ExoForm: Shape Memory and Self-Fusing Semi-Rigid Wearables

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ABSTRACT

Semi-rigid and rigid structures have been utilized in many on-body applications including musculoskeletal support (e.g., braces and splints). However, most of these support structures are not very compliant, so effortless custom fitting becomes a unique design challenge. Furthermore, the weight and space needed to transport these structures impede adoption in mobile environments. Here, we introduce ExoForm, a compact, customizable, and semi-rigid wearable material system with self-fusing edges that can semi-autonomously assemble on-demand while providing integrated sensing, control, and mobility. We present a comprehensive and holistic engineering strategy that includes optimized material composition, computationally-guided design and fabrication, semi-autonomous self-morphing assembly and fusing steps, heating control, and sensing for our easy-to-wear ExoForm. Finally, we fabricate wearable braces using the ExoForm method as a demonstration along with preliminary evaluation of ExoForm's performance.

CCS CONCEPTS

• **Human-centered computing**; • **Human computer interaction (HCI)**; • **Interactive system and tools**;

KEYWORDS

4D printing, Semi-rigid wearables, Personal fabrication, Shape change, Tangible interaction

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1 INTRODUCTION

Until recently, the majority of orthotic devices were designed and hand-crafted by medical professionals. Therefore, the quality and design corresponded directly to the specialist's skill and experience [39]. Off the shelf solutions are usually temporary and not customized for each user, while custom casts require 3D scanning and printing or form casting [29]. The desire for user-specific, time-efficient, lightweight, and adjustable solutions is of great importance, especially when access to clinical facilities is restricted.

This paper introduces ExoForm, a novel design and fabrication solution for dynamic orthotic devices. Our technique augments semi-rigid wearables for immediate, self-morphing, adjustable, and repeatable use that offers user-specific conformability even at remote sites, without dependence on medical professionals.

We were inspired to use heat to soften a flat thermoplastic sheet to then remold and adjust it around the body for user specificity [14, 19]. Distinctively, these wearables are easy to store and transport through flat-packing their initial, 2D form. Unfortunately, existing artifacts were either small (e.g., a finger splint in [19] or simple shapes (e.g., a wristband in Hotflex [14]). Furthermore, they cannot successfully support complex parts of the body. Finally, preheated pieces may cool before tricky, manual on-body adjustment is finished.

Building on prior work, we propose an active, semi-autonomous self-morphing process for light wearables that have initially flat forms and morph when heated. ExoForm furthers the advantageous, on-body adjustment procedure, suggested by Hofmann et al. [14, 19], with a self-folding behavior that establishes a loose-fit before on body adjustment forms a personalized fit, allowing for easier application. These behaviors are initialized in ExoForm's multilayer composite structure and controlled through a combination of material selection, directionality, and design. Moreover, by choosing many body areas to cover, we demonstrate how ExoForm can be applied to various sizes and geometries, well beyond those which have been demonstrated.

2 RELATED WORK

2.1 4D Printing and Shape Changing Interfaces

Shape changing interfaces have been developed using pneumatic actuation [62], particle jamming [3, 12, 18, 40], foam material expanding with heat [23], and 4D printing. With 4D printing, novel

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Figure 1: ExoForm is a set of semi-rigid wearables that demonstrate morphability and customizability in splints.

and dynamic designs emerge via embedded, pre-programed stimulus responses in 3D printed shape memory materials [31, 60] like polylactic acid (PLA) [2, 48, 56, 57, 67], polycaprolactone [22, 49], polyurethanes [17, 33], and shape memory alloys [5, 68]. Mimicking morphing behaviors in nature [38], these are triggered with stimuli including humidity, temperature, or solvents. 4D printing has been used in biomimetic applications [21, 34, 50] and robotics [47], and, in Human-Computer Interaction (HCI), it has even been applied to furniture assembly [57] and cooking approaches [58]. Many shape changing interfaces were developed by transforming 2D, PLA meshes and sheets into 3D geometries [2, 57]. Unfortunately, this transformation cannot be reversed and requires external heating tools. Other approaches, Printed Paper Actuator [55] and particle jamming [40], demonstrated reversible shape changes but were limited by structural rigidity or external energy sources.

2.2 Custom Wearables

Thermoforming has been used to fabricate custom wearables using the softening properties of thermoplastics at elevated temperatures in mouth guards [51, 52], contact lenses [10, 43], and casts [20] (FastForm, Breg. Inc). In HCI, Hoffman et al. customized a supportive wearable using thermally moldable thermoplastics [19]. However, it required external heating sources to reach a moldable state, and, without an initial shape change, it is difficult to apply these wearables in a timely manner, over complex body structures.

Conversely, user-specific wearables have been developed with 3D printing. In the HCI community, a common approach involves modelling before 3D printing to achieve a personal fit for rigid [29, 65] or stretchable wearables [30]. One industry example, Osteoid, also used this approach for their cast [39]. While these achieve perfect custom fits for each user, they require complex, time-consuming editing of body scans.

2.3 Resistive Heating

Resistive heaters enable heat interactive interfaces without external triggering tools. These have been used in thermoreactive interfaces [26, 54], tunable skin interfaces [24], and shape-changing mechanisms. Resistive heaters are also effective on flexible circuit composites [16] and paper [55]. Prior work has applied resistive heaters to shape memory pre-stretched polystyrene (PSPS) for self-folding robots [11]. However, the temperature for triggering that effect is up to 160°C, too dangerous for wearable applications. Hotflex [14] showed free-form remodeling of PLA objects at lower temperature, but the heater primarily provided heat to a region without active actuation. In designing these heaters, there are also many conductive materials to consider alongside fabrication including sewing, weaving, or cutting conductive thread [6, 8, 26], inkjet printing silver ink [37, 54], etching copper plates [11], 3D printing composite filament [55], compressing and laser cutting conductive polymer pellets coated with liquid metal [44] and applying gold leaf [25].

3 DESIGN STRATEGY

ExoForm augments existing technology by demonstrating morphability and customizability with closed-loop feedback for sensing and control in wearable splints. To best support the body and healing process, we introduce a shape memory semi-autonomous wearing procedure, self-fusing edges, and reversible actuation. For our wearing procedure, we use shape-memory materials that are pre-programmed to fold into a specific shape upon heating. ExoForm has a multi-step deployment procedure: Users wrap 3 layers of gauze around the body to protect the skin. Then, off-body standardized bending via shape-memory and resistive heating initializes a rough fit (Figure 2 a-b). Finally, an on-body tight fit is established via manual sculpting (Figure 2 c). To join multiple parts or modules, ExoForm also features self-fusing edges which heal over time at room temperature to form cohesive structures. Additionally, we introduce reversible actuation for functional, temporal adjustment which allows users to readjust the wearable as they heal. The user can also use this feature to flatten the part and store it for future use.

Figure 2: (a) Initial flat state of ExoForm. (b) Layers of gauze wrapped around the body part. (c) Step 1: off-body rough fit with self-folding. (d) Step 2: on-body manual tight fit with conformability.

4 EXOFORM COMPOSITION

To achieve our design strategy, we propose the following basic layer-composite (Figure 3). It is made of multiple layers: a constraint and protection layer, an actuation layer, a resistive heating layer, self-fusing edges, and a sensing and control layer for augmenting the design. Literature has shown that PLA is the one of the most commonly used biodegradable polymers in clinical applications with examples including long-term implantable devices [45]. Thus, the use of PLA is safe to be used in external wearable applications. Double sided tape (3M VHB tape, F9560PC, 0.05mm) is used to bond functional layers. This layer-composite is also suitable for on-skin applications.

4.1 Actuation and Constraint Layer

It has been difficult to control the transformation of PLA actuators longer than 10cm [57], so we adopt a novel PET constraint layer to improve bending performance. Figure 4 shows a simple PLA

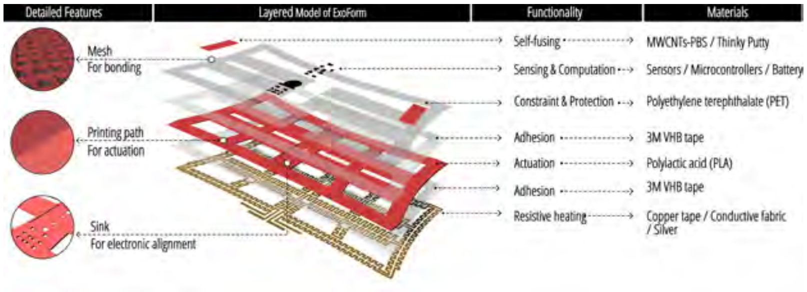

Figure 3: Layered structure for each semi-rigid wearable.

actuator, large enough to wrap halfway around the neck (15cm x 1.5cm), with and without PET film (0.6mm). The PET film helps achieve reversible actuation and increases the beam's effective strength compared to paper [55, 57]. This works with PET's higher glass transition temperature such that PET is not impacted during PLA actuation. This actuation also depends on PLA's thickness. Figure 5 shows how the thickness of PLA, deposited by a Makerbot (Replicator 2x) 3D printer at 4000mm/s, affects the composite's bending angle. Considering maximum bending curvature, effective strength, and efficiency of heating, we choose a thickness of 1mm for the PLA, actuation layer in our sample artifacts.

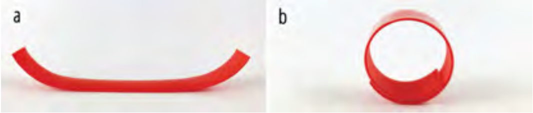

Figure 4: Bending actuator at neck brace scale (15cm x 1.5cm) using: (a) PLA 0.5mm actuator and 0.5mm constrain layer (b) PLA 1mm actuator taped to PET film, each triggered in an oven at 75oC for 1 min.

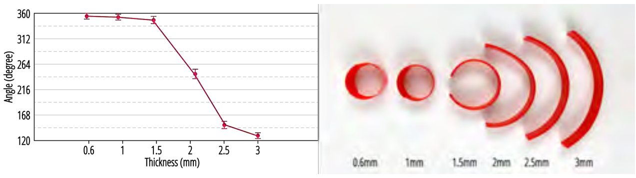

Figure 5: Bending angles with different PLA layer thickness, all samples are triggered in an oven at 75oC for 1 min.

While conventional 4D-printed actuators were for non-reversible self-folding, the addition of a stiff PET layer, with a higher glass transition temperature, also enables reversible bending and flattening, which allows for readjustment of the cast. This property is leveraged to develop the functional feature mentioned earlier for reversible actuation and temporal readjustment of the wearables.

4.2 Self-fusing Layer

With ExoForm's self-fusing edges, users apply each part or module sequentially, so ExoForm fuses into one piece on the body (Figure 6). This approach simplifies transport and assembly of larger wearables. Literature has reported very effective re-healability of the self-fusing materials (Thinking Putty, Crazy Aaron's) we adopted [61]. Mechanical and electrical properties recover completely after 6 hours, and the self-fusing process begins immediately after the two edges come into contact, as demonstrated in Self-healing UI [36]. According to our test, after 2 mins of healing, we can move the body without breaking the self-fusing edges. Additionally, the self-fusing edges can be broken down and re-joined repetitively for reuse.

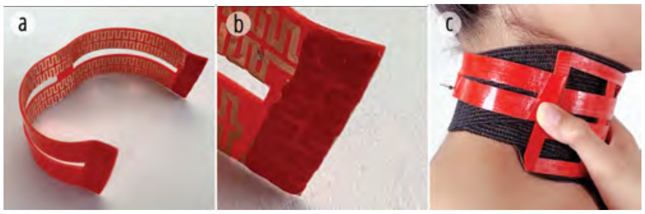

Figure 6: (a-b) Thinking Putty applied to each module's edges. (c) Self-fusing edges connect modules.

4.3 Resistive Heating Layer

Alongside investigating resistive heater materials, we contribute a strategy to select, characterize, and design heater patterns. We use a 70 to 80°C temperature range [2, 56] to morph ExoForm for off-body rough fitting, which takes 60 seconds. Our prototypes use rechargeable 9V lithium batteries with a maximum power supply (Vmax) of 10V, and maximum current (Imax) is set to 2.5A for user safety. We also design a handle for users to hold while heating to avoid burns. To select a heater material, we consider conductivity, flexibility, and manufacturability. We first evaluated power consumption by calculating the normalized power per area to heat to 75°C within 60s (Pn) [15]. Pn is defined by P/LW, where P is total power consumption, L is the length, and W is the width of the trace. We fabricated 5 mm (W) x 20 mm (L) samples and placed them on a PLA sheet. The thickness of each material is determined by fabrication, for silver ink and MWCNTs-PBS, and by off-the-shelf availability, for fabrics and foil. Power is then provided to heat the samples to 75°C within 60s, and trials were repeated three times. Figure 7 shows these results. For ExoForm, the selected material depends on each design's required trace length. Designs with large surface area used

Material	Thickness (mm)	Sheet resistance (Ω/sq cm²)	Normalized power (W/cm²)	Max total length (cm)
4wt% MWCNTs-PBS	1.2	1388.9	0.2179	0.1573
7wt% MWCNTs-PBS	1.2	539.5	0.25	0.775
Silver (ChemCubed)	0.01	0.0173	0.3868	110.02
Woven Conductive fabric (Suzhou Wanhe Electronics Co.LTD)	0.08	0.04	0.327	78.69
Conductive fabric (3M)	0.11	0.05	0.208	88.25
Copper foil tape	0.03	0.0011	0.4893	387.93

Figure 7: Heater property characterization with each material heated up to 75°C within 60s.

copper foil while smaller designs had silver printed directly on the PET film.

Inspired by Cartolano et al. [6], we use the pattern in Figure 8(a-b), where w is the trace width and g is the gap. To demonstrate, our neck design uses a 1.5mm trace width and 1mm gaps, with calculated trace length of 574.08cm. Copper foil is the best material, and two 9V batteries are required to heat the part. Our theoretical calculation found a 9 V, 800 mAh battery will last at 4.5 A for 10.7 mins for this sample. Figure 8(c-d) shows the fabricated copper heater and final heating map.

4.4 Augmented Sensing and Control Layer

We integrated a sensing and control system to assist users. A temperature feedback control unit maintains a heating temperature of 75°C, a temperature sensor with an LED indicates when a safe handling temperature (60°C) is reached, and an optical sensor and LED indicates tightness. Figure 9 shows these.

An Arduino microcontroller, negative temperature coefficient (NTC) thermistor, and n-channel power metal–oxide–semiconductor field-effect transistor (MOSFET) keep the 75°C heating temperature using proportional control [41]. The microcontroller monitors this by translating thermistor resistance to temperature through a Steinhart-Hart equation [14]. Experimentally, the temperature sensing accuracy is 1 ± 1°C.

A red LED shows when ExoForm is unsafe to touch, above 60°C, and a separate white LED shows when the sample cools below 60°C (Figure 10a-b). A light sensor detects ambient light density close to the skin to detect tightness. The white LED glows brightly and dims as the wearable is tightened (Figure 10c-d).

5 EXOFORM PROCESS

5.1 Design and Simulation

ExoForm patterns are designed by interweaving active actuators with passive grids. While the actuators morph to fit around a user, the grids enhance mechanical performance to support the body and restrict motion. An Abaqus FEA simulation can then be run to visualize that structure's approximate morphing behavior, using material properties obtained from [64]. Results show how a sample's deformation is affected by design changes, in a trial and error approach, that helps ensure ExoForm fits complex target geometries, as seen in Figure 11

5.2 Fabrication

The generic fabrication process is shown in Figure 12. For other samples, silver traces were printed with an inkjet printer (ElectroUV3D, ChemCubed), MWCNTs-PBS was doctor-bladed, and other layers were CNC cut (Curio, Silhouette America) and bonded using double sided tape (VHB, 3M).

For better self-fusing material adhesion, we propose the doctor blading and curing procedure depicted in Figure 13 (a-c). First, we spread dispersed, uncured MWCNTs-PBS on the PET side of a design (Figure 13a) and then use a film applicator to make a film of 0.5mm (Figure 13b). The sample is cured at 50 °C for 12 hours (Figure 13c). Alternatively, for Thinking Putty, by printing the edges as a mesh and adding the putty, we ensure optimal adhesion between the two layers (Figure 13b) as the pores act like a cage to hold the putty while allowing it to fuse with the opposite edge. Both materials perform well, with a tradeoff between fabrication time and consistency; Thinking Putty application time is short but not as precise as MWCNTs-PBS.

6 DEMONSTRATIONAL ARTIFACTS

Using ExoForm's pipeline, we fabricated five different wearables which act as brace structures to restrict joint motion. Echoing the

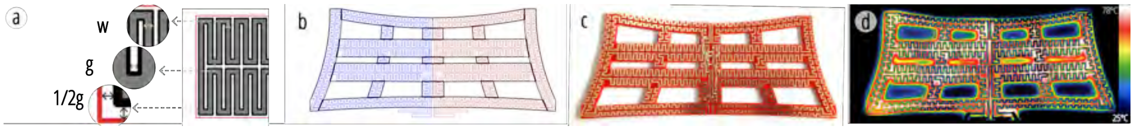

Figure 8: (a) Heater pattern design and parameter definition. (b) Neck model with designed heater trace. (c) Real photo of neck sample with heater fabricated. (d) Heat map when the piece is uniformly heated up to 75 °C.

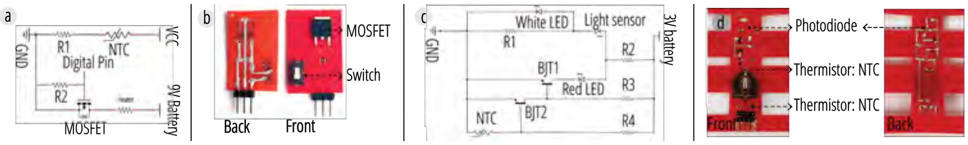

Figure 9: Temperature feedback control circuit: (a) Circuit diagram and (b) Fabricated circuit on PLA. Temperature and light sensing circuit: (c) Circuit diagram and (d) Fabricated on neck support.

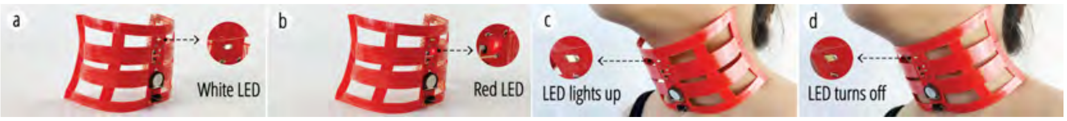

Figure 10: (a-b) Red glows above 60°C, turns white once below (c-d) White LED indicates tightness of fit.

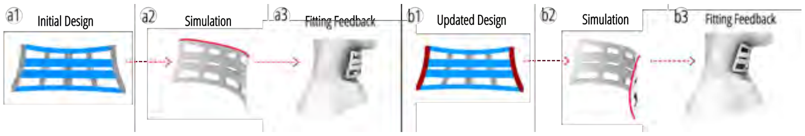

Figure 11: (a1) Initial design (a2-a3) Visual simulation feedback for bending and fit (b1) Designer updates design with two actuated curves on the sides (b1-b3) Simulation shows the updated design fits better.

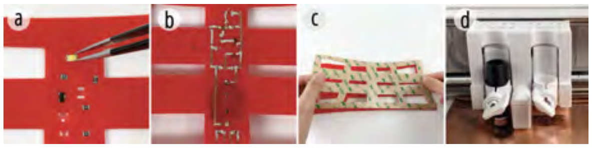

Figure 12: (a) electronics assembly (b) building connections (c) bonding tape (d) cutting heater.

design strategy mentioned earlier, we highlight the following common design features.

6.1 Semi-autonomous Two Step Assembly

Figure 14 shows how ExoForm was designed for different joints and follows the two-step process of an off-body loose fit and subsequent on-body tight fit.

6.2 Self-fusing Edges

With examples in Figure 15, we added self-fusing edges to ensure ExoForm will form one, cohesive piece on the body. If a brace has multiple modules, users can place each sequentially and fuse the bonding regions by pressing the self-fusing edges together.

6.3 Reversible Actuation

We introduced functional, temporal adjustment to accommodate changes throughout the healing process. To maintain tight fit for support, the wearer can reheat and sculpt their wearable. Using resistive heating, the piece unfolds to its more flattened shape, and the user can either create a tighter fit or flatten completely to store the part for future use (Figure 16).

6.4 Flat-Packing

Flat-packing saves space for ease of transport. Figure 17 compares the total volume taken up before and after ExoForm assembly. Flat packing saves nearly 95% of the volume taken up by the assembled parts.

7 TEMPERATURE EVALUATION

Users' hands will mold PLA at 60°C, but literature [14] and commercially available products [69] have demonstrated this safely because PLA has high heat capacity, low thermal conductivity, and a fast cooling rate [14]. To reduce the temperature experienced on the skin to 43.5°C, the pain threshold for nerve fibers [32], we recommend users wrap gauze around their body. Figure 18(a) shows ExoForm cooling for about a minute from 60°C to 43.5°C. Using a hot plate at 60°C, we conclude 4 layers of gauze (Johnson and Johnson, 0.45mm) constricts the top layer's temperature to 43.5°C for a minute, shown in Figure 18(b).

8 LIMITATIONS AND FUTURE WORK

In the future, we are interested in constructing more rigid casts. This may require a method to safely provide enough power to heat thicker materials uniformly. Still, ExoForm's designs have demonstrated their capability to restrict local motion. Currently, designers must carefully consider electronic components' placement as they are rigid and cannot morph alongside ExoForm. We plan to integrate computational design features to optimize such electronic layouts. Additionally, light sensing could only sense a limited area, but we could integrate more sensors along the edges for a more holistic approach. For the safety issue of inhalation of airborne MWCNTs, large bundles are formed in MWCNTs which were too heavy to become airborne. We anticipate some users will try ExoForm on their bare skin and for this reason, we are planning to integrate an insulating layer into ExoForm's structure to consistently protect the user from heat and electricity. Still, many of these concerns and limitations will be better addressed through a user study letting multiple users wear ExoForm to better evaluate fit and support, comparing ExoForm to similar technologies.

9 CONCLUSION

Through this paper, we present ExoForm, a novel approach to the fabrication and design of semi-rigid wearables that incorporates semi-autonomous self-morphing process assembly, self-fusing material, and on-board heating. This pipeline also addresses the addition of augmented sensing and control to aid in the fitting process. The work further investigates optimal resistive heating strategies. With these tools, we produce five moldable braces which support different joints to demonstrate the versatility of ExoForm. By introducing material-assisted semi-autonomous assembly, in addition to a user interface, ExoForm outperforms existing technologies in

Figure 13: (a) Spread MWCNTs-PBS on the PET. (b) Use a film applicator to make a thin film. (c) Cured MWCNTs-PBS after 12 hours in the oven. (d) PLA with printed mesh. (e) Applied Thinking Putty. (f) Two healed pieces.

Figure 14: Two-step assembly process for finger, ankle, elbow, and wrist braces.

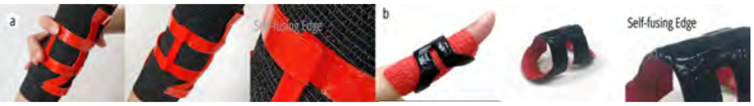

Figure 15: (a) Using thinking putty on the edge for elbow support (b) Using 1wt% MWCNTs-PBS for finger support.

Figure 16: Reversible folding and flattening process of the wearable with cables for batteries.

Figure 17: (a) Total volume of flat artifacts is 224.22 cm^3 (b) Total volume of artifacts after assembly is 3314.7 cm^3.

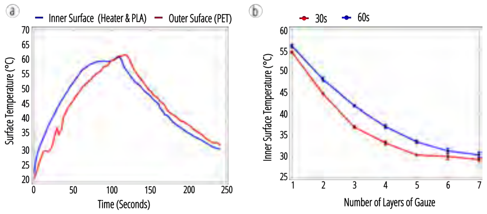

Figure 18: (a) The heating and the cooling curve of ExoForm surfaces (only reach 60°C on copper traces, PLA surface and PET surface. (b) The temperature of the inner surface with different numbers of layers of gauze.

creating on-demand, personalized wearables. Ultimately, through technology integration, the ExoForm process effectively produces sustainable solutions that work across body types, in any environment. This level of accessibility means that future devices can be tailored to fit users' needs without leaving anyone behind.

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