2021 IEEE 4th International Conference on Soft Robotics (RoboSoft)
April 12-16, 2021, Yale University, USA

Soft Robotic Compliant Two-Finger Gripper Mechanism for Adaptive and Gentle Food Handling

Andrija Milojević, Sebastian Linß and Heikki Handroos, *Member, IEEE*

2021 IEEE 4th International Conference on Soft Robotics (RoboSoft) | 978-1-7281-7713-7/20/$31.00 ©2021 IEEE | DOI: 10.1109/RoboSoft51838.2021.9479337

Abstract— **In the field of soft robotics there is still a great need for a versatile, simple, and affordable gripper with a high level of adaptability to unknown objects of different sizes, shapes, and stiffness. Most of the existing soft robotic grippers are complex solutions realized with fluid-mechanically driven actuators, active smart materials, cable-driven actuation, and different form-closure principles. However, soft grippers based on compliant mechanisms are rarely introduced and explored so far. Therefore, we present a novel compliant two-finger gripper mechanism for adaptive and gentle gripping, especially of soft and easily squeezable objects like fruits, vegetables, sweets, and sushi. The structurally inherent adaptability is achieved using an optimally synthesized compliant mechanism in combination with a conventional linear actuator. Furthermore, the two-finger gripper passively realizes pinch (parallel) or/and encompass (power) grasping. It is shown by FEM simulations and confirmed by prototype tests that the developed gripper realizes both pinch and encompass grasping with high adaptability. A special advantage of the gripper is the possibility to achieve gentle food-handling of objects with comparable weight independent of the object shape, size, and position without the need for sensors. Moreover, the precise, safe, and fast manipulation of very delicate objects is exemplarily demonstrated for different sushi pieces using the gripper mechanism with an industrial robotic arm.**

I. Introduction

In robotic systems, end-effectors or grippers are typically used to realize repetitive tasks for object grasping and manipulation. Conventional industrial grippers are usually designed based on rigid-body mechanisms considering inherent safety aspects [1]. In comparatively new areas of robotic applications, like collaborative robots and the food industry, a certain compliance of the structural gripper components is needed. Furthermore, adaptability is required to grasp a wide variety of objects (with different shapes, sizes, and weights as well as soft objects) with the same gripper. One common approach to reach adaptability with rigid-body grippers as well as to reduce the number of actuators and the control effort are underactuated grippers. These grippers are usually realized with conventional mechanisms and drives [2], for which software assistance [3], an adjustable compliance concept [4] or a reconfigurable mechanism concept [5] can be additionally used. Rarely, camera-based, visual-haptic grippers equipped with soft material jaws [6] are suggested, which make a rigid-body gripper system partially flexible but also bulky and heavy. To grip delicate, fragile, and compressible objects, specially designed end-effectors are developed that are often called soft robotic grippers which are built fully or partially by soft and elastic materials [7, 8]. For their use, actuation is generally necessary, for which there are certain different actuation principles, e.g. cable-driven [9], fluid-mechanically driven [10], active material-based [11], or form-closure-based [12] grippers. Moreover, air propulsion is used for gripper finger actuation as well [13]. The combination of pressure chambers with inelastic fabrics and helically wound threads leads to complete hand-like dexterous grippers [14]. Rarely, pneumatic-based grippers are developed as complex bionic hands using multiple types of sensors and actuators in combination with artificial intelligence [15]. However, each existing gripper solution is mostly complex and has specific limitations, especially regarding the ability to realize the adaptive gripping of varying soft and delicate food objects like fruits, vegetables, or sushi.

A different approach to simply achieve adaptive and gentle soft robotic gripping, that has not yet been fully investigated, is the use of compliant mechanisms. These mechanisms represent elastic structures that realize force and motion transmission based on the elastic deformation of its structural parts, rather than from rigid-body joints [16]. Mostly, compliant mechanisms are monolithic structures and thus, easy to produce, assembling-free, maintenance-free, friction-less, and lightweight [17]. Although compliant gripper mechanisms are common in the fields of high-precise micromanipulation [18] and MEMS [19], only a few prototypes of passively self-adaptive grippers are suggested that utilize mechanisms with distributed compliance [20]. Therefore, we present a novel approach for the realization of a simple, yet versatile soft robotic compliant two-finger gripper mechanism with a high force and motion transmission.

In our previous work [21] we introduced the development and synthesis of the soft robotic compliant two-finger gripper. The focus of the presented results here is on further investigating the ability of the gripper to realize both pinch (parallel) and encompass (power) grasping of different prismatic and cylindrical objects with varying size and gripping position, which was not done in [21]. Another goal is to demonstrate the adaptive gripping and gentle food handling with the novel soft robotic gripper mechanism. Both, adaptability and an inherently gentle touch are realized by utilizing a compliant gripper mechanism in combination with only one conventional linear actuator. It is shown by finite elements method (FEM) simulations that the gripper realizes reliable grasping independent of the object shape, size, and position. The gripper fingers further adapt to the object shape in encompass mode due to increasing input forces without destroying the object which leads to high adaptability and reliable grasping in general. Furthermore, it is demonstrated

*Research supported by Academy of Finland Research Council for Natural Sciences and Engineering (No. 318390).

A. Milojević is with the Department of Mechanical Engineering, Lappeenranta University of Technology, Lappeenranta, Finland (phone: +358465389189; e-mail: Andrija.Milojevic@lut.fi).

S. Linß is with the Compliant Systems Group, Technische Universität Ilmenau, Ilmenau, Germany (e-mail: sebastian.linss@tu-ilmenau.de).

H. Handroos is with the Department of Mechanical Engineering, Lappeenranta University of Technology, Lappeenranta, Finland (e-mail: heikki.handroos@lut.fi).

by tests with a gripper prototype that different soft and delicate food objects can be grasped with a simple on/off control of the actuator which leads to structurally gentle gripping to some extent. Moreover, precise, safe, and fast manipulation of different sushi pieces is newly demonstrated with the gripper mechanism mounted on a robotic arm.

II. Optimization-Based Design of Compliant Gripper

The presented soft robotic gripper is realized by utilizing a compliant mechanism with distributed compliance. These mechanisms are usually designed with topology optimization methods [22]. Thus, a similar approach is adopted here, for the initial design of the compliant gripper finger mechanism (Fig. 1a). As the synthesis methodology is not the focus of this paper, more about this can be found in [20-22]. Here only a short description is presented.

In topology optimization, the designer needs to define the desired set of input parameters (like design space, input motion/force, material characteristics, desired outputs, boundary conditions, and constraints), i.e. to set an initial problem. Then throughout an optimization process, a design solution that can realize the desired goal is automatically obtained (Fig. 1a). For the case of gripper synthesis, only one finger of the gripper is optimally designed as based on this a two-finger (Fig. 2) or multiple-finger gripper can be realized.

The topology-optimized gripper finger mechanism (Fig. 1a) is further improved by additionally using shape optimization [22], see resulting shape-optimized design (Fig. 1b). The shape optimization is implemented via the node wandering approach where endpoints of the structural gripper elements are allowed to wander within predefined regions (Fig. 1a); further optimizing lengths and position of individual segments of the gripper finger mechanism [21]. Compared with the literature [20], this is done here to realize a higher force transmission ratio (defined as the ratio of output to input force) in combination with a comparatively high motion transmission ratio (defined as the ratio of output to input displacement) of the gripper concerning a better gripping performance independent of the gripped object. Table 1 shows the force and motion transmission ratio values of the initial and final gripper finger mechanisms.

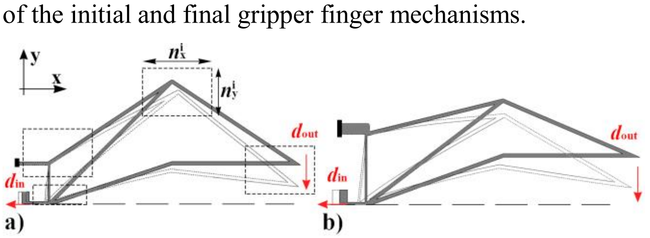

Figure 1. Gripper finger design optimization (opened position is shown in solid and deformed position in transparent lines): a) initial design of topology-optimized mechanism (node wandering regions marked with dash rectangles); b) final design of the additionally shape-optimized mechanism.

TABLE I. Gripper Finger Force and Motion Transmission Ratio

Gripper finger mechanism	F_{out} / F_{in}	d_{out} / d_{in}
Topology-optimized design (Fig. 1a)	0.13	6.2
Shape-optimized design (Fig. 1b)	0.18	4.0

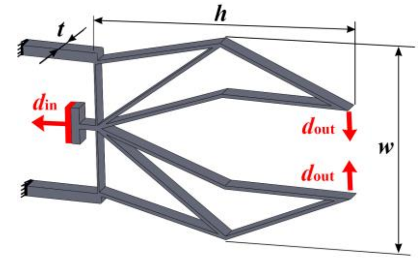

Figure 2. 3D CAD model of the soft robotic two-finger gripper mechanism with basic dimensions (h = 155 mm, w = 120 mm, t = 10 mm).

The shape-optimized design is further adopted to realize a monolithic and thus fully compliant soft robotic two-finger gripper mechanism (Fig. 2). Hence, when an input displacement d_{in}, which correlates with a required input force, is applied at the input port, both gripper fingers elastically deform and realize force and motion transmission to the output. Thus, the gripper fingers realize closure motion with displacement d_{out} (Fig. 1). A part of the applied input force is used to realize the deformation of the gripper mechanism structure and, thus, the closure motion of the fingers. The other part of the force is transmitted to the output and so the gripper can realize the holding force to grip objects. Without applying any input force, the gripper itself returns to its initial state due to the stored elastic deformation energy.

III. FEM-Based Investigation of Adaptability

To investigate the motion i.e. deformation behavior of the compliant two-finger gripper, a geometrically nonlinear FEM simulation is performed as a common analysis method in the field of soft robotics [23]. First, the deformation behavior is investigated without gripping an object. Then, several gripping cases for different objects are simulated.

A. Deformation Behavior of the Gripper without Object

For the FEM analysis setup, the 3D CAD model (Fig. 2) is used. To simulate the gripper fingers closure motion, the maximum linear input displacement d_{in} = 10 mm is applied at the input port in direction of pulling. Fixed supports are applied at both ends of the gripper frame (Fig. 2 and Fig. 3a). A typical PE (Polyethylene) plastic material with a Young's modulus of 800 MPa is defined like it is used for the implemented prototype too. Additionally, a rough contact pair is set between the grasping surfaces of the gripper fingers, to avoid penetrations during the closure motion. The input force is analyzed at the input port and readout from the FEM solver. Fig. 3 shows the resulting deformation behavior of the gripper and the von Mises stress distribution. The results show that self-contact occurs, and that the gripper realizes full closure, while the grasping surfaces tend to realize a larger contact area with increased input displacement. Further, the output displacement (measured at the tip and middle of one gripper finger) and the needed input force to realize closure of the two-finger gripper are shown in Fig. 4. Until the first contact between the gripper fingers is realized (initial closure), there is a linear dependence between the realized output and applied input displacement, where the same can be noted for the required input force. After this, the gripper undergoes larger nonlinear deformations (Fig. 4). The results show that a relatively small input force is needed to deform and actuate the gripper, meaning that a large part of the force is transmitted to the output.

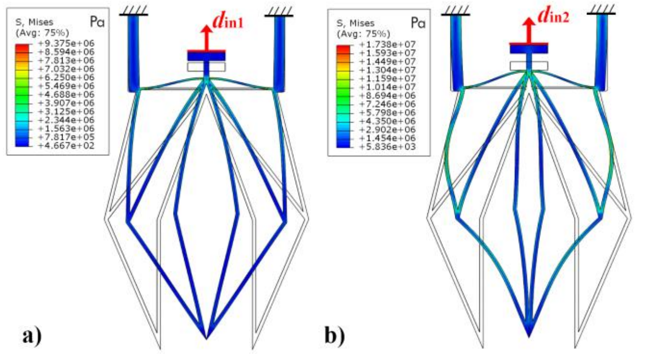

Figure 3. FEM results of the two-finger gripper deformation behavior and von Mises stress distribution for closure without object gripping: shown when initial closure is realized for d_{in1} = 6.2 mm (a) and the end value of the input displacement d_{in2} = 10 mm of the used actuator (b).

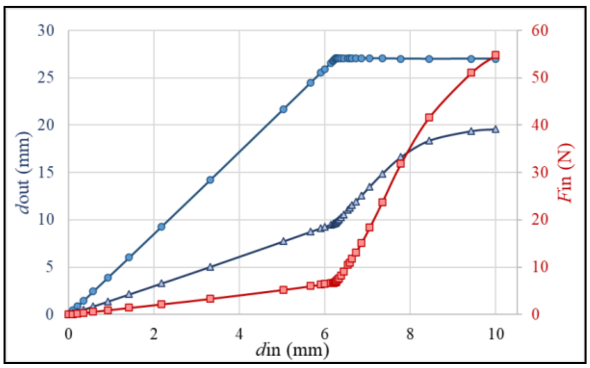

Figure 4. FEM results of the realized output displacement (analyzed at the tip and middle of one gripper finger) and the required input force for the two-finger gripper concerning the applied input displacement.

B. Adaptability and Grasping Mode in Dependence of Gripped Object

To investigate the capability of the gripper to realize pinch and encompass grasping and if the gripper can adapt to different shaped and sized objects, another set of FEM analysis is done. Different cases are investigated when prismatic (Fig. 5) and cylindrical objects (Fig. 6) are gripped. An additional rough contact pair is defined between the gripper fingers grasping surfaces and the object surfaces which are in contact with the gripper. Objects are considered deformable where the same material definition is used for the gripper. Objects can move freely in in-plane directions, while other degrees of freedom are fixed. This is done to simulate the gripping more realistically. For all investigated cases, the same FEM setup is used. Fig. 5 and Fig. 6 show the results of gripper deformation behavior when the object type (prismatic and cylindrical), size (relatively large and small), and location (at the tip and near the middle/end) are varied. The figures depict states of gripping for each of the investigated cases when adaptive gripping is realized. The results show that in the case of prismatic and cylindrical objects (both large and small), located at the tip, the gripper tends to conform its grasping surface to the object shape realizing pinch (parallel) grasping to some extend (Fig. 5a, 5c, 6a, 6c). For the case when prismatic and cylindrical objects (both large and small) are located near the middle or near the end, the gripper fingers start to adapt and encompass the objects, realizing power grasping (Fig. 5b, Fig. 5d, Fig. 6b, Fig. 6d).

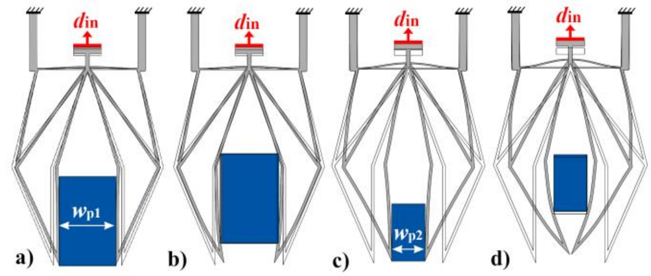

Figure 5. FEM results of the soft robotic two-finger gripper adaptability and grasping mode for different cases of prismatic objects: a large object at the tip (a), a large object near the middle (b), a small object at the tip (c), a small object near the middle (d) – w_{p1} = 45 mm, w_{p2} = 26 mm.

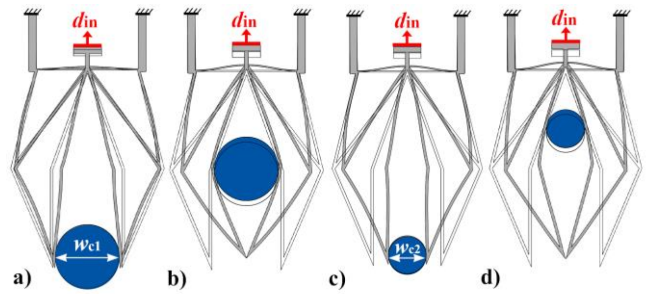

Figure 6. FEM results of the soft robotic two-finger gripper adaptability and grasping mode for different cases of cylindrical objects: a large object at the tip (a), a large object near the middle (b), a small object at the tip (c), a small object near the end (d) – w_{c1} = 50 mm, w_{c2} = 30 mm.

With a further increase of the input displacement, the gripper would undergo a significant deformation while still realizing stable grasping (not presented here). The results also show that the introduced soft robotic gripper mechanism can be used to grip different relatively stiff objects without the need for controlling the actuation input force as the gripper would rather adapt to the gripping object.

IV. Gripper Prototype and Experimental Investigations

Based on the 3D CAD model (Fig. 2), a prototype of the monolithic soft robotic two-finger gripper mechanism is exemplarily produced from PE plastic material (Fig. 7a), via CNC milling process. The gripper frame is further designed to fit a conventional linear actuator, where here a solenoid actuator is used due to its fast actuation speeds and high forces. It is to be noted that any other type of linear actuation can be used as well. At one end the actuator is fixed to the gripper frame, and at the other end, the actuator plunger is connected to the gripper input port, forming the full gripper device together (Fig. 7b). Additionally, a common anti-slip tape (PVC adhesive anti-slip tape) is added to the gripper surface to increase the friction when objects are gripped (which corresponds with the simulated case of the rough contact pair). Furthermore, an additional connecting part is designed to attach the gripper to an industrial robotic arm (Fig. 8a). Similar tests are done like for the FEM simulation cases, where first the gripper prototype behavior is investigated without any objects, and then for the cases when different real prismatic and cylindrical objects are gripped.

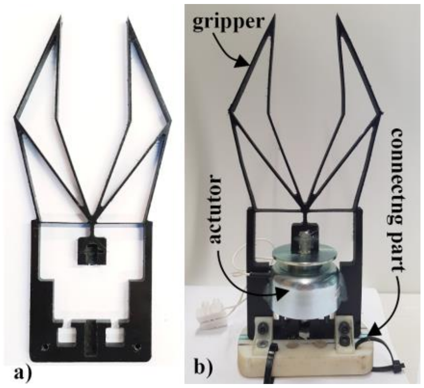

Figure 7. Realized prototype of the soft robotic two-finger gripper: monolithic compliant gripper mechanism with frame for the actuator (a) and gripper with solenoid actuator and connecting part for the robot arm (b).

A. Deformation Behavior without Object

To investigate the deformation behavior of the developed soft robotic two-finger gripper prototype, input power is supplied to the actuator. Fig. 8c shows the gripper in a deformed closed state when the actuator realizes its full stroke. It could be seen that for the given actuator input stroke, the gripper realizes more than a full closure, meaning that the gripper can reach a closed state (tips of the two fingers are in the first contact) with even smaller input strokes (Fig. 8b). Compared to the FEM results shown in Fig. 3b, it could be seen that the gripper behaves similarly. After the input force is released (by turning off the power supply), the gripper itself returns to its initial undeformed state due to releasing of its stored deformation energy. This is one of the advantages of the introduced compliant gripper concept as no restoring forces are needed to return the gripper to its initial opened position.

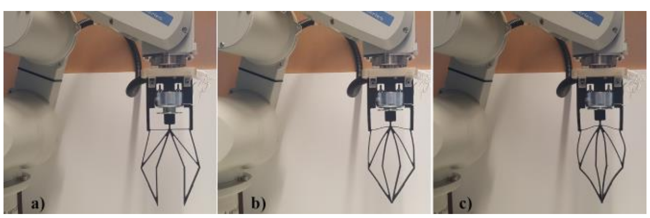

Figure 8. Soft robotic two-finger gripper mechanism mounted on an industrial robotic arm: shown in initial opened state (a), when first closure (self-contact) is realized (b) when actuator realizes full stroke (c).

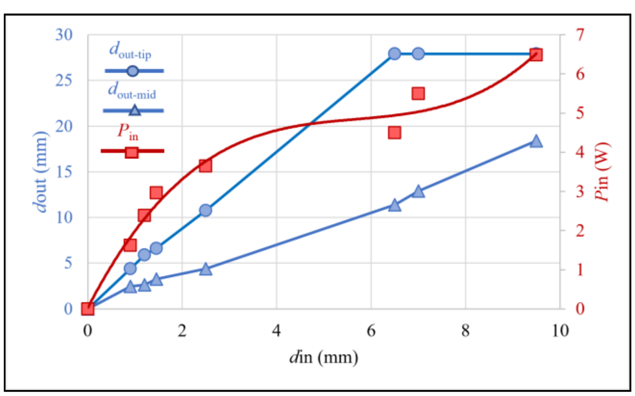

Figure 9. Measurement results of the realized output displacement (analyzed at the tip and middle of one gripper finger) and the required input power for the two-finger gripper concerning the applied input displacement.

Fig. 9 shows image-based measurement results for the realized output displacement (at one fingertip and in middle position) and the needed actuator input power, concerning the applied input displacement. Similar trends could be observed as in Fig. 4, where there is a good match with FEM results concerning the realized output displacement.

B. Investigation of Adaptability and Grasping Mode

To investigate the capability of the two-finger gripper to realize pinch and encompass grasping, as well as the structural adaptability, different prismatic and cylindrical stiff objects are gripped (Fig. 10 and Fig. 11), similar like for the FEM investigation (Fig. 5 and Fig. 6). Therefore, the two-finger gripper mechanism is attached to an industrial robotic arm, where the objects used in the test have a much larger stiffness than the gripper (object dimensions and positions are the same as in Fig. 5 and Fig. 6). The investigations are done by placing the objects between the gripper fingers and then increase the actuator input stroke (by supplying the corresponding input power) until the gripper realizes stable grasping of objects (with minimal required holding force). The input stroke/force is then further increased until the adaptive gripping is noted i.e. the gripper starts to conform or encompass the object. Fig. 10 and Fig. 11 depict the tests for different cases when the object type (prismatic and cylindrical), size (big and small), and position (at the tip, middle, and end) are varied. For all the cases the same test procedure is done. The figures show the adaptive gripping state. Through the experiment, it is further observed that when the actuator realizes its full stroke, the gripper undergoes a significantly larger deformation (without damage) while still adapting to the object shape and thus realizes stable grasping.

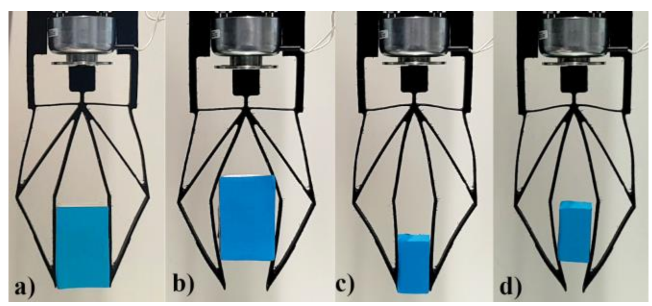

Figure 10. Test of the soft robotic two-finger gripper adaptability and grasping mode for different cases of prismatic objects: a large object at the tip (a), a large object near the middle (b), a small object at the tip (c), a small object near the middle (d).

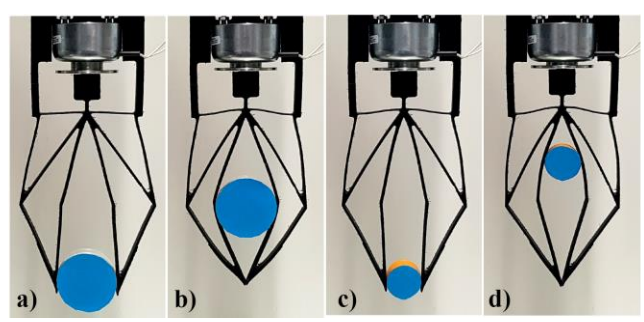

Figure 11. Test of soft robotic two-finger gripper adaptability and grasping mode for different cases of cylindrical objects: a large object at the tip (a), a large object near the middle (b), a small object at the tip (c), a small object near the end (d).

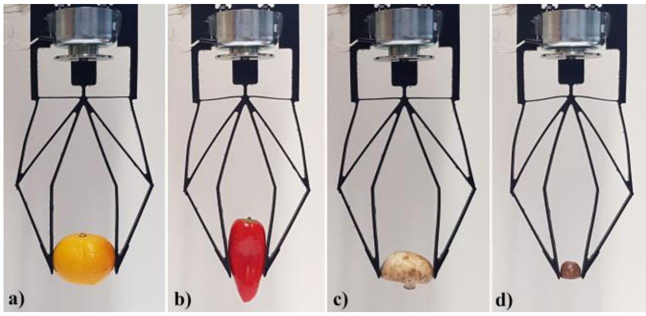

Figure 12. Examples of adaptive and gentle gripping of different food objects: clementine – 61.4 g (a), paprika – 15.9 g (b), mushroom – 7.0 g (c), sweet – 2.1 g (d); gripping of paprika, mushroom, and sweet is realized with the same value of actuator input power.

Based on the test results (Fig. 10 and Fig. 11), similar conclusions can be made as in the case of the FEM investigations. When the objects are located near the tip, the gripper surface tends to conform to the object realizing pinch or parallel grasping. Furthermore, when the objects are located near the middle or the end, the gripper adapts and encompasses the objects. Thus, the test results with real soft and delicate objects confirm the self-adaptability of the gripper and that both pinch and encompass grasping can be inherently realized.

V. Gentle Food Gripping and Manipulation Examples

The handling of different and varying objects, especially of delicate food products, with only one universal gripper and no or little control efforts, remains a challenging task in the field of robotics. With the introduced concept of the soft robotic two-finger gripper mechanism adaptive and gentle grasping of different soft objects can be simply realized, like demonstrated in this section for different gripping examples of fruits, vegetables, sweets, and especially sushi pieces.

A. Gripping Examples

Different object groups are used to show the versatility of possible objects for food-handling with the soft robotic two-finger gripper. Fig. 12 exemplarily demonstrates a part of the results when a clementine, paprika, mushroom, and sweet are gripped. In all cases, the gripping is realized successfully without damaging the objects, where all the objects could be picked from the ground. The gripping is realized by only on/off control of the actuator, where for the cases of handling paprika, mushroom, sweet, and others the same value of input power is supplied to the actuator (see Fig. 13). It is also important to mention that very fast gripping is realized, ranging from 30 ms to 120 ms, depending on the object size.

A further challenging task is the reliable handling of soft and delicate objects like sushi pieces without deforming them. Fig. 14 shows the results of gripping for the cases when the sushi type (Maki, Uramaki, Nigiri) and orientation are varied. In all tested cases, the gripping is realized successfully and safely without damaging the sushi, where the sushi pieces can be picked from the ground. It is important to note that, like for the most objects in Fig. 12, the gripping of all objects in Fig. 14 is realized with the same value of actuator input power and with only on/off control too.

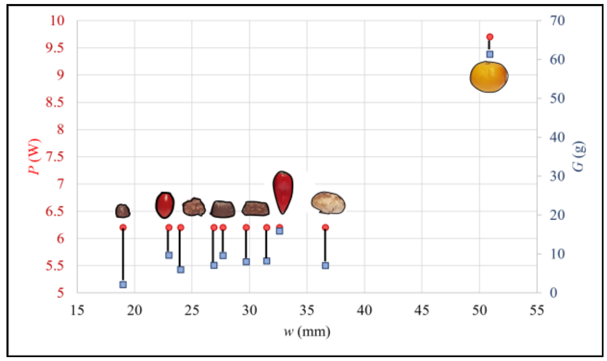

Figure 13. Object width and weight compared with applied actuator input power, for the realized gripping examples of different food-based objects.

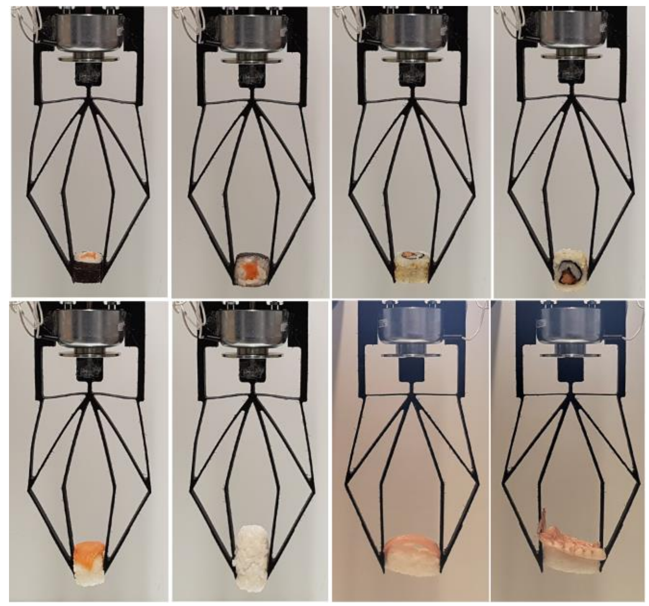

Figure 14. Examples of adaptive and gentle gripping of different delicate sushi pieces; the gripping is realized with the same value of actuator input power for all cases.

The realized tests exemplarily show that the gripper enables adaptive and gentle handling of delicate food objects that vary in size, shape, weight, and stiffness where no sensors or complicated control algorithms are necessary. This further proves that the gripper possesses "self-adjustment" of the needed gripping force, without damaging or deforming the objects but still realizing reliable and fast grasping.

B. Manipulation Examples

To further demonstrate that reliable and stable grasping can be realized even during manipulation at high velocities of the robotic arm, different tests are done where the gripped objects are moved in space (translation and rotation). Fig. 15 shows examples of manipulation with several sushi pieces. The robotic arm is programmed to pick the objects placed at a different location, to do manipulation in space with several operations, and to place the objects back at the plate. The velocity of the robotic arm is 3.3 m/s, where the total time of the manipulation process is set to approximately 3.4 s. Fig. 15 exemplarily shows manipulation with only one sushi piece, but reliable and stable grasping has been realized for all other sushi pieces too.

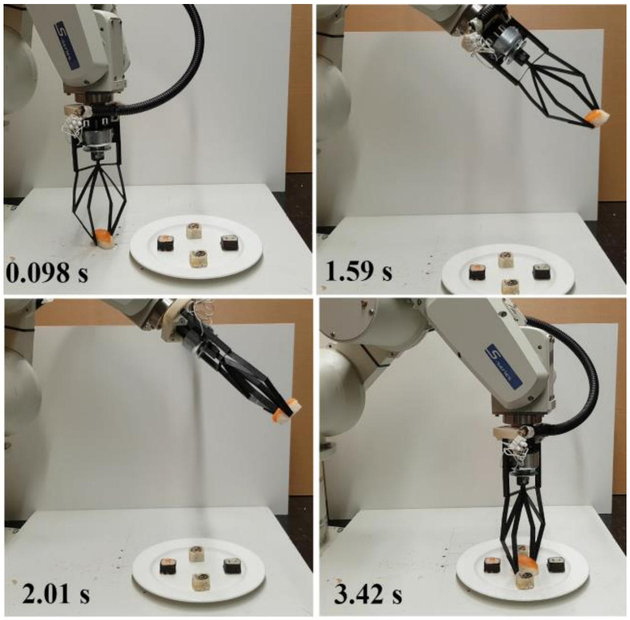

Figure 15. Manipulation of different sushi pieces in space, realized for a high velocity of the robotic arm (figures show different time intervals).

VI. Conclusion

This paper further investigates a novel soft robotic compliant two-finger gripper mechanism that can realize adaptive gripping of different relative stiff objects but also gentle gripping of varying soft objects. The optimization-based synthesis method and the gripper design are briefly explained. Comparted to our previous work [21], here novel FEM-based investigations are performed to study the pinch and encompass grasping as well as structural adaptability of the gripper i.e. if the gripper can conform to the object shape. Furthermore, a gripper prototype is introduced, and the FEM results are confirmed by tests. The investigations show that the gripper can realize adaptive gripping for both pinch and encompass grasping when differently shaped and relative stiff objects are gripped. Moreover, different examples are shown when very soft and easy squeezable objects like fruits, vegetables, and sushi are gripped and manipulated (not investigated in [21]). Compared to the other existing soft gripper solutions, the presented compliant gripper realizes very fast gripping, stable manipulation at high speeds of the robotic arm, and a simply realizable concept with only two parts. In general conclusion, various stiff and soft example objects can be gripped without sensors or control which is further advantageous and expands a possible application of the introduced soft robotic gripper. Further research will include a more detailed investigation of the developed gripper properties as well as using different actuation principles.

References

[1] A. Raatz, S. Blankemeyer, G. Runge, G. Bruns, and G. Borchert, "Opportunities and Challenges for the Design of Inherently Safe Robots," in *Soft robotics: Transferring theory to application*, A. Verl, A. Albu-Schäffer, O. Brock, and A. Raatz, Ed. Berlin: Springer, 2015, pp. 173–183.

[2] L. Wang, J. DelPreto, S. Bhattacharyya, J. Weisz, and P. K. Allen, "A highly-underactuated robotic hand with force and joint angle sensors," in *Proc. of the 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems,* San Francisco, USA, 25-30 (2011) September 2011, pp. 1380–1385.

[3] L.-A. Larouche, and Birglen L, "Assisted design of linkage-driven adaptive soft fingers," *Industrial Robot: An International Journal*, vol. 40, pp. 337–346, June 2013.

[4] R. A. J. Stavenuiter, L. Birglen, and J. L. Herder, "A planar underactuated grasper with adjustable compliance," *Mechanism and Machine Theory*, vol.112, pp. 295–306, June 2017.

[5] I. I. Borisov, O. I. Borisov, V. S. Gromov, S. M. Vlasov, and S. A. Kolyubin, "The UHVAT Gripper: Usable Holding Versatile Adjustable Tool to Grasp Different Objects," *IFAC-PapersOnLine*, vol. 51, pp. 722–727, November 2018.

[6] J. Xu, N. Alt, Z. Zhang, and E. Steinbach, "Grasping posture estimation for a two-finger parallel gripper with soft material jaws using a curved contact area friction model," in *Proc. IEEE International Conference on Robotics and Automation (ICRA)*, Singapore, May 29-June 3, 2017, pp. 2253–226.

[7] J. Hughes, U. Culha, F. Giardina, F. Guenther, A. Rosendro, and F. Iida, "Soft Manipulators and Grippers: A Review*," Frontiers in Robotics and AI*, vol. 3, 69(p), November 2016.

[8] J. Shintake, V. Cacucciolo, D. Floreano, and H. Shea, "Soft Robotic Grippers," *Advanced materials*, e1707035, May 2018.

[9] F. Chen *et al.,* "Topology Optimized Design, Fabrication, and Characterization of a Soft Cable-Driven Gripper," *IEEE Robot. Autom. Lett.*, vol. 3, no. 3, pp. 2463–2470, July 2018.

[10] J. Zhou, S. Chen, and Z. Wang, "A Soft-Robotic Gripper With Enhanced Object Adaptation and Grasping Reliability," *IEEE Robot. Autom. Lett.*, vol. 2, no. 4, pp. 2287–2293, October 2017.

[11] H. Yin, C. Kong, J. Li, and G. Yang, "Modeling of grasping force for a soft robotic gripper with variable stiffness," *Mechanism and Machine Theory*, vol. 128, pp. 254–274, October 2018.

[12] T. Zhu, H. Yang, and W. Zhang, "A Spherical Self-Adaptive Gripper with shrinking of an elastic membrane," in *IEEE ICARM 2016: 2016 International Conference on Advanced Robotics and Mechatronics*, Macau, China, pp. 512–517, August 2016.

[13] M. C. H Chua and R. C. H Yeow, "Propulsion-Based Soft Robotic Actuation," *Robotics*, vol. 6, 34(p). November 2017.

[14] R. Deimel and O. Brock, "A novel type of compliant and underactuated robotic hand for dexterous grasping," *The international journal of robotics research*, vol. 35, pp. 161–185, August 2016.

[15] Festo AG & Co. KG (2019) BionicSoftHand: Pneumatic gripper based on the human hand. Available at: www.festo.com/net/SupportPortal/Files/597078/ Festo_BionicSoftHand_en.pdf (accessed 1 August 2019).

[16] L. Zentner and S. Linß, *Compliant systems: Mechanics of elastically deformable mechanisms, actuators and sensors*. Berlin, De Gruyter Oldenbourg, 2019.

[17] L. L. Howell, S. P. Magleby, and B. M. Olsen, *Handbook of Compliant Mechanisms*. Chichester: Wiley, 2013.

[18] X. Chen, Z. Deng, S. Hu, J. Gao, and X. Gao, "Design of a Compliant Mechanism Based Four-Stage Amplification Piezoelectric-Driven Asymmetric Microgripper," *Micromachines*, vol. 11, December 2019.

[19] M. Cauchi, I. Grech, B. Mallia, P. Mollicone, and N. Sammut, "The Effects of Structure Thickness, Air Gap Thickness and Silicon Type on the Performance of a Horizontal Electrothermal MEMS Microgripper," *Actuators*, vol. 7, p. 38, July 2018.

[20] C.-H. Liu, C.-H. Chiu, M.-C. Hsu, Y. Chen, and Y.-P. Chiang, "Topology and Size–Shape Optimization of an Adaptive Compliant Gripper with High Mechanical Advantage for Grasping Irregular Objects," *Robotica*, pp. 1–18, February 2019.

[21] A. Milojević, S. Linß, Ž. Ćojbašić, and H. Handroos, "A Novel Simple, Adaptive, and Versatile Soft-Robotic Compliant Two-Finger Gripper With an Inherently Gentle Touch," *Journal of Mechanisms and Robotics*, vol. 13, no. 1, 011015 (14 p.), February 2021.

[22] J. A. Gallego and J. L. Herder, "Synthesis Methods in Compliant Mechanisms: An Overview," in *Proc. of the ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE2009)*, August 20-September 2, 2009, San Diego, USA, 2009, 22 p.

[23] S. Liu, H. Zhang, R. Yin, A. Chen, and W. Zhang, "Finite Element Analysis and Application of a Flexure Hinge Based Fully Compliant Prosthetic Finger," in: *Advanced Computational Methods in Life System Modeling and Simulation ICSEE 2017, LSMS 2017. Communications in Computer and Information Science*, vol. 761. M. Fei, S. Ma, X. Li, X. Sun, L. Jia, Z. Su, Ed. Singapore, Springer, 2017.