

Y-zipper: 3D Printing Flexible–Rigid Transition Mechanism for Rapid and Reversible Assembly

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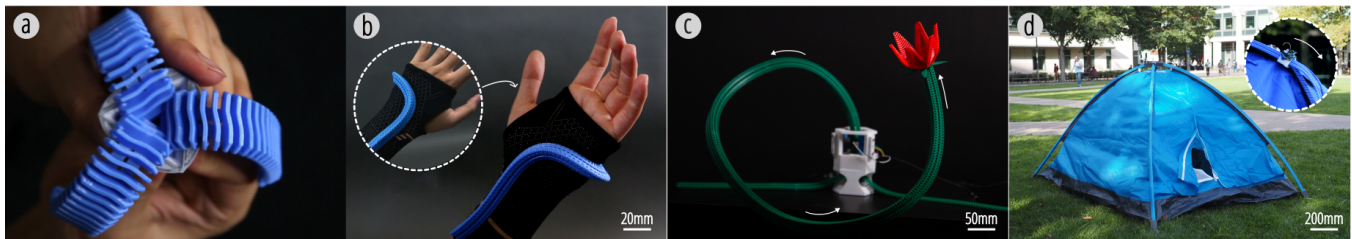


Figure 1: Four 3D-printed objects demonstrating applications of Y-zipper, including (a) a single Y-zipper being zipped, showing the zipping process of flex-rigid transition mechanisms, (b) a wrist brace for TFCC rehabilitation, (c) a growing kinetic art installation, and (d) rapid assembly and disassembly in tent architecture.

Abstract

We present Y-zipper, a novel three-sided 3D-printed zipper structure that enables three flexible strips to interlock and transform into a rigid rod-like form. Building on this flex–rigid transition mechanism, we further design a specialized slider to achieve rapid and reversible zipping interactions. This slider serves as the basis for three actuation methods—manual, dynamic mechanical, and static mechanical—which enable both remote control and automated closure and release. In addition, Y-zipper provides four motion primitives: straight, bend, coil, and screw, whose combinations extend the flex–rigid transition mechanism to spatial curve structures. To support customization, we develop a computational design tool that automatically generates zipper geometry based on input primitives,

unfolds the structure for 3D printing, and embeds both teeth and compliant bridges. Controlled experiments evaluate its mechanical properties, repeatability, and actuation speed, demonstrating robustness and reliability. Finally, we showcase a series of functional prototypes, including a medical wrist brace, a kinetic art installation, and a rapidly deployable tent structure.

CCS Concepts

• **Human-centered computing** → **Human computer interaction (HCI); Systems and tools for interaction design.**

Keywords

Flexible-rigid Transition, Zipper structure, Personal Fabrication, 3D Printing

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1 Introduction

The rise of personal fabrication in HCI has led to the creation of various customizable structures capable of dynamic transformation, including movement and transitions between distinct physical states, such as 4D-printing [41, 44, 45] and bistable mechanisms [17, 34]. One class of such structures involves rigid-to-flexible material transitions, where an object can switch between being compliant and rigid, a property sometimes referred to as tunable stiffness [8]. This capability is becoming increasingly central in HCI research, as it enables the development of more adaptable, responsive, and user-driven physical interfaces. Prior work has explored a range of strategies to achieve tunable stiffness, including inflatable structures [16], origami-inspired mechanisms [9, 46, 49], and Velcro-based assemblies [1].

One approach to achieving flexible-rigid transition is through the use of zippers that are stiff when zipped and compliant when unzipped. Some researchers have begun to redesign zipper geometries to endow them with new physical capabilities, as zippers provide a highly efficient, reversible fastening mechanism, making them ideal for applications requiring quick, repeatable, and customizable transitions in stiffness. StructCurves [43] reconfigures zippers into block-like modules to increase closed-state stability, while Touch-n-Curl [33] introduces branched zipper topologies to stabilize complex, curved surfaces. Although these designs enhance geometric expressiveness and support transitions from flexible to rigid, their intricate tooth geometries require manual, piece-by-piece assembly, ultimately undermining one of the zipper's core advantages: its rapid and reversible operation.

On the other hand, zip-chain actuators can be used to form column-stiff extensions from interlocking metal links. For example, Kim and Jung [22] compactly store a chain that becomes rigid when fed and locked, Kuroda et al. [26] apply zip-chains to assist sit-to-stand motion, Khatiwada and Sanders [21] integrate a rigid zip-chain actuator in a hand exoskeleton, and Collins and Yim [7] introduce a Spiral zipper prismatic joint, which winds a patterned strip into an extendable, compression-stiff tube for long-reach robotic arms. These deliver rapid, reversible extension with high axial stiffness, yet require specialized hardware and tolerances, cannot be automatically adapted to different geometries and are not printable all-in-one. This leaves three open questions: (1) How can we design and personally fabricate flexible-to-rigid mechanisms that retain fast, reversible assembly; (2) How to customize 3D curved structure suitable for a broader range of scenarios and (3) How can new actuation methods be introduced to support such mechanisms?

In response to these questions, we present Y-zipper, a 3D-printed, **three-sided zipper** that joins three independent flexible straps into a single, rigid, and stable triangular prism shaped rod, whose bending stiffness increases by a factor of 160. We were inspired by an early patent that proposed a three-way slide fastener forming a triangular column: *Multi-way slide fastener and structural support* [12]. The design interlocks three zipper strips with a single slider to

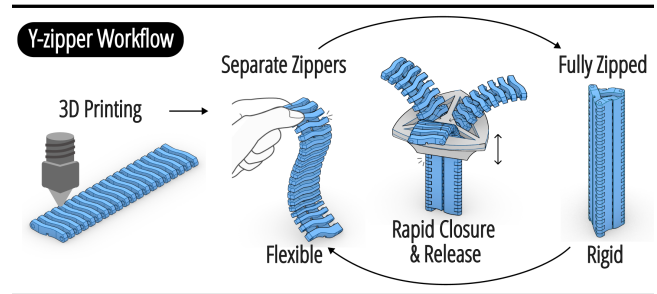


Figure 2: The Y-zipper workflow: Three Y-zipper strips are first 3D printed. Then, they can be assembled into a Y-zipper, where they transition between flexible and rigid states using the Y-zipper slider.

create a load-bearing, collapsible column, but existed only as a hand-made prototype and a now-expired patent. Our work formalizes and extends this idea by introducing a fully 3D-printed, *three-sided* zipper geometry, a design tool for arbitrary spatial curves, and an evaluation of rapid, reversible soft-to-rigid transitions mechanism.

Unlike prior work that relies on complex teeth, Y-zipper's stability comes from its three-way interlocking structure, allowing for smooth, rapid closure (at speeds of 30 cm/s) while enabling transitions between soft and rigid states. This smooth operation supports diverse actuation modalities, including manual, pull-cord, and robotic, and scales to extended lengths (up to 3 m), accommodating a wide range of form factors and applications. To support design, we provide a tool that, given any spatial curve, automatically generates a three-sided zipper by synthesizing the teeth, compliant joints, and a slider for actuation. We evaluate the system's mechanical performance, repeatability, and closure speed, demonstrating its robustness and reliability in interactive use. Finally, we highlight the versatility of Y-zipper through a series of application scenarios across different scales. In general, our contributions are as follows:

- A 3D-printed, three-sided zipper mechanism (Y-zipper) that closes three independent flexible straps into a rigid, load-bearing rod, providing rapid and reusable fastening with stiffness controllability; it supports multiple actuation modalities (manual, dynamic kinetic, static kinetic), scales to meter lengths (up to ~3 m), and achieves smooth, fast closure (~20 cm/s).
- An interactive design tool that converts an arbitrary spatial curve into a Y-zipper by automatically generating the teeth, compliant joints, and a slider, while exposing parameters for shape, scale, and actuation to support exploration and customization.
- A technical evaluation that quantifies mechanical performance (stiffness and load support), closure speed, and repeatability under repeated cycles, and characterizes how geometry and printing parameters influence reliability.
- A set of 3D-printed demonstrations across scales showcasing rapid, reversible assembly and stiffness control in practice, including reconfigurable supports, deployable structures, and interactive artifacts.

2 Related Work

2.1 Rapidly Constructable Structures in HCI

Shape-changing physical systems enable interactive objects to adapt to varying scenarios. For large-scale use—such as tents, pavilions, and frames—prior HCI and adjacent work accelerates construction by simplifying parts, merging fabrication steps, or enabling compact-to-3D deployment. Here we review approaches that emphasize rapid construction or deployment, similar in spirit to *Y-zipper*, but that lack *reversibility* and a clear *flexible-to-rigid* transition actuated by a single motion.

Truss-based systems exemplify fast, human-scale assembly. *TrussFab* [24] enables users to fabricate sturdy truss structures from PET bottles and 3D-printed nodes, while *TrussFormer* [23] extends this approach to large kinetic trusses. These pipelines scale quickly and support substantial load, yet they still require multi-step assembly and disassembly of discrete members rather than transforming a continuous flexible strip into a rigid, load-bearing element on demand.

Inflatable fabrication provides another strategy for rapid deployment at human scale. *Printflatables* [37] produces large inflatable structures from heat-sealed laminations that can be erected within minutes, though they remain compliant unless continuously pressurized or otherwise reinforced. *AeroMorph* [31] designs inflatable hinges that fold on demand, offering compact-to-3D transformation, but stiffness is limited and dependent on internal pressure.

For context, broader shape-changing HCI explores deformable, rigid-module, and hybrid interfaces. Boem et al. [5] survey non-rigid interfaces made from soft materials that respond to input. Digital fabrication has also produced building blocks for transformation, including origami mechanisms with high stiffness-to-weight ratios [9] and printed metamaterial mechanisms that enable rotational, translational, or torque-transmitting motion [13]. We reference these to situate the broader design space; the focus here remains rapid deployment and its limits with respect to reversibility and stiffness transition.

Taken together, these approaches prioritize speed—fast assembly, single-pass shaping, or compact deployment—but typically either rely on discrete assembly, remain compliant unless pressurized or jammed, or require non-instantaneous reversal (e.g., reheating or reconditioning). In contrast, *Y-zipper* integrates structure creation and actuation in a print-in-place mechanism: three flexible strips zip into a rigid, load-bearing rod and unzip back to a compliant state via a single, continuous motion. This provides rapid *and* repeatable flexible-to-rigid transitions not addressed by the above large-scale rapid-construction pipelines.

2.2 Structures that Transition Between Stiffness States

Some shape-changing systems transition between stiffness states, allowing one artifact to occupy multiple mechanical regimes (for example, flexible versus load-bearing). This capability is relevant to HCI because it adapts mechanics to users and tasks. Applications span wearables, such as Frozen Suit [2] and jamming-based haptics [39], and hand-held or environmental devices, such as Haptic Links [40] and ElaStick [36]. In these scenarios, *Y-zipper* can serve

Table 1: Feature comparison of zipper-inspired transformable structures.

	Flex-Rigid Transition	Rapid & Reversible	Automatic Actuation	Curved Geometry	Customizable Design Tool
Zippables [38]		✓		✓	✓
StructCurves [43]	✓			✓	✓
Touch-n-Curl [33]	✓			✓	✓
Spiral Zipper [7]	✓		✓		
Zip Chain [22]	✓	✓	✓		
Y-zipper	✓	✓	✓	✓	✓

as a structural, user-facing component that switches between compliant and load-bearing modes on demand while retaining low cost, simple zipping actuation and fast, reversible operation.

Variable stiffness can be realized through inflatable, origami-inspired, jamming-based, phase-change, or material-programmed solutions, each trading off control, speed, reversibility, and robustness. Jamming User Interfaces [10] introduce particle jamming; JamSheets [32] extends this to thin deformable sheets; Multi-Jam [47] demonstrates 3D-printed jamming interfaces; and xSlate [15] employs deformable frames for stiffness-controlled panels. *Y-zipper* avoids external pumps or tubing, achieving rapid transitions through mechanical engagement in a single zipping motion.

Material-centric strategies provide another route. VabricBeads [35] uses woven beads to mimic artificial muscles for tunable stiffness; MilleCrepe [28] proposes multi-layer, fluid-driven interfaces whose phase change modulates stiffness; and Zappetti et al. [48] embed phase-changing materials in tensegrities. These can offer continuous control, although thermal or fluid dynamics may slow transitions. *Y-zipper* instead provides large, short-interval stiffness changes with simple, reversible mechanical engagement.

Mechanism design also supports stiffness change. MimicTile [30] offers a variable-stiffness mobile interface using deformation as input. Ninja Track [20] employs 3D-printed segments and longitudinal hinges that become rigid when folded; unlike *Y-zipper*, it requires manual assembly. X-Bridges [42] creates tunable, printed bridges, and metamaterials can be reprogrammed to achieve variable stiffness [19]. Relative to these, *Y-zipper* emphasizes assembly-free, print-in-place fabrication that forms rod-like struts capable of rapid, reversible rigidization.

Several expressive shape-changing interfaces focus on actuation rather than stiffness modulation, for example rigid-rod arrays (*inFORM* [11]), attachable modules (*ShapeClip* [14]), kinetic mechanisms (All-in-One Print [27]). These highlight alternative modalities and infrastructure requirements; our contribution targets *rapid*, *reversible*, *soft-to-rigid* transitions with low hardware overhead.

2.3 Zipper-like Mechanisms

Zippers are attractive for rapid, reversible assembly because they actuate quickly, align repeatably, and integrate with digital fabrication workflows. Prior HCI work has mainly used zippers for *enclosures*, *shaping*, and *input*, rather than as mechanisms for converting flexible strips into rod-like, load-bearing rods.

Within HCI, *Zippro* [25] established zippers as interactive structures, documenting how people operate zippers and outlining zipper-based inputs and sensing. Sun et al. [43] employ two-dimensional zippers on fabric to create three-dimensional structures and curves, using interlocking seams to stabilize shape while preserving flexibility. Schüller et al. [38] algorithmically flatten closed geometries so that a single zipper can drive assembly, and Masuda et al. [29] design interlocking 3D-printed zippers that, when bonded to textiles, assemble into 3D forms with varied curvature. These methods excel in fast, repeatable closure, yet primarily serve as enclosures rather than independent structural supports.

In contrast, *Y-zipper* uses zipper engagement as the *primary* mechanism to toggle a 3D-printed strip between compliant and rod-stiff states, using three-sided rails that are printable in one piece. To our knowledge, prior zipper work in HCI has not realized tunable-stiffness *structural struts* with three-sided zipper geometries.

3 Y-zipper Mechanism

This section presents the method of creating Y-zippers, a 3D-printed zipper system that transitions from flexibility in the open state to rigidity in the closed state. Our three key design goals are: (1) ensuring the individual zipper strips are sufficiently flexible; (2) achieving high rigidity in the assembled rod; and (3) enabling smooth actuation, where the strips interlock easily during zipping but remain securely fastened without accidental detachment.

Y-zipper's structural strength arises from its *three-sided* design, where the three sides form a rigid triangular prism when zipped up, which raises extra design challenges over designing standard *two-sided* zipper mechanisms like those found on clothes or bags. Below, we describe the main components of a Y-zipper object (the zipper itself and the zipper slider) and how they meet our key design requirements and overcome these challenges.

3.1 Zipper Strip Design

We begin by identifying the key components that make up a single "strip" of a Y-zipper (which we define as one of the three sides of the zipper mechanism) shown laid out flat in Fig 3. The Y-zipper strip is built on classic zipper mechanisms and consists of three primary elements: (1) **Teeth**, (2) **Bridges**, and (3) **Ball Nodes & Sockets**, as illustrated in Fig. 3. Below, we describe the characteristics and design of each component.

Teeth: The teeth, shown in Fig. 3, are the prongs that jut out on the side of each zipper strip that will interlock with those of another strip when zipped up. Compared to conventional zipper teeth, whose main function is to hold together the two sides of the thing being zipped up (such as the lid and body of a suitcase), the most critical role of the Y-zipper teeth is to provide sufficient structural support to the Y-zipper in the zipped up state.

In Fig. 3, we illustrate three Y-zipper teeth, a_1 , b_1 , and c_1 , that together make up one vertical "segment" of the Y-zipper. The zipper support arises from the teeth's wave-like profile: when zipped, the left end of a_1 sits above the right end of b_1 , the left end of b_1 sits above the right end of c_1 , and the left end of c_1 sits above the right end of a_1 , so that the load carried by one tooth is reinforced by the next. The result is a cyclic, mutually supporting chain of interlocked teeth that transforms the flexible strips into a rigid structure.

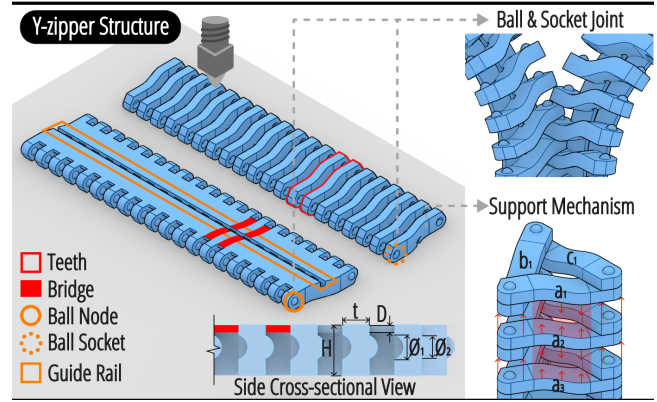


Figure 3: A diagram of the components of Y-zipper strips. Left: Each strip consists of teeth, bridges, ball nodes, ball sockets and a guide rail. Right: The joining mechanism of multiple zipper strips together.

This mutual interaction results in a stable triangular configuration. The tooth thickness t governs the smoothness of closing and separation, with smaller t values producing smoother zipper engagement. The tooth height H plays a role analogous to the wall thickness of a cylindrical shell: larger H values increase compressive strength and structural stability. Repeating this cyclic segment n times along the zipper's longitudinal axis forms the full interlocking chain, which provides enhanced vertical load-bearing capacity. In this way, the Y-zipper maximizes compressive resistance, allowing the material's intrinsic strength to be fully utilized.

Bridge: We define bridges to be the connecting structures that link individual teeth together, forming them into a continuous strip. The functional requirements of the bridges differ significantly depending on the zipper's state. When the zipper is in an unzipped state, the bridges must provide enough flexibility for the zipper strip to freely bend and twist. When the zipper is zipped up, as illustrated in the support mechanism of Fig. 3, the bridges need to act as the tensile-force-bearing unit, ensuring that the two segments of teeth (e.g., a_1 and a_2) are firmly pulled together.

This firm inter-segment coupling is what maintains the structural integrity of the entire chain. The bending and tensile resistance of the Y-zipper is therefore governed largely by the bridge thickness D . In practice, TPU bridges with D ranging from 0.4 mm to 2.0 mm provide a good balance between compliance and post-assembly strength, and the exact value of D can be adjusted according to the scale and requirements of specific cases. Material choice also strongly influences performance: while flexible TPU provides compliance, its limited strength motivated us to explore alternative designs, such as replacing bridges with high-strength textiles or articulated joints. These strategies are discussed in the Design Space section and validated in the evaluation.

Ball Node & Socket: In the Y-zipper design, each tooth integrates a ball node on its top side and a socket on its underside, creating Lego-like interlocking structures that engage when zipped. These features provide additional alignment during closure and primarily

function to resist shear forces, preventing the zipper teeth from sliding against each other. As the zipper closes, the bridges straighten out (Fig. 3), pulling the ball nodes securely into their corresponding sockets. This ensures that the two strips of teeth are securely locked in the horizontal direction, preventing displacement or detachment under lateral loads. Unlike the teeth, which provide vertical support, and the bridges, which serve as primary tensile load-bearing units, the ball node and socket are specifically designed to enhance the overall shear strength of the structure, ensuring that the Y-zipper remains stable under complex loading conditions.

To balance ease of zipping with post-closure stability, in our implementation we set the ball node diameter to $\varnothing_1 = 2.4\text{mm}$, the socket diameter to $\varnothing_2 = 3.0\text{mm}$, with the fitting tolerance of 0.3 mm. We explored different diameter ratios and tolerance settings, which is validated in the evaluation section 9.1 through closure results and force measurements. Overall, the Y-zipper integrates *Teeth*, *Bridges*, and *Ball Node & Sockets* to provide vertical support, tensile bonding across segments, and lateral shear stability. In addition, an auxiliary *Guide Rail* (also shown in Fig. 3) interfaces with the slider, ensuring synchronized motion and smooth constraint during opening and closing so the three strips move in unison. Together, these four elements balance load-bearing strength, closure stability, and operational smoothness.

3.2 Slider Design

We describe the design of the Y-zipper slider, which enables rapid zipping and unzipping of the three strips. Compared to existing flexible-rigid transition zipper structures [33, 43], we present a slider design that is highly adapted to the Y-zipper strips. This structural compatibility is the key factor enabling the Y-zipper to achieve rapid and reversible closures. The slider consists of two main parts: the upper Separator, which splits the strips when unzipping, and the lower Converger, which joins them when zipping. Longitudinal pulling on the slider is thus converted into outward or inward forces that drive the opening or closing process.

Separator: As shown in Fig. 4, during unzipping, the slanted surfaces of the Separator gradually guide the three zipper strips outward. This converts the downward force along the sliding direction into lateral separating forces.

Converger: In contrast, the inward-sloping geometry of the Converger converts the upward force on the slider into inward radial forces that direct the strips toward the center. This enforces the sequential meshing of the teeth, assembling a stable rod-like structure after closure.

The Separator and Converger can detach and reconnect via a rotational lock, simplifying the challenging initial alignment of three separate strips. The workflow is: (1) manually align a short section; (2) pull the Converger upward to close the zipper; (3) lock both parts together for smooth bidirectional operation. This coupling of separating and converging forces ensures low-friction movement and stable engagement, forming a robust foundation for rapid, reversible closure of the Y-zipper.

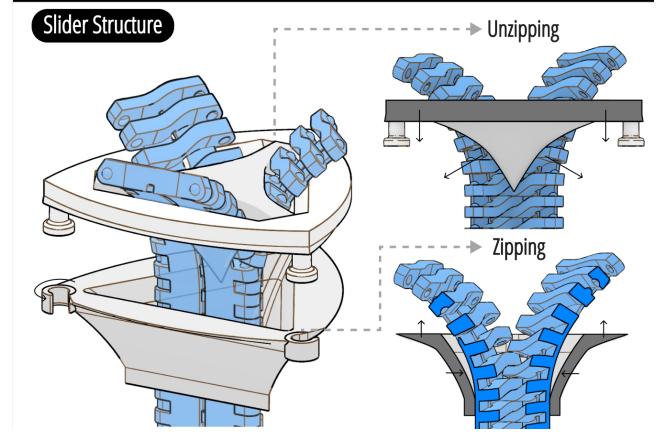


Figure 4: Y-zipper slider has two modules: Separator for unzipping and Converger for zipping. The Separator guides strips outward, and the Converger directs them inward for closure. A rotational lock enables easy engagement and stable bidirectional use.

4 Actuation method

Having established the structural components of a Y-zipper, we now discuss how the Y-zipper can be operated in practice. Below, we detail three actuation methods for Y-zippers: manual, dynamic mechanical, and static mechanical, that offer different trade-offs between simplicity, automation, and scalability.

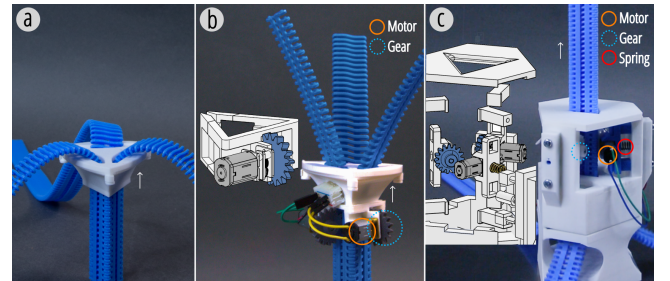


Figure 5: Actuation methods for the Y-zipper: (a) manual slider; (b) dynamic actuator with one set of motor-gear; (c) static actuator consists of three sets of motor, gear, and spring.

4.1 Manual Actuation

Manual actuation is the most straightforward approach for operating a Y-zipper, where the user operates the zipper by manually pushing or pulling the slider along the Y-zipper strips to achieve opening and closing. To support this mode, our slider design includes an under-surface grip that enables a more secure and controlled application of force. The advantages of this method lie in its electricity-free operation and intuitive use, making it particularly suitable for small-scale prototyping and wearable applications. Its

main limitation, however, is that it does not scale well to scenarios demanding high-frequency use or remote control.

4.2 Dynamic Mechanical Actuation

While manual actuation provides a simple and smooth means of operation, automated control enables broader application scenarios. Dynamic mechanical actuation addresses this need by enabling the slider to autonomously crawl along the Y-zipper strips while simultaneously opening and closing the zipper. The main challenge in this design lies in achieving sufficient performance while keeping the system lightweight, making it suitable as part of large structures to control distributed flexible-rigid transitions.

To achieve dynamic mechanical actuation, the motion module integrates an N20 motor and two custom 3D-printed gears, in addition to the Separator and Converger that guide opening and closing. The gears are designed with a tilted profile that perfectly interlocks with the parallelogram geometry of the zipper, while their width matches the rail track precisely. This prevents tilting or torsion during motion and ensures overall dynamic stability.

During actuation, the actuator's gears advance through local interlocking with the teeth structure. Each gear-tooth engagement produces a discrete pulling step, and the Guide Rail geometry enables the slider to self-align and continue advancing without any predefined step control. As long as the local radius of curvature of the strip is larger than 20 cm, the geometry of the gears and the Converger can maintain the slider's center alignment, allowing it to move not only along straight column-shaped configurations but also along gently curved arc trajectories.

To further reduce weight, we designed a compact electronic module that integrates the ESP32-C3 microcontroller, an A4950 motor driver, a wireless receiver, and a battery into a 15 mm × 25 mm × 35 mm package weighing only 18 g. With this module, the actuator can be wirelessly controlled via Bluetooth at distances up to 25 m, far exceeding the range of manual operation.

Overall, the advantages of dynamic mechanical actuation lie in its ability to achieve automation and distributed control. The lightweight design makes it portable and stable, suitable for high-frequency or remote-use scenarios.

4.3 Static Mechanical Actuation

In contrast to the moving-slider approach of dynamic actuation detailed above, static mechanical actuation keeps the actuator module fixed in place. Instead of crawling along the zipper, it performs closure by “stitching and extruding” multiple Y-zipper strips, forcing them to interlock with each other at the output point. Rather than moving the actuator along the strips, the strips are fed into a stationary drive module at a single location, eliminating the need for a traveling slider and enabling a force-injection strategy that is fundamentally different from the lightweight, mobile mechanism used in dynamic actuation.

In the static mechanical actuator design, we employ three batteries, three motors, and spring mechanisms to provide continuous and evenly distributed force. Concentrating the actuators in a fixed location relaxes the mass and footprint constraints that prevent a multi-motor system from crawling along the strip, enabling the use of higher actuation capacity that would be too heavy for dynamic

motion. This configuration not only overcomes the gravitational limitations associated with closing long strips but also adapts to a variety of geometries. Whether the zipper closes into a straight column, a curved column, or complex shapes with large curvature, the system ensures stable and reliable closure.

Overall, the advantage of static mechanical actuation is that it is unaffected by the weight of the unclosed portions of the zipper strips. We connect each of the three motors to its respective spring, allowing the spring force to press the motor-mounted gears more tightly against the teeth. This provides a stable pushing force that conforms to curved surfaces, enabling geometries with relatively large curvature to pass through the actuator. With these capabilities, it is particularly suited for closing complex geometries, such as the vine example shown in Section 8.3.

5 Motion Primitives

Having described the design and actuation of Y-zippers, we now turn to the types of motions they can perform. To capture these motions, we define four fundamental primitives that serve as building blocks for closing zipper strips into different shapes.

In mechanical engineering, a one-degree-of-freedom (one-DOF) pair is the simplest type of mechanism that enables relative motion between two components, typically classified into Prismatic, Revolute, and Screw pairs [3]. In the case of the three-sided Y-zipper mechanism, the trajectory of the slider is determined by the geometry of the three zipper strips, analogous to how the motion of a screw is defined by the thread of its nut. Based on these fundamental mechanism types, we define four key one-DOF motion primitives: Straight, Bend, Screw, and Coil; as illustrated in Fig. 6. These primitives abstract common slider trajectories and corresponding zipper geometries, providing standardized elements for complex forms and serve as the foundation for the subsequent design tool in Section 7. By presenting these primitives progressively from simple to complex, we aim to illustrate the range of possible shapes, enabling inexperienced users to intuitively envision and construct their desired geometries within the design tool.

5.1 Straight

Straight motion is the simplest Y-zipper motion, with the slider moving linearly in one direction to form a closed, columnar zipper. This motion is consistent with that of a Prismatic pair, which has one degree of freedom and permits only sliding along the z -axis. Assuming the slider moves with velocity v , its trajectory can be expressed as $z = v \cdot t$. In all other primitives, the motions are fundamentally derived from this z -axis sliding, but with additional rotations or lateral displacements of the slider that modify the trajectory and orientation of the motion.

5.2 Bend

The bend primitive, as shown in Fig. 6b, is realized by rotation about the y -axis. The bending effect arises from the fact that zipper strips α and β are constructed with non-uniform teeth and curved bridges. Specifically, the thickness of the teeth at the interface between strips α and β , denoted as $t_{\alpha\beta}$, is smaller than that at the interface between strips α and γ , denoted as $t_{\alpha\gamma}$.

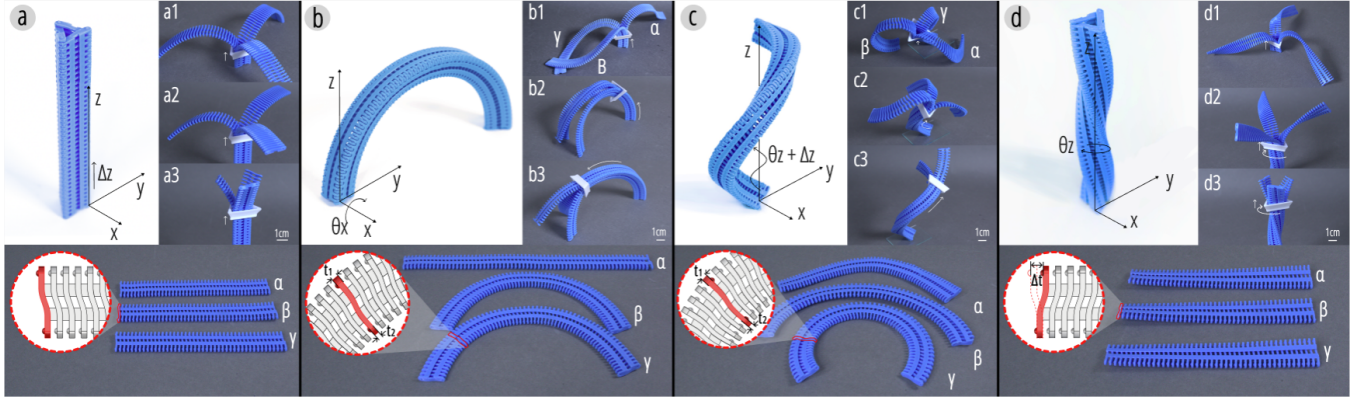


Figure 6: The four basic motion primitives of Y-zipper: Straight, Bend, Coil and Screw.

Along the entire triangular prism, we accumulate these tooth thickness values to quantify the difference between the two interfaces. The accumulated values define the geometric bending behavior and are used to compute the bending angle θ and effective bending radius R (full derivation provided in Appendix A.3).

When the slider moves over the structure at velocity v , the trajectory of its endpoint can be modeled using the effective bending angle φ over time t , resulting in a parametric spatial motion path.

The bend primitive is generated and flattened using the parametric design tool Grasshopper. We begin by inputting a base curve, which is then swept along a single rail to create a twisted triangular prism. The three sides of the prism are evenly divided into an equal number of teeth, with a minimum thickness of $t = 0.5$ mm to ensure print quality. The divided sections are then pairwise connected using lofting operations. Finally, the spatial angle is computed and flattened onto a plane using a recursive algorithm, after which bridges are inserted to connect the strips. The detailed algorithm and user interface will be presented in the Design Tool section.

5.3 Coil

Building on the Bend Primitive, we developed a Coil Motion Primitive by adjusting the inter-segment angles in the flattened state, as illustrated in Fig. 6. Unlike the Bend Primitive, the Coil Primitive introduces an additional displacement Δz along the z -axis during rotation. This displacement causes the resulting motion path to deviate from a planar curve and instead form a non-axis-aligned helical trajectory.

The primary geometric parameters of the coil primitive—including the flattened length L , radius R , and pitch h —are derived based on the cumulative tooth thicknesses and axial increments, where L denotes the arc length of the flattened strip's centerline. The full mathematical formulation is provided in Appendix A.3.

When the slider moves over the structure at velocity v , the endpoint motion evolves into a helical path defined by a time-varying coil angle φ , which governs the spatial trajectory of the endpoint.

The 3D modeling workflow of the coil primitive is similar to that of the bend primitive, but the key distinction lies in the introduction of the axial displacement Δz alongside each bending increment. In

the bend primitive, the flattened structure accumulates only in-plane angular offsets, whereas in the coil primitive, each segment not only rotates but also increases its axial height, creating a non-axis-aligned helical structure.

In practice, after lofting connections between teeth, each segment is assigned both a rotation angle and an axial offset according to the prescribed radius R and pitch h . The resulting structure exhibits a continuous helical geometry when actuated, rather than a purely planar bending profile.

5.4 Screw

The Screw Primitive generates a helical rotational motion around the longitudinal axis of the zipper, achieved by modifying the tooth geometry (Fig. 7). The screw angle is determined by the accumulated geometric offsets applied to the tooth interface. As shown in Fig. 7b, when the teeth follow a standard wave-like profile, the normal vector v of each ball node aligns with the z -axis, resulting in a vertically oriented structure. However, shifting the lower side of each tooth upward by a distance equal to its thickness ($\Delta t = t$) causes the normal vector to rotate, producing a clockwise screw of angle θ . A larger offset ($\Delta t = 2t$) generates a stronger clockwise twist, while applying a negative offset ($\Delta t = -t$) results in a counterclockwise screw.

Through empirical tuning, we found that the total screw angle varies linearly with the applied offset, expressed as $\theta_z = k \cdot \Delta t$, where k is an experimentally determined proportionality constant. This relationship holds within the feasible geometric range ($-1.5t \leq \Delta t \leq 2.5t$); beyond this range, the engagement stability degrades due to excessive angular mismatch between adjacent teeth.

Because the screw induces rotation along the longitudinal axis, the effective vertical height L_z becomes shorter than the flattened strip length L , and the position and orientation of the slider follow a time-dependent helical motion. The full mathematical formulation is provided in Appendix A.3.

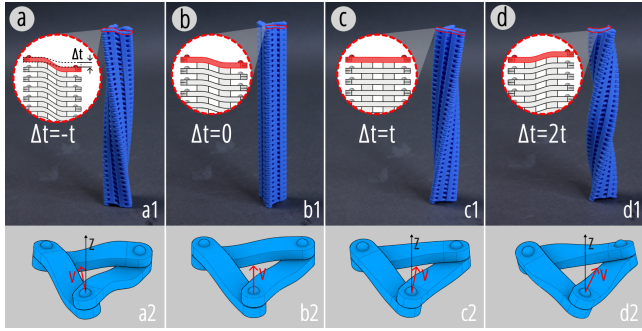


Figure 7: Examples of different Y-zipper screw primitives with varying angles, which is achieved by modifying the teeth shape.

6 Design Space

6.1 Integrating Motion Primitives Into a Single Rod

In the previous section, we introduced the fundamental motion primitives. When multiple primitives are connected sequentially to form a series combination, they can achieve more complex shapes and functions, thereby supporting richer flexible-rigid transitions. In a series combination, the closure motion of the slider begins at the base of the mechanism and gradually zip-up the strips, resulting in cascading deformations along the sequence.

The advantage of this combination lies in its ability to construct linear structures with Eulerian path, where a single slider can be used to form and actuate spatial shapes. In such spatial configurations, flex-rigid transitions can not only achieve stable closure of complex geometries, but also perform efficient mechanical transformations under limited control input. This makes the approach particularly suitable for scenarios that require temporary, mobile, or reconfigurable forms, ranging from disaster relief to medical rehabilitation. The mathematical formulation of the total structure length and cumulative slider trajectory, including the transformation composition across primitives, is provided in Appendix A.3.

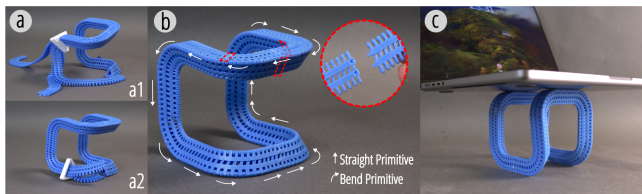


Figure 8: Series mechanism with nine straight and eight 90° bend primitives. (a) Sequential assembly in 5 seconds; (b) cube-like structure formed with 9 straight primitives and 8 bend primitives; (c) supporting a MacBook.

As shown in Fig.8b, this is an example of a series mechanism. We combine 9 straight primitives and 8 bend primitives into a cube-like structure, where each straight primitive has a length of $L = 30$

mm and each bend primitive has an angle of $\theta = 90^\circ$, arranged sequentially. The bend primitives are oriented in different directions, and when flattened, they form three strip-like structures. These primitives are then actuated by a single slider. As illustrated in Fig.8a, the strip-shaped structures eventually fold into a cube-like configuration, completing the transformation from flexible to rigid in just 5 seconds. As shown in Fig. 8c, the structure weighs only 120 g yet can easily support a 1.5 kg MacBook, with a maximum load capacity of around 6 kg.

6.2 Joint Mechanisms for Connecting Multiple Rods

To enable connections between multiple zipper rods, we designed a specialized joint structure as shown in Fig.9. The interface between the joint and the zipper strips is shaped to match the hollow interior of the zipper rods, ensuring a precise snap-fit assembly. During the closure process, the strips naturally lock into the joint, providing secure attachment. Unlike earlier approaches that rely on Eulerian circuits to form continuous paths, this design expands the design space by enabling branching and network-like configurations. Such flexibility facilitates the construction of more complex and versatile spatial topologies for flex-rigid transitions.

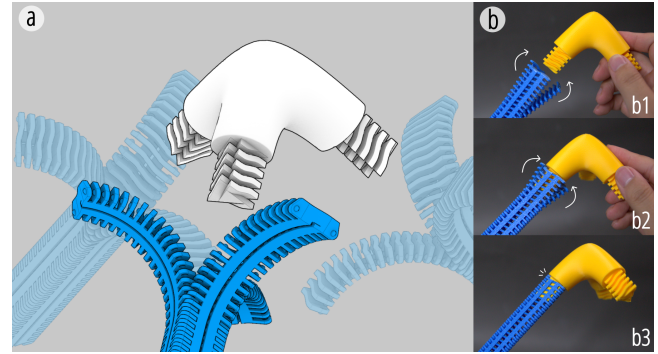


Figure 9: A joint design for connecting multiple Y-zipper rods.

6.3 Bridge Designs with Material Diversity

In the design of the Y-zipper, bridges not only serve as connectors and load-transmitting elements, but are also critical factors influencing the overall mechanical performance and adaptability of the structure. By introducing different materials and structural forms, the bridges in the Y-zipper can achieve diverse properties, thereby expanding the design space in terms of material choice. Below, we present three types of bridge structures explored in our study.

TPU Bridges: This material choice uses TPU 68D to form compliant bridges that are printed simultaneously with the teeth. The TPU bridges remain elastically deformable across a thickness range of 0.6–2.4 mm. With a ball-node and socket tolerance of 0.1 mm, the teeth can smoothly snap in and out under load, enabling clean separation and rejoining. Due to the limited elongation of TPU 68D, assembled zippers below approximately 30 cm do not exhibit

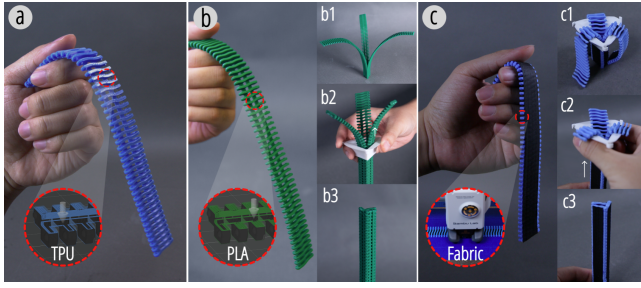


Figure 10: Y-zipper bridges with different material and structure: (a) compliant bridges with TPU 68D; (b) kinetic bridges with articulated joints; (c) fabric-integrated flexible bridges via on-fabric printing.

noticeable bending after assembly, maintaining good structural stability. We use TPU bridges in our primitive demonstrations, and robotic prototypes.

PLA Bridges: PLA, as one of the most common printing materials, is better suited for longer objects. PLA bridges retain a certain degree of flexibility within a 0.4–1.2 mm thickness range; however, the printing path should be oriented perpendicular to the teeth to improve toughness and avoid fracture between adjacent print paths. Due to its higher stiffness, a larger tolerance of 0.2 mm is required to ensure smooth snapping between the teeth. PLA-based Y-zipper rods can maintain their form without noticeable gravity-induced deformation up to approximately 2.5 m in length. We use PLA bridges for large-scale applications as the vine and tent.

Fabric-Integrated Bridges: Fabric-integrated bridges combine textile substrates with 3D printing, directly printing the teeth structures onto the fabric surface. In this case, the flexibility and tensile strength of the fabric substitute for the 3D-printed bridges, offering high flexibility and wearable characteristics. These bridges combine the comfort and deformability of textiles with the design controllability of 3D printing, making them particularly suitable for applications in section 8.1 involving interaction with the human body or other flexible surfaces.

By exploring and combining these different types of bridge structures, the Y-zipper gains greater freedom in material diversity, enabling customized designs tailored to different application needs and significantly expanding its potential use in wearable devices, flexible mechanisms, and interactive structures.

6.4 Space-Efficient Storage Strategies

Although the Y-zipper enables rapid assembly from flexible to rigid states, saving space before deployment and facilitating transportation, the question of how to efficiently store long zipper strips remains. To address this, we designed two storage structures. As shown in Fig. 11a, we take advantage of vertical space by coiling a 0.5 m zipper into a cylindrical container with a height of only 10 cm and radius of 25mm. In contrast, Fig. 11b demonstrates a spiral storage approach: it occupies a larger footprint in the plane but maintains a total height of just 3 cm. These storage structures

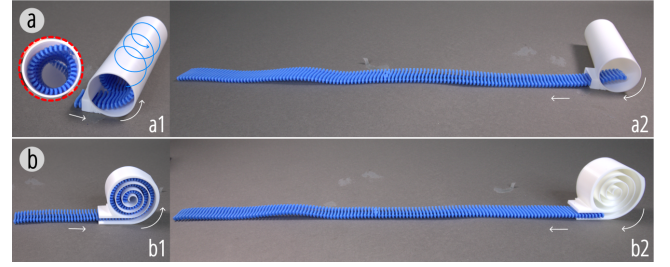


Figure 11: Two storage structures for long Y-zipper strips: (a) vertical coil storage; (b) planar spiral storage.

significantly improve the spatial efficiency of long zipper strips and provide flexible solutions for different application scenarios, such as embedded storage in portable devices or bulk transport and rapid deployment in engineering contexts.

7 Design tool

We present a design tool for the automated design of Y-zippers. It uses Rhinoceros 8 for the design environment and Grasshopper as both a computational tool and an intermediary user interface. The primary function of this tool is to help users customize a single Y-zipper with complex structures by combining primitives and setting their parameters. The user workflow is as follows: (1) select and generate a motion primitive of a basic shape; (2) repeat the step until the design requirements are met; (3) finally generate the flattened file.

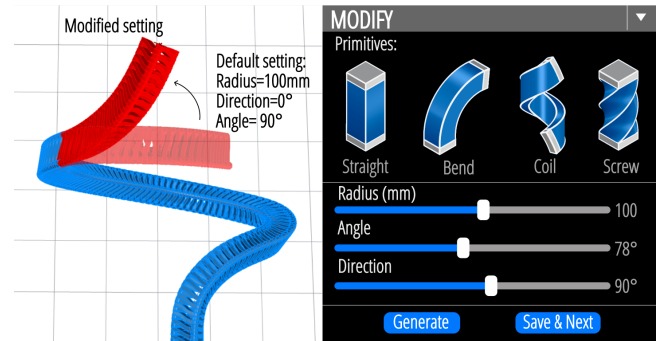


Figure 12: Primitives Embedding process in Y-zipper system.

Generating Shapes: Users can specify the shape of the closed zipper structure according to the application scenario, including its thickness, width, and height. The Y-zipper system starts by placing the first primitive on the xy -plane. When opening the Y-zipper system in the Rhinoceros environment, users can select a primitive from our library (as shown in Fig. 12). The main interface displays the currently edited segment (shown in red) and the other segments (shown in blue). By adjusting the sliders in the interface, users can modify the bending angle and length. We also provide some pre-tested reference values to help users quickly achieve typical examples of primitives.

Continuing Generation: Once a primitive has been implemented in a segment, the user can click *save & next* to add a new segment along the normal direction of the existing shape, thereby creating other primitives. In the example shown in Fig. 12, the generated blue parts are sequentially composed of Straight, Bend, and Coil primitives, while the red part currently being edited represents a new Bend.

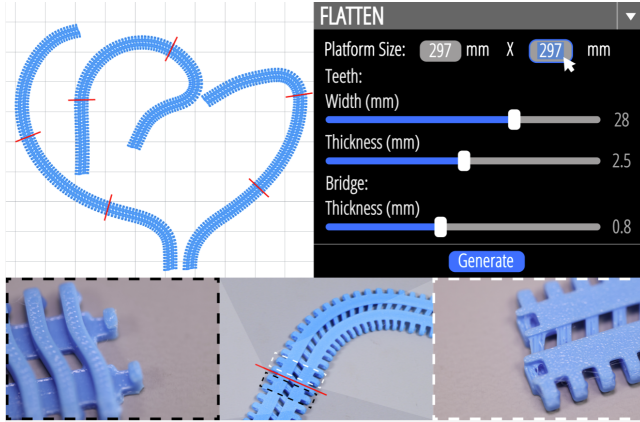


Figure 13: Strip flattening and splitting in Y-zipper system.

Flattening and Splitting: Once the user is satisfied with the generated zipper structure, the next step is flattening. We implement this process using a recursive unfolding algorithm, which incrementally rotates and positions each lateral face into a planar layout while preserving geometric adjacency. The detailed algorithmic logic is provided in Algorithm 1. The primary purpose of this step is to ensure the print quality of the zipper. In addition, due to the limited size of the printing platform, longer zippers need to be divided into split sections. Based on the platform size provided by the user, the system automatically generates the split sections and inserts interlocking joints at the cut locations, as shown in Fig.13. These joints are distributed across different parts of the closed rod, preventing them from localizing together (as shown in 8), which would otherwise create weak points prone to breakage.

8 Applications

Having detailed the structural design and actuation methods of the Y-zipper, we now demonstrate its utility through a variety of application scenarios.

8.1 Wearable Wrist Brace for TFCC Rehabilitation

Y-zippers could be deployed in medical applications such as wearable exoskeletons, casts, and rehabilitation braces [4, 6], where fast and easy flexible-rigid deployment is key. To demonstrate this potential, we integrated a Y-zipper into a wearable wrist brace to support the rehabilitation of triangular fibrocartilage complex (TFCC) injuries. TFCC injuries are typically caused by excessive wrist rotation or sudden loading [18]. While patients can consciously avoid improper motions, unconscious loading or unexpected movements

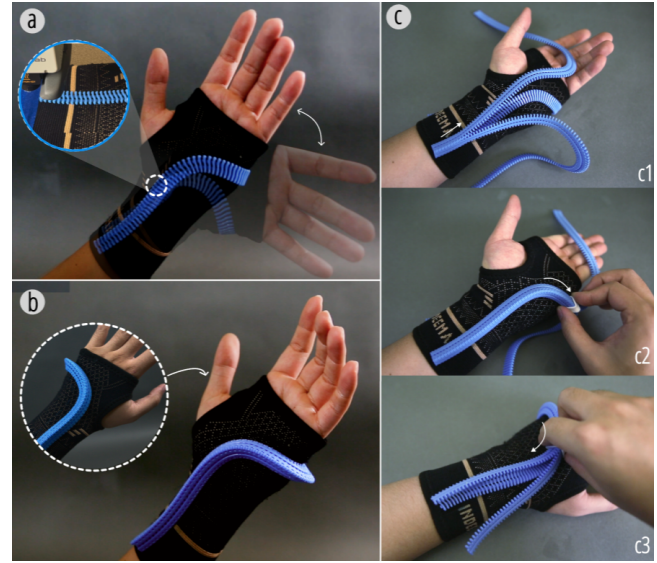


Figure 14: Wrist brace for TFCC rehabilitation: (a) flexible state during conscious use, allowing free wrist movement; (b) rigid state after closure, providing stability and protection against unconscious impacts; (c) single-handed closure while wearing the brace.

in daily life (e.g., overstretching during sleep or sudden ground support) can easily result in secondary injuries. Therefore, a wrist brace must maintain sufficient flexibility during conscious activities to avoid stiffness and muscle atrophy caused by over-fixation, while also providing timely and stable support during unconscious or high-risk moments.

The Y-zipper wrist brace enables rapid and reversible transitions between flexibility and rigidity, with one zipper strip directly 3D-printed onto the fabric. As shown in Fig.14a, when the other two strips remain unzipped, the brace stays soft, permitting natural wrist motion during conscious activities; as shown in Fig.14b, when the Y-zipper is closed, the structure transforms into a rigid frame that provides the necessary support and stability to counteract unexpected impacts. Notably, the closing motion can be completed single-handedly while wearing the device, without removing the brace or relying on external assistance. This property of on-demand stiffness modulation not only enhances wearing comfort and adaptability but also offers a wearable solution for TFCC rehabilitation that better aligns with clinical needs.

8.2 Quadruped Robot with Actively Adjustable Leg Length

In this section, we demonstrate the use of Y-zippers as continuously tunable structural members in a quadruped walking robot. Each of the robot's four legs is constructed from a 360 mm-long zipped Y-zipper rod and driven by a dynamic mechanical actuator with an encoder for closed-loop length control. At the proximal end of each leg, three 46 mm-diameter retraction spools (Section 6.4) neatly store and deploy excess zipper strip during zipping and unzipping cycles (Fig. 15.b). By coordinating all four actuators, the

robot can rapidly adjust its height from 60 mm to 245 mm in under 3 s (Fig. 15.a). We further implemented a dynamic trot gait, enabling stable and agile locomotion during leg-length transitions.

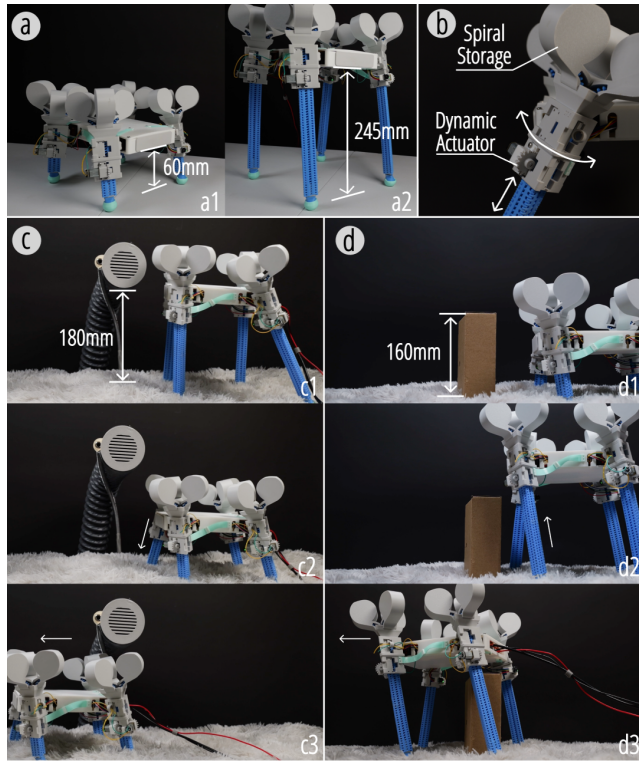


Figure 15: Quadruped robot with actively tunable leg length enabled by Y-Zipper. (a) Reversible transition between lowered (60 mm) and raised (245 mm) configurations in <3 s. (b) Single leg module showing the three 46 mm-diameter retraction spools at the hip and the geared DC motor with encoder for precise closed-loop length control. (c) Robot crawling under a low ceiling (180 mm clearance) in retracted configuration. (d) Robot stepping over an obstacle (160 mm height) in raised configuration.

The key advantage of this robot lies in its rapid and fully reversible length adaptation enabled by the Y-zipper legs. Compact planar-spiral storage at the hip minimizes volume in the retracted state, allowing the robot to crawl beneath 180 mm-clearance obstacles (Fig. 15.c). When extended, the legs provide sufficient ground clearance to step over tall terrain features (Fig. 15.d). Unlike traditional telescoping or multi-joint mechanisms, the Y-zipper achieves tunable leg length using only four lightweight tubes, without additional linkages or complex kinematics. This application demonstrates that Y-zippers can serve not only as flexible–rigid transition mechanisms, but also as continuous, controllable telescoping elements for adaptive robotic structures.

8.3 Kinetic Art Installation

In stage and theme park environments, movable installations bring vitality to the scene, allowing static set pieces to dynamically respond to narrative progression. By synchronizing with performances and audience movement, they transform spatial storytelling into an interactive and immersive experience that enriches both the spatial atmosphere and the audience’s emotional engagement. We designed a growing vine to demonstrate such application as shown in Fig. 16a, when unextended, the vine takes the form of a flower bud, with the unzipped portions remaining flexible and a height of 12 cm. It then “grows” into a winding vine shape, first extending upward by 26 cm and then bending downward to simulate the natural growth trajectory of a vine, during which the flower appears half-open. Finally, it extends fully upward to a length of 1.3 m, with the flower reaching a fully blossomed state as shown in Fig. 16b. The opening and closing of the flower are controlled by fishing lines inside the petals. The other ends of these lines pass through the vine and are connected to a tensioned spool. As the vine grows, it drives the fishing lines, pulling the petals to blossom.

This process not only demonstrates the expressive capability of Y-zipper in reversible flex-rigid transitions into rigid, highly curved geometries entirely through static mechanical actuation. But also highlights its potential in dynamic art and spatial installations. Through the sequential closing and unfolding of the structure, the work conveys the rhythm and tension of organic growth, allowing viewers to perceive the continuous transition between natural and artificial structures.

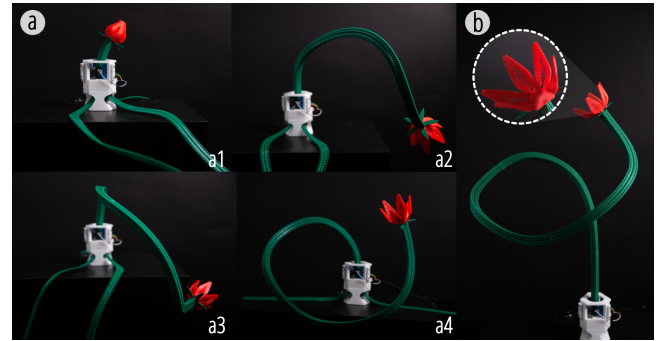


Figure 16: A kinetic art installation using Y-zipper. Using a static actuator, three zipper strips are drawn together and form a vine that grows, with a flower that opens.

8.4 Rapid Assembly and Disassembly in Tent Architecture

Y-zippers can be deployed for large scale structural applications. We modified a commercial pole-based tent by replacing its support poles with Y-zippers, demonstrating the feasibility of using Y-zippers as a large-scale structural framework. The frame consists of four Y-zippers, a joint connecting them, and four corner anchors of the tent. Each Y-zipper has a length of 1.5 m, spanning the full structure when assembled, which has overall dimensions of 196 × 145 × 102 cm. The closure of the frame can be achieved in two modes: manual operation and dynamic mechanical actuation.



Figure 17: Tent assembly with Y-zippers: (a) initial state before setup; (b) completed tent structure; (c) manual closure, achievable by a single person in 1 min 20 s; (d) dynamic actuator closure, four actuators operating in parallel to complete assembly in <1 min.

As shown in Fig. 17b, under manual operation, a single person can complete the setup, with each zipper requiring approximately 15 s to close, and the overall assembly time being about 1 min 20 s (including corner insertion and positional adjustments). As shown in Fig. 17c, with dynamic actuators, four units can work in parallel, closing each zipper in about 21 s, and completing the entire assembly in under 1 min. More importantly, the Y-zipper structure can also be dismantled with high efficiency, requiring only about 40 s to fully disengage the zippers. Once opened, all rigid structures revert to flexible strips that can be easily coiled or folded, greatly improving reusability and portability.

Before modification, assembling the tent took 4–6 minutes, and bending the poles was difficult for a single person. With our method, both the setup time and the operational effort are significantly reduced. Its demonstrated efficiency in both rapid setup and rapid disassembly highlights its potential for applications in emergency shelters, outdoor exploration, and portable architectural systems.

9 Evaluation

9.1 Investigating the Effect of Ball–Socket Dimensions and Tolerances on Zipping Performance

Ball–Socket Dimensions: To balance zipping resistance with post-closure stability, we systematically investigated how different combinations of ball-node diameter ϕ_1 and socket diameter ϕ_2 affect performance. Fig. 18a shows the tensile testing setup used to quantitatively measure zipping force. The results of this parametric study are summarized in the performance map in Fig. 18b, where the horizontal axis represents the ball-node diameter and the vertical axis represents the socket diameter. Each cell displays both the measured maximum zipping force and an image of the interlocked state, with color coding indicating overall performance.

The results show that as the diameter increases, the force required for zipping increases correspondingly. When the diameter

exceeds 2.8 mm, the required average pulling force rises above 15 N, resulting in noticeably high resistance. When the tolerance $\phi_2 - \phi_1 > 1.4$ mm, the interlocked teeth become loose after closure and may easily detach. Conversely, when $\phi_2 - \phi_1 < -0.8$ mm, the ball and socket cannot interlock properly, causing zipping failure. Overall, configurations with diameters between 1.0–2.8 mm support smooth zipping, and tolerance values between 0.2–0.8 mm provide reliable stability after closure.

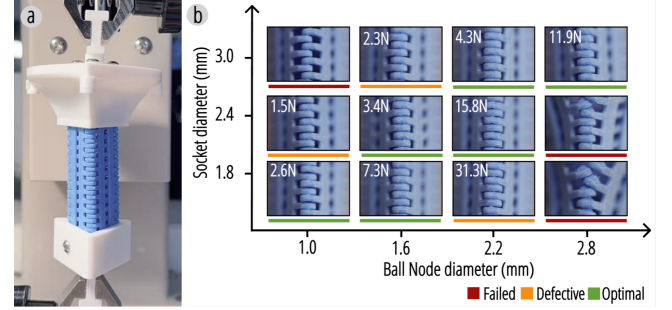


Figure 18: Experimental evaluation of ball-node and socket geometry on zipping performance and post-closure stability: (a) Custom tensile testing setup used to measure zipping force during closure. (b) Performance map summarizing the effect of ball-node diameter and socket diameter.

9.2 Exploring the Load-bearing Limits and Systematic Stiffness

To understand better how geometry and material choice influence the stiffness of a Y-Zipper structure, we performed three-point bending tests on specimens with controlled parameters (Fig. 19). We combine a simplified bending model with experimental measurements to characterize how tooth height H , bridge thickness D , and the zipped configuration affect overall rigidity.

Bending stiffness and tooth height H . When zipped, the three faces form a closed triangular tube whose bending stiffness depends on EI . For a beam of span L loaded at mid-span, the approximate stiffness is

$$k = \frac{F}{\delta} = \frac{48EI}{L^3}.$$

Therefore, the bending stiffness of the zipped tube is influenced by both the modulus E of the filament and the tooth height H . Indeed, the PLA modulus ($E \approx 2.6$ GPa) gives a TPU–PLA ratio of $\sim 2.2\times$, which matches the greater bending stiffness observed in PLA samples.

Bridge thickness D . Bridge thickness governs shear transfer between faces. Increasing D decreases shear deformation and raises the load at which shear-related damage begins. This matches the tests: increasing D from 0.8 mm to 2.0 mm raises the maximum supported load from about 11 kg to about 18 kg (Fig. 20).

Zipped versus unzipped. In the three-point bending tests (Fig. 20), specimens with identical geometric parameters were tested both in their strip (unzipped) and rod (zipped) states. The measured bending rigidities are

$$EI_{\text{strip}} \approx 1.9 \times 10^3 \text{ N mm}^2, \quad EI_{\text{rod}} \approx 3.1 \times 10^5 \text{ N mm}^2,$$

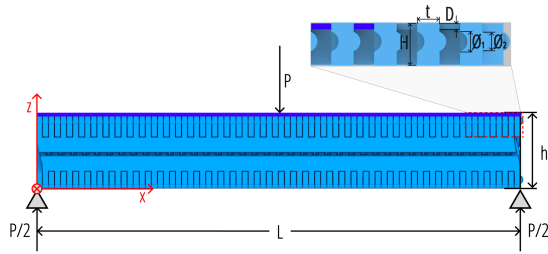


Figure 19: Beam model for a straight Y-zipper rod in three-point bending. H = tooth height, t = face (tooth base) thickness, D = bridge thickness, L = support span, P = applied transverse load at mid-span on edge of the prism

corresponding to an approximately $160\times$ increase in bending rigidity once the faces are locked into a closed triangular tube.

Three-point Bending Test: For the physical experiments, samples were fabricated using TPU and PLA materials via 3D printing. For each group, both the bridges and teeth were composed of a single material (as shown in Fig. 20). Three types of TPU samples and one type of PLA sample were printed with length of 200mm and with three specimens per type. Three-point bending tests were conducted on a universal testing machine with a span of 100 mm and a centrally applied load at a displacement rate of 30 mm/min. Each type was tested three times, and the resulting curves represent the average of these experiments.

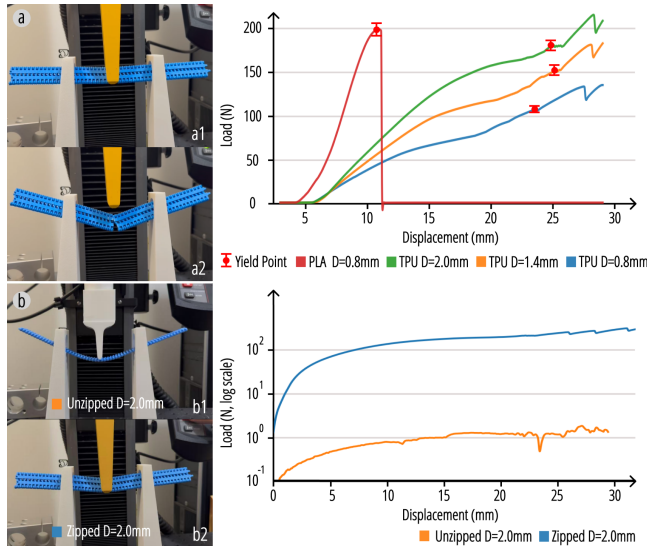


Figure 20: (a) Our setup for physically testing a Y-zipper with a bending resistance mechanical test and load-displacement curves from the mechanical tests. (b) the difference between unzipped and zipped state of one sample.

Experimental results show that increasing the bridge thickness D significantly enhances the bending resistance limit. For instance,

a rod with $D = 0.8$ mm can withstand a maximum load of approximately 11kg (blue curve), whereas a rod with $D = 2.0$ mm can withstand up to 18kg (green curve), clearly illustrating the influence of bridge thickness on bending strength. In addition, PLA, with its higher stiffness, tends to fracture directly under maximum load, while TPU undergoes larger deformations to counteract the applied pressure.

9.3 Simulations

We ran structural simulations of a single Y-zipper rod in Fusion 360 to evaluate its mechanical response under load (Fig. 21). The rod was fixed at both ends and subjected to a central downward point load, following a standard three-point bending protocol.

Figure 21b shows the displacement field, with colors ranging from blue (minimal deflection) to red (maximum deflection). Figure 21a shows the corresponding safety factor distribution, defined as the ratio of the material's yield strength to the simulated von Mises stress at each point. Most of the structure remains in the "above target" region (blue), while localized zones near the mid-span fall into the "below target" range (red), marking where yielding would initiate. The deflected profile exhibits the smooth curvature characteristic of bending rods, consistent with our physical experiments showing that the Y-zipper deforms elastically and distributes load along its length.

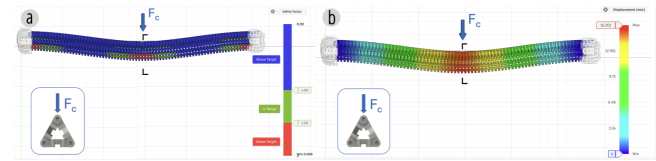


Figure 21: Fusion-360 simulations of a Y-zipper showing (a) safety factor and (b) displacement.

9.4 Fatigue Limits Test of Zippers

We conducted a fatigue test on the Y-zipper samples, using the same dimensions and part parameters as the straight primitive. The samples were mounted vertically with the bottom end fixed to the ground, and an A4950 driver module was used for dynamic mechanical actuation. When the actuator reached the lower limit and fully opened the zipper, a contact switch at the base was triggered and sent a signal to the ESP32. The ESP32 then output an inverted driving signal, causing the actuator to move in the reverse direction and re-close the zipper. Once the zipper was fully closed, a new cycle began.

Each cycle lasted 8 seconds: 3.5 seconds for downward motion, 3.5 seconds for upward motion, and 0.5 seconds for pause and reversal. The experiment ran continuously for one day and 15 hours, completing more than 18,000 cycles. The final fracture occurred at the interface between the teeth and the bridges.

10 Limitations and Future Work

We next address the limitations within our work and explore potential directions for future research.

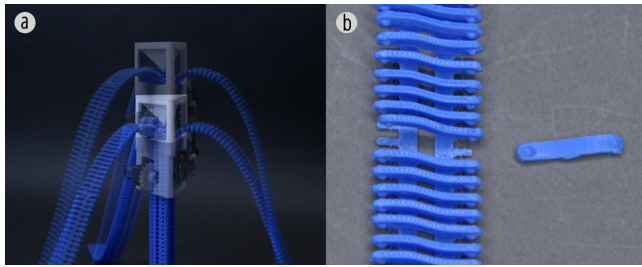


Figure 22: Fatigue limits test:(a)experiments process, repeated for more than 18,000 cycles; (b)The final fracture position.

10.1 Material Performance

At present, Y-zipper relies on FDM 3D printing and a limited range of materials such as PLA and TPU. The strength, wear resistance, and flexibility of these materials restrict the use of Y-zipper in high-load or extreme environments. For example, when the width $w = 25$ mm and the zipper length exceeds 1 m, noticeable sagging due to gravity occurs. We have accounted for this in the tent application scenario, but there is currently no explicit algorithm to compensate for the displacement caused by material deformation. In future work, we plan to explore both stronger materials and computational methods to predict and compensate for gravitational sag.

10.2 Printing Resolution and Precision

The accuracy of Y-zipper is limited by 3D printing resolution. When the tooth thickness falls below 1.2 mm, the precision of the ball node and socket is insufficient, leading to weak interlocking and easy detachment. The narrowest functional strip width we achieved is 8 mm; reducing it further makes the wave-shaped teeth unable to interlock effectively. In the future, we plan to adopt higher-resolution printing methods such as SLA to fabricate smaller-scale components, which may open new opportunities for applications in the medical field.

10.3 Size and Actuation

According to our evaluation results, the maximum viable zipper length is approximately 3 m. Beyond this length, bridges near the base tend to fracture due to gravity, and significant force is required at the start of closure to counteract the weight of the unclosed portion. In vertical motor tests, the maximum closure length achievable with a single dynamic motor was 1.2 m; beyond this, the unclosed portion's weight caused motor stalling. In static actuation tests with three motors, the maximum length achieved was 1.8 m; beyond this, tipping occurred and compressed the springs. Although these results highlight the current limitations of our prototypes, future work could explore multi-motor coordination, counterweight mechanisms, or lightweight reinforcement strategies to extend the operable length.

11 Conclusion

We present Y-zipper, which introduces a novel three-sided zipper mechanism that enables rapid, reversible, and structurally stable transitions between flexible and rigid states. By integrating a specialized slider and supporting multiple actuation modalities, Y-zipper achieves remote and automated control while supporting diverse transformation types, including straight, bend, coil, and screw. Our computational design tool further lowers the barrier for customization, allowing designers to efficiently generate complex zipper geometries with embedded compliant features. Controlled experiments demonstrate the robustness, repeatability, and speed of our approach, while functional prototypes highlight its versatility across domains such as assistive devices, interactive furniture, and deployable structures. Together, these contributions illustrate how Y-zipper expands the design space for flex-rigid transitions and opens new opportunities for rapidly assembled, reconfigurable, and interactive 3D-printed artifacts.

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A Appendix

A.1 3D Printing Settings

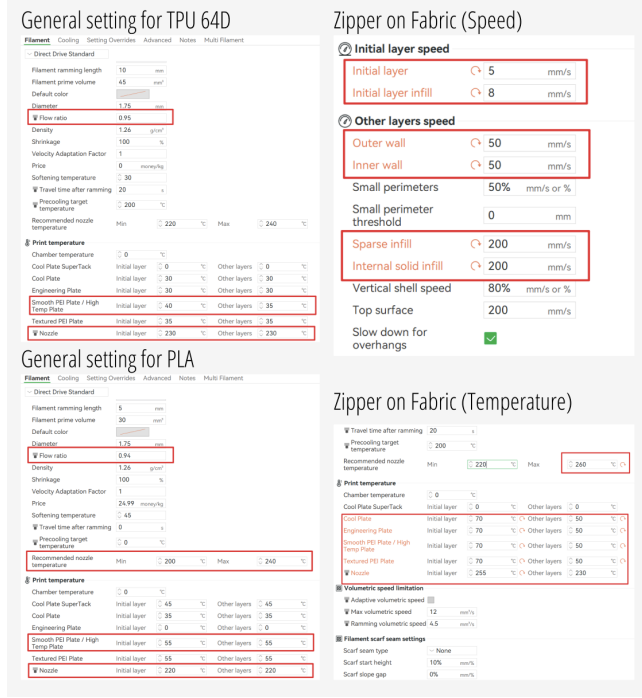


Figure 23: Example printing parameters for fabricating the Y-Zipper using the Bambu Lab series (including A1, X1, and H2D). With the provided design tool, most FDM 3D printers can fabricate the zipper structure using materials such as TPU and PLA, and also support direct printing onto fabrics.

A.2 Sizes of Primitives and applications

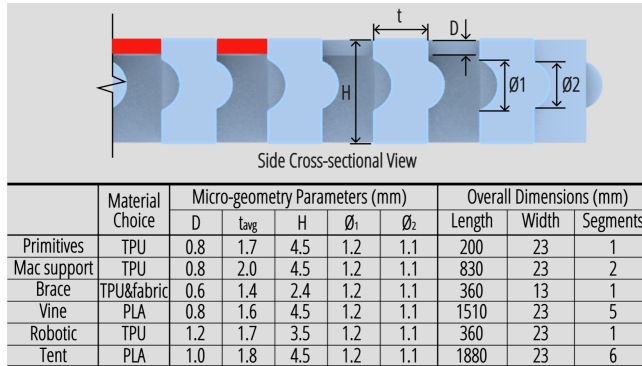


Figure 24: Micro-geometry parameters and overall dimensions of the Y-zipper structures. Here, t_{avg} denotes the average tooth thickness (with minor variation in curved geometry), and segments indicate the number of print sections required when the strip exceeded the printer's build volume.

A.3 Formula for the Primitives

Bend primitives:

The accumulated tooth thickness values for each interface are computed as:

$$T_1 = \sum_{i=1}^{2n} t_{1,i}, \quad T_2 = \sum_{i=1}^{2n} t_{2,i}. \quad (1)$$

The bending angle θ and the effective bending radius R are expressed as:

$$\theta = \frac{2}{\sqrt{3}w} (T_1 - T_2), \quad R = \frac{T_1 + T_2}{2\theta}. \quad (2)$$

When a slider travels along the strips at velocity v , the endpoint motion in 3D space is modeled as:

$$(x, y, z) = \left(0, R \sin \varphi(t), R(1 - \cos \varphi(t)) \right), \quad \varphi(t) = \frac{vt}{R}. \quad (3)$$

Coil primitives:

The primary geometric parameters are defined as:

$$L = \frac{T_1 + T_2 + T_3}{3}, \quad h = \frac{\Delta z}{\theta}, \quad R = \frac{1}{2\pi} \sqrt{\left(\frac{L}{\theta}\right)^2 - \left(\frac{\Delta z}{\theta}\right)^2}. \quad (4)$$

The coil angle as a function of time t is expressed as:

$$\varphi(t) = v \cdot t \cdot \frac{2\pi}{\sqrt{h^2 + (2\pi R)^2}}. \quad (5)$$

The resulting spatial trajectory of the slider endpoint is:

$$(x, y, z) = \left(-R \sin \varphi(t), R(1 - \cos \varphi(t)), \frac{h\varphi(t)}{2\pi} \right). \quad (6)$$

Screw primitives:

The vertical height reduction due to screw rotation is computed as:

$$L_z = \sqrt{L^2 - (r\theta_z)^2}, \quad r = \frac{\sqrt{3}}{2}w. \quad (7)$$

The slider's spatial position over time, assuming constant actuation velocity v , is:

$$(x, y, z) = \left(0, 0, \frac{L_z}{L} v t \right). \quad (8)$$

The corresponding orientation of the slider is modeled as:

$$\varphi(t) = \frac{\theta_z}{L_z} v t, \quad \hat{u}(t) = (-\cos \varphi(t), -\sin \varphi(t), 0). \quad (9)$$

Series combinations:

The total flattened length of a series mechanism composed of m primitives is:

$$L_{\text{total}} = \sum_{i=1}^m L_i, \quad (10)$$

where L_i corresponds to the length of the i th primitive (e.g., straight length or effective arc length for bends and coils).

The spatial trajectory of the slider is computed by accumulating the local displacements of each primitive using homogeneous coordinate transformations:

$$\mathbf{r}(t) = \sum_{i=1}^m \mathbf{T}_{i-1} \cdot \mathbf{r}_i(t_i), \quad (11)$$

Algorithm 1 Flatten Algorithm for Zipper Strips**Require:**

- 1: $\mathcal{M}_{3D} = (\mathcal{V}, \mathcal{E}, \mathcal{F})$: Input doubly-curved triangle mesh;
- 2: $\mathcal{T}_{Left} = \{(u_k^{start}, u_k^{end})\}_{k=1}^N$: Normalized topology intervals for left boundary;
- 3: $\mathcal{T}_{Right} = \{(v_k^{start}, v_k^{end})\}_{k=1}^N$: Normalized topology intervals for right boundary;
- 4: $K_{stiffness}$: Elastic spring constant for relaxation;
- 5: ϵ_{tol} : Convergence tolerance for position updates.

Ensure:

```

6:  $\mathcal{P}_{Fabrication}$ : Set of 2D unrolled strip geometries.
7: Phase 1: Mesh Initialization and Planar Projection
8: Compute centroid  $\mathbf{c} \leftarrow \frac{1}{|\mathcal{V}|} \sum \mathbf{v}_i$ 
9: Compute average normal  $\mathbf{n}_{avg} \leftarrow \frac{1}{|\mathcal{F}|} \sum \mathbf{n}_f$ 
10: Construct projection plane  $\Pi$  defined by  $(\mathbf{c}, \mathbf{n}_{avg})$ 
11:  $\mathcal{V}_{2D} \leftarrow \emptyset$ 
12: for each vertex  $v_i \in \mathcal{V}$  do
13:    $\mathbf{p}_i \leftarrow \text{Project}(v_i, \Pi)$   $\triangleright$  Orthogonal projection to 2D plane
14:    $\mathcal{V}_{2D}.\text{append}(\mathbf{p}_i)$ 
15: end for
16: Phase 2: Iterative Elastic Relaxation (Unrolling)
17:  $iteration \leftarrow 0$ 
18: repeat
19:    $\Delta_{max} \leftarrow 0$ 
20:   for each vertex  $v_i \in \mathcal{V}_{2D}$  do
21:      $\mathbf{F}_{net} \leftarrow \mathbf{0}$ 
22:     for each neighbor  $v_j \in \text{Neighbors}(v_i)$  do
23:        $L_{rest} \leftarrow \text{GeodesicDist}_{\mathcal{M}_{3D}}(v_i, v_j)$   $\triangleright$  Target length from 3D
24:        $L_{curr} \leftarrow \|\mathbf{p}_i - \mathbf{p}_j\|_2$   $\triangleright$  Current 2D length
25:        $\mathbf{d}_{ij} \leftarrow (\mathbf{p}_j - \mathbf{p}_i) / L_{curr}$   $\triangleright$  Unit direction vector
26:        $\mathbf{F}_{spring} \leftarrow K_{stiffness} \cdot (L_{curr} - L_{rest}) \cdot \mathbf{d}_{ij}$ 
27:        $\mathbf{F}_{net} \leftarrow \mathbf{F}_{net} + \mathbf{F}_{spring}$ 
28:     end for
29:      $\mathbf{p}_i^{new} \leftarrow \mathbf{p}_i + \alpha \cdot \mathbf{F}_{net}$   $\triangleright$  Apply displacement
30:      $\Delta_{max} \leftarrow \max(\Delta_{max}, \|\mathbf{p}_i^{new} - \mathbf{p}_i\|)$ 
31:   end for
32:   Update all positions in  $\mathcal{V}_{2D}$ 
33:    $iteration \leftarrow iteration + 1$ 
34: until  $\Delta_{max} < \epsilon_{tol}$  or  $iteration > \text{MaxIter}$ 
35: Phase 3: Boundary Topology Extraction
36:  $\mathcal{B}_{edges} \leftarrow \text{FindNakedEdges}(\mathcal{M}_{2D})$ 
37: Sort  $\mathcal{B}_{edges}$  into two continuous chains:  $C_{Left}$  and  $C_{Right}$ 
38:  $C_{Left}(t) \leftarrow \text{Reparameterize}(C_{Left}, \text{Method} = \text{ArcLength}, \text{Domain} = [0, 1])$ 
39:  $C_{Right}(t) \leftarrow \text{Reparameterize}(C_{Right}, \text{Method} = \text{ArcLength}, \text{Domain} = [0, 1])$ 
40: Phase 4: Zipper Strip Generation
41:  $\mathcal{P}_{Fabrication} \leftarrow \text{List}()$ 
42: for  $k \leftarrow 1$  to  $N$  do
43:    $\triangleright$  Extract sub-segments based on input topology
44:    $S_L \leftarrow \text{TrimCurve}(C_{Left}, \mathcal{T}_{Left}[k])$ 
45:    $S_R \leftarrow \text{TrimCurve}(C_{Right}, \mathcal{T}_{Right}[k])$ 
46:    $\triangleright$  Check orientation to prevent twisted surfaces
47:   if  $\text{DotProduct}(\text{Tangent}(S_L, 0.5), \text{Tangent}(S_R, 0.5)) < 0$  then
48:      $S_R \leftarrow \text{ReverseCurve}(S_R)$ 
49:   end if
50:    $\triangleright$  Loft segments into planar strip
51:    $\text{Strip}_k \leftarrow \text{CreateRuledSurface}(S_L, S_R)$ 
52:    $\mathcal{P}_{Fabrication}.\text{append}(\text{Strip}_k)$ 
53: end for
54: return  $\mathcal{P}_{Fabrication}$ 

```

where $\mathbf{T}_{i-1}$ denotes the transformation introduced by all previous primitives and can be recursively calculated from their geometric parameters.

A.4 Flatten Algorithm

The generation of the 2D zipper patterns is achieved through an unrolling process that maps the spatial geometry onto a planar domain while preserving geodesic distances. The algorithm takes a doubly-curved or developable reference surface $S \subset \mathbb{R}^3$ as input, characterized by two longitudinal boundary curves, denoted as C_1 and C_2 .

The process begins by unrolling the reference surface S onto the xy -plane to obtain a flattened representation $S' \subset \mathbb{R}^2$. This transformation is constrained to minimize metric distortion, ensuring that the lengths of the longitudinal boundaries are preserved (i.e., $\|C'_1\| \approx \|C_1\|$ and $\|C'_2\| \approx \|C_2\|$).

Subsequently, the planar boundaries C'_1 and C'_2 are segmented based on two input arrays of parametric intervals, $\mathcal{D}_1$ and $\mathcal{D}_2$, where each element is a tuple (t_{start}, t_{end}) . These intervals define the connectivity topology of the zipper structure. Corresponding segments from each boundary are then paired sequentially.

Finally, a lofting operation is performed in the 2D domain between each pair of corresponding segments. This generates a series of planar strips which, when physically zipped together, will buckle out of plane to approximate the stiffness and curvature of the original spatial tube. The detailed procedure is outlined in Algorithm 1.