Advances in soft grasping in agriculture

Advances in agri-food robotics

Leylavi Shoushtari, Ali

https://doi.org/10.19103/AS.2023.0124.10

Chapter 12

Advances in soft grasping in agriculture

Ali Leylavi Shoushtari, Wageningen University & Research and Wageningen Robotics, The Netherlands

1 Introduction

Despite remarkable progress in agri-food robotics, no commercially available autonomous harvesters have been developed to date due to gaps in scientific and technological knowledge (Adamides and Edan, 2023; Bac et al., 2014; Droukas et al., 2023; Kumar and Mohan, 2022; Martin et al., 2022; Wang et al., 2022). In the process of automating agricultural tasks, robotic technologies face a wide variety of challenges. From a robotics point of view, these challenges can be classified as follows:

- Challenges of perception; and
- Challenges of action (CoA).

The core of the perception challenge is to comprehend, reason, and make sense of the unknown and cluttered environment surrounding the robot, e.g. on arable farms and in greenhouses. The challenges of action (CoA) concern agile maneuvering in and physically interacting with an unstructured environment characterized by high diversity and uncertainty. From a robotics point of view, the former class of challenges is formulated as computer vision

http://dx.doi.org/10.19103/AS.2023.0124.10

and artificial intelligence (AI) problems, while the latter is framed as a set of manipulation, grasping, and navigation problems. Six decades of research have enabled computer vision and AI (Szeliski, 2011) to be applied to agricultural tasks, while robotic grasping, manipulation, and navigation require further research.

Conventional robots are usually made up of rigid materials that limit their ability to adapt to objects and obstacles. The physical interaction of robots with their environment is inevitable, whether in locomotion or manipulation, or even in the form of collision, potentially making rigid robots unsafe. Adaptability and safety, in particular, are limiting factors for rigid robots, especially when implemented in a real-world scenario and in an unstructured environment with high diversity and uncertainty, as is the case in agriculture. Furthermore, maintaining the quality of often delicate products that robotic systems handle in agricultural tasks is a particular challenge. For this reason harvesting using rigid robots (in this case with rigid grippers) has not seemed a feasible option.

Soft robots can be defined as robots and machines that are 'primarily composed of easily deformable matter such as fluids, gels, and elastomers that match the elastic and rheological properties of biological tissue and organs' (Majidi, 2014). There are machines and robots made of materials that have much less elasticity than elastomers but which can still provide large deformations due to their particular geometry. Compliant mechanisms are an example of this group of robots or mechanisms (Howell et al., 2013). The change in material used from one that is rigid to a deformable and stretchable material provides robots and machines with an adaptable shape and a locomotion (Ansari et al., 2015) or manipulation strategy for a broad range of tasks and environments (Majidi, 2014).

Soft robotics is a relatively new yet promising field of research aimed at enhancing robot safety and adaptability while maintaining simplicity and affordability. In agricultural robotics, crops are generally vulnerable and delicate, have high variation (i.e. different shapes, sizes, surface textures and roughness, and softness), and are often affected by environmental conditions such as moisture and dust, which makes them challenging to handle using conventional rigid robots. Soft robotics can significantly contribute to robot versatility, making it an ideal solution for agricultural robotic challenges. This chapter aims to understand how and to what extent soft robotics can enhance the versatility of robots, especially in grasping and manipulation.

Section 1 focuses on the types of challenges that any robotic system would face in agricultural tasks. The chapter then reviews how soft robotics can help deal with these challenges. The chapter includes a case study which, in a nutshell, shows how soft agricultural robotic research is carried out. The chapter concludes with a summary and a short list of sources of further information about agricultural robotics, including review papers and open-source websites.

2 Challenges of action in agricultural robotics

The challenges of action (CoA) in agricultural robots are as follows:

- High diversity in agricultural products: Products all have different pose (position and orientation), shape, size, mechanical properties (structural stiffness), and surface properties, i.e. roughness and adhesion of crops.
- Diversity between different crop variants: Even crops that genetically belong to the same family can have different variants with quite diverse shapes and sizes. For example, cucurbit crops can have several variants, including cucumber, melon, watermelon, and squash, which have completely different shapes and sizes (Fig. 1a–d).
- Diversity within a crop variant (inherent diversity): Although crops within a variant look similar, they are not identical. This diversity is also time-dependent and dynamic. Figure 2a shows the diversity in shape and

Figure 1 The high diversity of shape and size of cucurbit crops. Panels a to d depict the diversity within different cucurbit variants, i.e. cucumber, melon, watermelon, and squash. Source: This figure is taken directly from Pan et al. (2020).

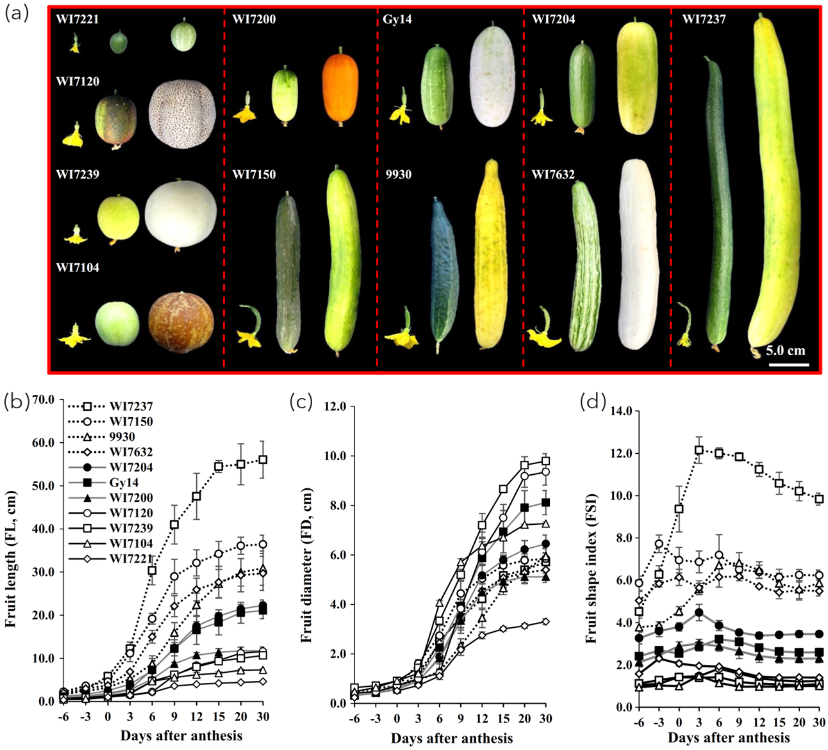


Figure 2 Growing dynamics of cucumbers with different genetic backgrounds. (a) Images of ovary and fruit of 11 cucumbers depicting the dynamics of growth at 0, 12, and 30 days after pollination. (b–d) The quantifications of size and shape dynamics, respectively. Source: This figure is taken directly from Pan et al. (2020).

size of 11 different variants of cucurbits. The quantified dynamics of size and shape variation can be seen in Fig. 2b, 2c and 2d, respectively.

- Safety/quality requirements in the handling of crops: Crops are commercial products and their quality should be maintained by the machines that interact with them. This means that robots are required to satisfy a high level of safety and quality during crop management and harvesting.
- Task complexity: Agricultural tasks are multifaceted. Harvesting requires not only grasping objects but also detaching and holding them robustly while dealing with dynamic perturbances during manipulation. This challenge requires robots (i.e. grippers) to be able to deal with a high variation in force and torque.
- Dense vegetation environments: Agricultural environments typically challenge the maneuverability of robotic systems. A bulky robot will not be agile and maneuverable enough to carry out its task within an

economically feasible amount of time while avoiding collisions with plants and other objects.

The following sections discuss ways of accounting for these challenges both in assessing the current range of soft gripper designs and in developing improved and more versatile future designs.

3 How soft robotics can address challenges of action

Soft robotics is a relatively new field of research aimed at making robots safer and more adaptive. High adaptability is useful, particularly for robotic grasping where robots are required to conform to objects with high variations (challenge 1). Moreover, when the objects to be handled are delicate/fragile, then safety (in handling) is also an important requirement (challenge 2). This means that safety and adaptability are the main requirements of agri-food robotics that increase demand for use of soft grippers.

During the last three decades, a large number of soft robotic grippers have been designed and developed for crop harvesting and handling (Fig. 3), mainly focused on the two challenges already listed. Meanwhile, two further challenges (challenges 3 and 4) need to be overcome in order for a soft gripper to be suitable for agricultural tasks such as greenhouse harvesting. Despite their high adaptability, most soft grippers are not strong enough to handle objects of various weights and are unable to deal dynamically with perturbations in load during harvesting (challenge 3). Although some soft grippers have sufficient strength to deal with variable loads, this strength is usually high along the axis of the gripper, while it is low along other axes, which make the gripper flexible along those axes.

Looking at Fig. 4b as a schematic representation of the strength of soft grippers, generally the gripper has high strength along the *y* axis and is adaptive under lateral forces applied along the *x* and *z* axis. A versatile robotic gripper in agriculture is required to be able to exert sufficient torque and force on crops in order to hold, detach, and manipulate them. Figure 4a shows such requirements for a manual harvesting process. Rigid grippers in slippage-free cases are more successful at applying such force and torque since their rigid links or bodies can endure the forces received during physical interaction with objects. Most soft grippers tend to stiffen in just one direction or plane (i.e. the plane in which the bending happens) and lacks the supporting stiffness in other directions or planes. As a result, their strength is maximized only in the bending direction or plane and minimized in the other planes. Soft grippers, therefore, bend once they undergo lateral loads and stress induced by object weight or during pulling, flicking, twisting, bending or accelerating, and deaccelerating. Figure 4b provides a schematic representation of the heterogeneous strength

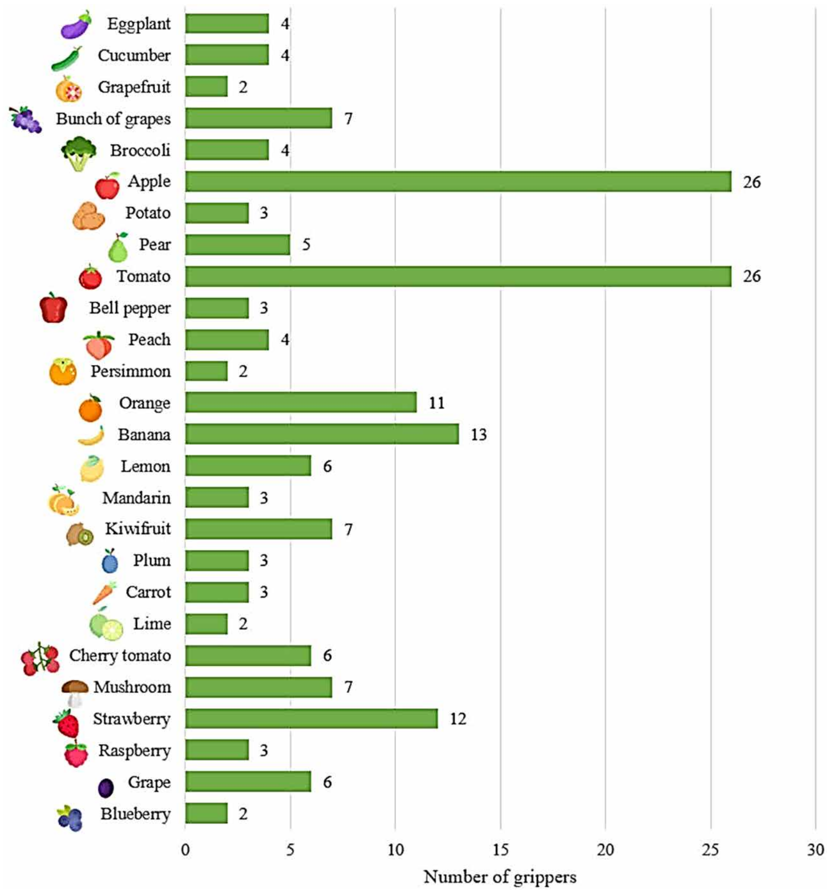


Figure 3 Number of soft grippers used to harvest various crops. Source: Adapted from: Elfferich et al. (2022).

of soft grippers in which the strength is maximized only along the grasping direction, i.e. Y in this example.

The abovementioned issue with soft grippers has been addressed in a recent study (Fig. 4c) in which researchers added an adaptive rigid bar mechanism to the soft fingers to limit the lateral bending of the finger and as a result obtained higher strength in the bending direction (Zhu et al., 2023). However, although these types of solutions have significantly increased the strength of soft grippers, they have also made them larger and heavier due to the size and weight of components (i.e. mechanical mechanisms and their actuators) added to the soft gripper. In contrast, challenge 4 demands thin and lightweight robotic grippers. Although ultra-thin, high-strength, and even

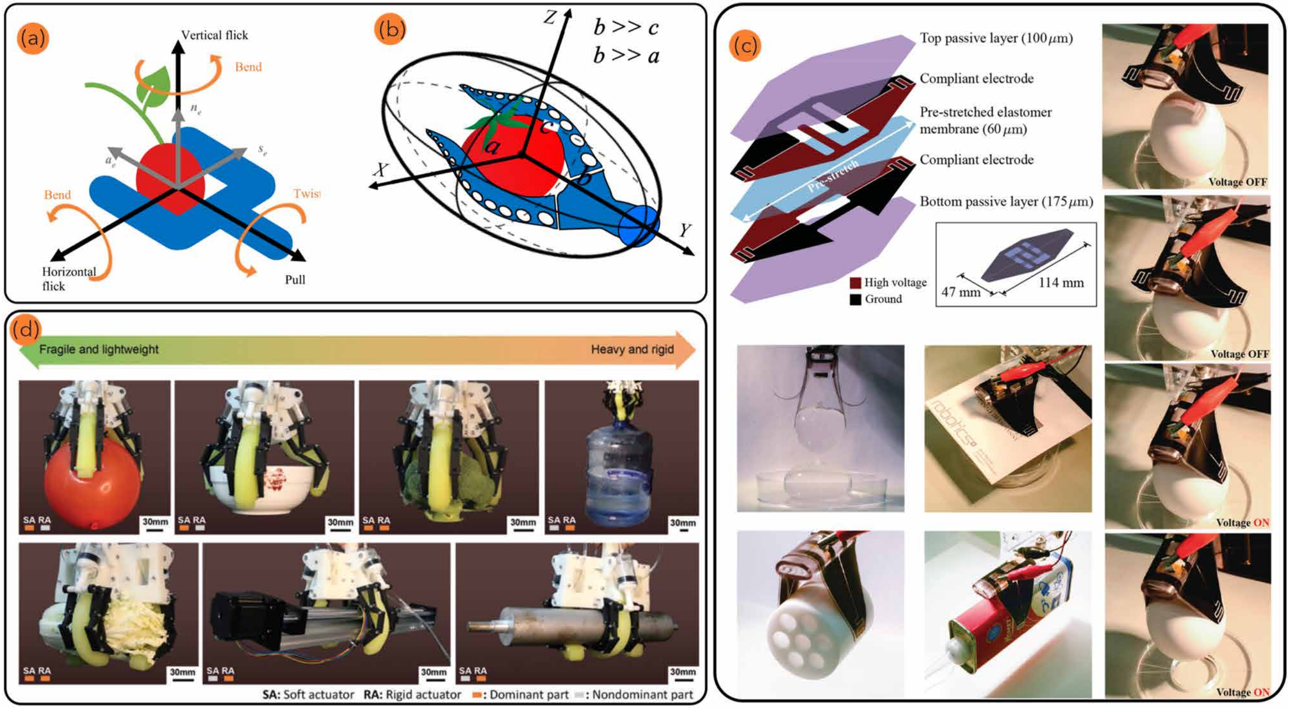


Figure 4 (a) Different ways of detaching crops from peduncle. [adapted from Elfferich et al. (2022)]. (b) Hypothetical ellipsoid of the strength of a soft gripper where a, b, and c represent the strength of the gripper in three different directions. The maximum strength is always in the direction of the bending (Y). (d) An example of a soft gripper that can apply grasping force in one direction when it would bend under lateral loads. (c) A soft gripper that is mechanically supported with the rigid bar mechanisms in order to deal with the lateral forces. Source: Figures (b) and (c) are adapted from Shintake et al. (2016b) and (Zhu et al., 2023), respectively.

ultra-fast soft grippers exist (Shintake et al., 2016a), they are challenged by the issue of strength heterogeneity (Fig. 4d).

4 Developing an assessment matrix for soft grippers

The abovementioned soft robotics solutions illustrate the multidimensional challenges in gripping options for agri-food applications. While one solution may enhance the performance of the gripper in one dimension, it tends to limit performance in other dimensions. This means that multifaceted criteria are required able to encompass the full range of challenges. The authors have developed a performance matrix to account for different factors affecting gripper performance (Fig. 5). This is based on grasping performance and variations in object handling.

Gripper factors to be considered are strength and bulkiness, related to challenges 3 and 4, respectively. In particular, an ideal soft gripper for agricultural tasks should be strong enough to handle loads and dynamic perturbations and be thin and agile enough to maneuver in dense vegetation. Strength can be defined as the maximum force and torque that a gripper can handle in different directions (XYZ directions in Fig. 4b). The strength factor of the gripper can be defined based on the payload to gripper weight ratio pwr in Eqn (1). The bulkiness factor can be represented by the ratio of gripper thickness t_g to the object's width/thickness t_o as expressed in Eqn (2).

$$pwr = \frac{Payload}{W_g} \qquad (1)$$

$$tr = \frac{t_o}{t_g} \qquad (2)$$

Soft grasping should also be carried out both quickly and safely so that automated harvesting is economically feasible. Safety is a qualitative factor; hence, it is weighted based on an expert's opinion range from 0 to 1 and follows the type of grasping mechanisms they are using, i.e. Bernoulli mechanism (Petterson et al., 2010), mechanical interlocking (Leylavi Shoushtari et al., 2019), friction-based, controlled adhesion, and controlled stiffness (Zhang et al., 2020; Shintake et al., 2018). The Bernoulli mechanism and the adhesion-based mechanism are ranked as the safest for grippers, followed by controlled stiffness, mechanical interlocking, and friction-based grasping at the other end of the spectrum of safe grasping mechanisms. Speed is also defined based on the time required for grasping.

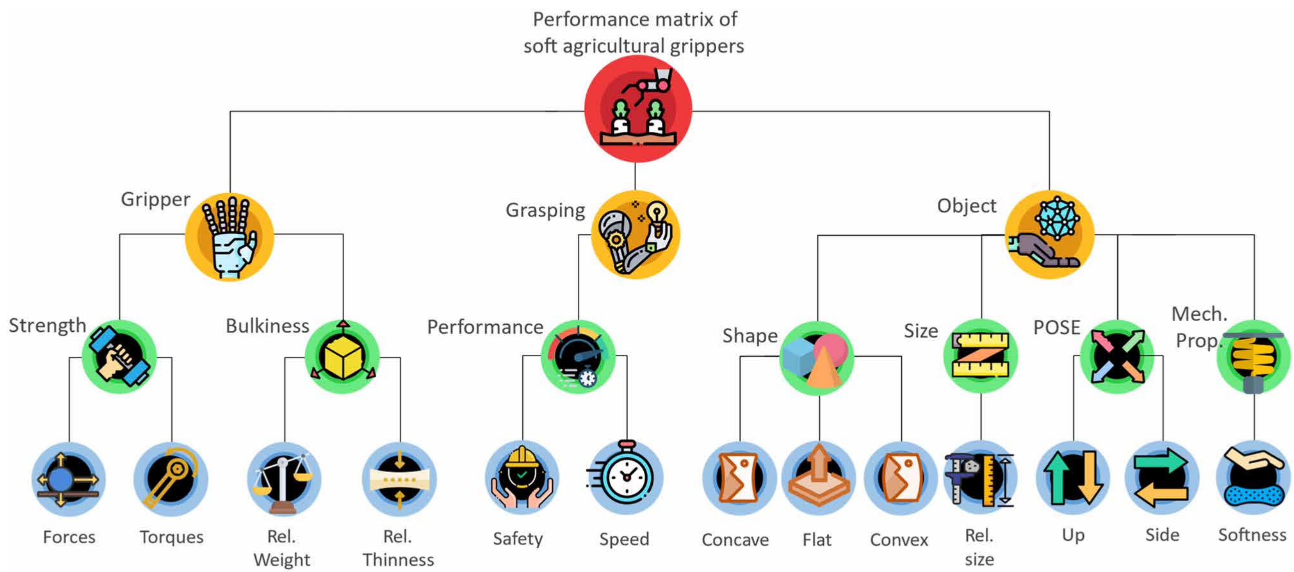


Figure 5 The performance matrix for a soft robotic gripper designed for agricultural applications. It embeds three folded aspects: gripper parameters, i.e. strength and bulkiness, grasping performance, and object variations. The gripper strength can be measured based on the maximum force/torque before the slippage of the object and the bulkiness could be measured by relative weight and thickness of the object to the gripper. Safety and speed are chosen as the most important indices representing the performance of grasping the crops. The shape, size, pose, and the mechanical properties are the indices representing the variability of the crops/objects to be handled. (Icons are downloaded from FlatICON (n.d.).)

Finally, the ideal soft gripper should be able to handle variations in crops, i.e. shape, size, pose, and their mechanical properties. Shape variations are defined as flat, convex, and concave. Size can be measured based on the aspect ratio of the maximum length of the object to the length of the gripper. Pose can be defined as whether the major part of the grasped object is on the side of the gripper (i.e. the weight of the object acts as a lateral load) or the grasped object is facing up or down (i.e. the gripper is either approaching from the top or from the bottom). Finally, the mechanical properties of the object can be simplified as the range of the stiffness of objects that the gripper can carry. The range of stiffness is defined based on Young's modulus, from the softest to the most rigid object as grasped by the gripper. Practically speaking, grasping a rigid object is feasible for soft grippers; the real challenge is when the object is extremely soft (softer than the gripper). This means that the range of stiffness of the objects that the gripper can grasp depends on Young's modulus of the softest object grasped by the gripper. A softness index for a gripper could be developed as the inverse of Young's modulus of the softest object that the gripper can handle as expressed in Eqn (3):

$$S_{index} = \frac{1}{E_{softest}} \qquad (3)$$

5 Performance analysis of current soft agri-food grippers

Although numerous soft grippers have not been developed specifically for – or integrated in – agricultural tasks, in order to demonstrate the effectiveness of soft grippers in agriculture, this chapter focuses only on those soft grippers designed for handling agricultural products. The authors have analyzed a database of soft grippers used in crop harvesting and crop handling using their performance matrix. This database is the same as that used in the study by Elfferich et al. (2022). Of 79 studies that used 'soft robotic grippers' and similar keywords [see Table 1 of (Elfferich et al., 2022)], 11 addressing aspects mentioned in the performance matrix were chosen. The grippers' scores for each parameter were then normalized with respect to the maximum scores of the given parameter for all evaluated grippers. The values of shape and pose were not normalized as they are binary parameters. The following three figures show the scores given to all 11 gripper designs for strength and bulkiness, grasping performance, and object variation.

Figure 6a shows the safety and speed of the selected grippers. The HASL-based gripper (Hydraulically Amplified Self-Healing electrostatic actuators) shown in Fig. 6b scores as the fastest gripper (Acome et al., 2018) together with the ElectroAdhesion-based gripper shown in Fig. 6c, since both of these grippers are based on the principles of electrostatic actuation, which acts rapidly (Shintake et al., 2016b; Cacucciolo et al., 2019). Such an actuation mechanism enables them to grasp in about 200 ms.

While the HASL-based gripper scores lower on safety (due to friction and mechanical interlocking-based grasping), the ElectroAdhesive gripper is the safest since it uses surface adhesion to grasp objects. Figure 6c illustrates how such a mechanism allows the gripper flaps to attach strongly to the surface of the crop, without applying any normal force which is generally the main cause of bruising and skin damage. Alongside this, a Bernoulli principle-based gripper

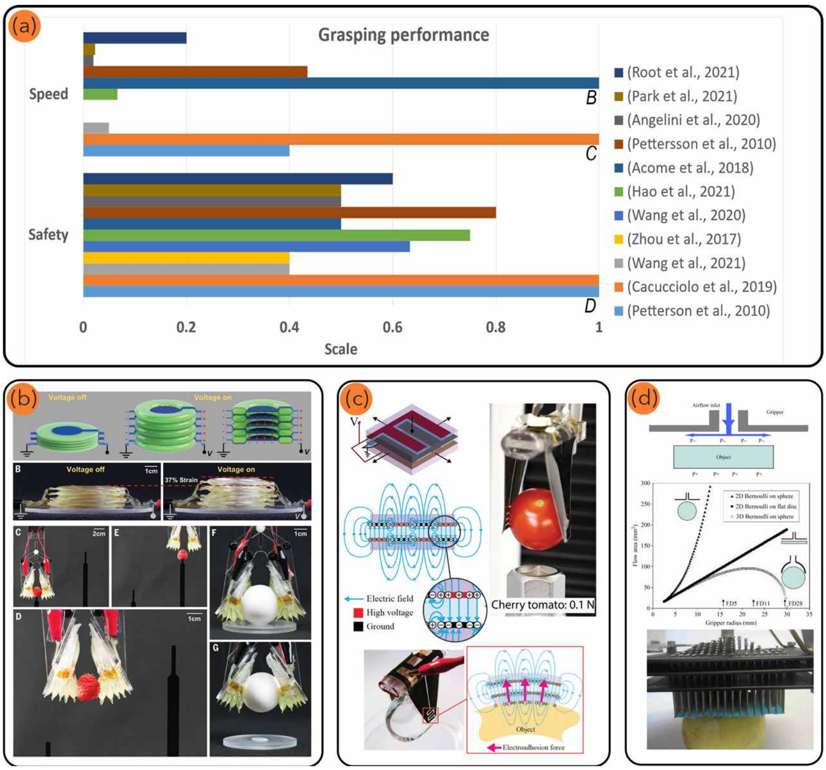


Figure 6 Grasping performance of 11 grippers. (a) Speed and safety scores. (b–d) Grippers with the top scores. (b) From top to bottom: HASL gripper mechanisms consisting of five ring-shaped HASL actuators, the strain gained when the voltage applied, and picking and placing a strawberry and an egg [adapted from Acome et al. (2018)]. (c) Electro-adhesive-based gripper, its mechanism, and grasping time [adapted from Cacucciolo et al. (2019) and Shintake et al. (2016b)]. (d) A Bernoulli principle-based gripper, its mechanism, performance, and deformation in interaction with the objects [adapted from Petterson et al. (2010)].

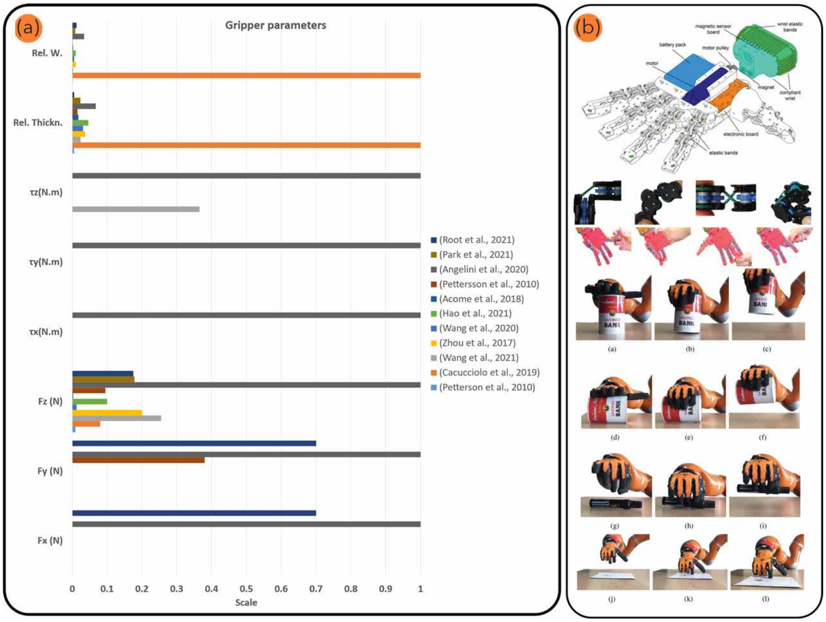


Figure 7 (a) Gripper parameters, i.e. relative weight and thickness, and maximum forces and torques in three dimensions. (b) Top to bottom: the Pisa/IIT SoftGripper; the stretchable ligaments make the gripper adaptive in interaction with its environment; grasping different objects using a synergy control. Photo is adapted from Catalano et al. (2014).

(Petterson et al., 2010) is also identified as one of the safest grippers since, like the ElectroAdhesive gripper, it uses an attachment mechanism to grasp objects. This attachment mechanism works based on the pressure drop between the gripper and the object caused by positive air pressure. The advantage of this attachment mechanism is that there is always a gap between the object and gripper, meaning the object is suspended, resulting in contactless grasping.

The ElectroAdhesive gripper (Shintake et al., 2016b) ranks as the lightest and thinnest gripper (Fig. 7a), capable of handling objects 1000 times heavier than its weight while being 172.5 times thinner than the object. Such a thin design allows it to be integrated in picking crops from a pile in a situation in which the gripper needs to be thin enough to get around the object. The Pisa/IIT SoftGripper is a tendon-driven anthropomorphic hand, which takes advantage of an adaptive ligament constraining system and is ranked as the strongest gripper (Fig. 7b). It is capable of handling loads in a vertical direction (z) up to 200 N, lateral loads of up to 50 N, and enduring torque up to 1, 0.5, and 2 Nm around the *x*, *y*, and *z* axis.

6 Performance analysis: dealing with object variations

Figure 8 shows the extent to which each soft gripper is capable of handling object variations. The figure shows that all 11 grippers are capable of grasping objects facing up (*up pose*) as well as objects with convex shapes. Indeed, for the other grippers, we can clearly see that testing (i.e. grasping objects that are round and facing up) can be used to show their performance. It is clear that these two variations (i.e. up pose and convexity) are not challenging for soft grippers. However, soft grippers do struggle with other object variations such as side pose, concave shapes, object softness, relative size, and flat shape.

6.1 Side pose

All grippers with a purely soft body, i.e. the ElectroAdhesive gripper (Cacucciolo et al., 2019), the adaptive soft hand (Zhou et al., 2017), the HASL-based gripper (Acome et al., 2018), and the dual-mode soft gripper for food packaging (Wang et al., 2020) are incapable of grasping objects from the side. The reason for this is that pure soft bodied grippers do not have sufficient support stiffness. On the other hand, hybrid rigid-soft bodied grippers, such as the soft grasping and conveying mechanism (Fig. 8h; Root et al., 2021), the stiffness-controlled gripper (Fig. 8b; Park et al., 2021), the Pisa/IIT SoftGripper (Fig. 8c; Angelini et al., 2020), the magnetorheological gripper (Fig. 8g; Pettersson et al., 2010), the multimodal enveloping gripper (Fig. 8d; Hao et al., 2021), and the circular shell gripper (Wang et al., 2021) are capable of side grasping.

Side grasping is also a challenge for the adaptive Bernoulli gripper (Fig. 6d) (Petterson et al., 2010) for different reasons. Despite the fact that Bernoulli grippers have been used in food industries before (Davis et al., 2008; Erzincanli and Sharp, 1997), they have always been used in a horizontal orientation. Indeed, in this position, the gripper performs best as the sheer force is minimized. Using a Bernoulli gripper for side grasping entails.

6.2 Object softness

The only two grippers that can handle objects as soft as Tofu have a very low stiffness profile in order to handle such a product (Park et al., 2021; Zhou et al., 2017). The soft segmented gripper (Zhou et al., 2017) uses an ultra-soft pillared interface to safely grasp and accommodate Tofu in a mechanical interlocking regime (Fig. 8f, on the right). Such a passive approach works until the shore hardness of the interface is lower than the object to be handled. Shore hardness is a measure of the hardness of a material, specifically its resistance to indentation or penetration by a hard object. However, if the object is relatively softer than the gripper's interface, then grasping could be challenging.

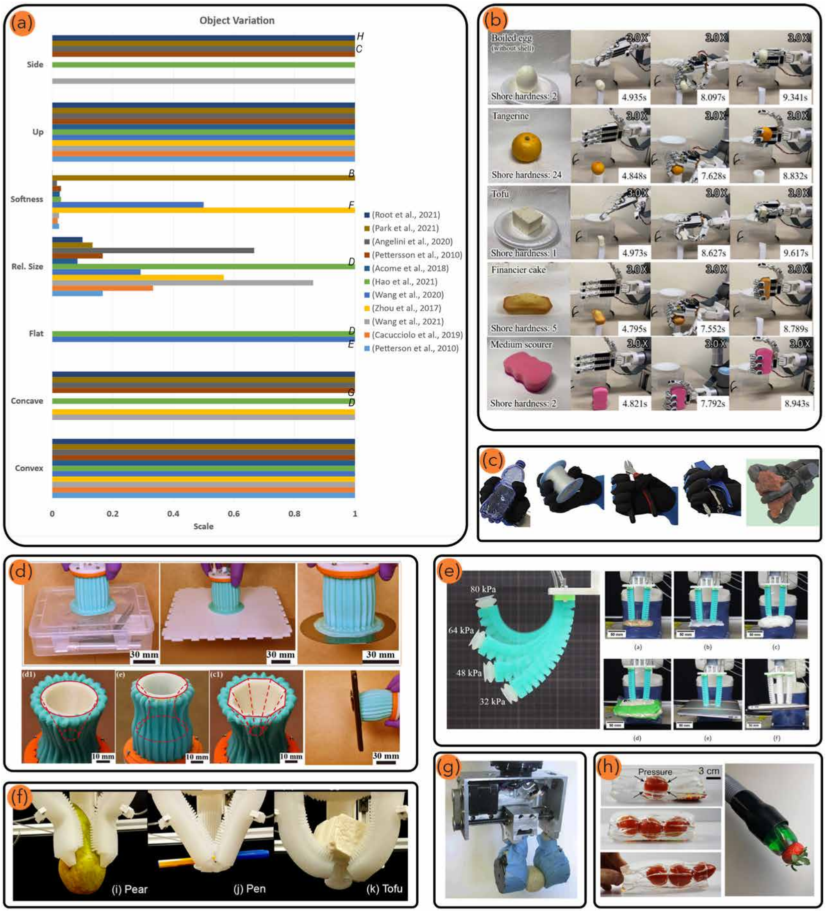


Figure 8 (a) The scores associated with the object variation. For each variation challenge factor (those for which just part of the gripper scored (1) two selected grippers with score 1 are shown with the capital letters on the bar. The capital letters refer to the visual representation of the gripper shown in B–H sections. (b) Variable stiffness anthropomorphic gripper with stiffness control, capable of grasping extra soft (Tofu), concave objects and grasping them from the side. Adapted from: Park et al. (2021). (c) Pisa/IIT SoftGripper capable of grasping concave and unstructured objects and side grasping. Adapted from: Santina et al. (2018). (d–e) A multimodal enveloping soft gripper (Hao et al., 2021) and a dual-mode soft gripper (Wang et al., 2020) both capable of grasping concave and flat objects and grasping from the side. Images of sections D and E are adapted from Hao et al. (2021) and Wang et al. (2020), respectively. (f) A soft gripper with enhanced object adaptation capable of grasping concave and ultra-soft objects. The image of section F is adapted from Zhou et al. (2017). (g and h) An adaptive magnetorheological gripper designed for food handling (Pettersson et al., 2010) and a soft bio-inspired mechanism for grasping, catching, and conveying (Root et al., 2021), both of which are capable of side grasping and lifting objects with concave shapes. Images of sections G and H are adapted from. Images of B-H are adapted from Pettersson et al. (2010) and Root et al. (2021), respectively.

In contrast, the anthropomorphic gripper with controlled stiffness (Park et al., 2021) can handle Tofu despite not having a soft interface by employing an adaptive stiffness approach. It enables the robotic gripper to automatically adjust the stiffness of its fingers to the stiffness and shore hardness of an unknown object once the gripper interacts with it. In particular, the peak force at fingers f_p is correlated with the shore hardness scale h_s (of the objects) and the damping ratio ζ_d of the object as expressed by Eqs (4) and (5). Using the resulting correlation between peak force and shore hardness h_s, as expressed by Eq. (5), allows the robot to estimate the hardness of an unknown object using the force feedback received at its fingertip. The estimated shore hardness is used in Eqn (4) to calculate the damping ratio. The resultant damping ratio is used by an impedance controller to adjust the stiffness of the gripper. To achieve this purpose, 21 objects with quite different shore hardness have been used for these experiments (Fig. 9a). Their standard shore hardness has been measured (Fig. 9b) and used for the correlation (Fig. 9c).

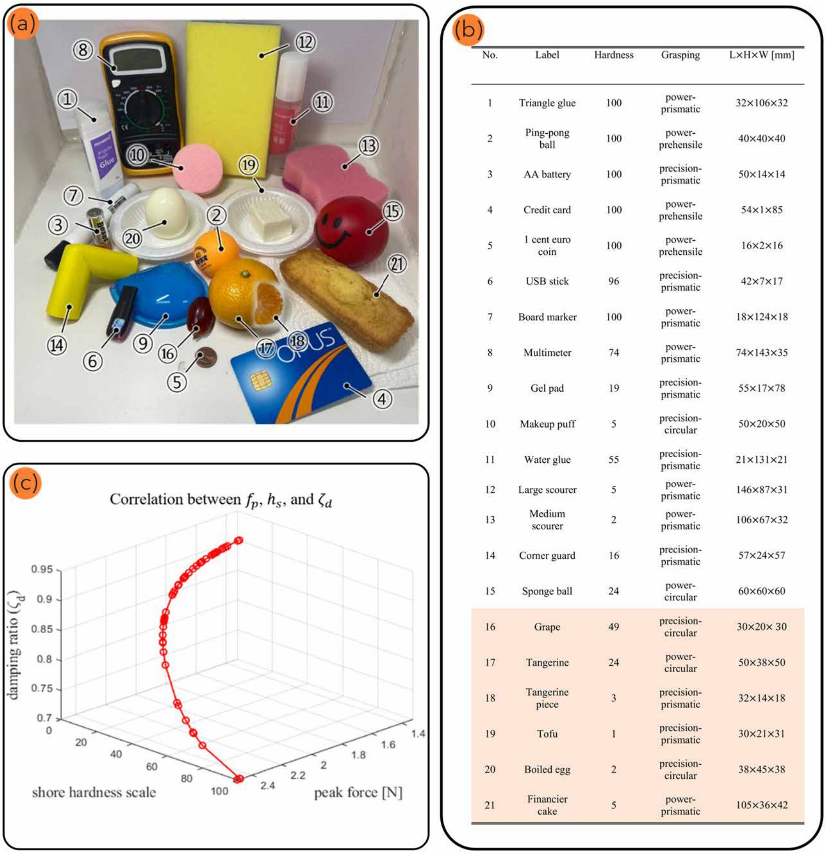
$$\zeta_d = \alpha_1 h_s^2 - \alpha_2 h_s + \alpha_3 \qquad (4)$$

$$h_s = \beta_1 e^{\beta_2 f_p} \qquad (5)$$

6.3 Flat objects

When it comes to handling flat objects, only those grippers that take advantage of suction-based adhesion succeed (Fig. 8a). Other types of adhesion such as electroadhesion or gecko-inspired dried adhesion cannot handle flat and non-lightweight objects due to the peeling-off effect (Ruotolo et al., 2021; Shintake et al., 2016a). The peeling-off effect could be solved for gecko-inspired adhesive pads by having a transmission mechanism to convert the normal load (which is an effect of object weight and causes the peeling phenomenon) to shear loads, which reinforces the attachments (Hawkes et al., 2016; Jiang et al., 2017).

By contrast, suction cup-based adhesion works best on flat (and non-rough) surfaces (due to guaranteed sealing) with normal loads and might fail due to the shear forces. Indeed, the two grippers successful at grasping flat surfaces were tested in this class (Fig. 8d, top row and Fig. 8e). Using a suction-based gripper for side grasping would be quite challenging since the weight of the object applies to the gripper as a shear load. Such a situation requires a stronger suction cup, equivalent to having a bigger suction cup or higher suction force, which is the case for the multimodal enveloping gripper (Hao et al., 2021; shown in the bottom right photograph of Fig. 8d). It is worth mentioning that the dual-mode gripper is unable to hold flat objects as shown in Fig. 8e in the side grasping scenario since it does not have rigid support. In



No.	Label	Hardness	Grasping	L×H×W [mm]
1	Triangle glue	100	power-prismatic	32×106×32
2	Ping-pong ball	100	power-prehensile	40×40×40
3	AA battery	100	precision-prismatic	50×14×14
4	Credit card	100	power-prehensile	54×1×85
5	1 cent euro coin	100	power-prehensile	16×2×16
6	USB stick	96	precision-prismatic	42×7×17
7	Board marker	100	power-prismatic	18×124×18
8	Multimeter	74	power-prismatic	74×143×35
9	Gel pad	19	precision-prismatic	55×17×78
10	Makeup puff	5	precision-circular	50×20×50
11	Water glue	55	precision-prismatic	21×131×21
12	Large scourer	5	power-prismatic	146×87×31
13	Medium scourer	2	power-prismatic	106×67×32
14	Corner guard	16	precision-prismatic	57×24×57
15	Sponge ball	24	power-circular	60×60×60
16	Grape	49	precision-circular	30×20× 30
17	Tangerine	24	power-circular	50×38×50
18	Tangerine piece	3	precision-prismatic	32×14×18
19	Tofu	1	precision-prismatic	30×21×31
20	Boiled egg	2	precision-circular	38×45×38
21	Financier cake	5	power-prismatic	105×36×42

Figure 9 (a) Different objects used in the shore hardness-peak force and damping ratio experiment. (b) Their standardized shore hardness. (c) Correlation between the three parameters. Adapted from: Park et al. (2021).

summary, without adhesion, it would be impossible to grasp flat or relatively big objects. This point was previously made as a design choice for versatile grippers (Langowski et al., 2020).

Bernoulli grippers are known as contactless grippers and are used to handle flat objects (Brun and Melkote, 2006; Journee et al., 2011). Although they are not used widely in handling crops, they have great potential for agricultural cases. One reason to why this integration has not taken place is that this category of grippers works best when the surface is perfectly flat and this is not generally the case for agricultural products. In fact, with slight modifications to deal with this issue, Bernoulli-based grippers have proven successful in handling non-flat objects (Petterson et al., 2010).

6.4 Concave objects

In this section, we analyze groups of grippers that have demonstrated both successful and unsuccessful grasping of concave objects. This analysis is based on the grasping mechanism (i.e. Bernoulli principle, controlled adhesion, i.e. surface adhesion or suction-base adhesion, controlled stiffness, mechanical interlocking, and controlled friction) and the materials of the gripper body (i.e. pure soft, hybrid soft-rigid) since these parameters are relevant in this context. The following will explain how these two factors can affect grasping of concave objects.

Four grippers (the adaptive Bernoulli, ElectroAdhesive, HASL-based, and dual-mode soft grippers) were unable to grasp concave (and non-lightweight) objects. The adaptive Bernoulli gripper (Petterson et al., 2010) is designed to approach objects from the top and cannot reach the side of the object where the concavity is a feature. Although the gripper is capable of deforming and conforming to the shape of the object, the deformation is insufficient to reach the side of the object. The ElectroAdhesive grasper (Cacucciolo et al., 2019) relies on a large surface contact area, which cannot be achieved when the object has a concave shape. By contrast, this gripper performs very well if the object is flat on the side or is convex. The dual-mode gripper (Wang et al., 2020) and the HASL-based gripper (Acome et al., 2018) both use friction-based and/or mechanical interlocking grasping mechanisms to pick up objects while having pure soft bodies.

Seven grippers demonstrated successful grasping of concave objects (Angelini et al., 2020; Hao et al., 2021; Park et al., 2021; Pettersson et al., 2010; Root et al., 2021; Wang et al., 2021; Zhou et al., 2017). Likewise, the anthropomorphic gripper (Park et al., 2021) and Pisa/IIT Soft gripper (Angelini et al., 2020) also use friction-based and mechanical interlocking grasping mechanisms while successfully handling concave objects. They both have a hybrid soft-rigid structure that enables them to grasp concave-shaped objects. Moreover, having stiffness control capability is of added value in handling such objects.

The magnetorheological gripper and the circular shelled gripper also have hybrid soft-rigid materials while using the controlled stiffness approach for grasping (Fig. 8). In both cases, having a rigid substrate allows their soft compartment to stiffen while they conform to the object. In particular, their rigid support allows soft pouches to be pushed towards the object (during actuation) that conform to the concavity of the object, which creates a large surface contact area. During the stiffening phase, the grippers can apply a well-distributed force to the concave objects, thanks to these large surface contact areas.

The same physics underlie the grasping of toroidal hydrostat and multimodal soft grippers, i.e. large surface contact area followed by stiffening.

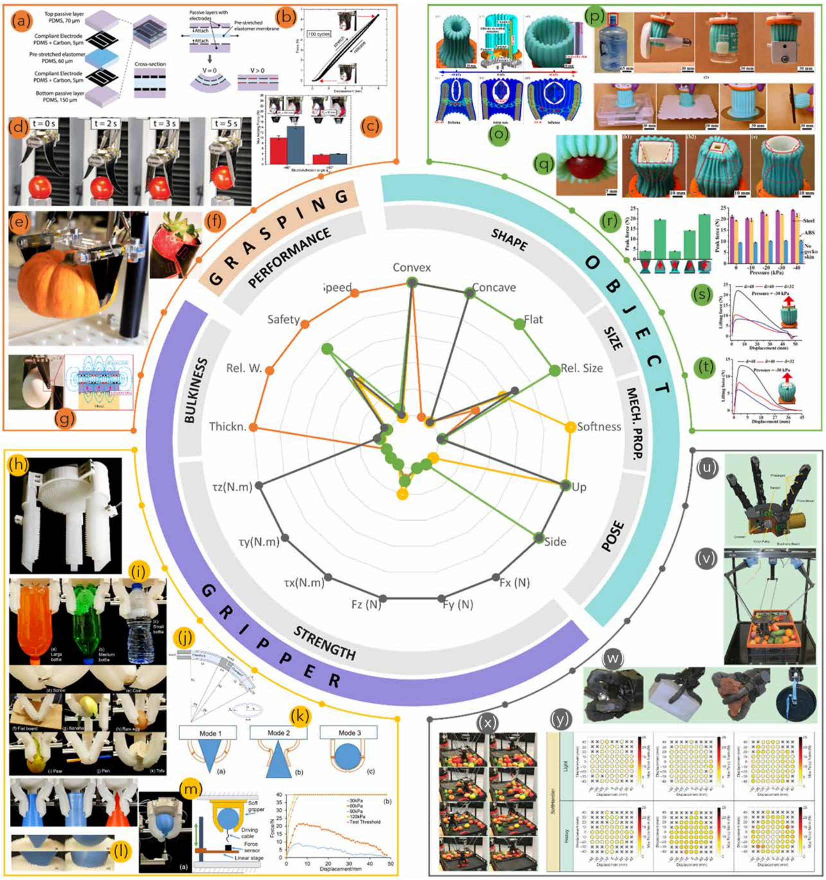


Figure 10 In the center: a graph illustrates the performance matrix measuring grippers' factors, i.e. strength and bulkiness, grasping performance, and the variation in objects that can be handled. The orange, yellow, green, and gray lines show four grippers with the highest scores (Cacucciolo et al., 2019; Zhou et al., 2017; Hao et al., 2021; Angelini et al., 2020, respectively). These grippers, their grasping performance, and the different objects that they handled are shown in four quarters, i.e. top left, bottom left, top right, and bottom right, respectively. The top left quarter depicts the electro-adhesion gripper: (a) mechanism underlying the dielectric-based actuation, (b) on-off cycle, (c) holding force objects with different size and electroadhesion angle, (d) rapid grasping of a cherry tomato, (e) grasping of a relatively large size pumpkin, (f) holding a strawberry safely, and (g) holding an egg while showing the mechanism of electroadhesion [images in sections (a)-(d) are adapted from Cacucciolo et al. (2019)]. The bottom left quarter shows (h) a three-finger gripper with a soft palm, (i) holding an object of various sizes, shapes, and weights and ultra-soft (tofu) using the segmented finger, (j) via different grasping modes (k). (l)–(m) the payload and the soft palm interacting with different objects, respectively. The top right quarter illustrates the multimodal enveloping soft gripper and its working principle, (o) holding a large object (with respect to the size of the gripper), a flat object, and grasping object from the side (p). (q) This gripper enveloping a cherry tomato and also grasping standard objects with convex and concave shapes. (r) Performance of

The only difference is that the grippers are using pure soft bodies to conform to the object and stiffen it. The toroidal hydrostat gripper uses an inversion mechanism known as a sloughing mechanism (Sadeghi et al., 2013) to drag a soft object in a ring pouch via rolling, while the multimodal gripper uses a soft shell structure to collapse in a programmed way to the object. The last gripper in this group (Zhou et al., 2017) uses a different mechanism to adapt to concave shapes. It takes advantage of a segmented finger capable of multiple bending curvatures to conform to objects with both concavity and convexity, such as pears (Fig. 8f). As with other grippers, it has a very large surface contact area with objects, which helps the gripper to apply a well-distributed grasping force during the actuation.

7 Designing the ideal versatile gripper

Analyzing the results to date, we can see that none of the grippers are able to satisfy all the requirements associated with agricultural tasks. Each design satisfies just one or some of the requirements and fails on the other aspects. The reason is simple: their designs are not meant to satisfy all agricultural task requirements. When it comes to design choice, soft robotics have a great deal to offer, despite current examples not yet meeting all potential requirements. One of the challenges with respect to grasping objects from the side is a lack of support stiffness, which could be resolved by jamming mechanisms (Brancadoro et al., 2020; Ibrahimi et al., 2021) or any other soft robotic solution that offers selective stiffness (Visentin et al., 2021). Some examples of such a combined design aim to compensate for the flaws of grippers designed for a certain purpose, such as increasing strength (Yang et al., 2019; Zhou et al., 2020). However, regardless of the combination of technology or gripper mechanisms, the final design will not satisfy all the requirements if they are not taken into account right from the beginning.

Studying natural grippers could help with the design of the ideal versatile gripper, either via inspiration or following biomechanical principles. Indeed, organisms in their natural habitats develop functionalities in order to adapt to their environments as a generic survival approach. For example, the

Figure 10 (*Continued*)

different grasping modalities, (s)-(t) grasping performance of object with different size and shape. The bottom right illustrates the SoftHandler grasping system, (u) and (v) capable of handling quite heavy and unstructured objects (w). (x) Picking and placing agricultural products and (y) force distribution at gripper's palm while handling objects of various sizes (i.e. small, medium, and large) and weights (i.e. light and heavy).

development of opposable thumbs helped chimps climb thin branches to get to fruits that grew at the tip. This could be inspiration for a more optimal versatile gripper. Moreover, studying the neuromusculoskeletal structure of chimpanzee hands could tell us much about their grasping mechanism. Researchers have shown that natural grippers use a hybrid grasping mechanism in order to deal with unpredictability and variations in their environment (Langowski et al., 2020), which is another excellent approach to enhance versatility.

To summarize what we have seen to date in reviewing previously mentioned grippers, not one single grasping mechanism is able to handle the set of requirements of a natural task, i.e. picking up a crop. Figure 10 uses a radar diagram to show how we can use all the soft robotic technologies we have reviewed to date to cover all requirements. Its illustration identifies a minimum number of complementary grasping technologies among the set of 11 grippers. Complementary grasping technologies mean that when a grasping technology fails to meet some requirements, another can compensate.

These technologies are as follows:

- Electroadhesion soft gripper (showed in orange in Fig. 10): it has low bulkiness, i.e. relative weight and thickness, and high grasping performance, i.e. safety and speed;
- The three-finger gripper with soft palm: it scores high when grasping soft objects;
- The multimodal enveloping soft gripper, which scored high in dealing with object variation, i.e. shape size and pose; and
- The SoftHandler: it is a tendon-based gripper, scored high in strength.

Hypothetically, the ideal gripper would be a hybrid design of such grasping technologies. Whether the hybridization of these specific technologies is feasible is a design research question and is addressed in the case study in Section 3.

8 Case study: the use of soft robotics in intercropping

A very good use-case of soft robotics being applied in agriculture is harvesting in intercropping system, as it has a wide range of requirements. The case study is taken from the 'Universal Soft Robotic Harvester for autonomous intercropping system' (USOROH) project (Leylavi Shoushtari and van Henten, 2020) and is a collaboration between Wageningen University and China Agricultural University as part of the Agricultural Green Development Plan. The purpose of this project is to enhance the versatility of soft grippers (through a hybrid design) to deal with the high variation of crops in the intercropping system. In particular, versatility is defined based on adaptability to the shape, size, weight, and mechanical properties of the objects to be handled. Each soft grasping technology has a list of pros and cons regarding adaptability. Through a hybrid design, their drawbacks can be traded-off or ideally canceled out.

Intercropping is a farming practice in which a set of crops with mutual benefits are planted next to each other, resulting in using fewer or no pesticides and fertilizers and enhancing soil health (Vandermeer, 1989). Having different crops in the same field is always a challenge when it comes to harvesting since it has both categories of diversity:

- Diversity within a crop variant; and
- Diversity between different types of crops.

Agricultural technologies are mainly designed for monocultures which are now seen as less sustainable, while traditional farming practices such as intercropping or mixed cropping have been proven to be more sustainable, particularly in improving soil health. Such farming practices have been abandoned in part due to intensive labor requirements for planning, crop maintenance, and harvesting.

Following a systematic approach (Fig. 11), a set of functional requirements for a gripper (i.e. grasping, stiffness and force adaptability) can be derived from the challenges of harvesting on an intercropping farm. Current soft grasping technologies can meet these requirements for individual crops but not simultaneously for two or more crops. Existing soft grasping technologies are assessed based on different functional requirements and a set of candidate technologies are chosen for hybridization. Three different grasping technologies, i.e. controlled stiffness, controlled adhesion, and grasping by actuation have been assessed (Shintake et al., 2018). Our aim is to combine these different technologies to conceptualize a design for the ideal versatile gripper. Knowing that each of these technologies has its own pros and cons, the candidate technologies are grouped based on the various task requirements set out in the assessment matrix.

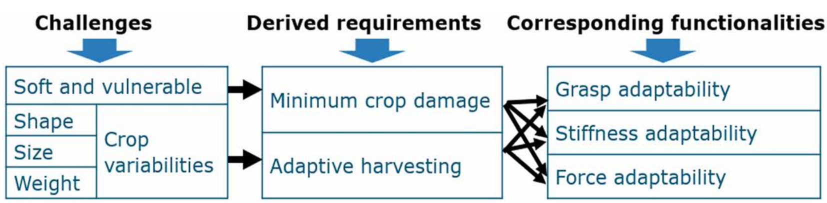


Figure 11 The chain of challenges, requirements, and functionalities for harvesting tasks in an intercropping system.

9 Conclusion

There is high demand for automated harvesting since this accounts for a significant proportion of production costs – around one-third of the entire cost of producing high-value crops (Bac et al., 2014). However, current rigid robots, machines, and automation technologies are not yet ready to meet the high requirements of mixed-crop harvesting.

This chapter has addressed the fact that integrating current soft grasping technologies in agri-food tasks (particularly in the case of harvesting) is a multifaceted research problem. Aspects such as gripper parameters (i.e. strength and bulkiness), grasping performance, and object variations need to be taken into account simultaneously. To determine to what extent soft grasping technologies are capable of being integrated at harvest, these triple aspects of each technology need to be assessed. This chapter has provided an assessment matrix which accounts for these three basic factors. Two parameters to assess soft grippers are strength and bulkiness. The former can be measured based on the maximum force/torque before slippage of the object and the latter by relative weight and thickness of the object to the gripper. Grasping performance is assessed based on safety and speed as the most relevant factors in crop handling. The shape, size, pose, and mechanical properties are all indices representing variability of the crops/objects to be handled. There were two main challenges in extracting data from the literature for use in performance assessment:

- There are insufficient data on the assessment matrix.
- Some measures (safety, shape, and roughness) are qualitative, which makes it difficult for benchmarking.

Comparing the different grasping technologies showed the grippers alongside each other. These results revealed that certain features of the objects (i.e. flat and concave shapes, softness, and side pose) are quite challenging for grippers, as very few scored highly. We also discussed why these grippers outperform their counterparts in such challenging cases.

The chapter then outlined a hypothetical design of an ideal gripper for a harvesting task, comprising a hybrid design of soft grasping technologies that complement each other in relation to the assessment matrix. The chapter then described a case study featuring the USOROH to illustrate the application of such a hybrid design. In a broader context, soft robotics could provide a safer, more flexible, and hence inclusive solution for harvesting mixed crops. The safety aspect discussed in this chapter refers only to maintaining crop quality during robotic handling, but soft robots also provide fairly safe interactions with humans too. I-support is a good (non-agricultural) example that demonstrates soft robots' safety in human–robot interactions (Arleo et al., 2020; Zlatintsi et al., 2020). Soft robotics also unlocks access to a range of affordable and available materials that are incompatible with rigid robots (Rus and Tolley, 2015). Moreover, having access to certain manufacturing technologies, such as 3D printing and casting, makes it even easier to design, customize, or reproduce a soft robot. Platforms such as the Soft Robotics toolkit (Soft Robotics Toolkit, n.d.) and FlowIO (Shtarbanov, 2021) are very good examples of open access soft robotics, helping to democratize soft robotics as a solution for all users, particularly farmers.

Soft robotics could potentially offer safe, versatile, affordable, and accessible solutions for harvesting in mixed crop farms. This chapter has addressed the technological gap between the actual performance of soft robotics and its potential for agriculture, particularly sustainable farming practices such as intercropping. In order to turn this potential into action, further research is required, such as the USOROH project, to take maximum advantage of current soft robotic technologies and sciences to develop tailored solutions for sustainable farming practices.

10 Where to look for further information

The following articles provide a good overview of the subject:

- Elfferich, J. F., Dodou, D. and Della Santina, C. (2022). Soft robotic grippers for crop handling or harvesting: a review. *IEEE Access* 10(June), 75428–75443. https://doi.org/10.1109/ACCESS.2022.3190863.
- Shintake, J., Cacucciolo, V., Floreano, D. and Shea, H. (2018). Soft robotic grippers. *Advanced Materials* 30(29). https://doi.org/10.1002/adma.201707035.
- Langowski, J. K. A., Sharma, P. and Leylavi Shoushtari, A. (2020). In the soft grip of nature. *Science Robotics* 5(49), 3–6. https://doi.org/10.1126/scirobotics.abd9120.
- Bac, C. W., van Henten, E. J., Hemming, J. and Edan, Y. (2014). Harvesting robots for high-value crops: state-of-the-art review and challenges ahead. *Journal of Field Robotics* 31: 888–911. https://doi.org/10.1002/rob.21525.
- Koerhuis, R. (n.d.). Wageningen University on a quest to develop the best robotic grippers. *Future Farming*. https://www.futurefarming.com/crop-solutions/wageningen-university-on-a-quest-to-develop-the-best-robotic-grippers/.
- Zhang, B., Xie, Y., Zhou, J., Wang, K. and Zhang, Z. (2020). State-of-the-art robotic grippers, grasping and control strategies, as well as their applications in agricultural robots: a review. *Computers and Electronics in Agriculture* 177(April), 105694. https://doi.org/10.1016/j.compag.2020.105694.

Magazine of Future Farming:

- https://www.futurefarming.com/crop-solutions/wageningen-university-on-a-quest-to-develop-the-best-robotic-grippers/.

Website of Dutch Soft Robotics Community:

- https://dutchsoftrobotics.nl/.

Open source soft robotics technologies:

- https://softroboticstoolkit.com/.
- https://www.softrobotics.io/.
- http://opensoftmachines.com/.

11 References

Acome, E., Mitchell, S. K., Morrissey, T. G., Emmett, M. B., Benjamin, C., King, M., Radakovitz, M. and Keplinger, C. (2018). Hydraulically amplified self-healing electrostatic actuators with muscle-like performance. *Science* 359(6371), 61–65. https://doi.org/10.1126/science.aao6139.

Adamides, G. and Edan, Y. (2023). Human–robot collaboration systems in agricultural tasks: a review and roadmap. *Computers and Electronics in Agriculture* 204, 107541. https://doi.org/10.1016/j.compag.2022.107541.

Angelini, F., Petrocelli, C., Catalano, M. G., Garabini, M., Grioli, G. and Bicchi, A. (2020). SoftHandler: an integrated soft robotic system for handling heterogeneous objects. *IEEE Robotics and Automation Magazine* 27(3), 55–72. https://doi.org/10.1109/MRA.2019.2955952.

Ansari, Y., Shoushtari, A. L., Cacucciolo, V., Cianchetti, M. and Laschi, C. (2015). Dynamic walking with a soft limb robot. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 9222, 13–25. https://doi.org/10.1007/978-3-319-22979-9_2.

Arleo, L., Stano, G., Percoco, G. and Cianchetti, M. (2020). I-support soft arm for assistance tasks: a new manufacturing approach based on 3D printing and characterization. *Progress in Additive Manufacturing* 89, 01234567. https://doi.org/10.1007/s40964-020-00158-y.

Bac, C. W., van Henten, E. J., Hemming, J. and Edan, Y. (2014). Harvesting robots for high-value crops: state-of-the-art review and challenges ahead. *Journal of Field Robotics* 31(6), 1–17. https://doi.org/10.1002/rob.

Brancadoro, M., Manti, M., Tognarelli, S. and Cianchetti, M. (2020). Fiber jamming transition as a stiffening mechanism for soft robotics. *Soft Robotics* 7(6), 663–674. https://doi.org/10.1089/soro.2019.0034.

Brun, X. F. and Melkote, S. N. (2006). Evaluation of Handling Stresses Applied to EFG Silicon Wafer Using a Bernoulli Gripper. In: *2006 IEEE 4th World Conference on Photovoltaic Energy Conference* 1346–1349.

Cacucciolo, V., Shintake, J. and Shea, H. (2019). Delicate yet strong: characterizing the electro-adhesion lifting force with a soft gripper. RoboSoft IEEE International

Conference on Soft Robotics. 108–113. https://doi.org/10.1109/ROBOSOFT.2019.8722706.

Catalano, M. G., Grioli, G., Farnioli, E., Serio, A., Piazza, C. and Bicchi, A. (2014). Adaptive synergies for the design and control of the Pisa/IIT SoftHand. *International Journal of Robotics Research* 33(5), 768–782. https://doi.org/10.1177/0278364913518998.

Davis, S., Gray, J. O. and Caldwell, D. G. (2008). An end effector based on the Bernoulli principle for handling sliced fruit and vegetables. *Robotics and Computer-Integrated Manufacturing* 24(2), 249–257. https://doi.org/10.1016/j.rcim.2006.11.002.

Droukas, L., Doulgeri, Z., Tsakiridis, N. L., Triantafyllou, D., Kleitsiotis, I., Mariolis, I., Giakoumis, D., Tzovaras, D., Kateris, D. and Bochtis, D. (2023). A survey of robotic harvesting systems and enabling technologies. *Journal of Intelligent and Robotic Systems* 107(2), 21. https://doi.org/10.1007/s10846-022-01793-z.

Elfferich, J. F., Dodou, D. and Santina, C. D. (2022). Soft robotic grippers for crop handling or harvesting: a review. *IEEE Access* 10(June), 75428–75443. https://doi.org/10.1109/ACCESS.2022.3190863.

Erzincanli, F. and Sharp, J. M. (1997). Meeting the need for robotic handling of food products. *Food Control* 8(4), 185–190. https://doi.org/10.1016/S0956-7135(97)00047-9.

Flat, I. C. O. N. (n.d.). *No Title*. Available at: https://www.flaticon.com/.

Hao, Y., Biswas, S., Hawkes, E. W., Wang, T., Zhu, M., Wen, L. and Visell, Y. (2021). A multimodal, enveloping soft gripper: shape conformation, bioinspired adhesion, and expansion-driven suction. *IEEE Transactions on Robotics* 37(2), 350–362. https://doi.org/10.1109/TRO.2020.3021427.

Hawkes, E. W., Jiang, H. and Cutkosky, M. R. (2016). Three-dimensional dynamic surface grasping with dry adhesion. *International Journal of Robotics Research* 35(8), 943–958. https://doi.org/10.1177/0278364915584645.

Howell, L. L., Magleby, S. P. and Olsen, B. M. (2013). *Handbook of Compliant Mechanisms*. John Wiley & Sons.

Ibrahimi, M., Paternò, L., Ricotti, L. and Menciassi, A. (2021). A layer jamming actuator for tunable stiffness and shape-changing devices. *Soft Robotics* 8(1), 85–96.

Jiang, H., Hawkes, E. W., Fuller, C., Estrada, M. A., Suresh, S. A., Abcouwer, N., Han, A. K., Wang, S., Ploch, C. J., Parness, A. and Cutkosky, M. R. (2017). A robotic device using gecko-inspired adhesives can grasp and manipulate large objects in microgravity. *Science Robotics* 2(7), 1–12. https://doi.org/10.1126/scirobotics.aan4545.

Journee, M., Chen, X., Member, S., Robertso, J., Jermy, M. and Sellier, M. (2011). An investigation into improved non-contact adhesion mechanism suitable for wall climbing robotic applications. In: *2011 IEEE International Conference on Robotics and Automation* 4915–4920.

Kumar, M. S. and Mohan, S. (2022). Selective fruit harvesting: research, trends and developments towards fruit detection and localization: a review. 095440622211284. https://doi.org/10.1177/09544062221128443.

Langowski, J. K. A., Sharma, P. and Leylavi Shoushtari, A. L. (2020). In the soft grip of nature. *Science Robotics* 5(49), 3–6. https://doi.org/10.1126/scirobotics.abd9120.

Leylavi Shoushtari, A. and van Henten, E. (2020). *Universal Soft Robotic Harvester for Autonomous Intercropping System*. Website: https://dutchsoftrobotics.nl/projects/universal-soft-robotic-harvester-autonomous-intercropping-system.

Leylavi Shoushtari, A. L., Naselli, G. A., Sadeghi, A. and Mazzolai, B. (2019). INFORA: a novel inflatable origami-based actuator. In: Proceedings of the - IEEE International Conference on Robotics and Automation. 7415–7420. https://doi.org/10.1109/ICRA.2019.8794422.

Majidi, C. (2014). Soft robotics: A perspective: current trends and prospects for the future. *Soft Robotics* 1(1), 5–11. https://doi.org/10.1089/soro.2013.0001.

Martin, T., Gasselin, P., Hostiou, N., Feron, G., Laurens, L., Purseigle, F. and Ollivier, G. (2022). Robots and transformations of work in farm: a systematic review of the literature and a research agenda. *Agronomy for Sustainable Development* 42(4). https://doi.org/10.1007/s13593-022-00796-2.

Pan, Y., Wang, Y., McGregor, C., Liu, S., Luan, F., Gao, M. and Weng, Y. (2020). Genetic architecture of fruit size and shape variation in cucurbits: a comparative perspective. In: *TAG. Theoretical and Applied Genetics. Theoretische und Angewandte Genetik*. Springer 133(1), 1–21. https://doi.org/10.1007/s00122-019-03481-3.

Park, H., Kim, M., Lee, B. and Kim, D. (2021). Design and experiment of an anthropomorphic robot hand for variable grasping stiffness. *IEEE Access* 9, 99467–99479. https://doi.org/10.1109/ACCESS.2021.3094060.

Petterson, A., Ohlsson, T., Caldwell, D. G., Davis, S., Gray, J. O. and Dodd, T. J. (2010a). A Bernoulli principle gripper for handling of planar and 3D (food) products. *Industrial Robot* 37(6), 518–526. https://doi.org/10.1108/01439911011081669.

Pettersson, A., Davis, S., Gray, J. O., Dodd, T. J. and Ohlsson, T. (2010b). Design of a magnetorheological robot gripper for handling of delicate food products with varying shapes. *Journal of Food Engineering* 98(3), 332–338. https://doi.org/10.1016/j.jfoodeng.2009.11.020.

Root, S. E., Preston, D. J., Feifke, G. O., Wallace, H., Alcoran, R. M., Nemitz, M. P., Tracz, J. A. and Whitesides, G. M. (2021). Bio-inspired design of soft mechanisms using a toroidal hydrostat. *Cell Reports Physical Science* 2(9), 100572. https://doi.org/10.1016/j.xcrp.2021.100572.

Ruotolo, W., Brouwer, D. and Cutkosky, M. R. (2021). From grasping to manipulation with gecko-inspired adhesives on a multifinger gripper. *Science Robotics* 6(61), eabi9773. https://doi.org/10.1126/scirobotics.abi9773.

Rus, D. and Tolley, M. T. (2015). Design, fabrication and control of soft robots. *Nature* 521(7553), 467–475. https://doi.org/10.1038/nature14543.

Sadeghi, A., Tonazzini, A., Popova, L. and Mazzolai, B. (2013). IEEE International Conference on Robotics and Automation, 3457–3462.

Santina, C. D. Della, Piazza, C., Grioli, G., Catalano, M. G. and Bicchi, A. (2018). Toward dexterous manipulation with augmented adaptive synergies: the Pisa/IIT SoftHand 2. *IEEE Transactions on Robotics* 34(5), 1141–1156. https://doi.org/10.1109/TRO.2018.2830407.

Shintake, J., Cacucciolo, V., Floreano, D. and Shea, H. (2018). Soft robotic grippers. *Advanced Materials* 30(29), e1707035. https://doi.org/10.1002/adma.201707035.

Shintake, J., Rosset, S., Schubert, B., Floreano, D. and Shea, H. (2016a). Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators. *Advanced Materials* 28(2), 231–238. https://doi.org/10.1002/adma.201504264.

Shintake, J., Rosset, S., Schubert, B., Floreano, D. and Shea, H. (2016b). Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators. *Advanced Materials* 28(2), 231–238. https://doi.org/10.1002/adma.201504264.

Shtarbanov, A. (2021). FlowIO development platform–The pneumatic "raspberry pi" for soft robotics. In *Extended abstracts of the 2021 CHI conference on human factors in computing systems* 1–6.

Soft Robotics Toolkit (n.d.).

Szeliski, R. (2011). *Computer Vision*. https://doi.org/10.1007/978-1-84882-935-0.

Vandermeer, J. H. (1989). *The Ecology of Intercropping*. Cambridge University Press. https://doi.org/10.1017/CBO9780511623523.

Visentin, F., Murali Babu, S. P., Meder, F. and Mazzolai, B. (2021). Selective stiffening in soft actuators by triggered phase transition of hydrogel-filled elastomers. *Advanced Functional Materials* 31(32), 2101121. https://doi.org/10.1002/adfm.202101121.

Wang, Z., Kanegae, R. and Hirai, S. (2021). Circular shell gripper for handling food products. *Soft Robotics* 8(5), 542–554. https://doi.org/10.1089/soro.2019.0140.

Wang, Z., Or, K. and Hirai, S. (2020). A dual-mode soft gripper for food packaging. *Robotics and Autonomous Systems* 125, 103427. https://doi.org/10.1016/j.robot.2020.103427.

Wang, Z., Xun, Y., Wang, Y. and Yang, Q. (2022). Review of smart robots for fruit and vegetable picking in agriculture. *International Journal of Agricultural and Biological Engineering* 15(1), 33–54. https://doi.org/10.25165/j.ijabe.20221501.7232.

Yang, Y., Zhang, Y., Kan, Z. and Zeng, J. (2019). Hybrid jamming for bioinspired soft robotic fingers. 1–17. https://doi.org/10.1089/soro.2019.0093.

Zhang, B., Xie, Y., Zhou, J., Wang, K. and Zhang, Z. (2020). State-of-the-art robotic grippers, grasping and control strategies, as well as their applications in agricultural robots: a review. *Computers and Electronics in Agriculture* 177(April), 105694. https://doi.org/10.1016/j.compag.2020.105694.

Zhou, J., Chen, S. and Wang, Z. (2017). A soft-robotic gripper with enhanced object adaptation and grasping reliability. *IEEE Robotics and Automation Letters* 2(4), 2287–2293. https://doi.org/10.1109/LRA.2017.2716445.

Zhou, J., Chen, Y., Hu, Y., Wang, Z., Li, Y., Gu, G. and Liu, Y. (2020). Adaptive variable stiffness particle phalange for robust and durable robotic grasping 1–15. https://doi.org/10.1089/soro.2019.0089.

Zhu, J., Chai, Z., Yong, H., Xu, Y., Guo, C., Ding, H. and Wu, Z. (2023). Bioinspired multimodal multipose hybrid fingers for wide-range force, compliant, and stable grasping. *Soft Robotics* 10(1), January, 30–39. https://doi.org/10.1089/soro.2021.0126.

Zlatintsi, A., Dometios, A. C., Kardaris, N., Rodomagoulakis, I., Koutras, P., Papageorgiou, X., Maragos, P., Tzafestas, C. S., Vartholomeos, P., Hauer, K., Werner, C., Annicchiarico, R., Lombardi, M. G., Adriano, F., Asfour, T., Sabatini, A. M., Laschi, C., Cianchetti, M., Güler, A., Kokkinos, I., Klein, B. and López, R. (2020). I-SUPPORT : a robotic platform of an assistive bathing robot for the elderly population. *Robotics and Autonomous Systems* 126(April), 103451.