Compliance in jumping robots improves gait stability and enables energy-efficient locomotion. Here, 3D printable auxetic tubular springs from thermoplastic polyurethane (TPU) for rapid and sustainable hopping are developed. Because the springs have negative Poisson’s ratios, they become stiffer as compression proceeds and theoretically stores 35.2% more energy than a linear spring with the same stiffness. As the stress concentrates on the hinges, it is revealed through experimental, numerical, and analytical investigations that hinge geometries, for example, the lattice angle and hinge radius, governs the global stiffness and robustness of the springs. The hopping robot leg composed of three auxetic tubular springs in parallel sustains more than 1,000 cycles of repeated, one-degree-of-freedom (1-DOF) vertical hopping and two-degree-of-freedom (2-DOF) forward hopping. The 2.5 kg-robot system requires minimum 420 mJ of elastic energy for repeated hopping. The springs are pre-compressed by tendon-driven actuators and stores 1.08 J during jumping and release the springs when touching the ground. The power stroke is calculated as 15–18 W. The average velocity of the hopping robot reaches 0.06 m s\(^{-1}\) with the increase of touchdown angle to 0.125 rad. The cost of transport is calculated as 6.7, similar to those of the living organisms.

1. Introduction

Traditional robots with rigid components and linkages can exert large force to achieve programmed locomotion rapidly and robustly. However, they are heavy and require large sized batteries to power the tasks. As a result, they often have limited degree of freedom (DOF) of motions and low adaptivity; to render individual DOF, it requires individual control of each actuator. Bio-organisms, in contrast, are lightweight, inherently compliant, and can adapt different environments with large DOF. Therefore, there have been significant efforts to exploit soft materials and structures with controlled compliance to improve robot’s freedom of movement, mechanical robustness, and environmental responsiveness.[1]

Compliance in legged robots will not only improve the robot stability passively by balancing the center of mass,[2–4] but increase the efficiency of storage and release of the elastic energy during jumping.[4–6] For example, to efficiently reduce the energy consumption, many legged animals and human gait store kinetic or elastic potential energy in their muscles and release it when lift-off.[6,7] Inspired by the dynamic behaviors in animals, series elastic actuators, where the motor (actuator) and the elastic components are connected in series, has been developed and applied in compliant robots.[6,8] The elastic components should respond rapidly to reduce the cost of transport, while being mechanically robust. To get the energy to lift-off, jumping robots have adopted elastic energy storage such as linear and torsional springs,[9–11] elastic strips,[12] pneumatic energy storages,[13] and fuel storages that are powered by combustion.[14] Among them, linear or torsional springs are most popular due to their simple mechanical structures, reversibility, and large energy storage.[9]

While soft materials are intrinsically compliant, they are usually lossy and have lower elastic energy storage than metals or ceramics do. This is because the polymer chains entangle or slip against each other under deformation, leading to loss of elastic energy to heat, and thus increasing the cost of transport, reducing the energy efficiency of the robot, and limiting their applications in quasistatic regimes. To overcome the intrinsic limitations of soft materials, architected mechanical metamaterials are of growing interests to improve the agility and power
density of the robots. Mechanical metamaterials are the materials whose mechanical properties are governed by their structural parameters in addition to the material’s intrinsic properties.\textsuperscript{[13–17]} Through bending, folding, rotation, and buckling of the building elements, mechanical metamaterials can perform different collective actions.\textsuperscript{[18]} Metamaterials with multistability can be utilized for energy storage, which improves the agility and the stroke of robots.\textsuperscript{[19–21]} Several jumping robots have borrowed these characteristics of metamaterials to develop compliant components that are lightweight and capable of storing the energy required for jumping.\textsuperscript{[12,22,23]} For example, a thin, rectangular-shaped elastic strip is initially curved and then the edges are repeatedly twisted and untwisted via snap-through buckling to store and release the strain energy for rapid and repeated jumps.\textsuperscript{[22]} Origami is a compact and lightweight platform whose kinematic properties are determined by the rigid facets and folding lines. Baek et al. develop a deployable jumping glider by introducing an origami joint structure with compliant facets, enabling both energy storage and self-locking for rapid jumping ($\approx$116 ms).\textsuperscript{[24]} Similarly, we have developed reconfigurable bistable origami springs that can improve the agility, compliance, and resilience of robotic legs by storing and releasing elastic energy in the folds and demonstrate dynamic, repetitive juggling, and hopping motions.\textsuperscript{[21,24]} However, utilizing elastic instabilities limits the accurate control of kinematic and driving force,\textsuperscript{[7]} which is further complicated by manual folding of the origami structures.

Here, we design 3D printable auxetic tubular springs that are agile and resilient for hopping robots with precisely controlled geometries and thus, dynamic behaviors, which can be maintained repeatedly. Auxetic structures are a class of cellular mechanical metamaterials with negative Poisson’s ratio, which expand or compress in all directions.\textsuperscript{[18,25]} It has been demonstrated that auxetic structures have higher indentation resistance than nonauxetic geometries even with the same structural density (or volume fraction).\textsuperscript{[26–29]} For example, Alderson et al. prepare a microporous structure from high molecular weight polyethylene with a wide range of Poisson’s ratios ranging from $-0.8$ to $0.2$.\textsuperscript{[28]} The one with a negative Poisson’s ratio shows two times greater indentation hardness than that with a positive Poisson’s ratio while maintaining the similar mass density. Li et al. demonstrate that auxetic-reinforced elastomer composite could have three times higher indentation resistance than the nonauxetic one under the same volume fraction of the reinforced frame.\textsuperscript{[29]} They also reveal that the indentation resistance could be increased as the Poisson’s ratio becomes more negative, confirming that the higher indentation resistance feature is originated from the negative Poisson effect. These studies imply that auxetics could have a greater compressive stiffness than nonauxetics with the same body mass under the same preset conditions. Therefore, it is attractive to create a lightweight spring with higher stiffness as a result of the negative Poisson’s ratio behavior of auxetics.

The complex open-cell geometries of our 3D auxetic tubular springs are achieved through additive manufacturing of thermoplastic polyurethane (TPU). The open-cell geometry together with the choice of TPU, which has a density $\approx$8 times lower than that of the conventional metal alloys used in springs, offer a lightweight elastic energy storage mechanism that reduces the cost of transport and improves the energetic efficiency of the hopping robot performance. We demonstrate both experimentally and numerically that the developed auxetic tubular springs have a wide range of tunability in mechanical properties by controlling the geometric parameters that defines the auxetic motif. Three auxetic tubular springs are connected in parallel and the hopping robot performs 1-DOF vertical hopping and 2-DOF forward hopping more than 20 s, corresponding to 1,000 cycles of repeated jumps (referred as sustainable hopping). A power-stroke of our auxetic tubular springs ranges from 15 to 18 W, and the cost of transport is calculated as 6.7, which is comparable to the values from the lizards and rats.\textsuperscript{[10]}

2. Results and Discussion

2.1. Preparation of the Hopping Robot Leg with Auxetic Tubular Springs

\textbf{Figure 1A} shows the layout of a hopping robot leg consisted of three tendon-driven motor modules, three compliant auxetic tubular springs, an elastomeric foot, and a force sensor. Similar to our prior work with origami spring legs,\textsuperscript{[23]} the three springs are connected in parallel upholding the motor modules, and each motor is set to compress the individual auxetic tubular spring. The piezoresistive force sensor is integrated between the auxetic tubular springs and the elastomeric foot to sense the ground.
contact. The tendon-driving motors and the force sensor are electrically connected to an on-board microprocessor and powered by an off-board 16 V battery. The integrated robot is mounted on a linear rail to constrain the motion only in the vertical direction (Figure 1B). The auxetic tubular spring (see Figure 1C) is modeled by computer-aided design (CAD) and manufactured by fused deposition manufacturing (FDM) of the TPU with 95 A shore hardness. The Young’s modulus of TPU material is 25–50 MPa, which is ≈10 times larger than that of the conventional silicone rubber materials. Based on the inherent mechanical property of the constituent material, we expect that our auxetic tubular springs can reliably support the weight of the hopping robot, while undergoing deformation during hopping. Also, the inherently low density of TPU (1.21 g cm\(^{-3}\)) compared to that of the metal alloys (7–8 g cm\(^{-3}\)) used in conventional springs helps to reduce the total weight of the robot and improves cost of transport.

2.2. Design Parameters and Compressive Behavior of Auxetic

Figure 2A shows the 2D view of the auxetic tubular spring unrolled into a flat film, consisting of three periodic motifs along the long axis of tube and four periodic motifs in the circumferential direction. Auxetic motifs can be classified into three groups, rotating unit motif, re-entrant motif, and chiral motif (Figure S2, Supporting Information).[31] Among various auxetic geometries, we choose the rotating unit auxetic motif for tubular springs because compared with other auxetic motifs it has shorter length ligament (also referred as the hinge), where compressive stress concentrates, thus, buckling instability of the tube could be minimized and achieve mechanically more reliable robot performance (See more discussions in the Supporting Information on our rationales not choosing other motifs).

Each motif is considered as the periodic unit of the tube connecting four rectangular units that can open and close through counterclock rotations via hinges, demonstrating negative Poisson effect under tension or compression (Figure 2B). The length of the long and short sides of the rectangle are 10 and 5 mm, respectively. This periodic motif is known to have stress concentration at the joint point where rectangular unit meets, so it is important to introduce rationally designed hinge to prevent mechanical breakdown.[32] Inspired from the prior study, we designed a circular-shaped hinge so that it can evenly distribute the stress generated during deformation as well as facilitating the modeling of hinge bending stiffness that will be discussed later. The radius of the curved hinge is designed to be 1.4 mm. Once the auxetic motif constitutes the tube, it shrinks radially when compressed in the perpendicular direction (Figure 2C).

2.3. Mechanical Characterization of Compressive Behavior of Auxetic Tubular Springs

Next, the mechanical properties of the auxetic tubular springs are characterized experimentally and numerically by finite element method (FEM). Figure 3 represents the compressive behavior of 3D-printed auxetic tubular spring with a 75° lattice angle (\(\theta_c\)), the angle between the adjacent rectangular units as illustrated in Figure 2A) and 1.4 mm hinge radius. Figure 3A shows the experimentally measured compressive force curve, which agrees very well with the numerical prediction by FEM, suggesting that the printed TPU units remain rigid, not buckled. A significant increase of the stiffness is observed when the tube is compressed over 12 mm. To reveal the mechanism behind the continued stiffening behavior during compression, snapshots of the compressed auxetic tubular springs are taken at the moments marked on Figure 3B as black dots. By matching the force–displacement curve and snapshots of the spring, it is clear that the sudden increase of stiffness is due to the contact of the closest hinges in the tube. The contact points are denoted by the red dashed-line circles in Figure 3B(ii). Upon further compression, the second closest hinges start to make contact with each other (see the blue dashed-line circles in Figure 3B(iii)), and the stiffness of the tube steadily increases.

Cyclic compression and relaxation results of the auxetic tubular spring are presented in Figure 3C. The perfect overlay of the curves from each cycle implies that the auxetic tubular spring deforms elastically, where the elastic strain energy is stored in compressed state and completely dissipated upon relaxation. The hysteresis shown in the compressive force–displacement curve is a result of the viscoelastic nature of TPU,[13] not due to geometry. The time-dependent relaxation test of TPU and the auxetic tubular spring further supports the hysteresis effect comes from TPU itself (Figure S3, Supporting Information). Under a constant strain, the tensile stress of TPU reduces to 64% from the peak value, and the compressive force of the auxetic tubular spring reduces to 68% from the peak.
value. Since most of the hinge is subjected to tensile stress when the tube is compressed, a similar degree of relaxation seems reasonable. The elastic energy stored in spring for jumping (the orange shaded area in Figure 3C) and dissipated due to damping (the gray-shaded area in Figure 3C) can be calculated by integration of the force–displacement curve. Approximately 32% of the energy is dissipated when the auxetic tubular spring is compressed to 25 mm and relaxed. As compression proceeds, the stiffening effect allows the auxetic tubular spring to store more elastic energy than a linear one. As discussed earlier, negative Poisson effect of auxetics can lead to generate higher indentation stiffness or compressive stiffness compared with nonauxetics under the same preset conditions with the same mass density. Here, assuming the auxetic tubular spring and the linear spring that have the same initial stiffness are compressed to the same level, the stored elastic energy is about 35.2% more for the auxetic tubular spring (Figure S4, Supporting Information).

2.4. Geometric Parameter Dependence on Compressive Behavior of Auxetic Tubular Springs

We then investigate the effect on the compressive behaviors of the auxetic tubular springs as a function of the lattice angle, $\theta_L$. For experimental investigation, the auxetic tubular springs with $\theta_L = 60^\circ$, $75^\circ$, and $90^\circ$ are designed and printed (the radius of hinge is 1.4 mm). The compressive force–displacement curves of the springs are plotted in Figure 4A. The solid line represents the experimental results, and the dash line represents the FEM simulation results, which show similar trends. Due to the convergence issues that originated from the contact of the model itself, compression of tube in FEM simulations of $\theta_L = 60^\circ$ and $75^\circ$ lattice angle models are terminated earlier than the experiments (see more detailed explanation in Supporting Information). The compressive force curves of $\theta_L = 60^\circ$, $75^\circ$, and $90^\circ$ are plotted in green, orange, and purple lines, respectively. All three angles show significant stiffness increase as the compression proceeds because they share the same stiffening mechanism, that is the adjacent hinges come into contact as the spring is continuously compressed. As the lattice angle is increased, the compression length at which stiffening occurs increases because the gap between adjacent hinges increases. Likewise, the stiffness value of the auxetic tubular spring increases. As seen from the von Mises stress contour map of

Figure 3. Quasistatic compressive behaviors of the auxetic tubular spring. A) Experimentally measured compressive force–displacement curve versus FEM result of the auxetic tubular spring with a $75^\circ$ lattice angle. (i), (ii), and (iii) marked on the curve represent three compressive states shown in (B). B) Snapshots of the compressed auxetic tubular spring at the moment denoted as (i), (ii), and (iii) marked on the curve in Figure 3A. C) Cyclic compressive force–displacement curves. The orange area denotes the capacity of the stored elastic energy in the tube under compression, and the gray area denotes the dissipated energy during relaxation. D) von Mises stress contour map of the compressed auxetic tubular unit. Stress is mostly concentrated at the hinge.
the auxetic tubular spring units (Figure 4B), where each unit is compressed by 28% from the initial height, the stressed volume increases as the lattice angle is increased.

Besides the stressed volume, we can also mathematically predict the relationship between stiffness and the lattice angle by establishing a simple analytic model. We assume the model is consisted with the curved hinge connecting two rectangular units, as seen in Figure 4C,D. The proposed analytical model assumes that the deformation only occurs in the hinge, which is suggested as a torsional spring with a spring constant, $\kappa$.

Here, we expect that the force in the perpendicular direction is proportional to $\kappa$ and inversely proportional to the length of the moment arm, $r$, according to the physics of torque (Figure 4D). $\kappa$ can be expressed as

$$\kappa \propto \frac{RtE}{\theta_h}$$

where $R$ is the hinge radius, $t$ is the thickness of spring, $L$ is the longer side length of the rectangular unit, $E$ is the Young's modulus of the constituent material, and $\theta_h$ is the hinge angle, which is equal to $\left(\pi - \theta_l\right)$, and $r$ can be expressed as

$$r = L\cos\left(\frac{\theta_l}{2}\right)$$

Figure 4. Quasistatic compressive behavior of the tubular auxetic spring varying with the lattice angle, $\theta_l$. A) Compressive force-displacement curve. Experimental results are plotted in solid lines and FEM simulation results are plotted in the dash lines. B) von Mises stress contour map of tubular auxetic spring units with different lattice angles compressed by 28% of the initial height. C,D) Schematic illustrations describing the analytic model of the compressive stiffness of auxetic units. E) Compressive force-displacement curve varying with the hinge radius. Experimental results are plotted in solid lines and FEM simulation results are plotted in the dash lines. F) Stiffness at the initial compression stage versus the radius of hinge. Solid dots represent the experimental results and hollow dots are the FEM results. The lattice angle was designed to be 75°.
Therefore, the force in the perpendicular direction is proportional to

\[
F_\perp \propto \frac{RtE}{L \cos(\theta_L/2)(\pi - \theta_L)} = \frac{RtE \sec(\theta_L/2)}{L (\pi - \theta_L)} \quad (3)
\]

Equation (3) represents the stiffness expression as a function of \( \theta_L \) seen in Supplementary Figure 5, which increases as \( \theta_L \) increases. The tendency of increased global stiffness of the spring predicted by the model agrees well with the obtained stiffness values from Figure 4A and Figure S5B, Supporting Information. The deviation from the experimental results could be due to the deformations in rectangular units (Figure S6, Supporting Information), which we assume to be rigid in the analytical model. Nevertheless, this relationship is capable to predict the general trend of how the initial stiffness varies with the lattice angle.

The third physical behavior change depending on the lattice angle is the compression length limit of the auxetic tubular spring. Here, we define the compression length limit of the spring when the auxetic lattice closes, or when the long side of the rectangular unit lay down parallel to the ground, as shown in Figure 3C(iii). For example, it is \( \approx 20 \text{ mm} \) for \( \theta_L = 60^\circ \) and \( \approx 25 \text{ mm} \) for \( \theta_L = 75^\circ \). In the case of \( \theta_L = 90^\circ \), buckling happens that deviates the longitudinal axis of the spring when compressed over 20 mm (Figure S6, Supporting Information). This instability locally deforms the auxetic tubular spring, leading to mechanical breakdown when further compressed. The experimentally obtained force-displacement of the spring with \( \theta_L = 90^\circ \) is smaller than that obtained by FEM simulation, confirming that buckling reduces the reaction force of the compressed spring. Therefore, we define the compression length limit of the spring with \( \theta_L = 90^\circ \) as 20 mm, which is lower than that of \( \theta_L = 75^\circ \). This instability implies a limiting criterion of the lattice angle when designing the auxetic tubular spring.

In addition to the lattice angle, the geometry of the hinge can govern the stiffness of the spring because the stress concentrates on the hinges when the spring is globally compressed. Figure 4E displays the compressive force–displacement curves of springs varying with the hinge radius. The radii of hinges are set to 0.8, 1.4, and 2.0 mm, with \( \theta_L = 75^\circ \). The solid line represents the experimental results, and the dash line represents the FEM simulation results, which show similar trends. Figure 4F shows that the stiffness at the initial stage of the compression increases monotonically with the increase of the radius of hinge, in both experiments and simulation. This relationship follows well with the suggested bending stiffness model of the radial hinge in Equation (3). A slight deviation between experiments and simulation is observed, which could be attributed to the assumption of rigidity of the analytical model.

Figure 5. A) Snapshots of the vertically hopping robot with auxetic tubular springs. B) Trajectories of the apex of the hopping robot varying with initial drop height. C) Steady-state apex height with respect to the precompression length of the auxetic tubular springs. D) Stored elastic energy in the auxetic tubular springs of different lattice angles with respect to the precompression length. Solid dots denote sustainable hopping and hollow dots denote temporary hopping.
and the simulation came from the feature size of the hinge: the tube was designed to have hinge radius of 0.8 mm but the actual printed one was 1.08 mm due to the printing path and the minimum size of the extruded TPU filament (400 μm).

2.5. Hopping Robot with Auxetic Tubular Springs

Based on the quasistatic compressive behaviors, we investigate the dynamic hopping performance of our auxetic tubular springs. Figure 5A is a series of snapshots of the jumping process of a hopping robot equipped with three auxetic tubular springs with a lattice angle of 75°. The hopping robot is mounted to the vertical rail and can only move vertically with respect to the ground. The tendons within the springs are pulled by the motors to compress the auxetic tubular springs to a specified length (Figure 5A(ii)) in order to store the energy required for jumping (see Figure 1A). The hopping robot, which is equipped with a force sensor positioned between the spring and the foot (Figure 1A) to detect pressure upon impact, is then dropped. When the foot contacts to the ground (Figure 5A(iii)) and the pressure is sensed, the microcontroller sends a command to release the tendons, and the compressed auxetic tubular springs are relaxed to release the stored elastic energy for jumping (Figure 5A(iii)). When the sensor no longer feels pressure after the robot jumps, the microcontroller instructs to tighten the tendons again, and the springs is reset to the compressed state and ready to jump in the next round (Figure 5A(iv)).

Figure 5B shows the apex positions of the hopping robot varying with the initial drop height at different time points. Here, the precompression length $l_0$ is set to 20 mm. The trajectory curves indicate that the hopping robot can go to a steady-state hopping regardless of the initial drop height. We note that the material for the auxetic tubular springs, TPU, itself shows viscoelastic damping behavior. Therefore, the result confirms that the hopping behavior is determined by the lattice structure, not the intrinsic property of TPU, allowing for jumping over 1,000 cycles (see Video S1, Supporting Information, showing the hopping robot operation over 1 min).

Next, the relationship between the precompression length of the auxetic tubular springs and the steady-state hopping height is examined (Figure 5C). The hopping height increases monotonically because the elastic energy stored in the spring increases as the compressed length increases. The amount of elastic energy stored in the auxetic tubular springs can be calculated by integrating the force relaxation curve, or $\int F(r) dr$ as shown in Figure 3. When the auxetic tubular spring with 75° lattice angle is compressed by 15, 20, and 25 mm, the elastic energy stored in the spring is 80, 168, and 361 mJ, respectively. Considering that the duration time for the release of the spring in contact with the ground is 60 ms according to experiments, the power output of the hopping robot can be calculated as $(0.361 \text{ J tube}^{-1} \times 3 \text{ tubes})/60 \text{ ms} = 18 \text{ W}$ when the springs are compressed to 25 mm.

Then, we investigate hopping behaviors of a robot by varying the lattice angle of the auxetic tubular springs and the precompression length. The elastic energy that can be stored in the three-spring legs for each model as a function of the precompression length is plotted in Figure 5D. Here, the entire body mass of the robot is 2.5 kg, including 1.05 kg from the motors. In the case of repeated hopping that the robot can hop stably and continuously for more than 20 s, the data is plotted with a solid dot, whereas in the case where hopping is temporarily stopped, the data is plotted with a hollow dot. Figure 6 reveals an energetic boundary condition for repeatable hopping. If the elastic deformation energy stored in the spring is too small, continuous hopping is impossible and it stops. If the hopping height is lower than the precompression length of the auxetic tubular springs, the force sensor continues to detect the pressure even when the robot jumps, the spring does not reset and hopping will be terminated, which we refer as temporary hopping (see Video S2 Supporting Information). Figure 5D shows that the minimum elastic energy for repeatable hopping is $\approx 0.4$ J. This value is the corresponding potential energy required for the hopping robot to jump to a height of $\approx 14.5$ mm. In other words, the precompression length lower than 14.5 mm cannot maintain repeatable hopping. Based on this consideration, we can predict whether hopping can be repeatable continuously by considering the relationship between the stored elastic energy obtained from the precompression length of the spring versus the precompression level.

Finally, we implement the repeatable forward jumping of the hopping robot equipped with the auxetic springs of properly controlled 2-DOF (Figure 6 and Video S3, Supporting Information), similar to the spring-loaded inverted pendulum model illustrated in Figure 6A. The kinematic control model is similar to our prior work with origami springs to evaluate the 3D-printed springs. We program the tendon-driving motors to precompress the auxetic tubular springs while in flight and release them when the robot touches the ground. In order to jump forward, the front spring has a larger precompression length than the rear springs, so that the hopping robot is preset to have touchdown angle, $\theta_{\text{tad}}$, before landing (Figure 6A). By mounting the hopping robot on the rotary boom, the DOFs of the robot limb are limited to angular and radial motions (Figure 6B). Once the robot lands, the precompressed springs are released, and so that the hopping robot propels forward.

We investigate the traveling distance and the average velocity of the hopping robot as a function of the touchdown angle. Here, the average velocity only considers the distance traveled in a horizontal direction. By adjusting the precompression length of the individual spring, the touchdown angle of the hopping robot can be controlled. The traveling distance and the average velocity of the hopping robot are calculated from the 3D position data recorded by the exterior encoder. The velocity of our robot is kept constant, which can be inferred from the linear relationship between traveling distance increase and time (Figure 6C). As seen in Figure 6D, the average velocity increases monotonically at first as the touchdown angle increases and then gradually becomes saturated at 0.06 m s$^{-1}$, or 0.3 BL s$^{-1}$ (body length/s). Compared with the categorized chart of running and crawling soft robots from Tang and colleagues as well as our prior work of bistable origami spring, the current work shows a relatively low velocity, which is attributed to a small force exertion. Here, since the precompression length of the front spring reaches the maximum limit, the touchdown angle is increased by reducing the precompression length of the rear spring. This results in the decrease of the total energy stored in the rear spring, and cause
velocity saturation despite the increase of the touchdown angle. Within the same precompression condition and the geometric design, the robot possibly stores more elastic energy in the leg by increasing the wall thickness of the spring to get higher speed if necessary.

The cost of transport, which is a nondimensional parameter that reveals the energy efficiency of transport, can be calculated as

\[
\text{Cost of transport} = \frac{E}{mgd} = \frac{P}{mgv} \quad (4)
\]

where \(E\) is the energy input to the system, \(P\) is the power input to the system, \(m\) is the mass, \(g\) is the gravitational acceleration constant, \(d\) is the moving distance, and \(v\) is the constant velocity in the moving direction. Using the average velocity, the cost of transport of 0.1 rad touchdown angle case as \(\text{Power/(mgd)} = \frac{(0.8 J)/(0.06 s)}{(3.2 kg \times 9.81 \text{ Nm}^{-1} \times 0.063 \text{ ms}^{-1})} = 6.7\), which is comparable to those of lizards or rats. We note the motor contributes to majority of the mass of the robot, 2.5 kg (or 3.2 kg if including the boom). If we can reduce the framing cost of the motor, the cost of transport could be significantly improved. Nevertheless, this is the first demonstration of robotic springs made from 3D-printed structures that can maintain repeated upward and forward hopping.

3. Conclusion

We report the design and additive manufacturing of auxetic tubular lattices made of soft materials as springs for a hopping robot’s legs. Additive manufacturing process allows us to precisely

Figure 6. A) Schematic illustration and corresponding kinematic drawing of pre-bent springs for forward hopping, \(\theta_{\text{td}}\) the touchdown angle. B,C) Snapshots of a hopping robot that jumps forward and performs angular movements from B) the top view and C) the side view. The lattice angle of the spring used here is 60° with 0.1 rad touchdown angle. D) Traveling distance–time curve depending on the touchdown angle of the hopping robot. E) Average velocity of the hopping robot with respect to the touchdown angle.
design and fabricate complex geometries of the springs with a wide range of tunability. Our tubular springs have negative Poisson’s ratio such that they shrink radially when compressed uniaxially, and demonstrate a self-stiffening effect through contact between the lattice units. This nonlinear elastic behavior allows the spring to enlarge elastic energy capacity compared to the spring with linear stiffness. Numerical simulation as well as analytical modeling reveal that the global stiffness of the auxetic tubular spring can be modulated by geometric parameters, such as the lattice angle and the radius of hinge. The hopping robot equipped with three auxetic tubular springs can maintain sustainable hopping despite that the lattice is made of viscoelastic damping material, TPU. The hopping robot performs 1-DOF vertical hopping and 2-DOF forward hopping with properly controlled individual springs that are arranged in parallel. By conducting the hopping tests on auxetic tubular springs with variable lattice angles and precompression lengths, we reveal the repeated hopping conditions of the springs. The power stroke and cost of transport of our hopping robot are calculated as 15–18 W and 6.7, respectively, which are comparable with those of lizards or rats in nature. The speed and energy efficiency of our hopper could be further improved. For example, we can replace the current tendon-driven motors that account for a large proportion of the total weight of the robot by integrating muscle-like fiber actuators that are responsive to external stimuli and weigh several orders of magnitude less.[1] We believe the study presented here will open a new horizon in the design of mechanical metamaterials for engineering dynamic soft robots.

4. Experimental Section

Preparation of Auxetic Tubular Springs: The 3D model of tubular auxetic spring is prepared with Rhinoceros 7 CAD software. The CAD model is then 3D printed with TPU 95A by fused deposition manufacturing. 223 °C. The empty space of the auxetic tubular springs were initially filled with the TPU supports, which is necessary to stack the layer with overhang geometry. The supporting material is manually removed during post-processing (Figure S1, Supporting Information). The infill ratio of the auxetic tubular was set to 100% to maximize the elasticity as well as to increase the mechanical reliability. Auxetic tubular springs with various lattice angles, 60°, 75°, and 90° are prepared.

Mechanical Test of Auxetic Tubular Springs: Quasistatic compression test of auxetic tubular springs were conducted using Instron 5564 mechanical testing equipment. The repeated compression and relaxation are performed for 5 cycles. The compression rate is 20 mm s⁻¹. Time-dependent relaxation test were performed with two different specimens made from 3D printed TPU: one is the dog-bone shaped, and the other is the auxetic tubular spring with lattice angle θ₀ = 60°. For the dog-bone shaped specimen, a constant tensile strain of 50% was applied, and a constant compressive strain of 33% was applied to the auxetic tubular spring. Once strained, each sample was held for 120 s.

Finite Element Simulation of Auxetic Tubular Springs: FEM simulations of compression of the auxetic tubular springs are conducted with ABAQUS/CAE. The representative volume element of auxetic tubular spring models is imported from the prepared 3D CAD model, and C3D8 mesh type was applied. Young’s modulus and Poisson’s ratio of TPU are 49 MPa and 0.32, respectively, which are experimentally obtained from the tensile test. A frictionless, hard contact properties were applied with contact stabilization. All the compressive simulations were done by displacement control. The simulations are conducted till the convergence error occurs.

Hopping Robot Demonstration: Two different hopping modes were demonstrated, vertical hopping and forward hopping. Vertical hopping test was performed by mounting the robot on the vertical rail, so that the robot only had 1-DOF to the vertical axis. The 240 fps slow-motion videos were captured, and the trajectory of the apex of the hopping robot was tracked. Vertical hopping motion was analyzed by changing the initial apex height of the robot and the pre-compression length of the auxetic tubular spring. The initial apex height was set to be 30, 40, and 50 cm and the pre-compression length of the springs vary from 15 to 25 mm, depending on the different design of springs. The trajectory of the hopping was analyzed by Tracker opensource software. For forward hopping demonstration, the hopping robot was fixed to a rotary boom, and was allowed only to move angular and radial motion, thus, having 2-DOF. Tubular auxetic springs with 60° lattice angles are used. To realize a forward jump, one front spring and two rear springs set to have different precompression length to generate the touchdown angle. The touchdown angle was set to be 0.05, 0.075, 0.1, and 0.125 rad. The pre-compression lengths of springs are given in Table 1. The angular position of hopping robot was recorded with the external encoder on the boom.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

auxetic, compliant legs, jumping robots, mechanical metamaterials, tubular springs

| Table 1. | Touchdown angle θₜ₉ with respect to the precompression lengths of the front and rear springs. |
|-----------------------------------------------|-----------------------------------------------|
| Touchdown angle [rad] | 0.05 | 0.075 | 0.10 | 0.125 |
| Precompression length of the front spring [mm] | 20.992 | 20.983 | 20.970 | 20.953 |
| Precompression length of the rear spring [mm] | 12.004 | 12.008 | 12.015 | 12.023 |

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