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GRACE: GeometRy-based Actuators that Contract and Elongate

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Abstract—**This paper describes a recently developed class of 3D-printable soft pneumatic actuators, named GRACE. They can be built as a whole with the robotic artefact, avoiding structural discontinuities in the soft robot's body. Their design is fully scalable and they can be built with different materials and additive manufacturing technologies. Their arrangements in series and/or parallel configurations enable the fabrication of complex bundles of muscle fibres for biomimetic machines.**

Index Terms—**soft actuator, pneumatic, 3D printing**

I. INTRODUCTION

Natural muscles come in a variety of sizes and arrangements, providing forces which span a large range [1]. Their versatility makes them a remarkable model in robotics for the development of dexterous and high-performance robots. Therefore, several researchers have aimed at the development of artificial muscles exploiting different working principles (e.g., [2], [3]). Pneumatic Artificial Muscles (PAMs), in particular, have attracted the interest of roboticists since the fifties, and have been proposed in different designs and built with various materials ([4], [5]). Most PAMs consist in deformable membranes coupled with strain-limiters that enable their contraction.

In this short paper, we report about a novel class of PAMs that do not require such strain-limiters and that can perform both contraction and elongation, based on their design and depending on the actuation pressure (that is, if positive or negative). They belong to the wider class of Pleated PAMs (PPAMs); as their working principle is based on the folding/unfolding of their pleats, with minimal strain, we named them GeometRy-based Actuators that Contract and Elongate (GRACEs). Here we briefly describe their geometry, and we present their main performances. A detailed discussion can be found in [6].

II. GRACES: DESIGN AND MODELLING

In general, a GRACEs consists of a membrane with an arbitrary number of pleats, which unfold when the membrane is pressurized, resulting in a longitudinal contraction and a radial expansion; conversely, they fold when the membrane is actuated with negative pressure, enabling the GRACE to elongate longitudinally while exhibiting radial contraction. The design concept is sketched in Fig. 1, for a 6-pleated actuator. To relate the shape of the pleats to the contraction and elongation ratio of the GRACE, we assume that the membrane is inextensible, i.e., the curved lines highlighted in Fig. 1(e) maintain their length unvaried under any actuation state. Then, for a GRACE with given geometry, the contraction (or elongation) ratio can be obtained by describing the geometrical transformation of those lines under maximization (or minimization) of the internal volume of the GRACE.

By exploring the design parameters space, it has been possible to determine the geometry of three optimal 6-pleated GRACEs: the one with the greatest contraction ratio (GRACE-C), with the greatest elongation ratio (GRACE-E), and a third that maximizes the sum of the two ratios, and then suitable for antagonistic behavior (GRACE-A). The three obtained designs are shown in Fig. 2. The resulting ratios have been validated against finite element models. We have found that, overall, the developed model overestimates the contraction ratio while it underestimates the elongation, consistently for any GRACE.

All designs are fully scalable: the GRACEs can be printed of any size, provided that the thickness of their membrane is chosen based on structural configuration, to ensure sufficient mechanical resistance under the operational conditions.

III. 3D PRINTING OF GRACE-BASED MONOLITHIC STRUCTURES

As starting point, we adopted stereolithography (SLA) as a 3D printing technology to fabricate single GRACEs of different sizes (from 10 mm to 100 mm length). Owing to the

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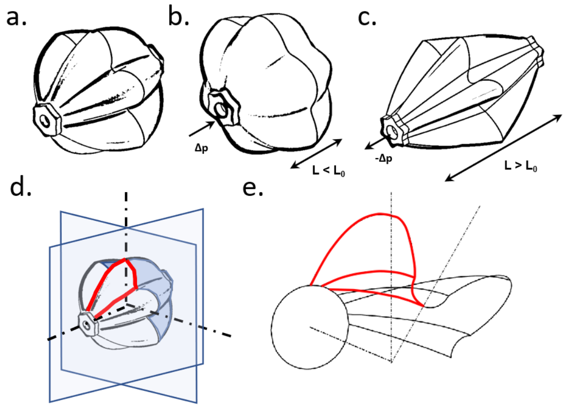

Fig. 1. A GRACE (a) can longitudinally contract under positive pressure (b) or elongate under negative pressure (c). Its surface is generated by the profiles highlighted in red (d, e).

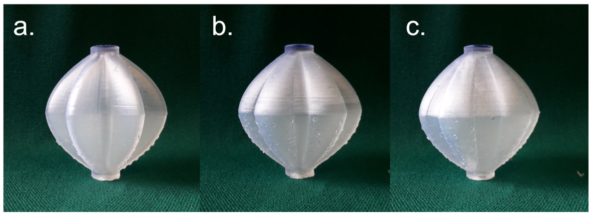

Fig. 2. GRACE-C (a), GRACE-A (b), and GRACE-E (c), optimized for maximum contraction, antagonistic behaviour, and elongation, respectively.

working principle, we opted for a relatively hard commercial resin (Shore Hardness A 80), which turned out to be a suitable material. However, the use of thermoplastic polyurethane (TPU) with Fused Deposition Modelling (FDM) provided satisfactory results as well, in terms of both mechanical integrity and resistance of the membrane, and durability of the GRACE.

Multiple GRACEs can be 3D printed in series and/or parallel, to build bundles of muscular fibres for robotic applications. For a soft/continuum robot, either if single GRACEs or bundles are required, the entire structure can be, at least ideally, 3D printed in a single step. An example is shown in Fig. 3: 18 GRACEs enable the movements of five independent fingers and a wrist in a robotic artefact, built by SLA technology and ready for plug-and-play. The only limitation is determined by the size of the workspace of the available 3D printer.

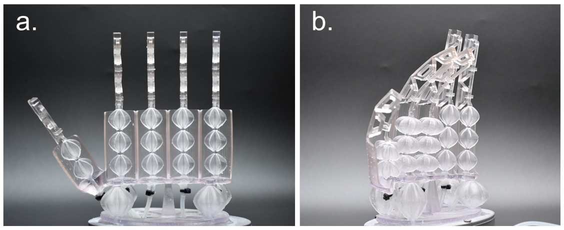

Fig. 3. Monolithic structure comprising 18 GRACEs. The artefact has been obtained in a single fabrication step by SLA technology.

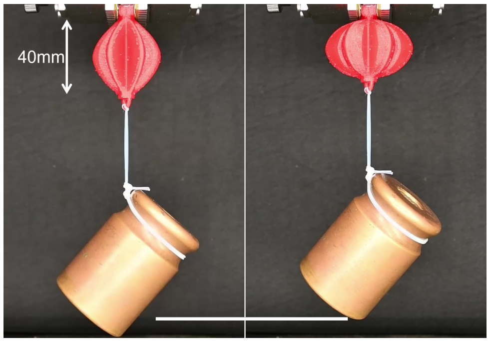

Fig. 4. A GRACE-C obtained by FDM is pressurized to lift a 1-kg load.

IV. MECHANICAL PERFORMANCE

Fig. 4 illustrates the result of the pressurization of a GRACE-C built by FDM: the actuator, 40 mm long in its starting configuration, is able to lift 1-kg suspended load by 20% of its length. The actuation pressure for GRACEs at this scale is less than 1bar. We performed a mechanical characterization of the three selected GRACEs built by SLA, performing both isotonic and isometric tests. While contraction and elongation ratios belong to the range 17%÷30% (depending on the specific GRACE and the working conditions) independently on the used material and the size, the longitudinal forces exerted certainly depend on the structural properties of their membrane. As an indication, a 40 mm long GRACE-C built with the commercial resin FlexFill 98A by FDM is able to lift 8 kg under ∼3 bar actuation pressure. Moreover, we found that a GRACE is able to perform at least 1000 cycles of free contraction/elongation without exhibiting signs of structural damage, proving that low-cost 3D printers can be used to build reliable pneumatic actuators.

V. CONCLUSIONS

The GRACEs can be used in diverse applications, owing to their scalability and the possibility to be printed by low-cost 3D printers and with commercial materials. They can enable the development of bioinspired robots actuated by a variety of artificial muscular arrangements.

REFERENCES

[1] A. A. Biewener, "Biomechanics of mammalian terrestrial locomotion," *Science*, vol. 250, pp. 1097–1103, 11 1990.

[2] J. Kim, J. W. Kim, H. C. Kim, L. Zhai, H.-U. Ko, and R. M. Muthoka, "Review of soft actuator materials," *International Journal of Precision Engineering and Manufacturing*, vol. 20, pp. 2221–2241, 12 2019.

[3] Miriyev, "A focus on soft actuation," *Actuators*, vol. 8, p. 74, 10 2019.

[4] S. Krishna, T. Nagarajan, and A. Rani, "Review of current development of pneumatic artificial muscle," *Journal of Applied Sciences*, vol. 11, pp. 1749–1755, 5 2011.

[5] F. Daerden, D. Lefeber, B. Verrelst, and R. V. Ham, "Pleated pneumatic artificial muscles: actuators for automation and robotics," pp. 738–743, IEEE.

[6] C. D. Pascali, G. A. Naselli, S. Palagi, R. B. N. Scharff, and B. Mazzolai, "3d-printed biomimetic artificial muscles using soft actuators that contract and elongate," *Science Robotics*, vol. 7, 7 2022.