A Bio-inspired Compliant 3D-printed Soft Gripper

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Abstract

A compliant 3D-printed soft gripper is designed based on the bio-inspired spiral spring in this study. The soft gripper is then 3D-printed using a suitable thermoplastic filament material to deliver the desired performance. The sensorless mechanism introduced here provides adequate compliance with a single linear actuator for interacting with delicate objects, such as manipulation of human biological materials and fruit picking. The kinematic and dynamic models of the monolithic gripper are derived analytically as well as by means of finite element analysis to synthesize its functionality. The fabricated gripper module is installed on a robot arm to demonstrate the efficacy of design for picking and placing fruits without damaging them. The presented mechanism could be customized and used in the medical and agricultural sectors with diverse geometry objects.

Keywords: Bioinspired; non-assembly; compliant; 3D-printed; soft robot

1. Introduction

Soft grippers are mechanical devices used to manipulate delicate items, such as living tissue, human organs and agricultural or food products, without causing any surface damage to items due to the gripper conformity [1-3]. The soft materials used in the soft grippers provide conformal capability to hold the objects with diverse geometries and stiffness with relatively uniform pressure [4, 5]. However, such grippers have many degrees of freedom (DOF), which increase their cost and control complexity [6-8], this is where soft grippers could be developed to mitigate these problems [9-11]. The soft grippers are commonly manufactured to utilize pneumatics or hydraulics to operate, requiring quite complex mechanisms and parts [12]. Tendon-driven compliant grippers, however, are alternative mechanisms that could be manufactured in a monolithic single piece using three-dimensional (3D) printing reducing the number of parts and complexity of the system while benefiting from consistent input and grip output force [13].

The range of materials that could be combined in multi-material 3D printing technique to develop a non-assembly mechanical structure with practical functionality is yet limited. Besides, physical and chemical properties of building materials, such as thermal expansion, as well as printing parameters constrain interlayer bonding and hence, printing feasibility [14]. However, there have been several cases successfully carried out using materials jetting 3D printing approach which is quite costly [15]. Fused deposition modelling (FDM) is one of the most economically efficient 3D printing methods which could reduce the production cost of the customized soft grippers in a variety of applications [4]. The easy accessibility and lower cost make the extrusion-based 3D printing a valuable choice for prototyping non-assembly mechanisms especially in settings where high-end technology is out of reach. The non-assembly 3D-printed soft gripper has significantly less parts as compared to conventional rigid ones leading to shorter manufacturing and assembly time and eventually reduce cost and processing errors [16].

A compliant mechanism is suitable for applications where small size, low power consumption, and simple control algorithms are required [17]. However, size and weight of tunable stiffness compliant mechanisms limit their implementation in many applications such as robotics and wearable systems [18]. Even though several compliant shapes have been proposed both in polymeric and metallic parts so far, there exist more joint type possibilities that could be fabricated with AM suited for certain industrial applications [19].

Depending on the ultimate use, correct design of compliant joints could smartly replace traditional joints, eliminating the tight tolerance requirements [20]. However, accurate joint clearances with satisfactory surface roughness are still difficult to achieve. Yet, use of bioinspired spiral spring to adjust the stiffness in the required parts of the soft robots to develop both structural parts and compliant joints is a proper approach. The compliant spiral spring joints could be a practical alternative approach for 3D printing fabrication of non-assembly mechanisms because there is no presence of joint clearance between links while their successful performances are not affected by the lack of high precision manufacturing [14].

Various notch flexure hinge profiles have been extensively used to provide off-axis stiffness [9]. However, the tension concentration causes localized stress which constrains the amount of motion. Other flexural hinge shapes such leaf style hinge was therefore proposed to distribute tension and deflection over the whole hinge. Yet, they were found to be difficult to achieve a large range of motion and high precision simultaneously [18]. For these purposes, spiral mechanism was selected in this study from various geometric shapes as a flexural hinge since it accommodates greater spans of beams inspired from mammalian cochlea while allowing for the maximum motion range [21] (Figure 1).

The spiral springs have been used in 3D printings due to their efficient utilization of space and characteristics based on the twist deformation [22]. These springs could store high elastic energy per unit volume leading to lightweight and less space requirements with practical applications such as energy storage 3D-printed Wi-Fi sensors [22] and headrest mechanism to prevent neck injury in rear-end collision [23]. Besides, the passive compliance is introduced via the implementation of torsional spring in the soft gripper joints offering low impedance impact whilst refraining sudden unexpected motion behavior and contact induced vibration [24, 25].

FIG. 1. ………………………………………………………………………………………….

There have been several compliant 3D-prints custom-designed to impose less computational control effort using various approaches such as torsion spring [24] (Figure 2A), mechanical advantage [26] (Figure 2B), magnetic stiffness variable [27], monolithic origami [28], and bi-stable mechanisms [29] (Figure 2C). The feature of such gripper is to generate constant displacement and force at the end effector for a range variable input force. However, this type of mechanism would not be appropriate if the gripper is required to grasp a wide range of objects or if the fingers do not fully comply with the shape of their payload.

FIG. 2. ………………………………………………………………………………………

In this paper, a method of designing and 3D-printing the non-assembly compliant gripper is presented. The desired force was produced using bioinspired spiral springs for the manipulation of fragile and irregular objects while minimizing the cost and control complexity of the system. The rest of paper is arranged in the following format. Section 2 describes the spiral spring design that is integrated to the 3D-printed soft gripper. Section 3 presents the analytical modeling derived for understanding the kinematic and dynamic of the soft gripper. Section 4 provides the details of 3D printing and the materials used in the fabrication. Section 4 presents the experimental results for picking and placing the arbitrary sized soft objects using the 3D-printed sensorless soft robotic system. Section 5 concludes the study.

2. Methodology

2.1. Spiral spring design

One main advantages of the spiral springs are the linear correlation between the torsion angle and the torque which could be calculated by considering various conditions. The maximum torque produced by a spiral spring at the maximum degree of angular rotation can be influenced by both the geometry of the spring and the material that it is made from. When designing the spiral spring it should be noted that the spring stiffness relies only on the geometric parameters of the rod, such as thickness and active length, not on the number of coils, the distance between them, or the outer diameter of the spring when is at rest [30]. Spiral torsional springs have a maximum angle of rotation that they can operate under whilst still outputting an approximately linear relationship between the displacement and the force required to move the end of the spring. However, when the spring is wound too far, the concentric layers of the spiral can close onto each other, greatly increasing the force needed to wind the spring any further.

A procedure for designing spiral springs using additive manufacturing technology was developed considering the geometry and expected output parameters such as the torque produced and the dimensions of the spring [30]. The earlier study is only based upon the design of the spring and therefore assumes a known desired stiffness of the spring, the inner radius, the maximum rotational deflection, the width of the spiral, and other variables that are undefined in the present work. However, the earlier work does not include the selection of the optimal materials and the spring stiffness based upon design criteria or desired outputs. In other words, in the present study, the dimensions of the springs are defined first while the materials and the desired stiffness are opted using 3D printing.

In order to design the spiral spring, the formula describing the position of the end of a spiral, shown in Figure 3, is given as follows [30]:

$$r = r_0 + m\theta \tag{1}$$

where r is the radius or distance from the centre of the spiral to the end point, r_0 is the inner radius of the spiral, $m = \frac{p}{2\pi}$, p is the pitch, distance between each coil of the spiral, and θ is the angle that the spiral twists from point r_0 to the end point. The radii are taken from the centre of each part of the spiral in CAD file shown in Supplementary Data Figure S1. θ_0 is the angle of spiral end-point to the x-axis measured in the counter-clockwise direction when spring is at rest, and the length of coil, L is expressed as follows [31]:

$$L = \int_0^L ds = \int_0^L \sqrt{(dr)^2 + (dr/d\theta)^2} = \int_{\theta_0}^{\theta_a} \sqrt{r^2 + m^2}\, d\theta \tag{2}$$

where θ_a is the angular deflection of the spring. The strain energy could be also calculated using the Castigliano's theorem [32] as follows:

$$U = \int \frac{T^2}{2EI} ds \tag{3}$$

where, T, is the torque delivered to the spring, E is the elastic modulus of the material, I is the moment of inertia of the cross-section of the spring.

The deformation angle of the end is expressed as follows:

$$\delta(\theta) = \frac{\partial U}{\partial T} = \int_0^l \frac{\partial}{\partial T}\left(\frac{T^2 ds}{2EI}\right) = \int_{\theta_0}^{\theta_a} \frac{Tr}{EI} d\theta \tag{4}$$

Assuming a rectangular cross-section for the spring coil, $I = \frac{ht^3}{12}$, where h is the width and t is the thickness of the coils.

$$T = \frac{\pi E h t^3}{12L} \delta(\theta) \tag{5}$$

where stiffness of spiral spring could be written as:

$$k = \frac{\pi E h t^3}{12L} \tag{6}$$

The Eq. (6) indicates the dependency of the moment output of spring to the Young's modulus of the 3D printing material used for fabricating the spiral spring. Also, the elastic force of the torsion spring is proportional to the third power of the thickness and is inversely proportional to the length. A calculation example for one of the spiral springs tested in this study is demonstrated in Supplementary Data: Section S1. Besides, the bending stress within the spring could be calculated as:

$$\sigma = \frac{6T}{bt^2} \tag{7}$$

FIG. 3. ………………………………………………………………………………………

2.2. Kinematics and force analysis of gripper

The frame assignment for the soft gripper is shown in (Figure 4) where L_1 and L_2 are the lengths of the lower and upper sections of the fingers respectively, d is the horizontal distance between the centres of each spring which is the same as the distance between the bases of the fingers, θ_1 and θ_2 are the angle of L_1 to the base for the left and right fingers respectively and φ_1 and φ_2 are defining the angle of L_2 to L_1. The position of the tip of each finger can be found by creating four frame transformation matrices. The kinematics of manipulator is defined as the relationship between the pose of the end-effector and its actuated joint coordinates regardless to masses or forces which caused it. The kinematics equation for the displacement of the end of each finger could be modelled by multiplying the transformation matrices, the forward kinematics problem defines the gripper end effectors position $E = [E_x, E_y, 1]$ (Supplementary

Data: Section S2). The inverse kinematics relating the actuated joint coordinates for a given pose of the end-effector is derived too for the position control of the soft gripper. Given the desired position of the end effectors ($E_1$and E_2), the inverse kinematics problem determines the required bending displacement of the active links (θ_1,θ_2) (Supplementary Data: Section S2). Various motion scenarios could be designed to achieve a specific trajectory within the soft gripper workspace. (Figure 5A) demonstrates the workspace of the soft gripper, while both θ_1 and θ_2 equally vary between $(0, \pi/6)$ and the values for $L_1, L_2, \varphi_1, \varphi_2,$ and d are 59.8 mm, 20.3 mm, 40°, 130°, and 70 mm respectively. This analysis of the grip force is simplified and does not include the stiffness of the finger as the main compliance is provided by spiral spring [4]. The theoretical moment of the spring can be used to calculate the theoretical grip force by using (5).

FIG. 4. ……………………………………………………………………………………

FIG. 5. ……………………………………………………………………………………

3. Results and Discussions

3.1. Material selection

Acrylonitrile butadine styrene (ABS), polylactic acid (PLA), and nylon are the three most used 3D printing polymers. All can be extruded by common 3D printing devices and are among the cheapest filaments available today. PLA is stronger than both ABS and nylon with a high printability due to low melting point. It does not exhibit multi-axial contractions upon cooling therefore the 3D printing can be done without a heated printing bed. However, PLA, has a relatively low glass transition (T_g) temperature (around 50 °C). At T_g due to relaxation of chains in amorphous regions, the polymer will suddenly become soft with loss of tensile strength, stiffness and exhibit low viscosity above T_g. Therefore, the print must be used under 50°C to avoid permanent deformation. ABS is an amorphous copolymer with a higher glass transition temperature of 105 °C. It can cope with high extrusion temperatures better and it is less brittle than PLA, hence less susceptible to wear and tear and more suitable for soft robotics applications. Additionally, an important advantage of ABS is that it has better extrusion properties as it can be extruded at lower extrusion forces than that required for PLA. Although ABS is lighter (1.04 g/cm^3) than PLA (1.24 g/cm^3) it has four times more impact and heat resistance. ABS is extruded at higher temperatures than PLA but has better heat deflection properties than PLA and Nylon making it a better choice than PLA in realistic uses such as prototypes and end-use components with low stress concentration. Nylon is more resistant to chemical substances and tougher than PLA and ABS, but this comes at the expense of rigidity. Recent developments in 3D printing materials have made provisions of nylon-fibre mixtures filament for affordable commercial 3D printing with higher strength and stiffness. Higher tensile strength and elasticity of nylon allows for more widespread industrial use; hence it is more suitable for functional prototypes in industries such as jigs and fixtures and robotics parts. However, a drawback of nylon is its moisture absorption. Polyamide molecules are alternating blocks of -CH_2- chains and amide linkages (-CONH-), to which water molecules attach via hydrogen bonding. Moisture susceptibility or nylon filaments may necessitate printing in controlled dry environments. As per the literature data and the experiments carried out in this work a decision matrix is formed (Supplementary Data: Table S1). The most suitable material among ABS, PLA, and nylon is opted based on the total functionality score in the present application where the best score is 10 and 0 is the least value.

3.2. 3D-printed gripper design and 3D printing

A computer aided design (CAD) model of the soft gripper with integrated spiral spring was designed as shown in (Figure 6A). A whipple mechanism was devised to be a semi-flexible component that joins the rings on the outsides of the springs. It is pulled backwards to provide the input force for closing of the fingers (Figure 6B). In order to grip objects automatically it is necessary to incorporate a linear micro motor given that its stroke is controlled for opening and closing the gripper. The compliant gripper was manufactured by FDM 3D printing using FORTUS 450MC, GrabCAD software, and two different materials, Formfutura Premium ABS and Taulman Nylon 645, in a single run as shown in (Figure 6C). The infill percentage in 3D printing is defined as 70% with other details of processing parameters and conditions are given in Table 1. The equivalent elastic modulus for the 70% infill 3D printing material was experimentally measured through a tensile test as 1.607 GPa and 0.793 GPa for ABS and nylon respectively.

TABLE 1. …………………………………………………………………………………....

FIG. 6. ………………………………………………………………………………………….

3.3. Spring stiffness experiment

A modular force and angular position measurements rig was set-up, as shown in Figure 7, to determine the FDM 3D-printed spiral springs stiffness used in this study. The force required to turn the angular position sensor is measured by a PASCOE PASPort force sensor. The spring was attached to one side of the angular position sensor by means of a threaded screw which held the spring firmly in place. The hook end of the spring was prevented from turning due to contact with one of the knobs on a carefully placed clamp on the retort stand (Supplementary Data Figure S2). The spiral springs, used in the gripper design, were tested using FEA (Supplementary Data Figure S3) and in the experiments. Each spring was printed into three replicates which were tested for three runs.

In the initial experimental tests of the soft gripper it was revealed that the ABS is not an ideal material choice for such compliant mechanism as it failed easily under cyclic loads though demonstrating higher mechanical advantage than 3D-printed nylon spiral spring as shown in Table 2. However, it did not warp and could be 3D-printed much easier than nylon. The force versus angular deflection of the 3D-printed nylon spiral springs to calculate the stiffness of spiral springs in the winding and unwinding is shown in (Figure 8A). The graph clearly shows a hysteresis or lag between the reduced force experienced by the force sensor and the angle of the sensor for the return portion of the run, which is common amongst spiral springs. Yet, the forward portion of the graph is almost linear which is important for the repeatability of the soft gripper.

FIG. 7. ………………………………………………………………………………………….

TABLE 2. ……………………………………………………………………………………

3.4. Gripper force analysis

To actuate the gripper an inextensible cable was attached from the whipple of the gripper to a Tower Pro SG-5010 double ball bearing servo motor. The motor was controlled by a battery operated CCPM Servo Consistency Master Servo motor. The servo motor pulled the cable which moved the whipple backwards, closing the fingers. An experimental setup for measuring the input-output force-displacement relationship of the compliant finger, shown in (Figure 7), was developed to measure the force. The compliant finger can be actuated by the displacement input specified at the input port. The relation between the linear displacement and the input force are roughly linear in 0~4 mm input range. A force sensor (Lutron FG-6100SD) is placed at the input port to measure the required input force to generate specific displacement input.

A gripper was printed each in Formfutura Premium ABS and Taulman Nylon 645 and these grippers were used to determine the grip force applied at the end of the fingers based on the applied force and the rotation angle of the fingers. Two PASCOE PASPort force sensors were used to measure the forces at the points on the gripper in order to determine the grip force. The output force was measured from the top corner of the left finger as shown in (Figure 7B). The input force was measured at the connection of the whipple to the servo from a string that was tied to the tab using the hole. The gripper was held securely in place whilst the force sensor attached to the tab was slowly moved away from the gripper. The gripper was placed above a protractor that allowed the angle of the fingers to be measured for each test. Three tests were conducted for each gripper.

The 3D CAD model of designed spring was developed with tetrahedron mesh configuration using ANSYS Workbench. Mesh convergence study was carried out to ensure the results are not affected by further mesh refinements. A transient structural analysis was performed for the mechanical analysis of the gripper. A remote displacement applied on at the centre of the gripper to simulate the translational input, as shown in FIG. 9, whilst the centre of spiral springs was fixed (shown as A in FIG. 9). To measure the blocked force, the end of the gripper was fixed and prevented them from moving while the input displacement and corresponding force were applied. Then, the reaction force was computed at the horizontal upper face of the gripper (which is where the force is measured in the experimental setup.

The output force for each gripper is displayed in Figure 8B with its corresponding input force. This shows the mechanical advantage of the grippers for the angles specified. The input force to input displacement relationship is measured and given in Figure 8C, which shows that the input force required to generate 4.5 mm displacement at the input port for the soft gripper is 6 N. From the experimental and FEA results, it was found that the output force and mechanical advantage varied approximately linearly with the input force (Figure 8B) and input displacement (Figure 8C) of the gripper (Supplementary Movie S1). It may be possible that the slight deviation from linearity for both material grippers at 15° is due to the interfacing of the spirals in the springs. The input force varies linearly with respect to the input displacement of the gripper for the majority of the working range of the gripper as shown. However, there was an upwards trend in the force required to move the input section of the gripper that is accentuated near the end part of the working range, meaning the graph of input force and displacement is not linear at large forces and displacements.

FIG. 8. ……………………………………………..……..………………………………

FIG. 9. ……………………………………….…………...………………………………

3.5. Gripper test in a soft robotic application

The gripper was attached to a DOBOT Magician robot arm which was used to move the gripper to the object position as shown in (Figure 10). The gripper successfully manipulated a variety of objects such as strawberries and a 3D-printed artificial ear with variable sizes (Supplementary Movie S1). The displacement inputs for the gripper module for grasping these objects were the same. The experimental results showed the system capability to pick and place a variety of fragile objects without causing damage to them.

FIG. 10. …………………………………………………………………………………….

Optimizing the cross-sectional areas of centre spirals and the attachments to the outer ring could reduce the stress experienced at these points allowing for greater part life due to the reduction of stress concentration. Further studies on 3D printing the spiral springs with other materials and their composites could be conducted in future. Moreover, the cross-section geometry and the infill percentage of the compliant gripper could be readily improved using 3D printing to limit the higher stress experienced at key parts of the gripper such as the whipple and the springs for different applications.

4. Conclusion

This study developed a bio-inspired compliant 3D-printed soft robotic gripper for handling fruits and similar fragile objects. The designed monolithic compliant gripper was modelled analytically and numerically to reveal and customize its functionality. The customized gripper was fabricated via FDM 3D printing in one step which is time and cost efficient. The monolithic mechanism actuates via a linear force only requiring no additional mechanical joints and sensors, which could reduce control complexity of the system. The sensorless soft gripper was mounted on the robotic manipulator to pick and place delicate fruits with arbitrary shape, such as strawberry. The experimental results proved the capability of the compliant gripper to pick and place the object with arbitrary size and shape. The mechanical advantage for the 3D printed compliant gripper is about 1.85 at the fingertip. The maximum payload of the current compliant gripper design is around 0.7 kg. The developed compliant gripper module can be integrated with industrial robots for safe manipulation of irregular objects.

Author Disclosure Statement

No competing financial interests exist.

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