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A novel simple, adaptive and versatile soft-robotic compliant two-finger gripper with an inherently gentle touch

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ABSTRACT

In soft robotics there is still a great need for a universal but simple gripper that realizes a high level of adaptability as well as a gentle touch to a wide variety of unknown objects of different size, shape, stiffness and weight without the use of sensors or vision. Various, mostly complex grippers already exist based on certain actuation concepts. However, each solution has specific limitations, especially regarding gripping different soft and delicate objects. Therefore, this paper introduces a new approach to design a simple, adaptive and versatile soft robotic two-finger gripper that is based on compliant mechanisms. More specifically, an inherently gentle touch is realized by utilizing an optimally synthesized mechanism with distributed compliance in combination with a conventional linear actuator. It is shown by FEM simulations

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that the gripper realizes a high force and motion transmission at the same time. Furthermore, it is demonstrated by tests with a gripper prototype that reliable, safe, and fast grasping as well as manipulation are possible for a wide variety of objects. It is shown that beside regular and stiff objects also very challenging objects can be easily gripped, e.g. small, irregular, soft, and squeezable objects like fruits, berries and vegetables. Moreover, it is confirmed that the developed compliant two-finger gripper can be used beneficially without sensors and control for differently sized and shaped objects with a comparable weight.

Keywords: soft robotic gripper, adaptive gripper, versatile gripper, two-finger gripper, compliant mechanism, soft object manipulation

1 INTRODUCTION

In many of today industries where automatization is present, robotic systems are often used to perform different tasks, like pick-and-place, manipulation, handling, assembling or assistance. In the field of human-centered robotics it is especially important to consider inherent safety aspects, which can be realized e.g. by control [1], by links with variable stiffness [2], by soft components with variable stiffness [3] or by variable stiffness actuation [4]. During the task, the robot comes into contact with objects or workpieces and realizes their gripping and manipulation by using end-effectors. Thus, end-effectors, which are also known as end-tools, material handling tools, grippers, graspers or robotic hands, represent an essential part of almost every robot. Therefore, the utilization of the full robot potential also depends on the capabilities of its end-effectors. This limits the robot flexibility regarding varying gripping tasks and at the end their application.

Classical grippers for the application in industrial environments are usually designed by utilizing rigid-body mechanisms. These grippers have limited grasping capabilities because they are designed to handle only one type of object in most cases leading to strong limitations in variation of shape, size, weight and stiffness of the gripped object. To reduce the uncertainty of the shape of unknown objects, a data-driven grasp synthesis can be applied [5]. To further realize dexterous grasping with anthropomorphic hands under shape uncertainty, multiple fingertip sensors and complex control algorithms are required [6,7]. Others use adaptive synergy schemes based on underactuated designs [8] or the incorporation of constraints into grasp planning [9].

As robotic tasks grow more complex and demanding, the working environment of robots is becoming very diverse. Especially for new application areas like collaborative robots and food industry, a certain compliance of the structural components themselves is needed. Furthermore, adaptability is required to grasp a wide variety of objects with different shape, size and weight as well as soft objects. Therefore, different kinds of grippers were developed that can achieve adaptability to some extent. 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 with conventional mechanisms and drives [10], for which software assistance [11], an adjustable compliance concept [12] or a reconfigurable mechanism concept [13] can be additionally used. Multistable rigid-body-based tensegrity structures can be used as self-adaptive grippers with mechanical compliance, too [14]. Rarely, inflatable pockets [15] or camera-based visuo-haptic grippers equipped with soft material jaws [16,17] are suggested, which make a rigid-body gripper system partially flexible but also very bulky.

In order to grip more delicate and compressible objects in the field of soft robotics, especially designed end-effectors are developed that are often called soft grippers or manipulators [18]. A quite common feature of these grippers is the design with soft material [19]. However, to use soft robotic grippers, actuation is generally necessary, for which there are various actuation principles. These mainly include cable-driven grippers, fluid-mechanically driven or vacuum-driven grippers as well as grippers based on active material, adhesion or the force- and form-closure principle, for which numerous different examples exist in research and in industry [20]. Rarely, highly complex mechatronic robot hands like the BionicSoftHand [21] are developed, which lead to a high grade of dexterous gripping and manipulation by using multiple types of sensors and actuators in combination with artificial intelligence.

A completely different approach to achieve simple adaptive soft robotic gripping, that has not yet been fully investigated, is the use of compliant mechanisms. These mechanisms gain their mobility fully or partially from the compliance of its deformable parts rather than from rigid-body joints only [22]. Generally, compliant mechanisms are monolithic structures and thus, easy to produce, assembling-free, maintenance-free, friction-less as well as lightweight. Although the use of compliant mechanisms for gripping is common in the fields of high-precision micromanipulation [23] and MEMS [24] for many years, only a few prototypes for passively self-adaptive soft grippers are suggested that utilize compliant mechanisms with distributed compliance [25,26]. The combination of highly-elastic materials with functional materials additionally allows the realization of multi-functional compliant systems with inherent sensor and actuator properties, which can be used for mechanically smart gripping, too [27]. With the acceptance of strong limitations, it is also possible to use a fully compliant structure as a totally passive gripper due to the inherent stiffness of the gripping fingers [28].

However, existing soft robotic end-effectors have certain disadvantages and restrict a widespread application mostly due to limited variability and adaptability, limited miniaturization potential, high complexity, high weight, high sensory as well as control effort and, thus, high costs. Therefore, in this paper a novel versatile, yet simple soft robotic compliant two-finger gripper is reported that realizes a high level of adaptability and dexterity. The elastic based gripper is mounted on an industrial robot arm to pick and place objects (Fig. 1). It will be presented that with such gripper concept a wide variety of objects with different size, shape, weight and stiffness can be grasped reliably and safely. Special emphasize is on gripping irregular, unknown and easily squeezable objects. The gripping is possible with only one conventional linear actuator and without the need of sensors and a force control for different objects (different dimension/shape/stiffness) of comparable weight due to the inherent adaptability of an optimally designed monolithic compliant mechanism in combination with the characteristics of the used actuator. Thus, the adjustment of the object-specific gripping force and exact input stroke is a structurally inherent property of the compliant gripper system with only on-off control of the input actuation.

Based on a literature review and the analysis of the related work, the new design approach for a soft robotic gripper is presented in this paper. The optimal synthesis of the compliant gripper finger mechanism is described together with an FEM-based characterization of the two-finger gripper deformation and motion behavior. A gripper prototype is introduced where several gripping and manipulation examples are demonstrated for grasping different delicate and especially soft objects like fruits, berries and vegetables. Moreover, it is shown that stiff and heavier objects can be gripped with the developed lightweight gripper.

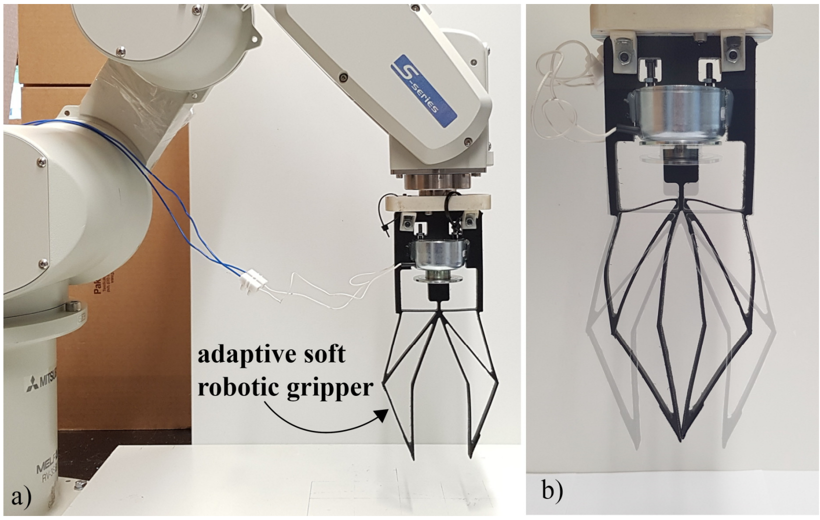

Fig. 1 Simple, adaptive and versatile soft robotic compliant two-finger gripper: a) mounted on an industrial robot arm; b) shown in unactuated/opened state (transparent color) and actuated/closed state (solid black color)

2 RELATED WORK

Developing a soft robotic gripper that realizes a high level of adaptability and dexterity, i.e. that can grasp a wide variety of objects with a simple control, represents a very challenging task that has been a research topic for many years. Existing actuation concepts can be assigned to several certain groups.

An early but still widespread actuation concept for adaptive robotic grippers is the use of underactuated cable-driven gripper fingers. Most of them are realized by opened kinematic chains based on geared mechanisms [29] or rigid-body mechanisms [30], while in-hand manipulation is also possible [31]. Furthermore, partially compliant mechanisms are applied [32], which offer the variation of the joint stiffness [33,34]. Fully compliant mechanisms with distributed compliance can help to grip a wider range of different objects [35], while also gripper fingers based on flexure hinges made of hyperelastic elastomer material [36], thermoplastic elastomer material [37] or two different elastomer materials [38] are suggested. Entirely soft elastomer structures allow the highest grade of adaptability in this group due to a bending-like motion with a non-constant curvature [39] or a tentacle-like crawling motion [40].

A quite common feature of many soft robotic grippers is the design with soft material [19]. This led to the development of numerous soft grippers in the large group of fluid-mechanically driven compliant elastomer actuators. For example, pneumatic bellow-type chambers, which are integrated in a multi-part system, are used to realize multiple bending motions of robotic fingers [41,42]. Furthermore, fully compliant fluidic actuators are used to create simple planar or complex spatial gripping motions, such as the single chamber-type [43], chamber-type with palms supported by pillars [44], three chamber-type [45], tentacle chamber-type [46], multiple cascaded chamber-type [47], bubble-type [27], bellow-type [48], modular bellow-type with additional vacuum suction cup [49], bellow-type with variable effective length [50], bellow-type with gecko-inspired adhesive [51] or ribbed-type [52] gripper. The combination of chambers with inelastic fabrics and helically wound threads leads to complete hand-like dexterous grippers [53]. Rarely, air propulsion is used for gripper finger actuation [54]. Moreover, a self-healing robotic hand is presented based on special polymers with the ability to heal micro and macroscopic damage [55]. Soft grippers with on-board untethered pressure generation [56] are slow and thus not appropriate at present.

A further soft robotic gripper group that has become important is based on the actuation through active materials, like Nitinol [57], SMA wires [58], SMA wires in combination with elastomer structures [59], magnetorheological fluids [60], magneto-sensitive elastomers [61], dielectric elastomers [62], dielectric elastomers in combination with electroadhesion [63] or ionic polymer-metal composites [64].

Moreover, some soft robotic grippers use special force- and form-closure combined principles, where the gripper end-effector partially or entirely envelops the object. Examples are the gripper based on jamming granular material [65], the FlexShapeGripper [66], the gripper based on shrinking of an elastic membrane [67], the rotary-actuated self-folding gripper [68], the pressure-driven gripper with a rolling bulge [69], the vacuum-driven cubical elastomer gripper [70] or the vacuum-driven origami-based gripper [71]. Rarely, soft grippers based on a completely closed suction cup [72] or micro-fibrillar geckoadhesion [73] are suggested.

The inclusion of compliance into an underlying mechanism structure itself has led to an improved gripper adaptability regarding a specific group of objects, while the grippers can be driven by only one actuator in most cases. For example, partially compliant mechanisms with classical hinges are used for adaptive grippers that are made of plastic material in most cases, e.g. the Fin Ray-type gripper [74], sensorized Fin Ray-type gripper [75] or sensorized Fin Ray-type gripper with geckoadhesion [76]. Furthermore, some adaptive grippers based on fully compliant mechanisms with notch flexure hinges – e.g. the compliant two-finger gripper [77], Fin Ray-type gripper [78] and buckling-type gripper [79] – or with distributed compliance – e.g. the Fin Ray-type gripper [80], two-material Fin Ray-type gripper [81] and ferroelastomer-actuated gripper [82] – are developed. Rarely, non-monolithic two-finger grippers with distributed compliance are suggested that are self-adaptive to some extend but separately require the mounting on the robot arm as well as the actuation either by a massive inner moving platform [83] or an outer drive [84]. Furthermore, auxetic compliant structures with a complex deformation behavior are used for soft gripper fingers [85], also combined with pressure sensors [86]. Because all these mechanism structures are not optimized, a large actuator stroke is required in most cases and reliable gripping at the fingertip, especially of small and flat objects, is difficult. The technical application of further actuator-less bistable compliant elastomer grippers, e.g. [87], is limited for differing objects.

More recently, optimally designed monolithic two-finger grippers made of hyperelastic elastomer material are developed with respect to an improved motion [88] or force transmission [25]. However, the presented approaches are not able to design gripper structures with a good trade-off between a high motion and force transmission. Furthermore, the output force of elastomer structures is generally limited. Then, these compliant mechanisms are mostly designed so that the closure motion of the gripper fingers is realized by pushing actuation, which can reduce the gripper performance. Moreover, the sensitivity to protuberances is highly increased due to small out-of-plane stiffnesses. Contrary, it has been shown in previous works that it is possible to design more robust and easier to produce monolithic adaptive grippers, for which stiffer plastic material can be used [89]. Moreover, embedded active actuator elements and flexible sensors can be considered at once [26], while the structural integration of the active elements is not yet suitable for end applications.

In conclusion, there is no gripper that can passively adapt and easily grasp a wide variety of object types – i.e. with different shapes (concave/convex, regular/irregular), sizes (big, small and tiny), stiffnesses (stiff and soft) or weights (heavy and light) – and especially delicate and squeezable objects. Therefore, a novel approach of a compliant two-finger gripper with distributed compliance that is made of lightweight solid elastic material is presented in this paper. The monolithic gripper is optimally designed regarding a relatively high motion and force transmission at once. The actuation is realized by one conventional solenoid actuator with only on-off control (no force/stroke control). Hence, the realization of a novel simple and versatile adaptive gripper with an inherently gentle touch is described in this paper.

3 DESIGN OF THE COMPLIANT GRIPPER FINGER

Compared with rigid-body mechanisms, the synthesis of compliant mechanisms is generally complex and non-intuitive [90]. As a fully compliant mechanism with distributed compliance is utilized here, the common structural optimization approach is applied for the gripper synthesis. Structural optimization can be classified into the three types: topology, shape and size optimization [91]. Based on a previous design idea of a simple gripper mechanism realized by topology optimization [89], in this paper, shape optimization is further implemented. Here, with shape optimization the optimization of the overall gripper mechanism shape and not the shape of its individual segments is considered. This is done to realize a universal soft robotic compliant gripper with a good trade-off between a high geometrical advantage (GA: ratio of realized output displacement to applied input displacement) and especially a high mechanical advantage (MA: ratio of output force to input force). Therefore, the node wandering approach is implemented. Here lengths (and position to some extend) of individual mechanism segments are optimized by allowing the segment nodes to change their position within a certain region (Fig. 2).

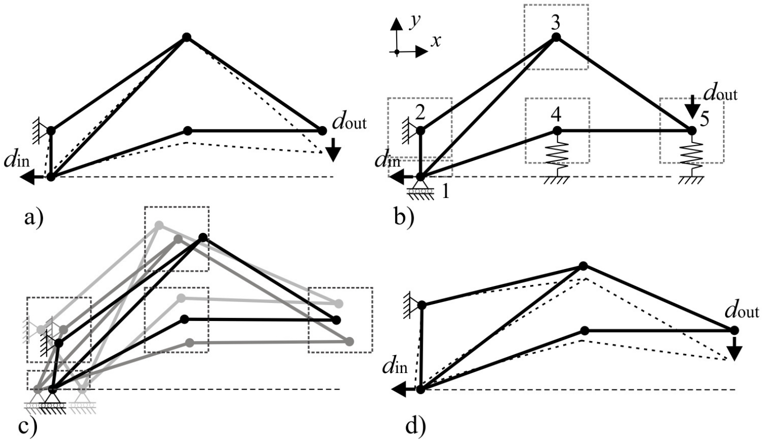

Fig. 2 Shape optimization of the compliant gripper finger mechanism: a) initial design and problem definition; b) parametrization; c) optimization by node wandering approach within the dotted area (springs are removed for clarity); d) optimal design of the gripper finger (without springs)

The shape optimization of the new compliant gripper finger includes the following design steps:

- problem definition – setting the desired input and output parameters (Fig. 2(a));
- parametrization – translating the problem to a set of variables that can be optimized and approximating object forces by springs (Fig. 2(b));

- optimization – applying the search algorithm in order to find the optimal solution for the given problem and thus the optimal mechanism shape (Fig. 2(c)).

The final and optimal design of the adaptive and universal compliant gripper finger with a relatively high geometrical and mechanical advantage at once is depicted in Fig. 2(d).

3.1 Problem definition and parametrization

In the first design step of the shape optimization, the problem specifications are defined based on an initial gripper design (Fig. 2(a)) that is obtained via discrete topology optimization approach [89]. Therefore, the gripper mechanism is formed as a monolithic structure comprising of individual long and thin segments, where the topology of the gripper mechanism is optimized. Only one finger of the gripper is designed as based on this two, three or multi-gripper fingers can be realized. When the input displacement (d_{in}) is applied at the input port of the mechanism, the gripper finger elastically deforms and realizes output displacement (d_{out}), i.e. the closure motion. One part of the input force is used for the elastic deformation of the gripper structure, while the other part is transferred to the output port, and thus the gripper can realize object holding force. The GA of the initial compliant gripper finger is comparably high with a value of 6.2, but with relatively low MA value of 0.13. Nonetheless, this design represents a good starting point for further shape optimization of the compliant gripper mechanism to reach an adaptive and reliable gripping performance with safe gripping and object manipulation.

The problem setup for shape optimization includes defining the initial gripper topology from which optimization starts (Fig. 2(a)), nodes that are allowed to wander, size of the node wandering region, fixed supports, boundary conditions, desired input and output direction, input displacement, characteristics of the used material (Young's modulus E), output conditions, external loads, and other constraints.

End-left part of the structure (node no. 2) is selected as a support. Symmetry boundary condition is applied at the symmetry axis of the gripper (Fig. 2(b)). All nodes in the structure of the initial design can freely wander within a predefined region (Fig. 2(b) and Fig. 2(c)), while constraint is set to node 1 (can wonder only along symmetry axis), and nodes 4, 5 (must have the same y coordinate in order to keep gripping surface horizontal). The size of the node wandering region is given in Table 1. At the input port a displacement in horizontal direction is applied while the vertical direction is set as desired direction of the output motion so that gripper can realize closure. A spring with corresponding stiffness is placed at the middle point of the grasping surface and at the output port in order to simulate resistance of the gripping object.

In the second step of the shape optimization process, parametrization is done. The given problem needs to be represented by set of variables that can be optimized. The initial topology of the gripping mechanism is represented by the number of nodes and the beam elements connecting these nodes (Fig. 2(b)). This represents the initial design of the soft robotic gripper finger, from which the optimal design will be searched.

Table 1 Parameters for the shape optimization of the compliant gripper finger mechanism

Design parameters	**Values**
Initial design overall dimensions (*w* x *h*)	75 x 150 mm
Total number of elements	6
Total number of nodes	5
Size of node wandering region (for all the nodes) in *x* direction, v^n_x = min : step : max	-20 : 0.2 : 20 mm
Size of node wandering region (for all the nodes) in *y* direction, v^n_y = min : step : max	-20 : 0.2 : 20 mm
Support (node no.)	2
Element thickness (in-plane)	2 mm
Element thickness (out-of-plane)	10 mm
d_{in}	2 mm
Young modulus (*E*)	500 N/mm^2
Spring stiffness	500 N/m
$d_{\mathrm{out}}^{\mathrm{min}}$	4 mm
$d_{\mathrm{out}}^{\perp}$	0.5 mm

For every node in the gripper finger mechanism two optimization variables exist:

- v^n_x as variable that defines the possible range of node wondering in *x* direction;
- v^n_y as variable that defines the possible range of node wondering in *y* direction;

where *n* is the number of corresponding wandering node.

The thicknesses of all elements (both in-plane and out-off-plane) are predefined rather than optimized as one assumption. Table 1 includes the parameters and values that are used for parametrization and shape optimization of the compliant gripper finger mechanism.

3.2 Optimization

A search method is applied to find the optimal design of the compliant gripper finger mechanism by shape optimization. The main goal is to realize a good trade-off between MA and GA while gripping. The force transmission behavior of a gripper can be expressed by the MA which is defined as the ratio of output force F_{out}, that gripper realizes at his tip, to applied input force F_{in} at the input port of the mechanism:

$$t_{MA} = \frac{F_{\mathrm{out}}}{F_{\mathrm{in}}} \tag{1}$$

The motion transmission behavior of a gripper can be expressed by the GA which is defined as the ratio of realized output displacement d_{out}, at the tip of the gripper, to the applied input displacement d_{in}:

$$t_{GA} = \frac{d_{\mathrm{out}}}{d_{\mathrm{in}}} \tag{2}$$

Thus, the goal is to obtain a gripper design that can efficiently transmit force from the input port to the out port of the gripper mechanism, while still realizing a relatively high GA (Eq. (1)). This is done by maximizing the MA (Eq. (2)) during optimization, while two springs are added to the gripper finger model (Fig. 2(b)). The assumption is, if the gripper finger can realize larger deformation of the springs, it means that the transmission of the input force to the output port will be maximized, i.e. MA increases (when the same input displacement/force is applied). By maximizing MA while realizing high GA, a gripper with better performance can be obtained, and actuators with smaller input forces and strokes can be used.

The form of the objective function that is used for the optimal design of the gripper finger mechanism is given as:

$$maximize\left[\frac{F_{\mathrm{out}}}{F_{\mathrm{in}}}\right] \tag{3}$$

In addition to the objective function, several constraints are used in order to obtain the desired optimal solution. A constraint that monitors the output displacement d_{out} is added. For the case that the output displacement is smaller than the predefined constant value ($d_{\mathrm{out}}^{\mathrm{min}}$ in Table 1), penalization is applied. To realize an approximated straight motion path of the gripper tip, the output displacement $d_{\mathrm{out}}^{\perp}$ in direction perpendicular to the desired direction of motion is monitored as well. The penalization is applied if $d_{\mathrm{out}}^{\perp}$ is greater than the predefined value given in Table 1.

Among many existing methods, genetic algorithms are proven to be very efficient for solving various optimization problems due to ease of finding global optima over a large space of design variables, especially for topology and design optimization of compliant mechanisms [89]. The genetic algorithm parameters used for the shape optimization of the presented compliant gripper finger mechanism are: initial population of 200 designs, a total of 1000 generations, selection function type roulette, crossover probability of 95%, elite count of two members, and mutation probability of 9%. The optimization process is done by simultaneously allowing each node of the gripper finger to move in both x and y directions within the defined region (Fig. 2(c)). For each of the selected combination/position of the nodes, the objective function is evaluated (Eq. (3)) by using linear FEA, which is implemented in the optimization algorithm (for more information about how this is implemented see [89]). In future works more details about how the linear FEA method is implemented in the optimization algorithm will be considered. The process is repeated until the solution that best satisfies the given objective is found or if there is no more improvement of the objective function value after a predefined time interval.

The obtained optimal shape of the adaptive compliant gripper finger mechanism is shown in Fig. 2(d). The GA (t_{GA}) and MA (t_{MA}) values that the optimal design realizes for the case of closure with gripping (springs) and the GA value ($t_{\mathrm{GA*}}$) without the consideration of a gripped object (no springs) are given in the Table 2; the case without springs is evaluated after the optimization. The results show that the shape-optimal design (Fig. 2(d)) realizes a considerably increased MA compared to the initial design (Fig. 2(a)), with a still relatively high GA. The results show that smaller input force is needed to actuate the shape optimal solution thus more force is transmitted to the output.

Table 2 Shape optimization results for the compliant gripper finger mechanism

Gripper version	**Results for closure with gripping (by two springs)**		**Results for closure without object (no springs)**
	t_{GA}	t_{MA}	$t_{\mathrm{GA*}}$
Initial design (Fig. 2(a))	2.34	0.13	6.2
Shape-optimal design (Fig. 2(d))	2.00	0.18	4.0

4 IMPLEMENTATION AND FEM-BASED CHARACTERIZATION OF THE MONOLITHIC COMPLIANT TWO-FINGER GRIPPER

Based on the obtained shape-optimal mechanism design (cf. Fig. 2(d)), the monolithic compliant two-finger gripper is designed with its embodiment (Fig. 3). To investigate the deformation and motion behavior of the two-finger gripper, a geometrically nonlinear finite elements method (FEM) analysis is performed by using the software ABAQUS.

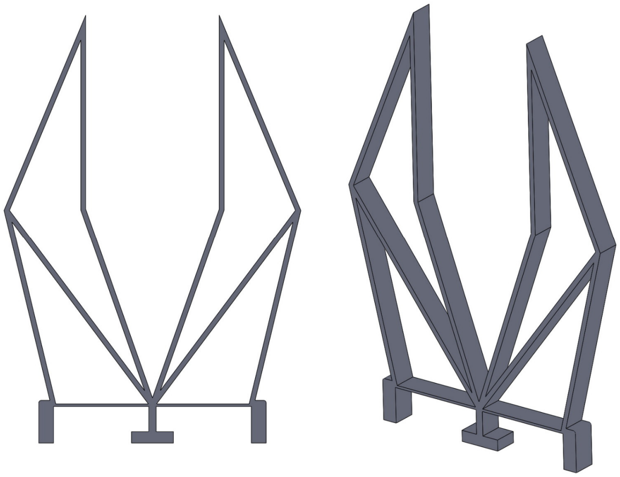

Fig. 3 CAD model of the monolithic compliant two-finger gripper

4.1 Deformation and motion behavior without object

To investigate the deformation and motion behavior of the gripper, a quasi-static structural 3D FEM simulation is performed. The FEM analysis set up is as follows: fixed supports are applied at the left and right part of the gripper frame (Fig. 4(a)), and an input displacement of 6.2 mm is applied at the face of the input port of the gripper (pulling direction) in order to simulate the full gripper actuation or closure (Fig. 4(a)). The material settings (e.g. *E*) are the same as for the case of the optimization (cf. Table 1). Furthermore, large (nonlinear) deflections are considered. The resulting deformation of the two-finger gripper is shown in Fig. 4(a), while the result for the von Mises stress distribution is shown in Fig. 4(b).

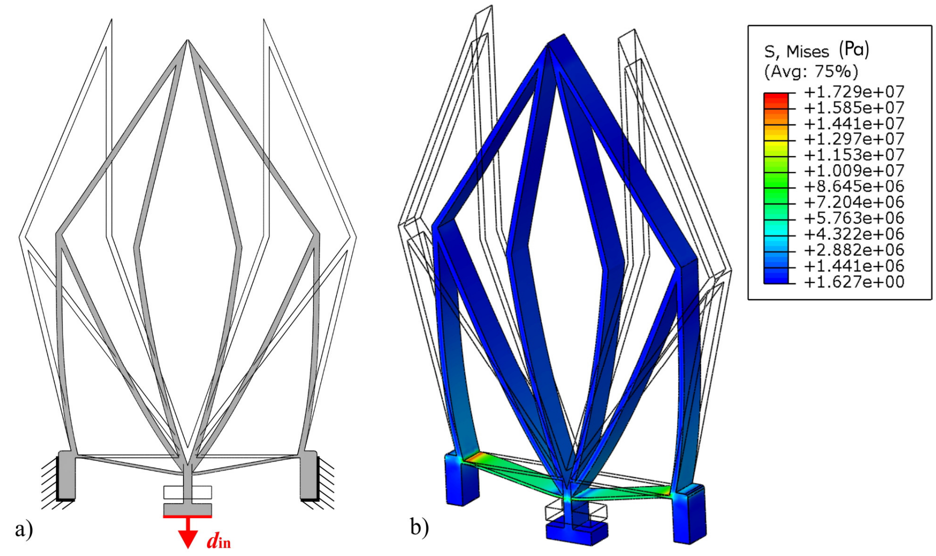

Fig. 4 FEM model and simulation of the compliant two-finger gripper for d_{in} = 6.2 mm: a) analysis set up and initial (white) and deformed (grey) state; b) von Mises stress distribution (stress values in Pa)

The output displacement that one gripper finger realizes at his tip without an object as well as the needed input force to realize closure actuation are shown in Fig. 5 with respect to the applied input displacement. Based on the FEM results it could be concluded that the relation of output to input displacement is linear, which means, that GA of the presented gripper is nearly constant with $t_{GA*} = 4.35$. This value also confirms the result from the optimization approach (cf. Table 2). The stresses induced by closure motion show a uniform distribution while the maximum value of 17.3 MPa is not critical at all.

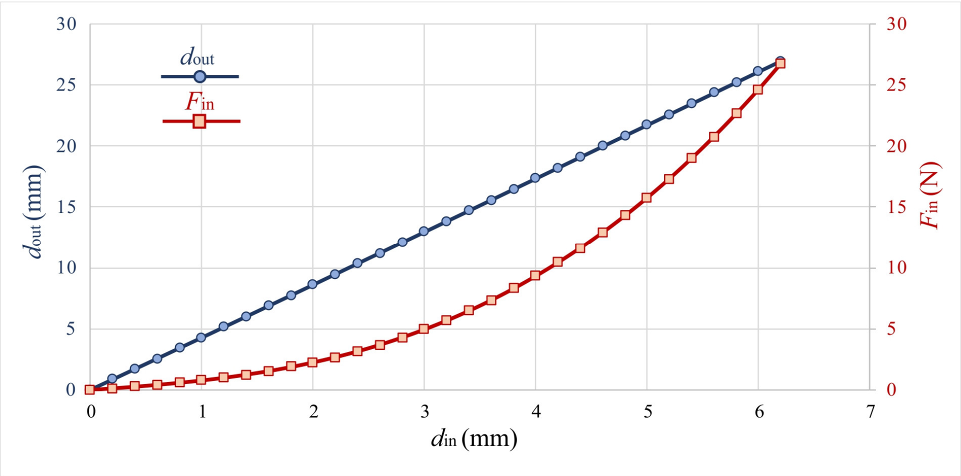

Fig. 5 FEM results of the two-finger gripper without object (cf. Fig. 4): needed input force and realized output displacement in dependence of the input displacement

4.2 Deformation and motion behavior in dependence of the gripped object

To further investigate the force transmission behavior and the MA value of the presented soft robotic gripper in dependence of the size and shape of an ideally stiff object that is gripped, different cases of grasping rectangular and cylindrical bodies (relatively large and small) are simulated (Fig. 6 and Fig. 7).

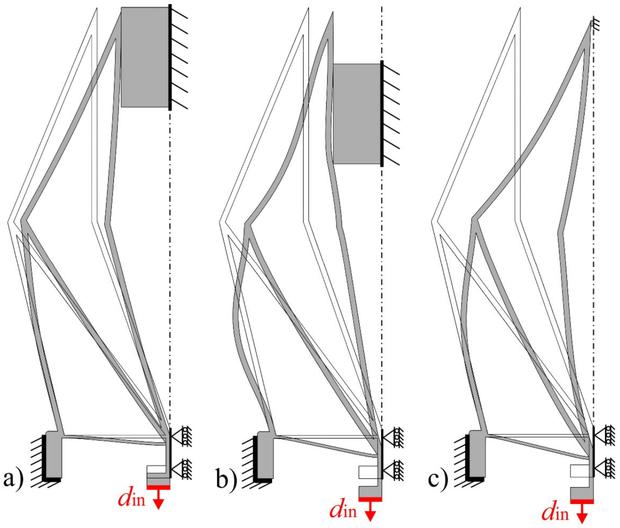

Fig. 6 FEM-based investigation of the deformation behavior and MA for the case when a rectangular object is gripped (one finger of the gripper is simulated for simplicity): a) large object near the tip (d_{in} = 2.7 mm); b) large object in the middle of the first part of the grasping surface (d_{in} = 7.3 mm); c) small object near the tip (d_{in} = 8.2 mm)

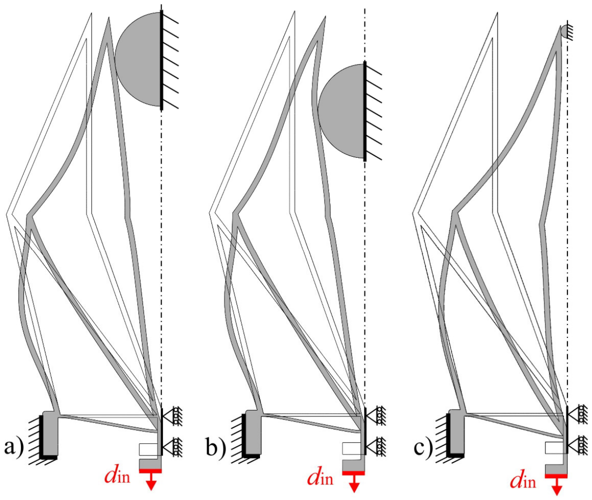

Fig. 7 FEM-based investigation of the deformation behavior and MA for the case when a cylindrical object is gripped (one finger of the gripper is simulated for simplicity): a) large object near the tip (d_{in}

= 5.9 mm); b) large object in the middle of a first part of the grasping surface (d_{in} = 6.6 mm); c) small object near the tip (d_{in} = 8.7 mm)

For the FEM analysis only one finger of the gripper with half object size is analyzed in order to be able to analyze reaction forces on the gripped object that are unequal to zero. Therefore, a symmetry boundary condition is applied at the symmetry axis part of the gripper and the object model. The contact pair between the first part of the finger grasping surface and the left object side surface is set as a rough contact as first approximation in order to reduce the numerical effort. A fixed support is applied at the gripper finger bottom frame and the maximum input displacement of $d_{in} = 10$ mm is defined in several convergence-dependent load-steps at the input port of the gripper finger, while the input force is read out. The stiff object is fixed too. For all the investigated cases the same FEM setup is used, while the object location (near the tip and in the middle of the first part of the gripper surface), object size (large and small) and object type (rectangular and cylindrical) are varied.

The force results (required input force and realized output force) and MA results for the different cases of gripped objects (cf. Fig. 6 and Fig. 7) are presented in Fig. 8 and Fig. 9 (the results and input displacement d_{in} are depicted for the whole gripping phase when each object is in contact with the gripper). For the case when a large rectangular object is gripped (object at the tip and middle position), the realized output force increases with an increasing input displacement (i.e. when input force increases), Fig. 8(a) and Fig. 8(b). This means that most of the applied input force is transmitted to the gripping object, while only small portion of force is spent on deformation/actuation of the gripper finger. For the case of a small rectangular object located at the tip, the realized output force increases incrementally small, although the input force increases, Fig. 8(c). This means that most of the applied input force is spent on deformation of the gripper finger, while only small portion is transmitted to the gripping object. These trends are also reflected in the results for the realized MA of the two-finger gripper (Fig. 9(a)). When a large rectangular object is gripped (located at the tip and middle), the realized MA increases significantly with increasing input displacement, while for the case of a small rectangular object (located at the tip), MA tends to drop due to a changing contact surface.

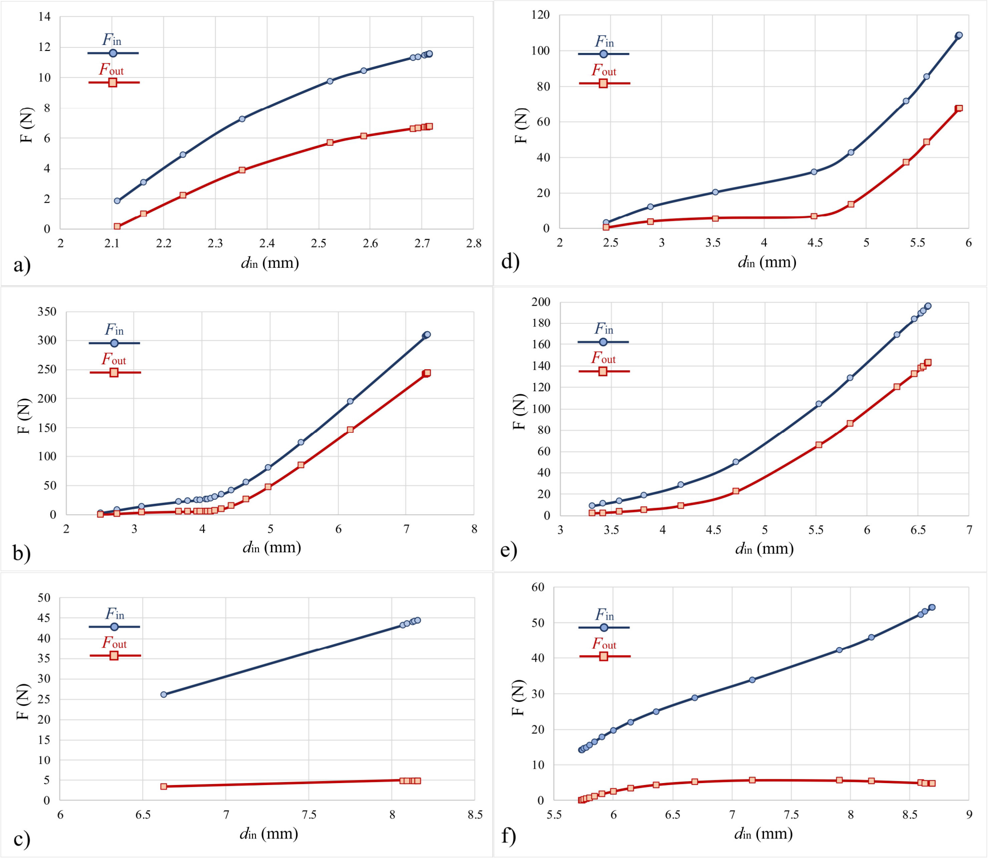

Fig. 8 FEM results for the input and output force of a gripper finger in dependence of the input displacement as well as the object size, shape and location (depicted for the phase when each object is in contact to be gripped): a) rectangular object (large) – tip; b) rectangular object (large) – middle; c) rectangular object (small) – tip; d) cylindrical object (large) – tip; e) cylindrical object (large) – middle; f) cylindrical object (small) – tip

A similar trend could be observed, when a cylindrical object is gripped. For the case of a large cylindrical object (located at the tip and middle), the required input force and the realized output force, increase significantly with increasing input displacement (Fig. 8(d) and Fig. 8(e)). This shows that large percentage of input force is transmitted to the griping object, while only small portion of the force is used to deform the gripper finger. In the case of a small cylindrical object (located at the tip), although the required input force increases, the realized output force increases very small, with the tendency to drop (Fig. 8(f)). This means that large percentage of the input force is used for gripper finger deformation, while only small portion of the force is transmitted to the object. The realized MA follow the similar trends as could be seen in Fig. 9(b). MA increases for the case of a large cylindrical object (at the tip and middle) and it increases first then starts to drop for the case of a small cylindrical object (at the tip).

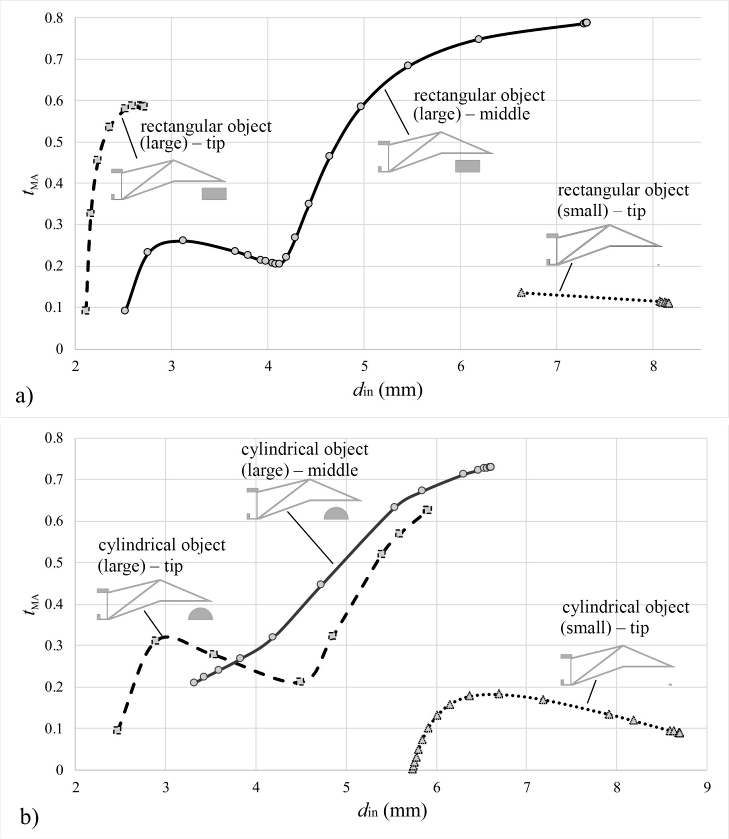

Fig. 9 FEM results for the mechanical advantage of the soft robotic gripper finger in dependence of the input displacement as well as the object size, shape and location: (a) when rectangular and (b) when cylindrical objects are gripped

4.3 Summarized gripper characteristics

Table 3 shows the summarized FEM results of the maximum realized MA value (t_{MAmax}) for the investigated cases with the corresponding results for the GA value (t_{GA}) as well as the maximum GA value (t_{GAmax}). Based on this, the following could be concluded:

- The MA values strongly depend on the size, form and location of the gripped object; which could be considered beneficial from adaptability point of view.
- The gripper realizes higher MA values at the middle of the grasping surface of a gripper finger (first vertical part), and smaller MA values at the fingertip; pointing that the MA values increases from the tip to the end of a finger gripping surface.

- Higher MA values are realized when larger objects are gripped; beneficial from adaptability point of view.
- The gripper realizes in average slightly larger MA values when cylindrical objects are gripped compared to rectangular objects.
- There is a difference between MA results obtained with shape optimization (Table 2) and MA investigated with FEM (Table 3). This is due to approximation that is used in the optimization. But still the results show that the solution obtained with shape optimization lead to a gripper that can realize even higher MA values.

In conclusion, the results show that unlike some existing grippers, e.g. [25], the presented novel soft robotic compliant two-finger gripper realizes:

- a generally high displacement transmission;
- a high force transmission due to much higher MA values while the corresponding GA values are also comparably high;
- reliable gripping due to very high absolute output force values and in most cases an increasing MA while the input displacement is increased too (with increasing input force, in general the output force increases as well which can be used advantageously to increase the gripping force on the object);
- universal gripping of objects with different size, shape and location (for the made assumptions).

Table 3 FEM results of the realized mechanical (Fig. 9) and geometrical advantage of the soft robotic compliant two-finger gripper with shape-optimal design based on Fig. 2(d)

Gripper characteristic	**Rectangular object**			**Cylindrical object**		
	Large		Small	Large		Small
	Tip	Middle	Tip	Tip	Middle	Tip
t_{MAmax}	0.58	0.78	0.13	0.62	0.72	0.18
t_{GA} (for t_{MAmax})	3.56	1.23	3.92	1.14	1.90	3.71
t_{GAmax}	4.30	4.30	4.35	4.30	4.30	4.35

5 PROTOTYPE AND TEST OF THE ADAPTIVE AND VERSATILE SOFT ROBOTIC GRIPPER

Based on the CAD model (cf. Fig. 3) a prototype is realized, and several different gripping and manipulation examples are tested in order to confirm its suitability and thus, to demonstrate the application potential for adaptive and universal soft robotic gripping and manipulation of various objects.

5.1 Prototype of the soft robotic two-finger gripper

The prototype of the monolithic two-finger gripper mechanism is exemplarily produced from a conventional plastic material (from the group of PE plastics) with mostly ideal linear properties (Fig. 10(a)). The typical value of the Yong's modulus is given in Table 1. The gripper bottom frame fits the used solenoid actuator, but in general it can be designed to fit any kind of desired linear actuation (e.g. pneumatic actuator, linear electromotor or some other type of actuators). To demonstrate the deformation behavior of the gripper mechanism, first the actuation is realized manually by pulling the gripper input port down (Fig. 10(a)).

The complete gripper prototype is realized by fixing a solenoid actuator to the gripper frame and fixing the actuator plunger at the gripper mechanism input port (Fig. 10(b)). A further connecting support is added in order to attach the gripper to a robotic arm. Furthermore, a thin anti-slip tape is fixed at the whole grasping surface of both gripper fingers in order to increase the friction between the gripper and objects, which is in accordance with the used rough contact in the FEM simulations. Then, the soft robotic gripper unit is attached to an industrial robotic arm (cf. Fig. 1(a)). To test the gripper deformation behavior without an object, an input power of 3.9 W is applied in order to realize the full stroke of the actuator of 10 mm (cf. Fig. 1(b)). The needed actuator power is determined experimentally by trial and error approach. After releasing the input force (power is off), the gripper acts as a spring and returns to its undeformed initial state due to the stored deformation energy. This is one main benefit of the presented gripper, that no force is needed to return both the gripper and the actuator in its initial position.

To verify the FEM results (Section 4.1), the realized input and output displacement of the gripper porotype is experimentally measured as well, i.e. the geometric advantage – GA of the gripper mechanism. The experiment is done by applying corresponding input power to the actuator in several steps, then simply measuring (image-based measuring) the realized actuator input displacement (at input port) and gripper finger output displacement at its tip. Fig. 11 shows the results of measurement in comparison with the FEM simulation results. A good agreement is achieved, which further proves the FEM model and investigations.

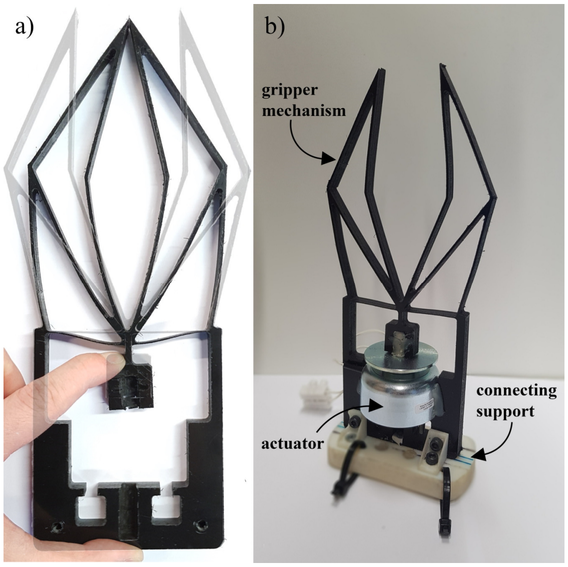

Fig. 10 Prototype of the simple, adaptive and versatile soft robotic compliant two-finger gripper: a) gripper in undeformed (transparent) and deformed state (solid black); b) assembly of the gripper unit with gripper mechanism, embodiment and solenoid actuator

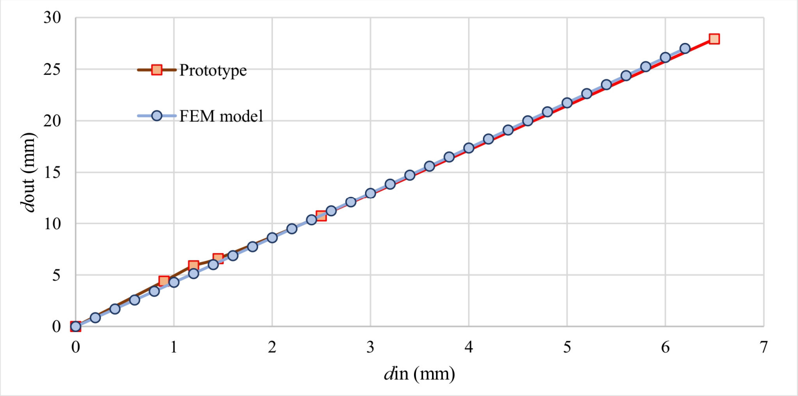

Fig. 11 Experimental investigation of the geometric advantage (GA) of the gripper prototype compared with results obtained with the FEM model

5.2 Gripping and manipulation examples

Different example objects are gripped to show the adaptability and universality of the developed soft robotic gripper (Fig. 12 and Fig. 13). The capabilities to realize adaptive griping of different relatively stiff objects and fragile objects, like a light bulb, are demonstrated. Beside this, special emphasize is on realizing griping of soft, delicate and easily squeezable objects, like fruits and vegetables, as well as at the same time objects with a wide variety in shape, size and weight.

Figure 12 shows examples of gripping fragile objects like light bulb, and different stiff objects like nut, plastic part, assembly of different parts, valve and tube elbow connector. The results show that when objects are located near the tip, the gripper can realize parallel grasping to some extent (e.g. Fig. 12(d)). While, when objects are located near the middle or end, the gripper fingers start to encompass the object realizing encompass/power grasp (e.g. Fig. 12(b)). In all tested cases with increasing actuator input power, gripper don't break or damage the objects but rather gripper fingers deform.

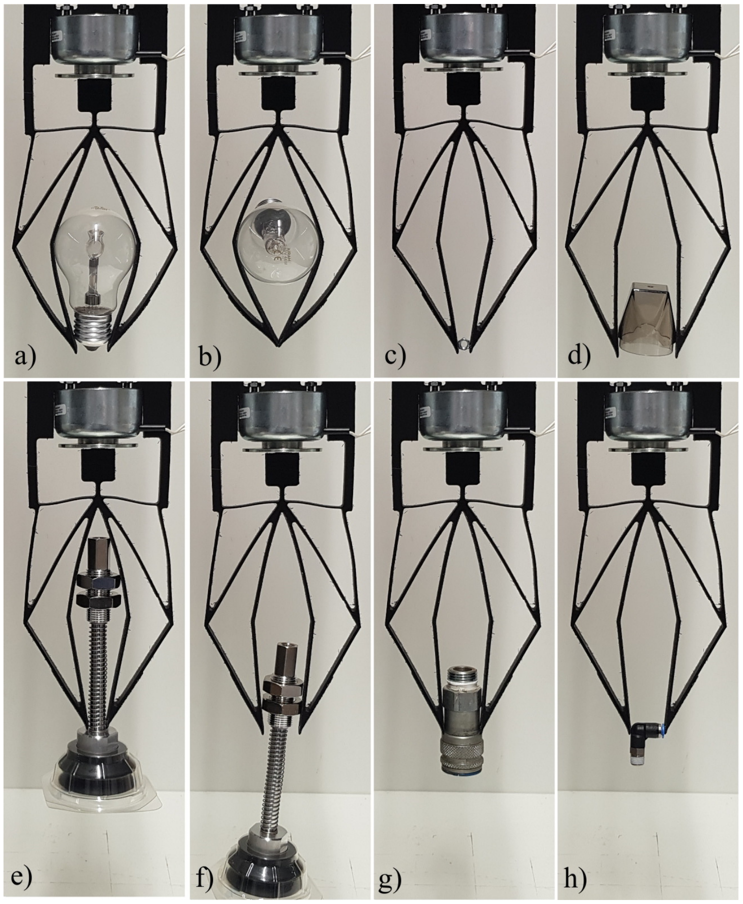

Fig. 12 Examples of gripping different fragile and stiff objects realized with different values of actuator input power: a) light bulb position upwards, b) light bulb, positioned perpendicular to gripper fingers near the middle; c) nut for bolt; d) plastic part; e) assembly of different parts, positioned near the end; f) assembly of different parts, positioned at the tip; g) valve; h) tube elbow connector

Figure 13 shows examples of gripping delicate food objects like raspberry, blueberry, strawberry, grape, cherry tomato and mushroom. The gripping is realized here only by on/off control of the solenoid actuator (no force/stroke control), i.e. by powering the actuator with the corresponding same value of the input power for all these investigated cases. Figure 14 shows further examples of gripping heavier food objects like a small and big paprika, tomato, egg, chocolate praline, kiwi, apple and banana, where the actuator input power is different for most of the gripped objects (as the object weight varies significantly). Figure 15 shows dimensions (width) and weight of objects used in the food gripping examples compared with the applied actuator power.

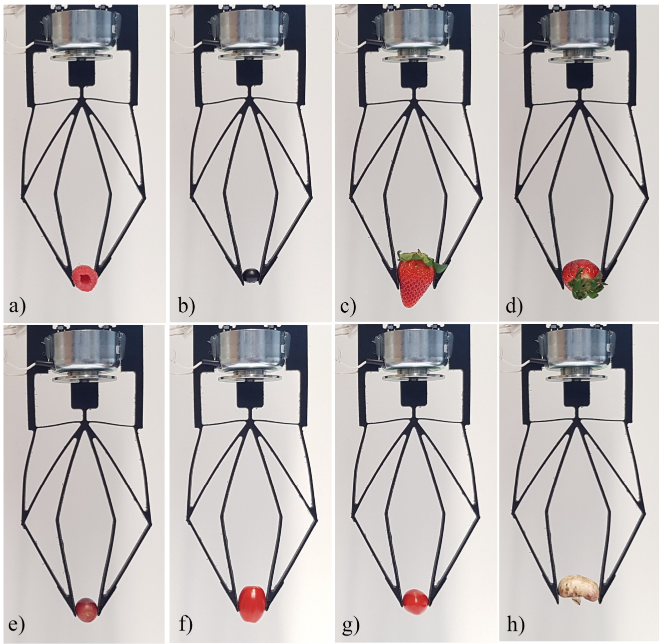

Fig. 13 Examples of gripping different delicate food objects like fruits and vegetables with the same value of actuator input power: a) raspberry (3.8 g); b) blueberry (1.6 g); c) strawberry (16.2 g); d) strawberry with different orientation; e) bean of grape (5.0 g); f) cherry tomato (7.9 g); g) cherry tomato with different orientation; h) mushroom (4.5 g)

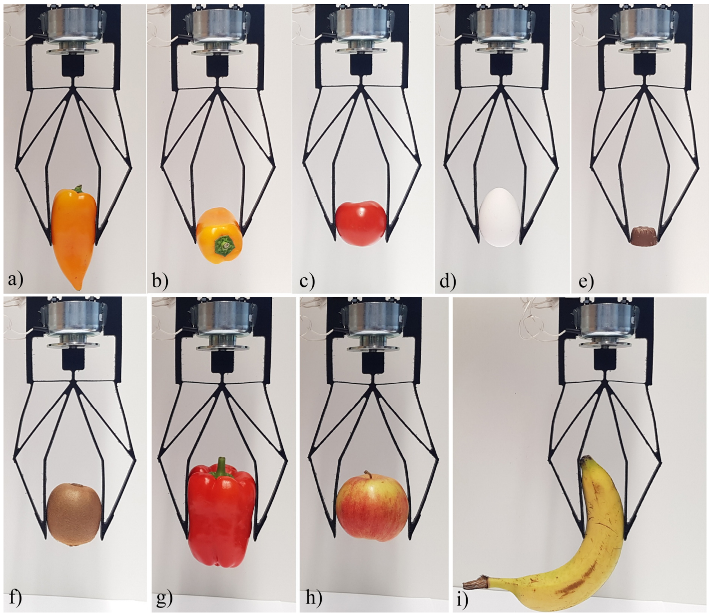

Fig. 14 Examples of gripping various food objects with different values of actuator input power: a) paprika (13.4 g); b) paprika with different orientation; c) tomato (66.2 g); d) raw egg (52.1 g); e) chocolate praline (9.6 g); f) kiwi (86.4 g); g) big paprika (131.2 g); h) apple (152.7 g); i) banana (160.0 g)

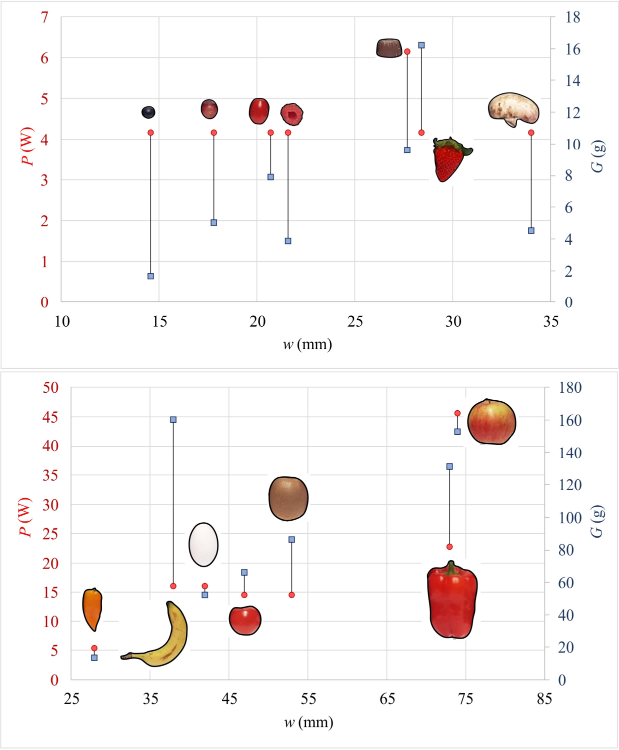

Fig. 15 Object width *w* and weight *G* of objects used in the food gripping tests (cf. Fig. 13 and Fig. 14) compared with the applied actuator power *P*

Based on the test examples it could be concluded that the developed soft robotic two-finger gripper simply realizes adaptive and versatile grasping of objects with different size, shape, stiffness and weight. It is important to mention, that the grasping is reliable, safe and fast (30 ms to 120 ms depending on the object size) without damaging the delicate objects in all tested cases.

Furthermore, Fig. 16 shows a test of heavier object weight gripping and lifting. Therefore, a filled bottle with 500 ml is gripped at first, which corresponds to a weight of 520 g (and width of 40 mm). To further increase the weight, a cylindrical shaped object is gripped and lifted (diameter of 30 mm), at which two filled bottes with 500 ml are attached, which corresponds to a weight of 1.08 kg. In both cases, the grasping was reliable and repeatable.

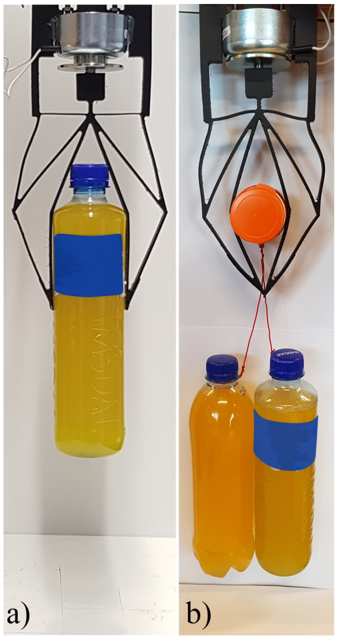

Fig. 16 Testing the weight for gripping and lifting of heavier objects: a) filled bottle (520 g); b) cylindrical object with two attached filled bottles (1.08 kg)

To further demonstrate the possibilities of reliable grasping in dependence of the gripper orientation and spatial motion, the robotic arm is programmed to perform manipulation in space with gripped objects at comparable high handling velocities of 2.2 m/s within a small total manipulation time of 5.8 and 7.5 seconds (including several handling operations). Figure 17 and Fig. 18 depict the position of the robotic arm in space in different time intervals, here illustrated when a raspberry and a raw egg are gripped. The tests are done with most of the objects depicted in Fig. 13 and Fig. 14, and the results show that reliable and safe grasping and manipulation is realized too.

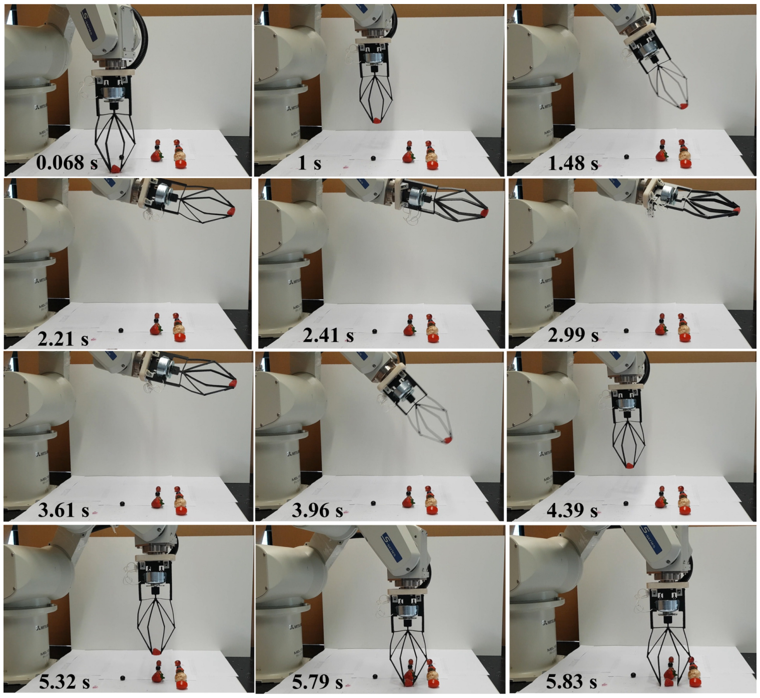

Fig. 17 Manipulation in space when a very soft object (raspberry) is gripped (pictures show different intervals of time)

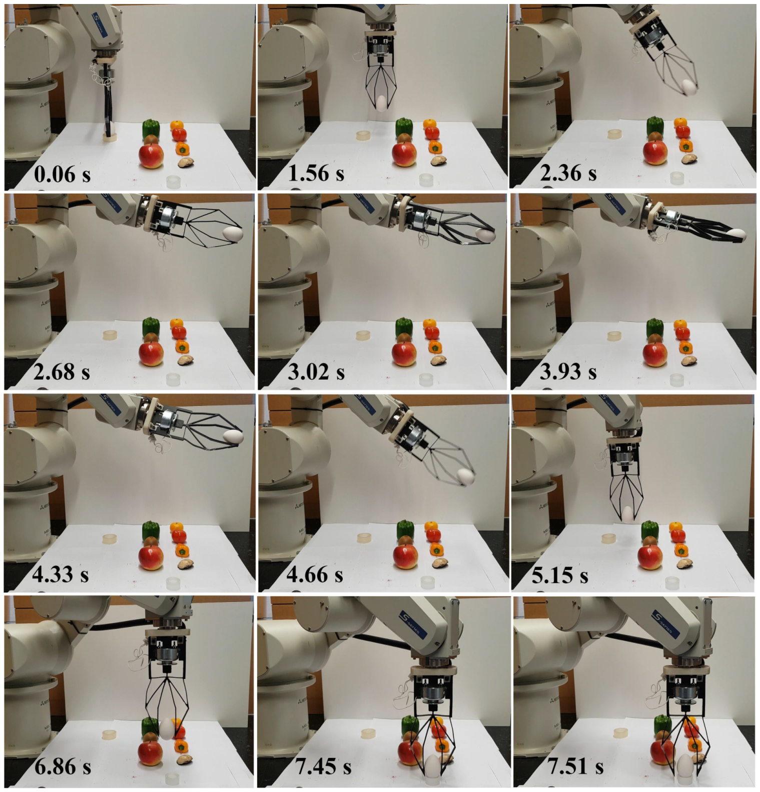

Fig. 18 Manipulation in space when a delicate object (raw egg) is gripped (pictures show different intervals of time)

6 DISCUSSION

A novel simple, adaptive and versatile soft robotic two-finger gripper is reported which is based on compliant mechanisms with distributed compliance. The basic mechanism design for one gripper finger is obtained through an optimization-based synthesis process. The gripper finger mechanism realizes a good trade of between MA and GA during the process of gripping different objects. Based on this, a complete two-finger gripper is designed and investigated by means of a geometrically nonlinear FEM simulation. The FEM results for different cases of gripping rectangular and cylindrical shaped objects with different size (small and big) show that the gripper realizes comparable high MA and GA values. Simultaneously, the output forces and MA values increase with the input displacement and input force. Furthermore, it is shown that the MA value of a compliant gripper mechanism generally depends on the object location within the gripping surface as well as the shape and size of the gripped object. However, this can be used advantageously regarding a high adaptability of the novel gripper solution.

Moreover, different tests with a realized prototype of the soft robotic compliant two-finger gripper made from plastic material are done in combination with a conventional solenoid actuator. The grasping is exemplified with various stiff, soft, delicate and easily squeezable objects, like fruits, berries and vegetables. It is shown that adaptive and very fast grasping is possible with a simple and compact gripper without the need for controlling the actuator stroke or force for different objects of comparable weight. This can significantly reduce the effort to realize universal and adaptive gripping of various different objects. Thus, the two-finger gripper represents a simple soft robotic gripping concept with only on/off control, while the actuator tends to realize its full stroke or holding force.

Table 4 shows a comparison of the soft robotic compliant two-finger gripper, developed in this paper, and the few other compliant mechanism-based grippers available in the literature. Resultingly, the novel gripper has several advantages over competing designs, especially when the GA, MA, adaptability, universality, and speed of grasping are taken into consideration as important gripping criteria. In general, significantly higher MA and GA values are realized at the same time compared to existing compliant gripper mechanisms, e.g. [25], [35], [83], [88]. Moreover, the speed of gripping is in average x50 times faster than in reported solutions.

Table 4 Comparison of the developed novel soft robotic gripper with other compliant-based grippers in the literature (*values are estimated based on the data provided in the corresponding reference)

References Parameters	Liu et. al., 2019, [25]	Chen et. al., 2018, [35]	Liu et. al., 2018, [83]	Liu et. al., 2018, [88], Gripper-B	Liu et. al., 2018, [88], Gripper-C	Devel. novel soft robotic Gripper
GA	2.6	0.57	1.41	3.53	1.8*	4.3
MA	0.28	Not reported	0.26 – 0.52	0.2*	0.19*	0.13 – 0.78
Speed of grasping	Slow*	6000 ms	6200 ms	Slow*	Slow*	30-120 ms
Soft fruit and vegetable handling	Not realized	Not realized	Not realized	Not realized	Not realized	Realized
On/off control possibility	No	No	No	No	No	Yes
Adaptability	Moderate	Moderate	Moderate	Moderate	Moderate	High
Precision of object positioning (pick and place)	Not reported. (low*)	Not reported (low*)	Not reported (low*)	Not reported (low*)	Not reported (low*)	High
Material	Silicone rubber	Termoplastic elastomer, TPE	Termoplastic elastomer by Bot-Feeder	Silicone rubber	Silicone rubber	PE plastic
Out-of-plane stiffn.	Moderate	Low	Moderate	Low	Low	High
Input drive direction	Push	Pull	Push	Push	Push	Pull
Required input force	43 N*	Not reported	64 N *	Not reported	Not reported	~ 26 N
Input displacement for full closure	30 mm	Not reported	50 mm	15 mm	15 mm	6.2 mm
Out-of-plane thickness	20 mm	~30 mm	20 mm	10 mm	10 mm	10 mm
Payload	2.5 kg	1 kg	2.1 kg	~18 g	Not reported	1.08 kg
Gripper volume	Large	Moderate	Large	Small	Moderate	Small
Actuation	Massive linear motor	Linear motor, cable-driven	Massive linear motor	Linear motor	Linear motor	Solenoid actuator
Miniaturization potential	Moderate	Low	Moderate	Moderate	Moderate	High
Actuator/input control	Displacement regulated	Motor current regulated	Displacement regulated	Displacement regulated	Displacement regulated	Electrical power
Parallel and encompass grasping	Not reported	Not reported, not possible*	Not reported	Not reported	Not reported	Yes
Hyperplastic and viscose effects	Yes	Yes	Yes	Yes	Yes	No
Finger actuation	Two fingers with one drive	Three fingers, each with one motor	Two fingers with one drive	Two fingers with one drive	Two fingers with one drive	Two fingers with one drive
Assembly	Complicated	Complicated	Complicated	Moderate	Moderate	Simple
Returning gripper to initial state	By using actuator	By using actuator	By using actuator	By using actuator	By using actuator	By inherent restoring force
Support	Gripper mid-point	Gripper frame	Gripper mid-point	Gripper mid-point	Gripper mid-point	Gripper frame
Overall gripper size with actuator	~300 mm	~200 mm	~300 mm	~140 mm	~140 mm	260 mm
Monolithic concept	Yes	No (fingers separated)	No (fingers separated)	Yes	Yes	Yes
Possibility of full closure of gripper	Yes	No	Yes	Yes	Yes	Yes

Beside mentioned, other advantages include: handling very soft fruits and vegetables, on/off control, high precision of object positioning, parallel and encompass grasping, simple assembly (only two parts), high miniaturization, relatively small input force/energy is needed to actuate the gripper, returning gripper to initial state realized by inherent restoring force of the mechanism, inherently genital touch, which are not possible or not reported with some of the existing compliant gripper solutions (Table 4).

The inherently gentle touch is possible due to the optimized elastic structure of the compliant gripper mechanism coupled with the solenoid actuator. In this context, the results for the gripping cases in Fig. 13 are of special interest, where gripping is realized with the same input power, and the object dimensions, shape, stiffness and weight vary. This is possible due to the inherent actuator characteristics with respect to the nonlinear dependence between the actuator stroke and the realized holding forces, considering that the compliant gripper mechanism represents an elastic structure with the typical characteristics analyzed in Section 4 (with different MA values along the grasping surface, which depend on the object shape/dimensions as well). Furthermore, easily squeezable objects like berries are not damaged due to the high "sensibility" of the compliant mechanism structure and the ability to "detect" even the smallest restoring forces while an object is gripped. Moreover, with increased input stroke/force, the gripper adapts to the object shape for most of the gripped objects that are stiffer than the gripper. This shows that stable grasping of stiff objects can be realized as well.

In conclusion, fast and reliable grasping of a wide range of example objects with different shape, size, stiffness and weight is demonstrated. Additionally, it is shown that reliable manipulation in space is possible under high manipulation speeds (not possible or not reported with other existing gripping solutions, Table 4). Based on the results, the characteristics and gripping performance of the developed compliant two-finger gripper are summarized in Table 5.

The results show that the novel gripper is simple, adaptive and versatile and has various further benefits in comparison to the already existing actuation principles (see Section 2 – Related work): like a monolithic structure with only a few parts, large possible deformations due to freeness of stress concentration, a good payload to weight ratio (the gripper can lift objects that are more than 18 times heavier than the two-finger gripper mechanism itself), smaller values of inertia of moved masses and a central actuator position, precise and fast griping and positioning objects to end-position, no need for control algorithms, and a high potential for miniaturization.

Table 5 Characteristics of the novel simple, adaptive and versatile soft robotic gripper prototype

Characteristics	**Value**
Gripper overall dimensions (without actuator) – *w* x *h*	120 x 155 mm
Gripper overall dimensions (with actuator) – *w* x *h*	120 x 260 mm
Gripper initial opening distance	54 mm
Weight of the two-finger gripper without actuator	54 g
Weight of the actuator	609.5 g
Actuator maximum stroke	10 mm
Actuator maximum force	218 N
Minimum weight of the gripped object	1.6 g
Maximum weight of the gripped object	1.08 kg
Minimum dimension of the gripped object (width)	12.7 mm
Maximum dimension of the gripped object (width)	73 mm
Gripping speed/time range (depending on object size)	30 ms – 120 ms

7 CONCLUSIONS

Developing universal and adaptive robotic end-effectors, in particular the gripper technology, is a very relevant, actual and challenging task, for which manifold, mostly complex gripper solutions exist. This paper presents a novel design approach and a prototype of a simple soft robotic compliant two-finger gripper with an inherently gentle touch realized by utilizing an optimally synthesized compliant mechanism in combination with only one conventional linear actuator.

Regarding reliable grasping, it is shown by FEM simulations that the gripper realizes a comparable high force and motion transmission at once, while the values of the mechanical and geometrical advantage depend on the size, shape and location of the gripped object. Furthermore, it is demonstrated by tests with an implemented gripper prototype that safe, fast, and precise grasping and manipulation are possible for a wide range of objects with different size, shape, stiffness and weight. The gripper can grasp and manipulate nearly any object with a weight ranging from 1 g to 1 kg. For a certain group of objects with different size and stiffness but with a comparable weight, the gripping can be realized without the need of sensors and even with only a simple on/off control. When the object weight varies significantly, the gripping can be still realized without sensors, but with a predefined setting of the specific actuator input power that would be enough for the gripper to lift the object, which simplifies the needed control algorithms. Thus, general (e.g. big, regular and stiff objects) and specific gripping tasks (e.g. small, irregular, soft and easily squeezable objects) can be solved with only one monolithic and compact two-finger gripper, which can be well miniaturized as well.

The gripper concept represents a promising solution for realizing versatile and adaptive soft robotic gripping of different objects, especially objects that are hard to grasp, like fruits, berries and vegetables. The presented compliant two-finger gripper may provide lots of benefits in agriculture, food or pharmaceutical industry and brings robots to places where they are previously considered hard or not possible to be applied. Moreover, the gripper is a good starting point for further research and development with the hope to get closer to human grasping capabilities and dexterity with simple, low-cost and all-in-one gripper designs.

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DECLARATION OF CONFLICTING INTERESTS

The Authors declare that there is potential conflict of interests relating to patent applications in relation to this research. A. Milojević, S. Linß, and H. Handroos have a patent Adaptive Gripper Finger, Gripper Device and Method of Using Adaptive Gripper Device accepted.

NOMENCLATURE

d_{in}	input displacement, mm
d_{out}	output displacement, mm
$d_{\text{out}}^{\text{min}}$	minimal desired output displacement, mm
$d_{\text{out}}^{\perp}$	output displacement in direction perpendicular to desired direction of motion, mm
E	Young's modulus, N/mm^2
F_{in}	input force, N
F_{out}	output force, N
G	weight of objects, g
P	actuator power, W
t_{GA}	ratio of realized output displacement to applied input displacement (geometrical advantage, springs included)
t_{MA}	ratio of realized output force to applied input force (mechanical advantage, springs included)
$t_{\text{GA*}}$	ratio of realized output displacement to applied input displacement (geometrical advantage, no springs)
GA	geometrical advantage
MA	mechanical advantage

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Figure Captions List

Fig. 1	Simple, adaptive and versatile soft robotic compliant two-finger gripper: a) mounted on an industrial robot arm; b) shown in unactuated/opened state (transparent color) and actuated/closed state (solid black color)
Fig. 2	Shape optimization of the compliant gripper finger mechanism: a) initial design and problem definition; b) parametrization; c) optimization by node wandering approach within the dotted area (springs are removed for clarity); d) optimal design of the gripper finger (without springs)
Fig. 3	CAD model of the monolithic compliant two-finger gripper
Fig. 4	FEM model and simulation of the compliant two-finger gripper for d_{in} = 6.2 mm: a) analysis set up and initial (white) and deformed (grey) state; b) von Mises stress distribution (stress values in Pa)
Fig. 5	FEM results of the two-finger gripper without object (cf. Fig. 4): needed input force and realized output displacement in dependence of the input displacement
Fig. 6	FEM-based investigation of the deformation behavior and MA for the case when a rectangular object is gripped (one finger of the gripper is simulated for simplicity): a) large object near the tip (din = 2.7 mm); b) large object in the middle of the first part of the grasping surface (din = 7.3 mm); c) small object near the tip (din = 8.2 mm)
Fig. 7	FEM-based investigation of the deformation behavior and MA for the case when a cylindrical object is gripped (one finger of the gripper is simulated for simplicity): a) large object near the tip (din = 5.9 mm); b) large object in the middle of a first part of the grasping surface (din = 6.6 mm); c) small object near the tip (din = 8.7 mm)
Fig. 8	FEM results for the input and output force of a gripper finger in dependence of the input displacement as well as the object size, shape and location (depicted for the phase when each object is in contact to be gripped): a) rectangular object (large) – tip; b) rectangular object (large) – middle; c) rectangular object (small) – tip; d) cylindrical object (large) – tip; e) cylindrical object (large) – middle; f) cylindrical object (small) – tip
Fig. 9	FEM results for the mechanical advantage of the soft robotic gripper finger in dependence of the input displacement as well as the object size, shape and location: (a) when rectangular and (b) when cylindrical objects are gripped
Fig. 10	Prototype of the simple, adaptive and versatile soft robotic compliant two-finger gripper: a) gripper in undeformed (transparent) and deformed state (solid black); b) assembly of the gripper unit with gripper mechanism, embodiment and solenoid actuator
Fig. 11	Experimental investigation of the gripper prototype geometric advantage (GA), compared with results obtained with FEM model
Fig. 12	Examples of gripping different fragile and stiff objects realized with different values of actuator input power: a) light bulb position upwards, b) light bulb, positioned perpendicular to gripper fingers near the middle; c) nut for bolt; d) plastic part; e) assembly of different parts, positioned near the end; f) assembly of different parts, positioned at the tip; g) valve; h) tube elbow connector
Fig. 13	Examples of gripping different delicate food objects like fruits and vegetables with the same value of actuator input power: a) raspberry (3.8 g); b) blueberry (1.6 g); c) strawberry (16.2 g); d) strawberry with different orientation; e) bean of grape (5.0 g); f) cherry tomato

	(7.9 g); g) cherry tomato with different orientation; h) mushroom (4.5 g)
Fig. 14	Examples of gripping various food objects with different values of actuator input power: a) paprika (13.4 g); b) paprika with different orientation; c) tomato (66.2 g); d) raw egg (52.1 g); e) chocolate praline (9.6 g); f) kiwi (86.4 g); g) big paprika (131.2 g); h) apple (152.7 g); i) banana (160.0 g)
Fig. 15	Object width w and weight G of objects used in the food gripping tests (cf. Fig. 13 and Fig. 14) compared with the applied actuator power P
Fig. 16	Testing the gripping and lifting of heavier objects weight: a) filled bottle (520 g); b) cylindrical object with two attached filled bottles (1.08 kg)
Fig. 17	Manipulation in space when a very soft object (raspberry) is gripped (pictures show different intervals of time)
Fig. 18	Manipulation in space when a delicate object (raw egg) is gripped (pictures show different intervals of time)

Table Caption List