends to be inserted into the corresponding slots (in white) lasercut on the gray base layer. The channels can be created in a similar manner with smaller H-shaped pieces for routing the strings on the body. The same method is used to create the tendon structure for releasing that connects all the foldable pleats. We laser-cut slots on the hoop pieces and symmetric inward cuts on the releasing strip to create tabs at a fixed distance equal to the gap between hoops. The releasing strip is then pulled through each pleat for connection.

We then assemble the moving parts, including the displacement layer and the repetitive harvesting strip, as shown in Figure 7 ii. The 3D-printed hook is sewn onto the strip, and the elastic rubber cord goes through the strip secured by tying a knot at the back. Rubber cords of different thicknesses are used for storing the energy and enabling repetitive harvesting motions.

Finally, the fixed base and the moving strips are assembled together (Figure 7 iii). The harvesting strip is connected to the base via the rubber cord such that the hook sits inside the housing and the displacement layer is routed through the hoops. The assembled mechanism weighs 22 grams.

4.2.1 Optimizing design parameters for mechanical durability. The detailed dimensions of the laser-cut pieces (shown in Figure 7) have been empirically iterated and are shown in Figure 8. The connecting points between the components are color-coded. To ease deployment on the body, we minimized the width of the control mechanism while guaranteeing the parts' compatibility with the fabrication methods and the mechanical durability of the assembled prototype. Here, we provide a brief walkthrough of the iterated dimensions and evaluate the mechanism's mechanical durability.

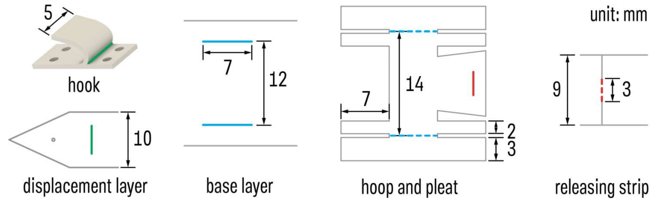


Figure 8: The iterated design parameters. The connecting points between different parts are color-coded.

The constraining factor in miniaturization is the width of the hook, which should be stably printed with off-the-shelf FDM printers and be mechanically strong. To successfully print the holes on the hook base for sewing, the width was iterated to be 5mm. Then to comply with the laser-cutting process, all the laser cut slots need to be at a minimum distance from the edge to avoid thin fabric elements that could break easily. We empirically determined this gap to be around 3 mm and adopted this in our design. Finally, to ensure the hook's smooth movement on the displacement layer under the hoop, we iterated the gap between the tabs on the hoop piece such that the assembled piece could form a hoop that the hook could pass through with minimal friction but could still stably engage. This is empirically determined to be 14 mm, which is 2 mm more than the gap between the slots on the base layer (12 mm).

We evaluate the mechanical durability of the assembled prototype made with our fabrication approach by testing the connecting points' performance under large force and repetitive use. The connection fails at 10 N between the base layer and the hoop and at 5 N between the pleat and the releasing strip, after which a new tab piece needs to be reassembled. While our slot-and-tab design helps with customization and simplifies prototyping, fabrics are generally subject to wear and tear under high force. The durability can be improved by replacing the textiles with stiffer ones (e.g., if the releasing strip is also made with the stiffer fabric, its connection with the pleat does not break under very high force), but this makes the assembly harder and is subject to availability of the textiles that designers can find.

4.3 Designing *Texergy* systems

To support the customization of *Texergy* systems, we provide suggestions and a dedicated design tool. When designing a customized end-to-end on-body actuation system, the designer should first think about what user actions to use for harvesting and releasing the energy, what output to trigger, and use inelastic strings to route these accordingly to one location where the central control mechanism needs to be placed. For routing the elements and creating an output to actuate, the designer can use the input and output modules we suggested in Section 3. Below, we provide a dedicated design tool for programming the core control mechanism. The tool's input parameters are designed to be highly flexible, ensuring

[1]https://wedofabric.com/collections/canvas/products/light-waxed-cotton
[2]https://swafing.de/leona-beschichtet-rueckseite-buegeln-beschichtete-baumwolle/074671

that *Texergy* remains generalizable and not restricted to specific use cases. Future work could extend it further to support more application-specific workflows or domains.

4.3.1 Design Tool. The design tool is based on a plug-in in Fusion 360 [3], as shown in Figure 9. The plug-in UI asks for the total displacement and the peak force the user wants to use for actuation (Figure 9 a). Based on the user input, the tool calculates the maximum length of the rubber cord that can generate the required force at the required displacement based on the Mooney-Rivlin model fitted on our empirically measured data (detailed in Section 5.1). Due to the energy lost to friction when *Texergy* is deployed on the body, we recommend overestimating the force and/or take a cord shorter than the calculated value to generate a larger force to ensure that the desired output can be successfully actuated. Changing the displacement and force values dynamically updates the vector design file displayed on the left and the rubber cord length recommendation. As Figure 9 b shows, the user can also switch to charging with repetitive motions and indicate the number of charging steps. The vector design file updates accordingly to add the additional pieces needed for charging with repetitive motion. After finalizing the design, clicking the "OK" button would export the dxf file that can be laser-cut with textiles. The user can also change other parameters and the sketch in Fusion directly to have finer control. We also provide stl files for the two hooks that can be 3D-printed with off-the-shelf PLA filament.

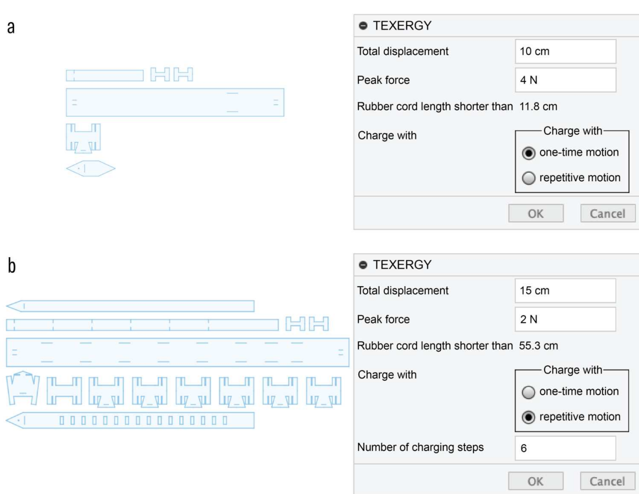


Figure 9: We provide a design tool for customizing the control mechanism. (a) The tool generates rubber cord length recommendations based on user-input displacement and force values and updates the vector design file. (b) The designer can switch to harvesting repetitive motion with a specified number of steps. The generated vector file can be laser-cut.

[3]https://www.autodesk.com/products/fusion-360

5 TECHNICAL EVALUATION

We perform a series of tests to characterize *Texergy* mechanisms. The mechanisms were tested over 50 cycles of the pipeline and the performance remains consistent. Below, we show evaluation of the energy stored in the rubber cord, the efficiency of harvesting and releasing when *Texergy* is deployed on varying body surfaces, and the force needed to release the energy.

5.1 Storing energy in elastic cords

To enable programming the energy stored, we performed characterization of the elastic cords. We used rubber elastic cords of 1 mm diameter and tested the stress-strain relation of cords with lengths of 10 cm, 15 cm, 20 cm, and 25 cm. With each rubber cord, we slowly pulled the cord connected to a force gauge (Baoshishan ZP-50N with 0.01 N accuracy) and measured the pulling force at each 1 cm elongation. The rubber cords were elongated to only twice their original lengths to prevent plastic deformation from damaging the material and to reduce the hysteresis. Since *Texergy* is compatible with elastic cords, not limited to the specific one used in our implementation, we chose not to characterize the chosen cord's hysteresis since it would not generalize. The measurements were repeated three times. We fitted a third-order Mooney-Rivlin model [30, 36] to the measurements, which is commonly used to characterize the nonlinear elastic behavior of rubber materials. To normalize the strain across cords of different lengths, we plot the measured force against the stretch factor (displacement over original length). The fitted Mooney-Rivlin curve is shown in Figure 10. The shaded area shows the standard deviation across the measurements.

The model fits the measured data with $R^2 = 0.97$ and yielded Mooney-Rivlin parameters $C_1 = 2.9602, C_2 = -5.9159, C_3 = 5.2137$. The measurements confirm that the chosen rubber cord is able to store a good amount of force that can be used to actuate lightweight on-body outputs. Rubber cords with shorter initial lengths and larger displacement can create a larger peak force during harvesting or releasing. The fitted model can then inform the length of the rubber cord that needs to be used in *Texergy* to satisfy the force and displacement values input by the users.

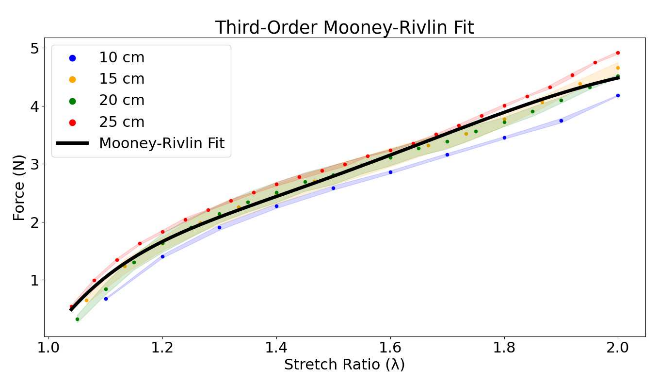
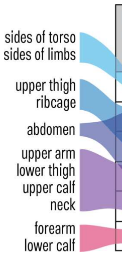


Figure 10: We characterize the energy stored in elastic rubber cords of four lengths by fitting a Mooney-Rivlin curve with $R^2 = 0.97$ to the empirical force-stretch ratio data.

5.2 Harvesting and releasing energy on the body

While the rubber cord stores the mechanical energy, the actual harvesting and releasing performance is significantly affected by *Texergy*'s control mechanism shown in Section 3.3 as well as the practical deployment on the body. Specifically, friction is introduced when the hook travels under a hoop and when the rubber cord stretches on a curved surface. This reduces the efficiency of both harvesting and releasing energy. We thus evaluate the required pulling force to harvest the energy and the actuation completion of *Texergy* on curved surfaces to understand its performance in practical uses. We deploy both one-time harvesting and repetitive harvesting mechanisms (with two and four charging steps) on surfaces with different curvatures. The mechanisms use 10 cm of 1 mm diameter rubber string to achieve 10 cm displacement. We measure the actual pulling force required to stretch the string by 10 cm to understand the efficiency of harvesting; and we assess whether the desired actuation is achieved (i.e., if the hook returns fully to the start position to deliver 10 cm displacement). For curved surfaces, we 3D-printed spheres with diameters from 12 cm to 20 cm and 2 cm apart, which were then covered with foam (shore hardness A15) to simulate soft human skin (shore hardness A10-30 based on [43]). The required pulling force changes based on the pulling direction. To simulate the worst-case scenario with the highest friction, we pulled along the surface. The forces are measured with a force gauge and repeated three times. We also label exemplary body parts that fall into the range of the tested curvature based on the ANSUR II dataset [11] and empirical measurements. However, since body dimensions differ significantly across individuals, we recommend empirically measuring the dimensions and adjusting the prototype for personalized designs. Alternatively, *Texergy* mechanisms can be created based on clothing sizes to generalize to similar body sizes. This also nicely integrates with mass manufacturing to potentially allow *Texergy*-embedded clothing to be bought off-the-rack.

The results are shown in Figure 11. For all mechanisms, the required pulling force increases significantly as the underlying surface curvature increases, and only increases by a small amount with the number of steps. This implies that to actuate the same output for users with smaller body sizes, a higher-force harvesting movement is needed to harvest the energy needed. Full actuation can be achieved on all surfaces for one-time harvesting. However,



curvature (diameter)	one-time		repetitive (2-step)		repetitive (4-step)	
	required pulling force	full actuation	required pulling force	full actuation	required pulling force	full actuation
flat	4.69 N	✓	4.77 N	✓	4.86 N	✓
20cm	7.08 N	✓	7.24 N	✓	7.95 N	✓
18cm	7.32 N	✓	7.49 N	✓	8.69 N	✓
16cm	8.1 N	✓	8.42 N	✓	9.1 N	✕
14cm	8.62 N	✓	8.86 N	✓	9.3 N	✕
12cm	9.06 N	✓	9.24 N	✕	10.78 N	✕

Figure 11: The efficiency of harvesting and releasing energy on curved surfaces. With increasing curvature, the harvesting force increases significantly, and actuation in repetitive harvesting mechanisms starts to fail. Examples of body parts are given for each curvature for reference.

curvature (diameter)	one-time			repetitive (2-step)			repetitive (4-step)		
	displacement			displacement			displacement		
	5cm	10cm	15cm	5cm	10cm	15cm	5cm	10cm	15cm
flat	2.05 N	2.75 N	3.55 N	2.11 N	2.87 N	3.68 N	2.24 N	2.96 N	3.84 N
20cm	1.65 N	2.08 N	2.87 N	1.74 N	2.2 N	3.11 N	2.11 N	2.44 N	3.36 N
16cm	1.49 N	1.83 N	2.23 N	1.65 N	2.1 N	2.38 N	1.72 N	2.27 N	2.69 N

Figure 12: The force needed to release the stored energy on curved surfaces with different mechanisms and stored energy. Strong forces are needed when more energy is stored on flatter surfaces and with a higher number of steps.

as the number of steps increases, the actuation begins to fail as the hook gets stopped by one of the hoops due to friction in highly curved surfaces. We therefore recommend avoiding using repetitive harvesting on highly curved surfaces to achieve more efficient energy harvesting and successful actuation. In practical deployment, the efficiency is further affected by the routing of harvesting movement and output end-effector in individual designs, which should be empirically determined.

5.3 Triggering the energy release

Based on the design parameters shown in Figure 8, pulling the releasing strip to release the energy requires a small displacement of 1.4 cm from the user. Here, we characterize how much pulling force is required to release the stored energy. We evaluate the required force in both one-time and repetitive harvesting mechanisms in relation to the energy stored and the underlying surface curvatures. We test one-time harvesting mechanisms and repetitive harvesting mechanisms with two and four steps, which affect the number of pleats the releasing strip routes through. We vary the energy stored by taking a rubber cord of 15 cm original length and harvesting the energy from displacements of 5 cm, 10 cm, and 15 cm. For different underlying surfaces, we used the same setup as in Section 5.2 and tested flat, 20cm diameter, and 16cm diameter surfaces.

The results are shown in Figure 12. The release force stays in a reasonable range of under 4N, which users are able to provide with daily body movements and clothing manipulations. The release force increases significantly with the amount of energy stored but decreases with increasing surface curvature. The force only increases marginally with the number of steps with a lower than 0.5 N difference between one-time mechanisms and 4-step repetitive ones. This is because the hook only engages with one of the hoops, while very little force is needed to move the other pleats in parallel with the releasing strip.

6 APPLICATIONS

We showcase four applications to demonstrate *Texergy*'s versatility and capability.

6.1 Automatic belt

Automatic umbrellas store energy to actuate the output (i.e., the umbrella opening) instantaneously by a small finger press to replace the cumbersome user motions (i.e., pushing the runner over a large distance) required in traditional umbrellas. *Texergy* can realize

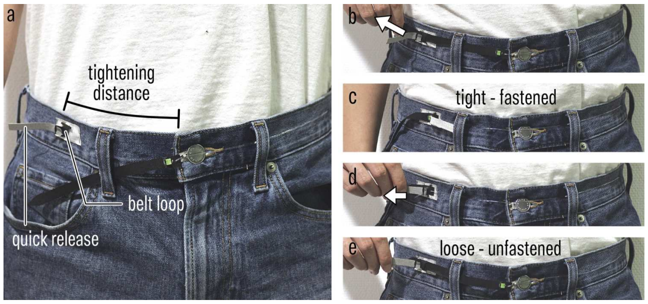


Figure 13: (a) We created a quick-release belt with *Texergy* that is integrated into the pants. (b-c) The energy is stored when the user tightens the belt and (d-e) can be released by a small pulling action to loosen the belt instantaneously.

similar functionalities but on the body and with a soft and flexible form factor. Specifically, *Texergy* can be leveraged to replace conventional long-distance and/or large-force clothing manipulations with shorter and easier user actions to achieve the same output.

As an example, we created an automatic belt that can be loosened instantly with a very small one-hand action as shown in Figure 13. This makes belts easier to unfasten and can be helpful when one hand of the user is occupied or for rapid removal in emergencies. (a) We sew the hoop part of a one-time harvesting mechanism at the left side, and the elastic rubber cord is routed on the denim on the right side of the waist. The displacement layer functions as the belt and the hoop the belt hole. (b) As the user pulls the belt through the belt hole, the rubber cord is stretched. (c) The hook on the belt locks onto the hoop to fasten the belt and securely tighten the jeans at the waist. (d-e) Later a very small and quick pulling action on the release strip can unfasten the belt instantly. Users can also additively modify the mechanism or change the color of the components to customize the appearance of the belt.

6.2 Passive exosuit with dynamic assistance

Passive exosuits are wearable devices that assist user movement by using non-powered mechanical components, such as elastic bands and springs. For example, passive exosuits that assist with knee extensions usually use an elastic tendon that runs across the knee and gets stretched during knee bends, like the tendon shown in Figure 14 a. The tension in the stretched tendon helps lift the foot to assist knee extension. While the assistance provided by current passive exosuits is always constant, i.e., the users feel the same force every time they bend the knee, *Texergy* can provide dynamic assistance and on demand to further help with effective training.

We demonstrate this with a *Texergy*-based passive exosuit for knee extension that, instead of having an elastic band with constant force, allows the user to dynamically change how tight the tendon is and adjust the assistance. The implemented prototype is shown in Figure 14. (a) A 4-step repetitive harvesting *Texergy* mechanism is added with the tendon as the output to control the tendon. The mechanism harvests energy from repeating knee bends during the exercise with a shorter harvesting strip that runs over the knee and connects to the calf. The rubber cord runs along the upper thigh with one end fixed at the waist.

The exosuit provides assistance dynamically to assist in a cycle of knee extension exercises. (b) To ease into the exercise, the user starts the exercise with the tendon tightened and maximum force support (~7N), which helps lift up the lower leg from the bent knee position. When the user returns to bent-knee, one step of energy is harvested and stored. This loosens the tendon a bit and reduces the assistance when the user performs the second knee extension. The knee extensions thus get progressively harder as the tendon gets looser with each step of energy harvested from knee bends to encourage improving the performance gradually. (d) After four extensions, the tendon is completely loose with no assistance, and the energy is completely charged. The user then performs the knee extensions independently without any help. (e) Later, when the user starts to get tired and is in need of assistance, he/she can pull the release strip to release the stored energy. The tendon is then

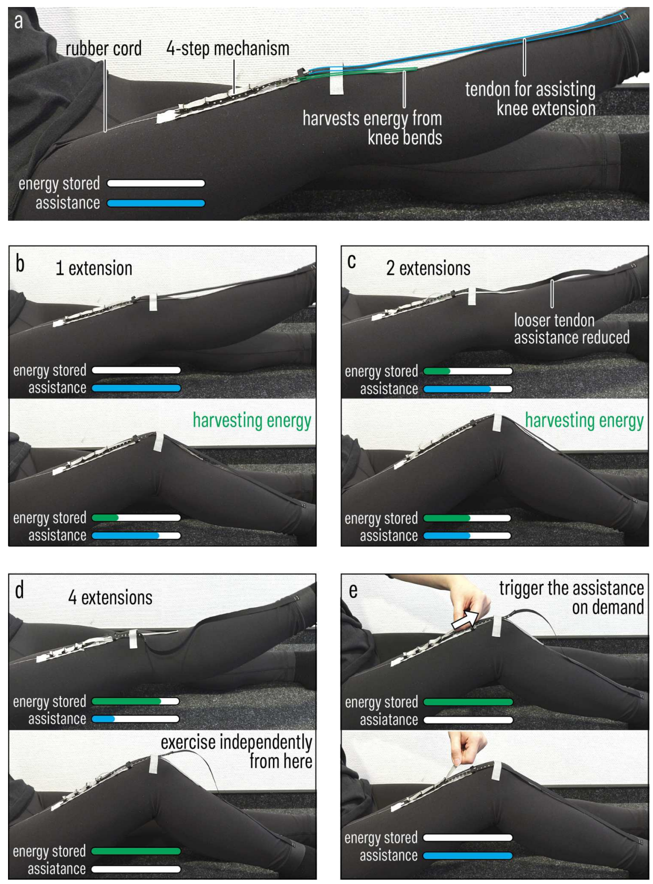


Figure 14: (a) We use a 4-step *Texergy* mechanism to control the tendon for knee extensions to achieve dynamic, user-triggered assistance. (b-c) The tendon provides kinesthetic force feedback during extension and one step of energy is harvested from each knee-bend. As energy is harvested, the assistance gradually reduces to progressively make the exercise harder. (d) After four extensions, the harvesting is completed and the user exercises independently. (e) Assistance can be triggered later on demand to repeat b-d.

tightened again to start the next cycle of assisted exercise, which repeat the steps from (b) to (e).

6.3 Self-powered VR haptic feedback

Virtual Reality technologies are becoming more wearable and mobile with Head-Mounted Displays that are able to create immersive visual experiences. *Texergy* has the potential to complement these immersive experiences with haptic feedback that can be directly integrated into clothing, providing untethered actuation that is entirely powered by user actions. To achieve this, the user interactions needed for harvesting and releasing the energy in *Texergy* can be cleverly mapped to user actions in the virtual experience to provide real-time haptic experiences. Though not as versatile as traditional actuators, many virtual experiences contain recurring actions and events in which tailored *Texergy* systems can provide power-free repeated actuation of the haptic feedback.

As an example, we create a simple VR application in which the user wears a rocket arm that can be fired to attack and later recalled to return back to the user's arm (similar to Iron Man's armor). We implement a *Texergy*-based haptic top that provides on-and-off squeezing haptic feedback that corresponds to wearing or not wearing the rocket arm. The working of the application is shown in Figure 15. (a) Similar to Figure 6, we route fishing lines around the arm to create squeezing haptic feedback. A *Texergy* mechanism is placed on the arm, and the elastic rubber cord connects to the shoulder. When no energy is stored, the fishing line is in its default squeezing state to simulate wearing the rocket arm. The user manipulates the two sliders on the rocket arm in VR for firing and recalling the arm, which correspond to the harvesting and the releasing movements, respectively. (b) When shooting a target, the user pulls the front slider to lock the target. This pulling movement is harvested by the mechanism to store some energy. (c) When the user releases the slider to fire the rocket arm, the energy is harvested which relaxes the fishing line and the squeezing feedback disappears. (d) To recall the rocket arm, the user pulls the back slider in VR and the releasing strip in the mechanism. This releases the stored energy to pull the fishing line tight, creating the squeezing sensation as the rocket arm flies back.

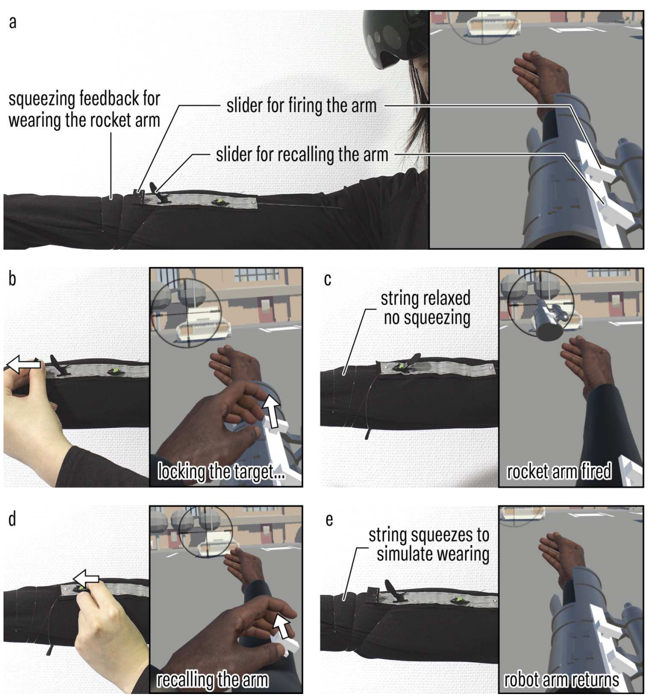


Figure 15: (a) *Texergy* can be driven by implicit user actions in VR to provide highly wearable passive haptic feedback, e.g., create squeezing sensations to simulate wearing a rocket arm. (b-c) Firing the rocket arm charges the energy and the squeezing disappears. (d-e) Recalling the arm releases the energy and actuates the squeezing as the arm flies back.

6.4 Shape-changing dancing costume

As shown in Figure 1, *Texergy* can be used to create instantaneous shape changes with a small and unobtrusive motion in the performance. This sudden change of visual appearance can amplify theater or fashion performances by creating a dramatic visual effect at the finale or seamlessly transforming a costume to reflect a plot twist, etc. We used a simple tendon-driven shape change to demonstrate the effect, but the same mechanism works for other on-body shape changes, offering designers new creative possibilities for dynamic visual storytelling.

Here, we show the detailed mechanism that realizes the presented shape-changing costume in Figure 16. The strings that are routed on the body are color-coded. The rubber cord is routed along the outer seams of the top and the pants. The harvesting string routes under the arm to harvest displacement during arm lifts and stretches the rubber cord. After the energy is harvested, the dancer can freely move around and continue the dance. The stored energy can be later released by twisting the body, which is enabled by the releasing string that connects the shoulder to the pleat on the mechanism. This then actuates the shape-changing output. This interactive shape-changing directly integrated into the costume can be used repetitively during a performance - the actuated output is automatically reset when the user is doing the harvesting motion to prepare for the next actuation.

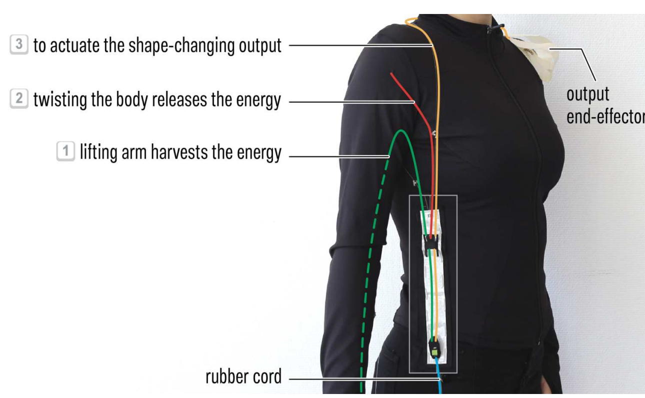


Figure 16: The dancing costume routes different body movements to control the actuation of the on-body shape change.

7 LIMITATIONS AND FUTURE WORK

Limitations on the latch mechanism. The latch mechanism requires a minimum displacement or force to engage, constrained by the size of each latch. In our design, we minimized this size while avoiding the 3D-printed hook breaking or tearing apart the fabric-based hoops. Further miniaturization could involve coating the fabric to reduce fraying at the cost of increasing stiffness, or using stronger materials (e.g., metal) for smaller, more durable hooks.

Currently, the latch mechanisms and the elastic string are laid out linearly to reduce friction. This constrains the total displacement and force by the lengths of the mechanism and the elastic string. Future work could explore more space-efficient routing geometries, which would require methods to minimize friction during routing (e.g., by developing wearable alternatives to pulley systems).

Limitations on soft elastic materials. Soft elastic materials, such as stretchy textiles and rubber cords that we considered for storing energy in *Texergy*, have some inherent limitations compared to metal springs. Stretchy textiles and rubber cords have nonlinear stress-strain behavior and are more prone to hysteresis, making it difficult to characterize the stored and released energy. They also produce less force and are less durable than metal springs. *Texergy* is thus not intended to replace high-strength actuation or precise motors, but rather to provide sufficient displacement for light-force on-body actuation using soft elastic materials that offer flexibility and body compatibility.

Extending types of actuation. As an initial exploration of textile-based programmable on-body actuation, *Texergy* creates a linear, one-time actuation with the same displacement that is harvested. Going forward there is a vast space to extend the types of actuation that *Texergy* can create to make such actuation even more dynamic and versatile. For example, the stored energy can be released in multiple steps to create an intermittent actuation effect. In our repetitive harvesting control mechanism, this can be achieved by pulling each pleat separately. However, this requires careful design of user interactions to perform the stepped release. *Texergy* requires harvesting the same displacement and force as the actuation. There is potential in creating textile-based pulley systems on the body to trade displacement for force or vice versa when the harvesting displacement and force do not equal those needed for actuation. For example, this can enable harvesting a short-distance, high-force user action to then actuate a long-distance, low-force on-body output. This can be done by routing the output strings through channels to create the pulleys, but would add a lot of friction. The output motion types, which is currently limited to linear actuation, can also be expanded. He et al. [14] achieved a wide range of motion types (e.g., rotation, reciprocation, and oscillation) in 3D-printed passive actuation systems. However, as these motion types are typically realized by rigid gears and mechanisms, clothing compatible alternatives will need to be developed. For example, soft robotics approaches like twisted string actuators can be used to create rotary outputs.

Decoupling stored energy and output. Currently, in *Texergy*, the energy stored and the output actuation are always connected - in the implementation, both are realized by moving the displacement layer. This implies that after releasing the stored energy to actuate the output, the output is gradually "unactuated" and returns to its original state during the next round of harvesting. This enables resetting the on-body output automatically without requiring an additional user interaction. However, we believe that an extension of the current *Texergy* control mechanism that decouples stored energy and output actuation can provide more flexibility in designing the interactions. This requires an engaging mechanism that temporarily connects the output to the stored energy during actuation and an output resetting action that the user can easily perform.

Wearability and daily use. The system is made primarily of fabrics with a minimal amount of plastics and therefore can be washed like regular clothing. The channels route and anchor the strings to the body, preventing slack or tangling. Enclosing the mechanism within the garment can further improve wearability and protect it from external damage in daily use.

Improving the durability of Texergy in mass manufacturing. Texergy require low-friction textiles and our fabrication approach, which enable easy and programmable customization of *Texergy* systems, require laser-cut-safe and non-fray ones. It was difficult to find off-the-shelf textiles that satisfied these requirements, hence the necessity of taping non-fray coated cotton textiles to reduce the friction. Our fabrication approach also introduces wear and tear at the connection points between the slots and tabs, making *Texergy* vulnerable to high force applications. The materials we used and the fabrication approach we contributed, therefore, are best suited for the customized prototyping of passive on-body actuation. On the other hand, *Texergy* has the potential to be directly integrated into off-the-rack clothing during mass manufacturing processes to make clothing more expressive and interactive. In that case, *Texergy* mechanisms would benefit from specialized textile materials that mechanically comply with the requirements and industrial fabrication method that can make the mechanism more robust.

8 CONCLUSION

Texergy presents a textile-based technical framework for passive, programmable, and interactive actuation of on-body output to enhance its functionality and versatility. Specifically, *Texergy* enables the designer to control when and at what scale of output is actuated by what user action. *Texergy* achieves this by harvesting energy from user actions, storing it mechanically on the body, and later releasing the energy on demand to actuate the on-body output. We provided components to enable creating end-to-end *Texergy* systems on the body, including input modules that harvest energy from user actions, elastic materials that can store the energy, energy control mechanisms that realize the store and release of the energy, and output end-effectors that connect *Texergy* mechanisms to existing on-body outputs. *Texergy* uses almost entirely textile materials and is created using a novel fabrication approach based on laser-cutting and simple manual assembly to enable integration into clothing and easy prototyping. The results of our technical experiments and a dedicated design tool are provided to support customizing *Texergy* mechanisms' actuation force and distance, type of harvesting, and deployment. Finally, we have demonstrated *Texergy*'s capabilities with four clothing-integrated, passive applications that enable user-defined actuation of on-body outputs for assistance, dynamic haptic feedback, and change of visual appearance that are "powered" entirely by the user's implicit actions.

ACKNOWLEDGMENTS

This work is partly supported by the Deutsche Forschungsgemeinschaft under Grant No. 521586817 within the Priority Program SPP 2199 Scalable Interaction Paradigms for Pervasive Computing Environments.

REFERENCES

[1] Roland Aigner, Andreas Pointner, Thomas Preindl, Rainer Danner, and Michael Haller. 2021. TexYZ: Embroidering Enameled Wires for Three Degree-of-Freedom Mutual Capacitive Sensing. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 499, 12 pages. https://doi.org/10.1145/3411764.3445479

[2] Lea Albaugh, Scott Hudson, and Lining Yao. 2019. Digital Fabrication of Soft Actuated Objects by Machine Knitting. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300414

[3] Thomas P. Chenal, Jennifer C. Case, Jamie Paik, and Rebecca K. Kramer. 2014. Variable stiffness fabrics with embedded shape memory materials for wearable applications. In *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2827–2831. https://doi.org/10.1109/IROS.2014.6942950

[4] Young-Man Choi, Moon Gu Lee, and Yongho Jeon. 2017. Wearable Biomechanical Energy Harvesting Technologies. *Energies* 10, 10 (2017). https://doi.org/10.3390/en10101483

[5] Laura Devendorf and Chad Di Lauro. 2019. Adapting Double Weaving and Yarn Plying Techniques for Smart Textiles Applications. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 77–85. https://doi.org/10.1145/3294109.3295625

[6] Laura Devendorf, Joanne Lo, Noura Howell, Jung Lin Lee, Nan-Wei Gong, M. Emre Karagozler, Shiho Fukuhara, Ivan Poupyrev, Eric Paulos, and Kimiko Ryokai. 2016. "I Don't Want to Wear a Screen": Probing Perceptions of and Possibilities for Dynamic Displays on Clothing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 6028–6039. https://doi.org/10.1145/2858036.2858192

[7] Jiachun Du, Panos Markopoulos, Qi Wang, Marina Toeters, and Ting Gong. 2018. ShapeTex: Implementing Shape-Changing Structures in Fabric for Wearable Actuation. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 166–176. https://doi.org/10.1145/3173225.3173245

[8] Jack Forman, Ozgun Kilic Afsar, Sarah Nicita, Rosalie Hsin-Ju Lin, Liu Yang, Megan Hofmann, Akshay Kothakonda, Zachary Gordon, Cedric Honnet, Kristen Dorsey, Neil Gershenfeld, and Hiroshi Ishii. 2023. FibeRobo: Fabricating 4D Fiber Interfaces by Continuous Drawing of Temperature Tunable Liquid Crystal Elastomers. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 19, 17 pages. https://doi.org/10.1145/3586183.3606732

[9] Jack Forman, Taylor Tabb, Youngwook Do, Meng-Han Yeh, Adrian Galvin, and Lining Yao. 2019. ModiFiber: Two-Way Morphing Soft Thread Actuators for Tangible Interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3290605.3300890

[10] Jun Gong, Yu Wu, Lei Yan, Teddy Seyed, and Xing-Dong Yang. 2019. Tessutivo: Contextual Interactions on Interactive Fabrics with Inductive Sensing. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 29–41. https://doi.org/10.1145/3332165.3347897

[11] Claire C. Gordon, Cynthia L. Blackwell, Bruce Bradtmiller, Joseph L. Parham, Patricia Barrientos, Steven P. Paquette, Brian D. Corner, Jeremy M. Carson, Joseph C. Venezia, Belva M. Rockwell, Marsha Mucher, and Sara Kristensen. 2015. *2012 Anthropometric Survey of U.S. Army Personnel: Methods and Summary Statistics*. Technical Report NATICK/TR-15/007. U.S. Army Natick Soldier Research, Development and Engineering Center, Natick, MA.

[12] Justyna Gołąbek and Michał Strankowski. 2024. A Review of Recent Advances in Human-Motion Energy Harvesting Nanogenerators, Self-Powering Smart Sensors and Self-Charging Electronics. *Sensors* 24, 4 (2024). https://doi.org/10.3390/s24041069

[13] Alice C Haynes and Jürgen Steimle. 2024. Flextiles: Designing Customisable Shape-Change in Textiles with SMA-Actuated Smocking Patterns. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 517, 17 pages. https://doi.org/10.1145/3613904.3642848

[14] Liang He, Xia Su, Huaishu Peng, Jeffrey Ian Lipton, and Jon E. Froehlich. 2022. Kinergy: Creating 3D Printable Motion using Embedded Kinetic Energy. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 69, 15 pages. https://doi.org/10.1145/3526113.3545636

[15] Meng He, Wenwen Du, Yanmin Feng, Shijie Li, Wei Wang, Xiang Zhang, Aifang Yu, Lingyu Wan, and Junyi Zhai. 2021. Flexible and stretchable triboelectric nanogenerator fabric for biomechanical energy harvesting and self-powered dual-mode human motion monitoring. *Nano Energy* 86 (2021), 106058. https://doi.org/10.1016/j.nanoen.2021.106058

[16] Cedric Honnet, Hannah Perner-Wilson, Marc Teyssier, Bruno Fruchard, Jürgen Steimle, Ana C. Baptista, and Paul Strohmeier. 2020. PolySense: Augmenting Textiles with Electrical Functionality using In-Situ Polymerization. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (<conf-loc>, <city>Honolulu</city>, <state>HI</state>, <country>USA</country>, </conf-loc>) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376841

[17] Kunpeng Huang, Ruojia Sun, Ximeng Zhang, Md. Tahmidul Islam Molla, Margaret Dunne, Francois Guimbretiere, and Cindy Hsin-Liu Kao. 2021. WovenProbe: Probing Possibilities for Weaving Fully-Integrated On-Skin Systems Deployable in the Field. In *Designing Interactive Systems Conference 2021* (Virtual Event, USA) *(DIS '21)*. Association for Computing Machinery, New York, NY, USA, 1143–1158. https://doi.org/10.1145/3461778.3462105

[18] Yu Jiang, Alice C Haynes, Narjes Pourjafarian, Jan Borchers, and Jürgen Steimle. 2024. Embrogami: Shape-Changing Textiles with Machine Embroidery. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology* (Pittsburgh, PA, USA) *(UIST '24)*. Association for Computing Machinery, New York, NY, USA, Article 63, 15 pages. https://doi.org/10.1145/3654777.3676431

[19] Thorsten Karrer, Moritz Wittenhagen, Leonhard Lichtschlag, Florian Heller, and Jan Borchers. 2011. Pinstripe: Eyes-Free Continuous Input on Interactive Clothing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 1313–1322. https://doi.org/10.1145/1978942.1979137

[20] Ozgun Kilic Afsar, Ali Shtarbanov, Hila Mor, Ken Nakagaki, Jack Forman, Karen Modrei, Seung Hee Jeong, Klas Hjort, Kristina Höök, and Hiroshi Ishii. 2021. OmniFiber: Integrated Fluidic Fiber Actuators for Weaving Movement Based Interactions into the 'Fabric of Everyday Life'. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 1010–1026. https://doi.org/10.1145/3472749.3474802

[21] Jin Hee (Heather) Kim, Kunpeng Huang, Simone White, Melissa Conroy, and Cindy Hsin-Liu Kao. 2021. KnitDermis: Fabricating Tactile On-Body Interfaces Through Machine Knitting. In *Designing Interactive Systems Conference 2021* (Virtual Event, USA) *(DIS '21)*. Association for Computing Machinery, New York, NY, USA, 1183–1200. https://doi.org/10.1145/3461778.3462007

[22] Jin Hee (Heather) Kim, Shreyas Dilip Patil, Sarina Matson, Melissa Conroy, and Cindy Hsin-Liu Kao. 2022. KnitSkin: Machine-Knitted Scaled Skin for Locomotion. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 391, 15 pages. https://doi.org/10.1145/3491102.3502142

[23] Asimina Kiourti, Cedric Lee, and John L. Volakis. 2016. Fabrication of Textile Antennas and Circuits With 0.1 mm Precision. *IEEE Antennas and Wireless Propagation Letters* 15 (2016), 151–153. https://doi.org/10.1109/LAWP.2015.2435257

[24] Kayla Kowalczyk, Mukul Mukherjee, and Philippe Malcolm. 2023. Can a passive unilateral hip exosuit diminish walking asymmetry? A randomized trial. *Journal of NeuroEngineering and Rehabilitation* 20 (07 2023). https://doi.org/10.1186/s12984-023-01212-w

[25] Pin-Sung Ku, Kunpeng Huang, and Cindy Hsin-Liu Kao. 2022. Patch-O: Deformable Woven Patches for On-Body Actuation. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 615, 12 pages. https://doi.org/10.1145/3491102.3517633

[26] Qiuyu Lu, Semina Yi, Mengtian Gan, Jihong Huang, Xiao Zhang, Yue Yang, Chenyi Shen, and Lining Yao. 2024. Degrade to Function: Towards Eco-friendly Morphing Devices that Function Through Programmed Sequential Degradation. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology* (Pittsburgh, PA, USA) *(UIST '24)*. Association for Computing Machinery, New York, NY, USA, Article 109, 24 pages. https://doi.org/10.1145/3654777.3676464

[27] Qiuyu Lu, Tianyu Yu, Semina Yi, Yuran Ding, Haipeng Mi, and Lining Yao. 2023. Sustainflatable: Harvesting, Storing and Utilizing Ambient Energy for Pneumatic Morphing Interfaces. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 32, 20 pages. https://doi.org/10.1145/3586183.3606721

[28] Yiyue Luo, Kui Wu, Tomás Palacios, and Wojciech Matusik. 2021. KnitUI: Fabricating Interactive and Sensing Textiles with Machine Knitting. In *Proceedings*

of the 2021 CHI Conference on Human Factors in Computing Systems (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 668, 12 pages. https://doi.org/10.1145/3411764.3445780

[29] Sara Mlakar and Michael Haller. 2020. Design Investigation of Embroidered Interactive Elements on Non-Wearable Textile Interfaces. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3313831.3376692

[30] M. Mooney. 1940. A Theory of Large Elastic Deformation. *Journal of Applied Physics* 11, 9 (Sept. 1940), 582–592. https://doi.org/10.1063/1.1712836

[31] Sachith Muthukumarana, Moritz Alexander Messerschmidt, Denys J.C. Matthies, Jürgen Steimle, Philipp M. Scholl, and Suranga Nanayakkara. 2021. ClothTiles: A Prototyping Platform to Fabricate Customized Actuators on Clothing Using 3D Printing and Shape-Memory Alloys. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 510, 12 pages. https://doi.org/10.1145/3411764.3445613

[32] Pham Huy Nguyen and Wenlong Zhang. 2020. Design and Computational Modeling of Fabric Soft Pneumatic Actuators for Wearable Assistive Devices. *Scientific Reports* 10 (2020). https://api.semanticscholar.org/CorpusID:219637918

[33] Oliver Nowak, René Schäfer, Anke Brocker, Philipp Wacker, and Jan Borchers. 2022. Shaping Textile Sliders: An Evaluation of Form Factors and Tick Marks for Textile Sliders. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 214, 14 pages. https://doi.org/10.1145/3491102.3517473

[34] Patrick Parzer, Adwait Sharma, Anita Vogl, Jürgen Steimle, Alex Olwal, and Michael Haller. 2017. SmartSleeve: Real-time Sensing of Surface and Deformation Gestures on Flexible, Interactive Textiles, using a Hybrid Gesture Detection Pipeline. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 565–577. https://doi.org/10.1145/3126594.3126652

[35] Yuecheng Peng, Danchang Yan, Haotian Chen, Yue Yang, Ye Tao, Weitao Song, Lingyun Sun, and Guanyun Wang. 2024. IntelliTex: Fabricating Low-cost and Washable Functional Textiles using A Double-coating Process. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 859, 18 pages. https://doi.org/10.1145/3613904.3642759

[36] R. S. Rivlin. 1948. Large Elastic Deformations of Isotropic Materials. I. Fundamental Concepts. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences* 240, 822 (1948), 459–490. http://www.jstor.org/stable/91430

[37] René Schäfer, Oliver Nowak, Lovis Bero Suchmann, Sören Schröder, and Jan Borchers. 2023. What's That Shape? Investigating Eyes-Free Recognition of Textile Icons. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 580, 12 pages. https://doi.org/10.1145/3544548.3580920

[38] Rachel A. Shveda, Anoop Rajappan, Te Faye Yap, Zhen Liu, Marquise D. Bell, Barclay Jumet, Vanessa Sanchez, and Daniel J. Preston. 2022. A wearable textile-based pneumatic energy harvesting system for assistive robotics. *Science Advances* 8, 34 (2022), eabo2418. https://doi.org/10.1126/sciadv.abo2418 arXiv:https://www.science.org/doi/pdf/10.1126/sciadv.abo2418

[39] Sneh K. Sinha, Yeonsik Noh, Natasa Reljin, Gregory M. Treich, Shirin Hajeb-Mohammadalipour, Yang Guo, Ki H. Chon, and Gregory A. Sotzing. 2017. Screen-Printed PEDOT:PSS Electrodes on Commercial Finished Textiles for Electrocardiography. *ACS Applied Materials & Interfaces* 9, 43 (2017), 37524–37528. https://doi.org/10.1021/acsami.7b09954 arXiv:https://doi.org/10.1021/acsami.7b09954 PMID: 29020777.

[40] Ruojia Sun, Ryosuke Onose, Margaret Dunne, Andrea Ling, Amanda Denham, and Hsin-Liu (Cindy) Kao. 2020. Weaving a Second Skin: Exploring Opportunities for Crafting On-Skin Interfaces Through Weaving. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 365–377. https://doi.org/10.1145/3357236.3395548

[41] Amit Talukder and Jeyeon Jo. 2025. Elastic textile-based wearable modulation of musculoskeletal load: A comprehensive review of passive exosuits and resistance clothing. *Wearable Technologies* 6 (2025), e11. https://doi.org/10.1017/wtc.2025.2

[42] Shan-Yuan Teng, K. D. Wu, Jacqueline Chen, and Pedro Lopes. 2022. Prolonging VR Haptic Experiences by Harvesting Kinetic Energy from the User. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 39, 18 pages. https://doi.org/10.1145/3526113.3545635

[43] Redent Tonna, Panagiotis E. Chatzistergos, Otis Wyatt, and Nachiappan Chockalingam. 2024. Reliability and Validity of Shore Hardness in Plantar Soft Tissue Biomechanics. *Sensors* 24, 2 (2024). https://doi.org/10.3390/s24020539

[44] Wen Wang, Lining Yao, Chin-Yi Cheng, Teng Zhang, Hiroshi Atsumi, Luda Wang, Guanyun Wang, Oksana Anilionyte, Helene Steiner, Jifei Ou, Kang Zhou, Chris Wawrousek, Katherine Petrecca, Angela M. Belcher, Rohit Karnik, Xuanhe Zhao, Daniel I. C. Wang, and Hiroshi Ishii. 2017. Harnessing the hygroscopic and biofluorescent behaviors of genetically tractable microbial cells to design biohybrid wearables. *Science Advances* 3, 5 (2017), e1601984. https://doi.org/10.1126/sciadv.1601984 arXiv:https://www.science.org/doi/pdf/10.1126/sciadv.1601984

[45] Mark Weiser. 1999. The Computer for the 21st Century. *SIGMOBILE Mob. Comput. Commun. Rev.* 3, 3 (jul 1999), 3–11. https://doi.org/10.1145/329124.329126

[46] Shanel Wu and Laura Devendorf. 2020. Unfabricate: Designing Smart Textiles for Disassembly. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376227

[47] Shuaitao Yang, Chengwei Li, Ningxuan Wen, Shihong Xu, Hui Huang, Tianze Cong, Yongpeng Zhao, Zeng Fan, Kun Liu, and Lujun Pan. 2021. All-fabric-based multifunctional textile sensor for detection and discrimination of humidity, temperature, and strain stimuli. *J. Mater. Chem. C* 9 (2021), 13789–13798. Issue 39. https://doi.org/10.1039/D1TC02755G

[48] Lining Yao, Jifei Ou, Chin-Yi Cheng, Helene Steiner, Wen Wang, Guanyun Wang, and Hiroshi Ishii. 2015. bioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/2702123.2702611

[49] Tianhong Catherine Yu, Manru Mary Zhang, Peter He, Chi-Jung Lee, Cassidy Cheesman, Saif Mahmud, Ruidong Zhang, Francois Guimbretiere, and Cheng Zhang. 2024. SeamPose: Repurposing Seams as Capacitive Sensors in a Shirt for Upper-Body Pose Tracking. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology* (Pittsburgh, PA, USA) *(UIST '24)*. Association for Computing Machinery, New York, NY, USA, Article 72, 13 pages. https://doi.org/10.1145/3654777.3676341

[50] Hongtao Zhao, Xiangjun Qi, Yulong Ma, Xuantong Sun, Xuqing Liu, Xueji Zhang, Mingwei Tian, and Lijun Qu. 2021. Wearable Sunlight-Triggered Bimorph Textile Actuators. *Nano Letters* 21, 19 (2021), 8126–8134. https://doi.org/10.1021/acs.nanolett.1c02578 arXiv:https://doi.org/10.1021/acs.nanolett.1c02578 PMID: 34570519.

[51] Jingwen Zhu, Nadine El Nesr, Christina Simon, Nola Rettenmaier, Kaitlyn Beiler, and Cindy Hsin-Liu Kao. 2023. BioWeave: Weaving Thread-Based Sweat-Sensing On-Skin Interfaces. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 35, 11 pages. https://doi.org/10.1145/3586183.3606769