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Characterization of finger joints with underactuated modular structure

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Abstract. The characterization of flexible joints of robotic underactuated fingers allows the investigation of the finger flexion trajectories using a tendon-driven actuation. In this paper, the characterization of TPU 3D printed joints used in underactuated robotic fingers, is experimentally and numerically performed. Since the mechanical properties of 3D printed materials are uncertain, this research helps to define the characteristics of robotic fingers in terms of stiffness. The role of the stiffness for the control of fingers' trajectories is fundamental and the obtained results are very useful for improving the method to track a certain predefined trajectory. Experimental and theoretical results evaluate the stiffness as a function of the infill density percentage of the material.

Introduction

In the last years, a novel generation of underactuated compliant hands is growing in the robotics community [1]. In these soft hands the simplification of actuation and control is central [2-7], as well as the reduction of the degrees of actuation with respect to the degrees of freedom (DoFs) and the intrinsic passive compliance at joint level. Underactuated compliant hands can be implemented using deformable materials that can be processed with Additive Manufacturing (AM) [8, 9]. Adding deformable elements allows the storage of elastic energy avoiding tendon slackness, passive compliance, the distribution of forces over a large contact area avoiding grasped object damage. Shape adaptation increases the grasp performance by compensating the uncertainties and stabilizing the grasp [10]. Soft grippers are commonly prototyped using different materials, e.g., elastomeric materials whose mechanical properties often present anisotropic, inhomogeneous, and nonlinear behaviours [11, 12]. Some recent development further exploits Interpenetrating Phase Composites [13] and topology optimization techniques for obtaining a multimaterial-like behaviour varying the 3D printing infill density [14, 15]. A proper mechanical characterisation is very important to predict the dynamic behaviour of the soft robotic component [16]. This work is focused on the mechanical characterisation of compliant joints of robotic modular fingers, providing methods and results that can be exploited in the design of new soft hands, improving dexterity [17]. A possible way to design a desired fingertip trajectory or a specific performance is to opportunely tune the stiffness of the compliant joints. For this purpose, this paper presents the characterization of a flexible joint for modular robotic fingers in terms of variation of stiffness depending on the density of the material, represented by the infill rate of the 3D printing process.

Joint characterization

Soft-rigid robotic fingers are modular structures composed of rigid or semi-rigid phalanges and soft flexible joints which reproduce the articulation function (Fig. 1(a)) [3, 8, 9, 18]. This work is focused on the analysis of the mechanical properties of flexible joints made in TPU (thermoplastic polyurethane, Ninjaflex Semiflex 85A, Lulzbot, USA) and rigid parts made in PLA (Polylactic Acid, ecoPLA, niceshops GmbH, Austria) by 3D printing techniques using a FDM (fused deposition modeling) 3D printer (Lulzbot TAZ 5, Lulzbot, USA). A TPU joint sample is represented in Fig. 1(b, c).

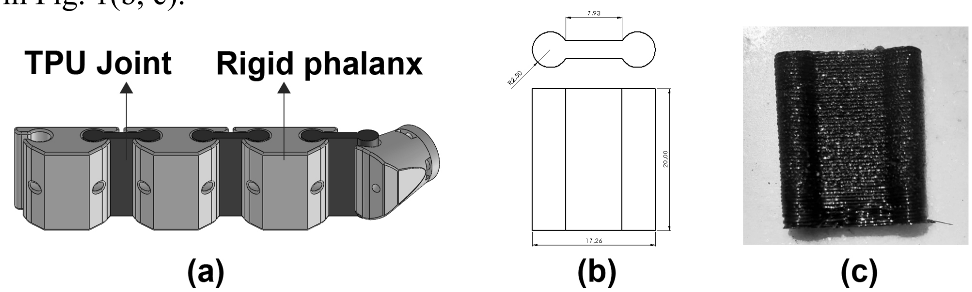

Fig. 1 – Modular finger: (a) assembly; (b) joint dimensions; (c) 3D printed joint

The objective of the joint characterization was to study the stiffness of the flexible component for different values of density. In fact, the stiffness of the deformable passive joint affects the trajectory of the fingers subjected to a tendon-driven actuation and thus the effectiveness of the grasping. For this purpose, both experimental and numerical analyses were performed. The experimental part of the work was based on the realization of 15 TPU joints with five different infill percentages. The stiffness was measured by using a digital force-displacement gauge. The numerical approach implied the use of FEM (finite element modelling) software. As the finger is composed of rigid modules and the length of the joint is comparable with the length of the rigid modules, the deflection is moderate and the problem can be modelled considering the theory of beams [19-20]. Analytical and experimental results can be compared to create a simple and validated numerical tool to design this kind of flexible joints with specific stiffnesses.

Experimental characterization

The experimental characterization of stiffness was performed for 15 joint samples with the same geometrical dimensions and five different infill percentages (20, 30, 40, 50 and 60%), in groups of 3 samples. A 3D printed rigid constraint made in PLA was used as support for the TPU samples, which were mounted between this rigid support and a finger phalanx (Fig. 2(a)). The phalanx was subjected to a vertical load by a flat tip to simulate the behavior of the joint during the flexion of the finger. For each flexion test the force-displacement curve was obtained and the stiffness value was extracted accordingly in two significative displacement ranges: [0 – 0.8 mm] and [0 – 4 mm]. In fact, a 2-grade polynomial approximation of the force-displacement curves demonstrates that the curve has an approximately parabolic trend with a quasi-linear increase in the first interval 0 – 0.8 mm. The maximum displacement was fixed at 4 mm as after this value the finger phalanx collides with the support.

Numerical analysis

The FEM analysis was performed analyzing the joint behavior when it is subjected to a static stress. A 3D CAD (Computer Aided Design) model of two simplified phalanges connected by a TPU joint was drawn and discretized and loads and constraints were applied as represented in Fig. 2(b).

Different simulations were performed by varying the infill conditions with the aim of observing the force required to obtain a fixed displacement. The stiffness and the force evaluated are compared to the experimental force-displacement curve. The TPU characteristics were extracted by the datasheets according with the infill percentages and a linear elastic model was used to study the deformations. Simulations were performed in displacement control, in large displacement hypothesis. In particular, the simulations results were compared to the following loads: 7.4, 13.7, 15.0, 16.9, 18.3 N. These values represent the mean values of the maximum loads measured during the experiments for the TPU joints with infill percentage equal to 20, 30, 40, 50 and 60 %.

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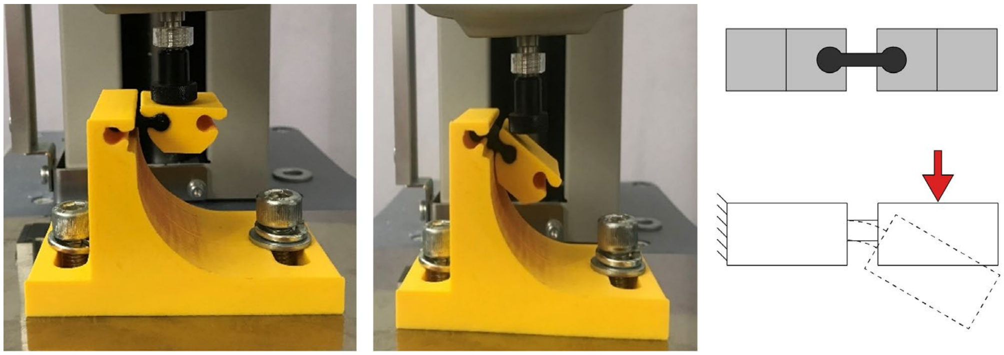


Fig. 2 – Experimental layout (a); 3D CAD model for FEM and load configuration (b).

Results

The mean force-displacement curves obtained by experiments are represented in Fig. 3. The fitting curves obtained by 2-grade polynomial approximation are also represented. The deformation map resulting by the simulations is reported in Fig. 4: setting the prescribed displacement as a boundary condition, the resulting plot is the same for all the infill percentages. Tab. 1 reports all the stiffness results obtained by experimental tests. The parameter K_{mean} represents the mean value of the stiffness. The force applied in the numerical analysis to allow the maximum displacement and the stiffness are reported in Tab. 2. Fig. 5 shows the comparison of numerical and experimental results.

Discussion

Results show that all the curves present similar shapes, with different load/deformation values. All the curves are characterized by a steep, almost linear part at the beginning (displacements 0-0.8 mm). In the 20% infill case, due to the higher flexibility, also in the first part of the curve a less stiff, nonlinear behavior is evident. For all the samples, a linear load/deformation behavior can be considered only for limited displacement values, and this is an important aspect that must be considered for the applications of these components as flexible joints of soft robotic fingers, which frequently undergo large deformations. This aspect must be considered both in the mechanical design phase and in the control system implementation.

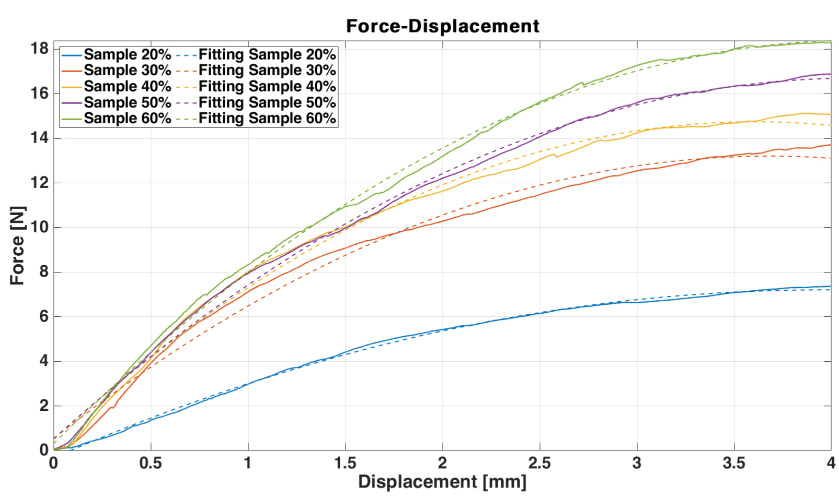
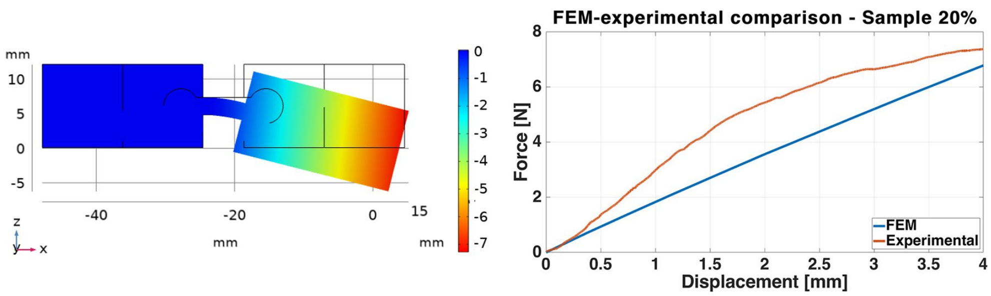


Fig. 3 – Mean force-displacement curves of the TPU joint with different infill percentages

Tab. 1 – Stiffness experimental results

		Stiffness [N/mm]			
Infill percentage	Displacement range	Sample 1	Sample 2	Sample 3	K_{mean}
20%	0 – 0.8 mm	3.19	3.39	2.19	2,92
	0 – 4 mm	2.39	1.55	1.59	1,84
30%	0 – 0.8 mm	7.06	7.87	7.68	7,53
	0 – 4 mm	3.25	3.50	3.54	3,43
40%	0 – 0.8 mm	8.00	9.23	8.10	8,44
	0 – 4 mm	3.56	4.02	3.73	3,77
50%	0 – 0.8 mm	9.05	7.10	9.13	8,43
	0 – 4 mm	4.24	4.00	4.43	4,22
60%	0 – 0.8 mm	6.57	10.78	9.25	8,87
	0 – 4 mm	4.06	6.97	4.69	4,57



(a) (b)

Fig. 4 – FEM results (a); Comparison between FEM and experimental behavior (b).

Tab. 2 – Stiffness numerical results

Infill percentage	Force measured at 4mm [N]	K [N/mm]
20%	7.07	1.77
30%	13.33	3.33
40%	14.26	3.56
50%	15.95	3.99
60%	17.35	4.34

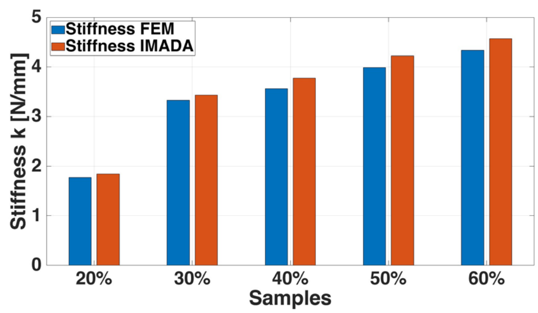


Fig. 5 – Comparison of experimental and numerical results

As expected, joints with higher infill densities present higher stiffness, but the infill density vs stiffness relationship is not linear: for lower infill percentages (20-30%) the stiffness sensitivity with respect to infill is much higher than for higher percentages. One can observe that all the samples show a higher stiffness in the linear elasticity interval with respect to the entire force-displacement curve. As the infill percentage affects the mechanical properties and consequently the joint behavior, it is necessary to find a compromise between desired mechanical properties, 3D printing time and material amounts. This suggests that it is not recommended to produce joints with too low (20%) or too high (>>60%) infill percentages to allow a correct joint work and a sustainable production process. Fig. 5 shows a correspondence between experimental and numerical outcomes. Differences between theoretical and experimental stiffnesses are more evident when the infill percentage increases. This discrepancy can be justified by the use of a linear elasticity model for the FEM analysis. For higher infill percentages the linear elasticity model is no more able to precisely approximate the joint deformation.

Conclusions

The results of the study show the relevant impact of manufacturing parameters, and in particular the infill density percentage, on the overall flexural stiffness of flexible joints for soft modular robotic fingers. The results show a relationship between load and displacement in flexible joints. Such behavior was both experimentally and numerically validated, and results will contribute at defining a more reliable characterization of deformable components of soft robotic hands. Future works can be focused on the improvement of the approximation of deformations through FEM simulations, introducing a comparison between different hyperelastic material models, also considering viscoelasticity and anisotropy. Furthermore, different load conditions and specimen shapes will be evaluated for experimental and numerical characterization. These models can be obtained from the force-displacement curves, to evaluate the behavior of the TPU joint.

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