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TOPICAL REVIEW

Soft Robotic Grippers for Crop Handling or Harvesting: A Review

JOHANNES F. ELFFERICH[1], DIMITRA DODOU[1], AND COSIMO DELLA SANTINA[2], (Member, IEEE)
[1]BioMechanical Engineering Department, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, 2628 CD Delft, The Netherlands
[2]Cognitive Robotics Department, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, 2628 CD Delft, The Netherlands
Corresponding author: Dimitra Dodou (d.dodou@tudelft.nl)

ABSTRACT Nowadays, harvesting delicate and high-value fruits, vegetables, and edible fungi requires a large input of manual human labor. The relatively low wages and many health problems the workforce faces make this profession increasingly unpopular. Meanwhile, robotic systems that selectively harvest crops are being developed. Whilst the moving platform, manipulator, and image recognition systems of such robots have been studied the past few decades, research on the gripping end of such robots is only since recently growing. This study analyzes the state-of-the-art of soft grippers for crop handling and harvesting, reporting on their quantitative and qualitative characteristics. Seventy-eight grippers are retrieved from the academic literature and compared with each other in terms of their design and reported performance, more specifically grasping and detachment methods, materials used, type of actuators and sensors employed, and the control of the gripping procedure. In addition, the identified grippers are classified into 13 distinct soft grasping technology categories. Moreover, the retrieved papers are analyzed with respect to their publication date and country of origin to observe trends in the recent growth in the field. Furthermore, a subset of soft grippers is identified that was tested on the task of selectively harvesting crops, where grip and detachment success rates and plant and crop damage are compared.

INDEX TERMS End-effectors, fruits, handling, harvesting, soft grippers, soft robotics, vegetables.

I. INTRODUCTION

Harvesting of delicate, high-value crops currently requires considerable input from the human workforce, whilst agricultural workers are hard to hire across the world [1]. Indicatively, in Dutch greenhouse horticulture, an average of 29% of the total costs goes to human labor, which amounts to €300,000 per company per year [2]. The required labor input is growing further because of a shift from bulk production to more specialized treatment of the (greenhouse) crops to grow higher quality produce [3]. For example, Italian precision farming adopters report a higher labor intensity on their farms than non-adopters [4]. Companies encounter problems trying to match this increase in human workforce demand as the availability of laborers is decreasing. Van Henten (2006) indicated that the wages are low, and many health problems arise because of the high humidity and heat and due to the repetitive movements of the tasks whilst working with uncomfortable postures [3]. Indicatively, agriculture as a whole is one of the most hazardous industries in both Canada and the United States, with the highest rates of occupational injuries and fatalities [5]. Out of necessity, this gap between the workforce need and demand is often filled with migrant workers. The UN Department of Economics and Social Affairs (UNDESA) estimated that the number of international migrant workers totaled 169 million in 2019, of which 7.1 percent, thus around 12 million, are employed in the agriculture sector [6].

Recently, the COVID-19 crisis has amplified the problems, as the pandemic made it more dangerous for international workers to work and be housed [7]. If supplied at a competitive price, robotization could provide a profitable solution for farmers [1]. Increased usage of automation could also mitigate much of the above undesirable consequences of agricultural manual labor.

As high-cost manual harvesting is usually performed in high-value crops, these are a good candidate for

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automation [8]. Unlike crops such as potatoes, wheat, and corn, which can be efficiently mass harvested by big machines, this group of crops ripen heterogeneously and must be selectively harvested [9], complicating the design of the tooling. The robot must detect and pick single ripe fruits whilst leaving the other fruits and the plant intact for further growth.

Improvements in robotics and computing made great strides over the last few years, and the first few companies have currently produced initial series of working harvesters. For example, in strawberry harvesting, there are three companies with robots that can find and grab the stem: Agrobot (www.agrobot.com), Dogtooth (www.dogtooth.tech), and Tortuga AgTech (www.tortugaagtech.com). Advanced Farm (www.advanced.farm) utilizes a vacuum cup surrounded by three pneumatic soft fingers, and Octinion harvests strawberries from below using cushioned fingers and a twisting motion with its Rubion robot (www.octinion.com/products/agricultural-robotics/rubion). Apples are collected via vacuum systems at Abundant robotics (www.abundantrobotics.com) and with gripper-equipped drones at Tevel (www.tevel-tech.com). Lastly, Fieldwork Robotics Ltd (www.fieldworkrobotics.com), a spinout company from Plymouth University, works on a compliant gripper for raspberries; see also their predecessor tomato harvester [10].

Several survey papers have already been written about robotics and automation in agriculture, spanning many subfields. Kootstra *et al.* discussed selective harvesting robotic systems in orchards, greenhouses and open fields [9]. Bac *et al.* compared performance metrics such as the localization and detachment success and damage rates between entire harvesting robots [8]. Li *et al.* reviewed the status of vegetable and fruit harvesting machines in China specifically [11]. Li *et al.* zoomed in on harvesting machines for citrus fruits [12]. Other studies focused on fruit localization using computer vision [13]–[15] or guidance and navigation strategies and sensors [16]–[20]. Zhang *et al.* compared the number of fingers in rigid grippers and their type, the sensors used, materials used and application [21], whereas Rodríguez *et al.* also looked at cutting functions and grasping methods [22]. Lastly, Navas *et al.* provided a technical analysis of 14 soft grippers [23].

In this work, we provide an analysis of the rising research field looking at soft grippers in agriculture. We systematically consider the entire academic literature (78 papers in total) and present trends in this field and how they relate to the grand challenge of crop handling and harvesting via soft grippers.

In this research, the term ‘crops’ includes fruits, vegetables, and edible fungi (such as mushrooms). We focus on academic literature instead of patents, as the latter provides little information on performance and the (rationale of the) design process. Lastly, we choose to review so-called mechanically intelligent grippers, as their characteristics match the problems faced in the agricultural use case very well. Mechanically intelligent grippers implement grasping primitives at the mechanical level and not the control level [24] by selectively introducing under-actuation and compliance/softness. Relatively simple embodied systems can thus show intelligent behavior through a limited set of functions and interaction with the environment [25]. This type of gripper is also called ‘soft robot/gripper’, with purposefully designed compliant elements in the mechanical structure [26]. An advantage of these soft grippers is that adequately designed compliance can replace the need for precise sensor-based control [27]. Furthermore, soft grippers are intrinsically more robust during interactions with the environment than conventional hard grippers, as the former can deform when they collide with the external world [28]. Thus, the inherent adaptability and simple control make soft grippers a good candidate for cluttered and unstructured environments such as the occluded canopy of most crops. The compliance also makes for a safer interaction for plants, crops, and humans compared to hard grippers [26], [29]. Lastly, the adaptability helps grab the wide range of crops, which have a high diversity between and within a crop in shape, size, weight, softness, and surface textures.

II. METHODS

First, based on existing literature review papers on soft grippers in this field [8], [21]–[23], relevant common keywords and their acronyms were summarized in a search-term table, see Table 1. This table served as input to Google Scholar, Scopus, and IEEE Xplore. The search queries contained at least one keyword in their full text or metadata from each category: soft, gripper, and crops and were searched until July 1, 2021. If multiple papers described a specific gripper design, the paper describing the version that showed experimental results with gripping real crops was used for further analysis. In other words, the year of publication is not necessarily the year of the inception of the idea/gripper, but the year the paper that tested the gripper on real crops was published.

We scanned the titles and abstracts of the retrieved papers from the three search engines to assess whether the topic of the paper indeed concerned soft gripper technology. If this was the case, then the whole paper was analyzed for relevance, using four independent exclusion criteria: (1) the paper should be written in English, (2) the gripper should not grip (and cut) the pedicel (the stalk bearing the fruit or vegetable) but grip the body of the product itself, (3) the experimental results should show that at least one real crop is successfully grasped by the gripper; this mainly excluded grippers that only show their workings on other, usually harder, objects or mock crops, and (4) grippers meant for harvesting crops (largely) grown in the soil, such as potatoes or asparagus, were excluded.

All papers that fulfilled the eligibility criteria were read in full, and their characteristics and performance measures were put in the overview table (see supplementary material). If the text did not explicitly mention the necessary information, we used the presented figures, tables, and pictures to extract as many details as possible. The list of characteristics and

TABLE 1. Search queries used in this literature review.

	←	AND	→
	Soft	**Gripper**	**Crops**
↑	soft	gripper*	*fruit*
OR	compliant*	"end of arm tool*"	crop*
↓	flexib*	manipulator*	vegetable*
	underactuat*	hand*	*berr*
	stiffness control*		cherr*
	variable stiffness		mushroom*
	ductil*		grape*
	delicate		bean*
			…

One term from each column had to be present in a paper. The * indicates a wildcard, e.g., stiffness control* could be stiffness control, stiffness controlling, stiffness controlled, etc. The crops column is cut short, as it consisted of 78 entries. For the entire table, see the supplementary material.

performance metrics used in the overview table was kept as broad as possible and was made by first combining all used metrics of previous gripper research for agricultural use cases [8], [21]–[23]. Subsequently, we added classifications and metrics from other (soft) robotic gripper and actuator reviews [30]–[32]. This process amounted to a list of 37 individual metrics in the overall overview table, which can be found as supplementary material. Lastly, all the papers referenced by these literature review papers were also considered for review in the current research.

III. RESULTS

A. METADATA AND APPLICATION

We first analyzed each paper in terms of the presented metadata and application, including the year the paper was published, where the authors performed their research, the approach direction of the gripper, and the type of gripped crops in the paper.

Of the analyzed papers, 76% were published in the last five years; see also Fig. 1. The oldest paper found was from 1994: a vacuum cup for mushrooms (Reed & Tillett, 1994). The largest number of papers that fulfilled the inclusion criteria were published in 2018, namely, 17. Fig. 1 also shows the number of analyzed papers as a percentage of the total published journal and conference articles findable on IEEE Xplore on July 1, 2021, for each year. We chose the totals of IEEE Xplore as its focus is mainly on the technical field to correct the shown temporal trend for the natural increase of (technical) papers over the years. From the results, it can be seen that also percentwise, the research on soft grippers for agricultural use cases is growing the fastest over the last five years. These results are congruent with the trend seen in robotic hands, which have a distinct growth after the year 2000 in the use of soft and underactuated mechanisms [34]. Furthermore, the first articles concerning soft robotics in general were published as early as 1990, with an increase after 2008 [35], which can also be observed, although with some delay, for agricultural soft grippers in Fig. 1.

The top five locations that produce the most papers in the soft gripper for crop handling and harvesting are China, the USA, the United Kingdom, Japan, and Taiwan. All five locations have six or more papers in the field, with China having the most papers in the field, with a total of 18 academic papers describing a soft gripper. Furthermore, the ranking is similar to the most active countries in the soft robotics field in general. Specifically as, between 1990 and 2017, the United States, China, and the United Kingdom are also in the top five most productive countries in the soft robotic area [35]. However, when accounting for the size of the agricultural sector, smaller locations output relatively more papers. Fig. 2 shows that Singapore, Hong Kong, Switzerland, the United Kingdom, Taiwan, the Netherlands, and Belgium contribute relatively the most to the field.

Table 2 shows the grasping/harvesting methods used. It can be seen that the pick-and-place operation is most often used. The other grippers also grabbed the crop but then used specific movements to detach the crop from the plant. A schematic description of these movements is given in Fig. 3. These included translations, pulling and flicking, rotations, and bending and twisting [33], [36]–[42]. Five grippers

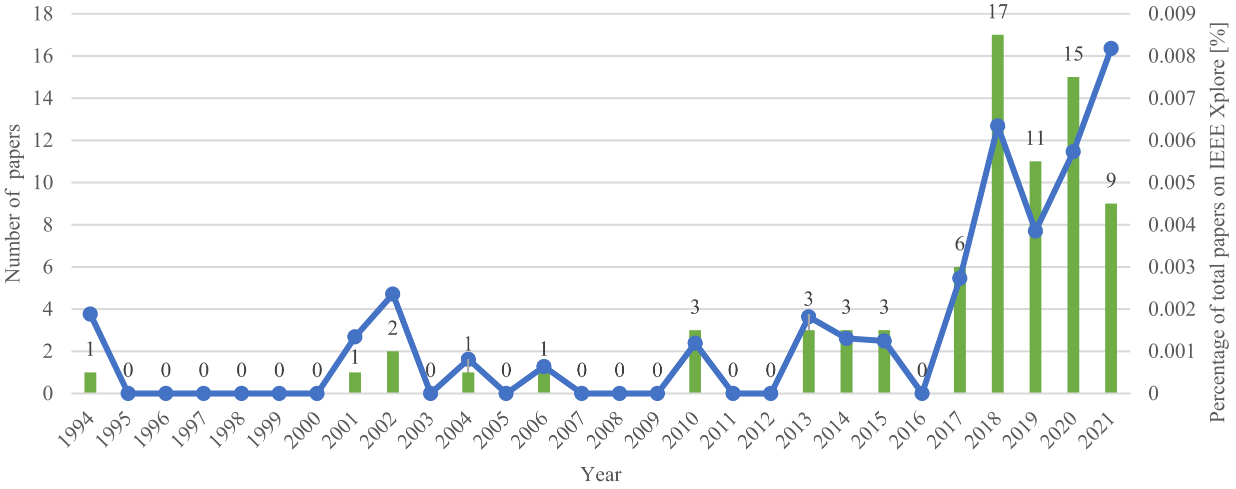

FIGURE 1. Bar chart of the number of academic papers considering a soft gripper for crops, published per year until July 1, 2021, and line-chart of the percentage of analyzed papers with respect to the yearly number of papers in the IEEE Xplore database on July 1, 2021.

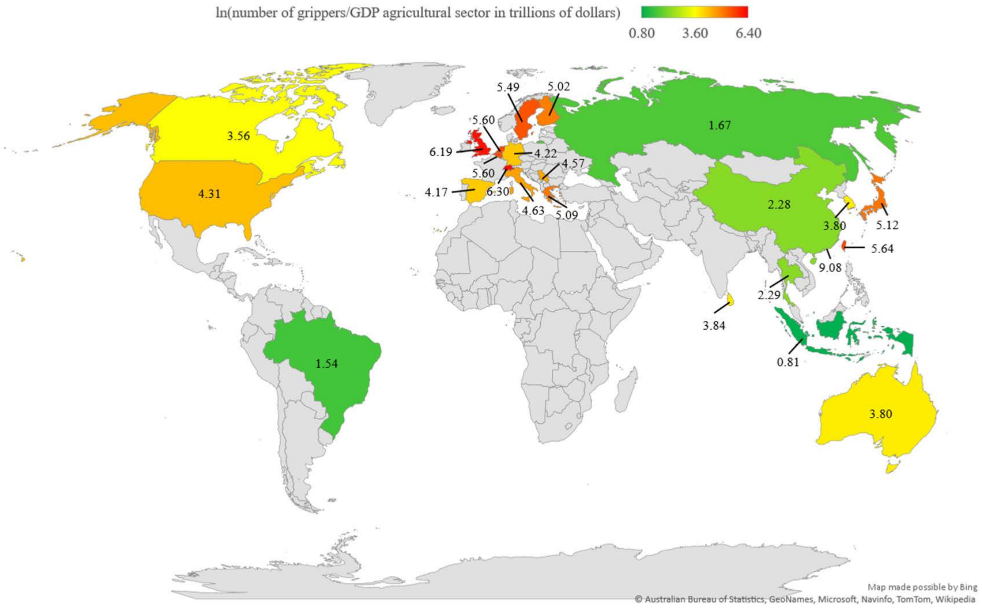

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FIGURE 2. Normalized contribution of locations of research institutes in the soft gripper for crop handling and harvesting research field, calculated as the natural logarithm of the ratio of the number of soft grippers found in literature with respect to the Gross Domestic Product (GDP) of the agricultural sector in 2017 in trillions of American dollars [118], [119]. If researchers from multiple countries cooperated on a single paper, each unique country gets added once to this overview. Note that Singapore contributed to three papers but could not be included as data about their agricultural sector is absent. Outlier Hong Kong is also excluded from this figure, as this location contributed on four soft gripper papers whilst having an agricultural sector of 456 million dollars, giving them the highest end result of 9.08. (Note that the source at the bottom right of the figure pertains to the world map only and not the portrayed data).

detached the crop by first holding it, followed by cutting the pedicel [43]–[46]. First grabbing and then pulling the crop is the most used form of detachment, with ten of the analyzed grippers employing it.

Along with the detachment method, the approach direction of the gripper towards the crop was also analyzed. We defined three main approach directions with respect to gravity, see Fig. 4. All analyzed grippers used approach directions close to, or the same as, one or multiple of these axes. Most analyzed grippers used vertical approaches from above, namely 46 out of 78 grippers, see also Table 3. Of these 46 grippers, only five used grasping/harvesting methods other than pick and place. A total of 15 grippers used only horizontal approaches, and 12 grippers demonstrated the ability to do both a horizontal and vertical approach.

Fig. 5 shows the types of crops tested in the papers. Tomatoes and apples are most often used for testing, with both having 26 grippers that were tested on them. Particularly remarkable is the limited number of tests performed on long and straight cylindrical crops such as cucumbers and carrots. On the other hand, the curved cylindrical fruit, the banana, is often used for testing, namely for 13 grippers. Furthermore, there seems to be no apparent trend in testing a certain range of weights of crops.

B. MECHANISM DESIGN AND TECHNOLOGY

We based the soft gripper grasping technologies classification used in this paper on a slight modification of the classification presented by Shintake *et al.* [47]. Specifically, Shintake *et al.* used the term ‘‘Electroactive polymers: Dielectric Elastomer Actuators (DEAs)’’, which we broadened to ‘‘Electroactive materials: dielectric actuators’’, as this allowed the inclusion of the liquid dielectric actuated gripper by Acome *et al.* [48]. Furthermore, the Fluidic Elastomer Actuators (FEAs) technology was altered slightly to include vacuum powered devices. Thus, elastic devices with both positive and negative pressures could also be included. See, for example, the vacuum-driven origami ‘‘Magic-ball’’ by Li *et al.* [49]. Also in the actuation category, we introduced a new classification term: ‘‘Pressure difference next to a deformable surface’’. This new term allowed the inclusion of multiple grippers that used deformable suction cups that conform and hold onto objects due to an introduced pressure difference between the internals of the suction cup and the atmospheric pressure. See, for example, the suction cup design by Morales *et al.*

TABLE 2. Number of soft grippers for crops per detachment/grasping method.

With and without detachment from plant	Grasping/harvesting method		Number of grippers
Without detachment	Pick and place		56
With detachment	Grab and	Cut	5
		Pull	10
		Pull and bend	2
		Pull and twist	4
		Bend and twist	1
		Twist	3
		Flick horizontal	1
		Flick vertical	1

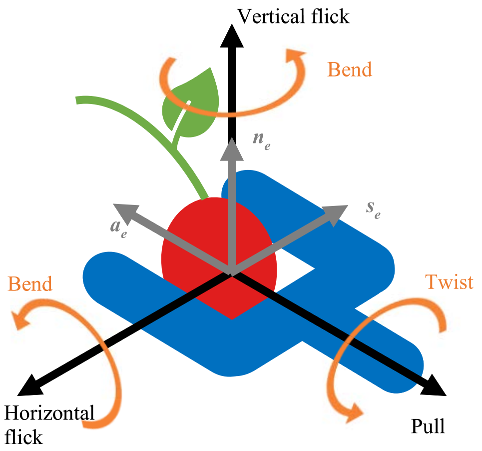

FIGURE 3. Schematic view of the harvesting methods of the blue gripper. The terminology is largely the same as in the analyzed literature, axes are local and fixed with respect to the center of the gripper (not the crop). The straight black arrows portray the translational movements, and the curved orange arrows show the rotational movements of the gripper. The straight grey arrows show a reference frame from literature on end-effectors, comprising unit vectors a_e in the approach direction, s_e in the sliding plane of the gripper, and n_e normal to the other two (Siciliano *et al.*, 2010).

TABLE 3. Number of soft grippers for crops per approach direction.

Approach direction gripper	Number of grippers
Horizontal	15
Vertical, above	46
Vertical, above and horizontal	7
Vertical, below	3
Vertical, below and horizontal	1
Vertical, above and below	1
Vertical, above and below and horizontal	4

that has flexible side concavities that help adapt to the shape of the crop [50]. The formulation of the new technology classification also allowed to retrieve technologies that did not require a seal around non-planar objects to be included, such as the three dimensional (3D) Bernoulli principle with a deformable surface [51]. Within the controlled stiffness category, we added the term “Actuated mechanical structure”. This principle includes grippers that independently actuate some mechanism that increased or decreased the compliance of the gripper structure, such as the gripper by Li *et al.*, in which sets of flexures were rotated with respect to each other to create different moments of inertia, altering the stiffness of its fingers independent of the locations of the fingers [52]. Another example of this principle can be seen in the CLASH hand by Friedl and Roa, which employed variable stiffness levers for their tendon-driven gripper [53].

Table 4 shows that 18 of the 78 studied grippers used two instead of one technology for grasping. None of the analyzed papers used more than two technologies. It also becomes clear that many possible combinations of grasping technologies are not present in the analyzed literature, i.e., only eight of the possible 78 combinations are found. Within the combinations that are present in the literature, the combinations between vacuum cups and FEAs [44], [54], [55], and vacuum cups with passive structures with external actuators are the most common [38], [56]–[60]. Within the large group of grippers that used one technology, FEAs and passive structures with external actuators are found most often, with 25 and 26 grippers, respectively. Furthermore, only one magneto-rheological robot gripper was identified that was tested on real fruits and vegetables [61]. Moreover, only one passive structure with an external actuator was found within the analyzed literature that also used granular jamming [62]. We identified two grippers that used particle jamming with vacuum cups to increase grip, see also Fig. 6 [63], [64]. Some of the other technologies explained by Shintake *et al.* [47]

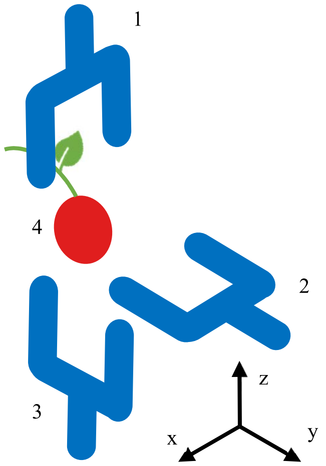

FIGURE 4. Schematic picture of possible approach directions. In this figure, Gravity is pointed along the negative z-axis. 1. Vertical approach from above, pointed in the direction of negative z-axis. 2. Horizontal approach, in the x-y-plane. 3. Vertical approach from below, pointed along positive z-axis. 4. Example of a crop hanging from a pedicel.

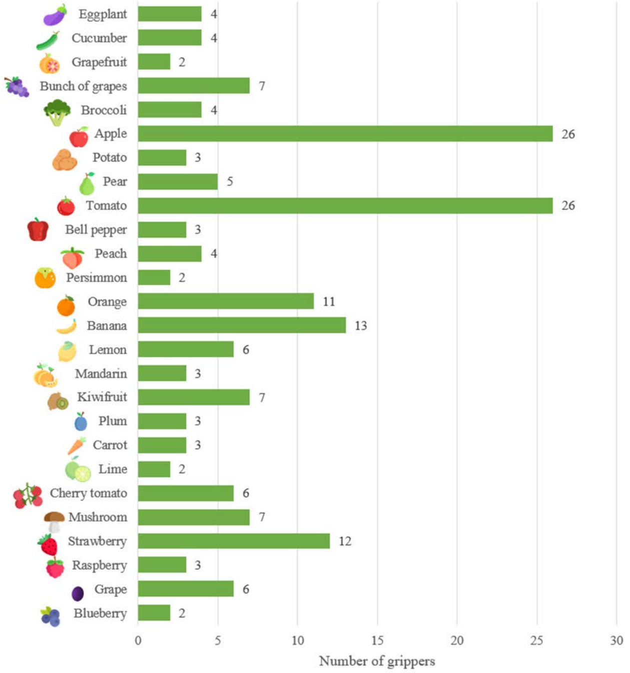

FIGURE 5. Number of soft grippers for crops that gripped different kinds of crops successfully. On the vertical axis, the crops are in descending order on approximate average weight. Only types of crops with more than one mention in the analyzed literature are presented in this figure. For the full list, see supplementary material. Crop icons: flaticon.com.

are not found within the analyzed literature at all, namely, ionic polymer-metal composites, shape memory alloys, low melting point alloys, and shape memory polymers.

Sixty-nine gripper designs used so-called fingers, and 13 did not. Designs without fingers were mostly suction cups, but there were also enveloping grippers, such as an origami-structured bowl that could shrink around objects to grab it [49]. Another enveloping design used 22 parallel coupled fluidic chambers that folded around the object and used a gecko-inspired inner surface for increased friction [65]. Lastly, an elastic-net design did not use fingers either; instead, it used eight parallel mechanisms to open and close the corners of the net to pick and place the crops [66]. The remainder of the grippers did use fingers: 28 grippers used two fingers, 26 grippers used three fingers, and 14 grippers used four fingers. Only one paper used five fingers, inspired by the morphology of a human hand, but with suction pads at the fingertips [67].

Next, we analyzed the configuration of the gripper fingers. The two-finger prototypes were all in-plane, i.e., directly opposed, which can be rationalized because a stable grip preferably does not impose a torque on the object. Most of the three-finger grippers were evenly spaced around the center of the gripper, separated by 120 degrees. Dimeas *et al.* deviated by using a spacing similar to a human thumb, index, and middle finger configuration [68]. Ariyanto also used a different configuration by using three FEA fingers, of which one is centrally opposed to the other two whilst all fingers move in parallel [69]. The four-finger grippers were also often spaced evenly with 90 degrees separation. Another frequently observed configuration for the four-fingered gripper consisted of two sets of two fingers in-plane [44], [45], [55], [70].

We also analyzed the total Degrees of Freedom (DoF) of each gripper. In our analysis, a soft gripper was considered infinite DoF if the structure was continuously deformable, e.g., a suction cup or a uniform, tube-like FEA. The other designs included countable hinges, such as a soft finger with weak spots along its length to enable bending at that point. These (partly) flexible designs are often called articulated soft robots [26]. The result of the analysis is shown in Fig. 7. Of the analyzed grippers, 59 had infinite DoF, and 19 grippers had a countable number of DoF. There were at most three soft grippers in the range from one to 15 DoF in the analyzed literature. The higher range of DoF usually corresponded with a finger design with multiple phalanges, e.g. three FEA fingers with each five phalanges result in a gripper with a total of 15 DoF [71], [72]. Another concept proposes modular phalanges, making the DoF adjustable and scalable, e.g., the gripper by Angelini *et al.* was tested up to 16 DoF [73].

In addition to the configuration of the gripper, most papers also described the manufacturing process and materials used. Direct 3D printing of flexible filaments, such as thermoplastic polyurethane (TPU), is commonly seen to form a complexly shaped gripper [74]–[77]. Indirect methods, such as 3D printing of a mold which is later filled with flexible silicone rubber, are also often used due to the ease with which complex flexible shapes can be manufactured [78]–[80]. Less common manufacturing processes include a coagulant dipping process to manufacture the gripper using natural rubbers compounds [81] and pre-stretching the silicone rubber during assembly to create internal stress that eventually is used to close the gripper [82]. Bao showed a design in which springs are embedded in the silicone rubber to enhance its stiffness [83]. Table 5 gives an overview of all the mentioned materials in the pool of analyzed grippers. Silicone rubbers are most popular with 26 grippers using it, and thermoplastic polyurethane (TPU) is the second most prominent material with ten grippers. Also noteworthy are the materials used for inextensible layers,

TABLE 4. Number of soft grippers for crops per grasping technology they employed.

Category	Technology	Number of grippers using only one technology	Number of grippers using two technologies													
			Passive structure with an external actuator, contact	Fluidic elastomer actuators (FEAs) *(incl. vacuum)*	*Electroactive materials: dielectric actuators*	Electroactive polymers: Ionic polymer-metal	Shape memory materials: shape memory alloys	*Pressure difference next to a deformable surface*	Granular jamming	Low melting point alloys (LMPAs)	Electro-rheological (ER) and magneto-rheological (MR)	Shape memory materials: shape memory polymers	*External variable stiffness actuation* a)	Electro-adhesion	Gecko adhesion
Actuation	Passive structure with an external actuator	26													
	Fluidic elastomer actuators (FEAs) *(incl. vacuum)*	25	1												
	Electroactive materials: dielectric actuators	1													
	Electroactive polymers: Ionic polymer-metal composites (IPMCs)														
	Shape memory materials: shape memory alloys (SMAs)														
	Pressure difference next to a deformable surface	7	6	3											
Controlled stiffness	Granular jamming		1					2							
	Low melting point alloys (LMPAs)														
	Electro-rheological (ER) and magneto-rheological (MR) fluids	1													
	Shape memory materials: shape memory polymers (SMPs)														
	External variable stiffness actuation a)		3												
Controlled adhesion	Electro-adhesion				1										
	Gecko adhesion			1											

a) Entries in italics are added to the existing classification of Shintake et al. [47].

FIGURE 6. Examples of soft grippers in literature using different grasping technologies. (a) Gripper with a passive structure using a tendon-driven external actuator [73]. (b) Gripper using a liquid dielectric actuator to grasp a raspberry. Adapted with permission from AAAS [48]. (c) A multi-material fluidic elastomeric actuator [71]. (d) Vacuum cup gripper (pressure difference next to deformable surface) along with C-shaped knife cutter. Adapted with permission from [45]. Copyright by 2017 Wiley Periodicals, inc.. (e) FEA gripper with gecko-like inner surface lifts a lightbulb [65]. (f) Passive structure with external actuator with external variable stiffness actuation due to rotatable compliant centers [52]. (g) Gripper using electro-adhesion to lift a cherry tomato [111]. (h) Suction cup with granular jamming in lip [64].

often used to create the bending behavior for FEAs: fabric cloth, glass fiber, Kevlar, and nylon fiber (cloth). Only one paper mentioned using metals in its main structure, aluminum alloy 7075 and titanium alloy Ti-6-Al-4V. These were made compliant through a variable stiffness design, operated via rotatable flexure hinges [52].

We also compared the dimensions of the manufactured grippers. From the 78 analyzed grippers, only 35 mentioned the depth, width, or height of the gripper. Most authors presented this in different (incomplete) ways, which made it hard to compare the space they occupy. So instead, we compared the maximum opening distance, which was sometimes indicated by the authors or otherwise conservatively estimated by using the largest object that could reportedly fit in the gripper. This distance is available for 30 of the studied grippers, and the results are shown in Fig. 8. The largest opening distance is 305 mm, achieved by a two-fingered gripper with FEA powered phalanges [84]. The kirigami shell gripper has the smallest possible opening distance of only 9.5 mm [85]. All other grippers have a maximum opening distance between 30 and 210 mm.

Lastly, we analyzed whether the considered paper optimized the size or operation range of the gripper using computational modelling. Three papers used the Finite Element Method (FEM) to optimize (part of) the structure [86]–[88]. Furthermore, one paper used shape optimization via node wandering [89]. A slight majority of five grippers, were designed using topology optimization [71], [90]–[93]. One compliant gripper even used a combination of topology and size optimization for its final design [94].

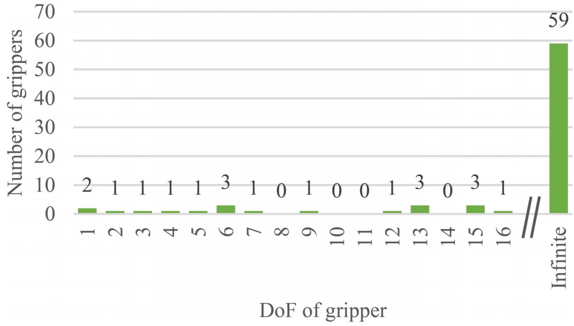

FIGURE 7. Number of soft grippers for crops having a specific number of DoF in the overall gripper design. Note how most grippers had continuously deformable soft components giving them virtually infinite DoF.

C. SENSORS, ACTUATORS, AND CONTOL

The previous section showed that the mechanisms analyzed could have up to 15 countable DoF. Most retrieved designs are underactuated, meaning that not every DoF of the gripper has a dedicated, independent actuator (Birglen *et al.*, 2008). Whenever the authors of the paper did not specify the number of inputs, we estimated it by looking at their presented figures and metrics. For 29 grippers, this estimation could be made, but, for three grippers, it was impossible to do this accurately, so the analysis seen in Fig. 9 excluded these three. The results show that a gripper with just one input is most often used in the analyzed literature, with a total of 37 grippers using this principle. We observed that up to seven inputs are utilized in the analyzed field and that a higher number of inputs is decreasingly common. For example, a five-fingered gripper with suction pads on the fingertips used seven individual inputs for operation (Ponraj *et al.*, 2019). Another example with many DoF is a gripper with two fingers, each controlled via a three DoF delta arm, which totals to six inputs and gives a grasp with high dexterity (Mannam *et al.*, 2021).

Fig. 10 breaks down which actuation sources are most commonly used. Electric motors such as DC motors, stepper motors, and servomotors are often used to actuate this class of grippers, namely by 24 grippers in total. Another common type of actuation is positive (pneumatic) or negative (vacuum) pressure. These solutions are used by 22 and five of the analyzed grippers, respectively. Combinations between these three are also often employed. Vacuum and pneumatic actuation are simultaneously used by ten of the considered grippers. Electromagnets are only used once by Yang *et al.* to close their kirigami gripper untethered [85]. It is also worth noting that some possible actuation methods are not found in the analyzed literature, e.g., thermal or hydraulic actuators. The power consumption of the actuators was only reported for one design, namely between 3.9 and 46 Watt in a closed position depending on the object gripped [89].

Of the analyzed grippers, 36 used stand-alone sensors in their gripper during their gripping cycle. These are reported

TABLE 5. Number of soft grippers for crops that mention the usage of certain materials (and specific brands) in their construction.

Material used in gripper	Manufacturer	Number of grippers
Acrylonitrile Butadiene Styrene (ABS)		1
Aluminum alloy 7075		1
Fabric cloth		1
Glass fiber		1
Kevlar		2
Latex		3
Natural rubber		2
Nylon		2
Nylon fiber (cloth)		5
PET-PVC-Kapton composite		1
Polycarbonate (PC)		1
Polydimethylsiloxane (PDMS)	Sylgard, Dow	3
Polyethylene (PE)		1
Polyethylene Terephthalate (PET)		1
Polylactic Acid (PLA)		2
Polypropylene (PP)		3
Polyurethane (PU)		5
Polyvinylsiloxane (PVS)		1
Silicone rubber	No brand mentioned	7
	RTV-52	1
	Smooth-On, Inc., PA	15
	Sylgard, Dow	1
	Taobao	1
	Wacker Chemie AG	1
Thermoplastic elastomer (TPE)		5
TPU	No brand mentioned	4
	NinjaFlex, NinjaTek	4
	Aurora	1
	eFlex, eSUN	1
Titanium alloy Ti-6-Al-4V (Ti64)		1

in Table 6, and some examples can be seen in Fig. 11. The mechanical pressure and the force exerted on the object are the most commonly measured quantities. Both aspects are used to give feedback during the gripping of soft objects to determine whether the grasp is firm enough to hold the object but not so forceful that the gripper crushes the object [58], [84], [95]–[100].

Position and angle sensors that measure the gripper configuration are used less often, namely by six and three grippers, respectively. Flexure sensors, used to measure the overall bending/curvature of the fingers, were found six times in the analyzed papers in total. These can be surface mounted or, for example, embedded in the finger [101]. Chen *et al.* introduced a custom sensor named the TriboElectric Nano-Generators (TENG), which measured contact pressure or bending of their FEA gripper [102]. Two FEA grippers and three suction cup grippers used the five air pressure sensors found in the analyzed literature. The sensors are used to control pressure and see whether successful suction has been achieved [59], [60], [64], [103], [104].

The gripper by Friedl and Roa included six different kinds of sensors, the largest range of sensors employed by a single gripper out of all of the analyzed grippers [53]. Their gripper used potentiometers and temperature sensors for their servos, analogue Hall sensors to read out their variable stiffness levers, an Inertial Measurement Unit (IMU) for the orientation of the hand, and a proximity sensor to detect whether there is an object in the hand. Furthermore, they utilized 3M Velostat foil or electrostatic discharge (ESD) foam as piezoresistor to act as tactile sensors for the fingertips.

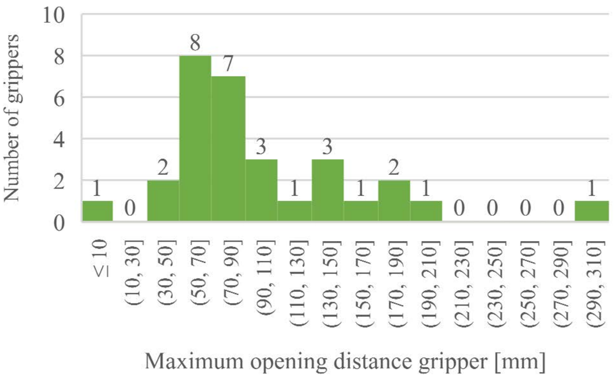

FIGURE 8. Number of soft grippers for crops with a certain maximum opening distance. This metric can be either directly indicated by the original author(s) or conservatively estimated as the largest object that was successfully grasped by the gripper. For each bin, the lower bound is excluded, and the upper bound is included.

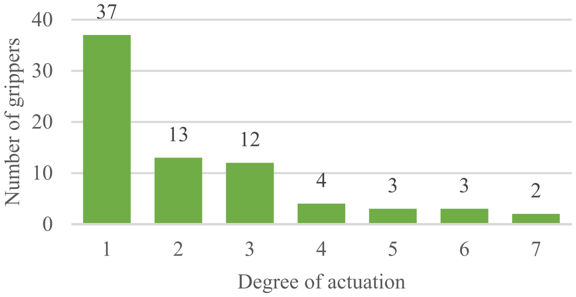

FIGURE 9. Number of soft grippers for crops that have a certain degree of actuation (number of individual inputs). Most grippers utilize only one input in their operation. Two grippers used seven inputs in their operation, and none used more than seven inputs.

Table 7 summarizes which control strategies were employed by 44 of the 78 analyzed grippers that mentioned this metric. Using the sensor values to stop/adjust the gripping actuation during operation was most often the case, as 27 grippers used methods with feedback. Sixteen grippers used feedforward control, and five grippers were manually controlled, i.e., the researchers used an interface whilst looking at and operating the gripper. The Proportional, Integral, and Derivative (PID) control method was only reported twice in the analyzed literature [61], [73], whilst a teleoperated solution was found three times [56], [57], [105]. Only one gripper was found in this study that used a neural network. This controller was utilized to hold an object without slipping with minimum force [106]. This whilst neural networks have been shown to be able to control soft hands to achieve grasp success rates over 80% for a wide range of objects [107], [108]. Furthermore, another soft gripper used a fuzzy force controller to minimize the error between the measured and reference force [95]. Moreover, to control the stiffness of another gripper, a variable impedance controller was used [109].

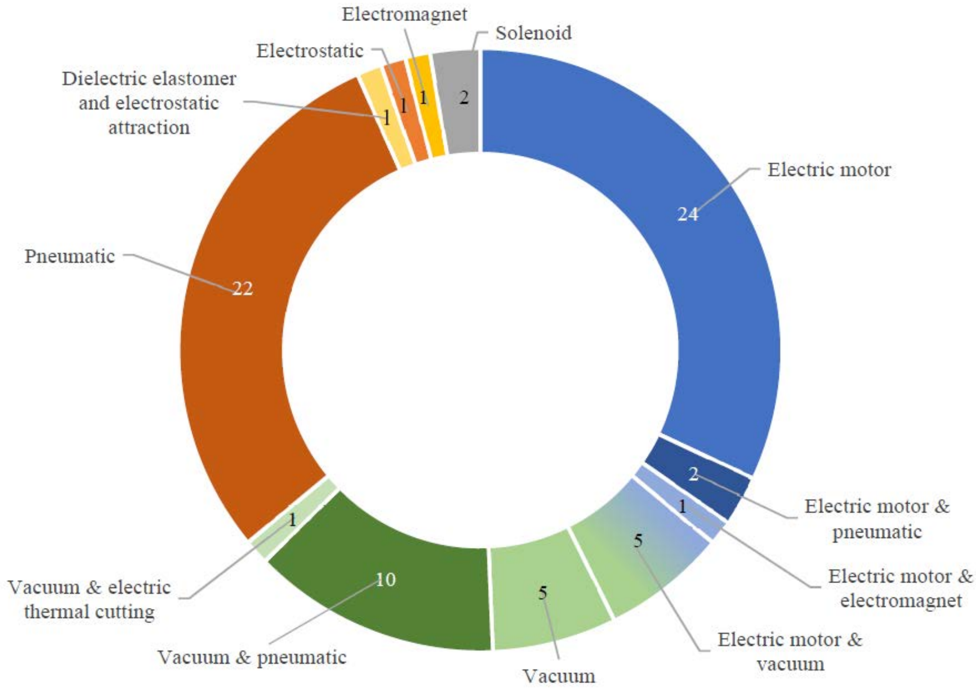

FIGURE 10. Number of soft grippers for crops using a specific type of actuator. Categories with electric motors are coloured in shades of blue and categories using vacuum are coloured in shades of green.

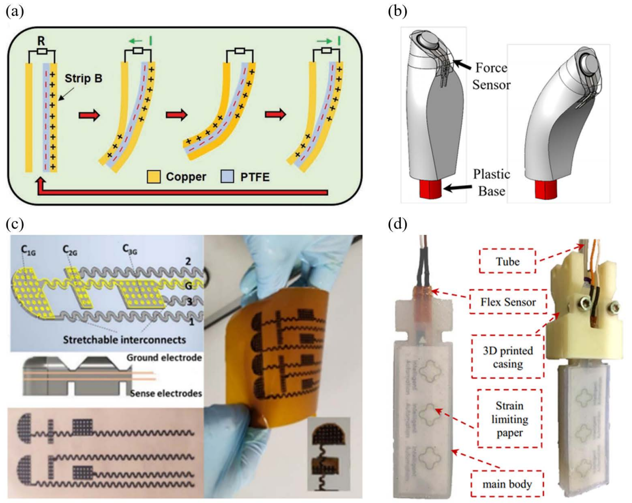

FIGURE 11. Examples of sensors used in the analyzed soft grippers. (a) TriboElectric NanoGenerators (TENG) to measure the bending angle. Adapted with permission from [102]. Copyright by 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (b) Resistive force sensor on fingertip in undeformed and deformed configuration [96]. (c) Design and fabrication of copper compliant capacitive sensors on Kapton, highlighted in yellow is the ground electrode [77]. (d) Embedded flex sensor for contact and position feedback [101].

D. METRICS AND PERFORMANCE

In this final subsection, we compare the overall design of the grippers based on some relevant performance metrics. First, we analyze the weight of the gripper and its payload. Then we set out the surface conditions the grippers were able to handle, followed by the contact forces the grippers applied. Finally, we present grip and detachment success rates, along with the measured damage to crop and plant.

TABLE 6. Number of soft grippers for crops that mention certain types of sensors in the gripper to measure aspects of the gripping cycle.

Aspect measured	Number of grippers
Pressure	8
Force	8
Flexing/bending	6
Air pressure	5
Position	6
Proximity	5
Touch/tactile	4
Light	4
Angle	3
Accelerations	1
Magnetic field	1
Temperature	1

Fig. 12 depicts the distribution of 16 grippers in terms of the weight of the gripper and the max payload (the remaining 62 grippers did not mention both metrics). The main cluster of grippers had their weight between 50 grams and four kilograms and could carry payloads in the range of 100 grams and 20 kg. The lowest payload to weight ratio is about 0.2, achieved by a controlled variable stiffness tomato gripper [52]. The largest payload to weight ratios are both achieved by the lightest grippers lying outside the aforementioned main cluster. The lightest gripper of 0.48 grams achieved a ratio of 383 [110]. The largest ratio was achieved by a dielectric elastomer with electro-adhesion on its fingertips, whilst weighing 1.5 grams; the gripper lifted a cylinder of 1.6 kg [111].

Table 8 summarizes the different surface types of objects and the number of grippers that successfully lifted them.

TABLE 7. Number of soft grippers for crops using certain control methods in their grasping cycle.

Control method	Specifics	Number of grippers
Feedback	*no specific operation mentioned*	19
	Teleoperation	3
	Adaptive neuro-fuzzy inference system (ANFIS)	1
	Fuzzy controller	1
	Variable impedance controller	1
Feedforward	PID	2
	no specific operation mentioned	11
	On-off	5
Manually controlled by an operator	*no specific operation mentioned*	5

This metric is important for the agricultural use case as not all crops have the same surface conditions. For example, all 78 analyzed grippers were able to grasp convex surfaces, such as apples. However, a relatively smaller amount of 16 grippers were proven to be able to also grasp irregular convex surfaces, such as raspberries and blackberries. Only one gripper was able to grasp irregular flat surfaces, by employing a vacuum cup with particle jamming lips [64]. What furthermore is shown in Table 8 is the sparse presence of only seven grippers capable of gripping concave surfaces.

To securely grasp a crop, a minimum amount of force has to be applied to be able to counteract gravity and accelerations of the manipulator using the friction between the surface and the crop. To enable an analysis of this concept, Fig. 13 presents an overview of the maximum measured contact force. From this figure, it can be seen that for 12 of the 26 grippers, this maximum force was below 5.0 N. The compliant mechanism apple gripper by Liu *et al.* generated up to 35 N [93]. Furthermore, Su *et al.* presented a gripper with two fingers, each composed of two FEA powered phalanges which generated up to 52.1 N at the fingertips, the largest force found in analyzed literature [84].

Finally, to analyze the grasping success rates of the analyzed grippers, it is important to note that only 18 works tested their gripper on more than ten individual exemplars within a type of crop, see Fig. 14. For example, if the gripper was tested on 1 strawberry, 2 apples, and 20 cucumbers, the largest sample size was considered to be 20, as in all analyzed papers, the subsequent performance metrics are based on this pool size. The majority of grippers, namely 60, were tested only in lab settings and usually just one picture of the gripper grasping a single crop was shown. These papers did not indicate their grip success rates and did not indicate whether they tested on more than one crop and were therefore excluded from the evaluation comparison below.

A total of 15 grippers reported either their grip or detachment success rates based on more than ten tests, and Table 9 shows an overview of their results. From this table, it can be seen that many different soft technologies are employed to grasp a wide variety of crops, with varying results. Furthermore, it can be noticed that the testing conditions also influence the results greatly. For example, Bac *et al.* reported detachment success rates of 4%, which was increased by removing leaves and clusters of crops to 46%. For harvesting strawberries specifically, the cushioned suction cup with two cushioned fingers by Yamamoto *et al.* surpasses a previous design which also used a suction cup but employed a pedicel gripper/cutter by Hayashi *et al.*, with a detachment success rate of 90.3% versus 79.7% [43], [59]. Furthermore, for the apple use case, the three-fingered, tendon driven gripper by Silwal *et al.* outperforms the three-fingered, fluidic elastomeric actuator by Hohimer *et al.*, with a detachment success rate of 84.6% and 67%, respectively [37], [75].

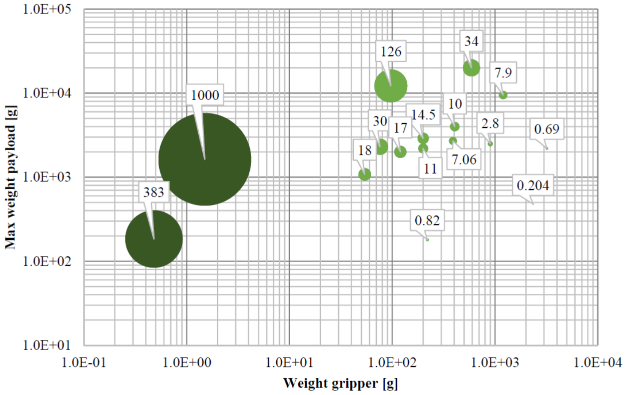

FIGURE 12. Weight of the soft gripper for crops on the logarithmic x-axis and the max weight of the payload the gripper could hold on the logarithmic y-axis, both in grams. The area of each bubble represents the payload to weight ratio of one analyzed gripper. The exact ratio is also given in a label next to each bubble. Note that not all researchers tested the absolute maximum payload. In these cases, the heaviest successfully lifted payload is used.

The detachment/grasping attempt ratio, i.e., how many times it was tried to grasp each crop, was often not reported or equal to one. Only a paper about the two grippers by Bac *et al.* reported that, for their simplified crop scenario, they used a grasp attempt rate of 1.2 [45]. The same applies to plant damage. Only the paper by Bac *et al.* reported that their fin ray type gripper damaged the leaves 35% of the time and the stem of the plant 4% of the time in the unmodified crop scenario. The vacuum cup with a cutter gripper investigated in the same paper did not damage the stem, but it did damage about 15% of the surrounding leaves. Damage to the crop is more frequently reported, but most papers do not mention how they classified the crop as being damaged. If reported, often the authors indicate that they saw no visible damage on the grasped objects. Some papers mentioned explicit damage rates, like the strawberry gripper by Yamamoto *et al.* and the eggplant gripper by Hayashi *et al.*, with both reporting 12.5% damage to the crops [44], [59]. Furthermore, the two grippers by Bac *et al.* reported between 20% and 28% damage to the crops whilst being used in greenhouse scenarios.

It should be stressed here that the results analyzed in this section are not all measured in realistic field scenarios. Of the 78 analyzed grippers, 17 were tested outside of a controlled lab environment. Namely, 13 grippers were tested in a greenhouse, two in an orchard [37], [75], one in a field [96] and one in a cropping tunnel [40].

TABLE 8. Number of soft grippers for crops able to grip different kinds of surfaces.

Type of surface	Number of grippers
Flat [a)]	20
Irregular flat [b)]	1
Convex	78
Irregular convex	16
Concave	7
Irregular concave	0

[a)] Flat surfaces are defined as having no macroscopic curvature at all.
[b)] Irregular surfaces needed to have multiple macroscopic curvature changes on the surface.

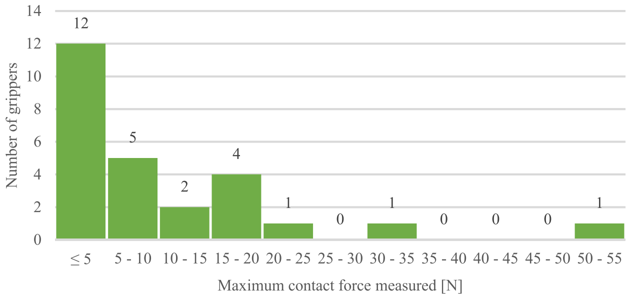

FIGURE 13. Number of soft grippers for crops with a certain maximum measured contact force (in N) at the gripping interface, bins do not include the lower bound but do include the upper bound. Note how 12 of the analyzed grippers did not generate contract forces above 5.0N.

IV. DISCUSSION

This study provided an overview of 78 soft grippers for crop handling and harvesting and compared their quantitative and qualitative characteristics. The grippers were classified into 13 grasping technology categories, and a relatively small subset of 15 grippers was found that provided performance metrics in realistic scenarios. The intended applications, technologies employed, and testing procedures of the grippers were quite differing, making it currently impossible to appoint specific grippers as more promising than others.

The types of crops the authors of the studied grippers have chosen seem to correlate with the global production quantity of those crops, see also Fig. 15. In Fig. 5 one can see that within the fruits category, apples, strawberries, oranges, and bananas are the most tested on. According to the statistic by Shahbandeh, apart from strawberries, these crops belong to the top four globally most produced fruits in 2019 ordered by weight [112]. It is imaginable that most authors took crops from an easily available, well-known pool, and that strawberries are included for increased diversity of size, shape and softness. The second most produced fruit, watermelons, was not found in the presented research. We reckon that the relatively heavy weight and large size of the fruit make it difficult for most grippers to securely hold and for manipulators to move the crop, thus making it less appealing to design for and test with. Moreover, the relatively hard shell of the melon could also make some of the advantages of the gentle touch of soft grippers superfluous compared to conventional grippers.

In Fig. 2, one can see that China and the USA published the largest quantity of papers in this field. This is congruent with the data from the World Bank which indicates the same two leaders regarding the absolute total scientific and technical articles published [113].

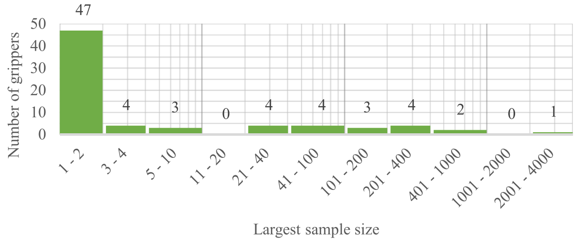

FIGURE 14. Number of soft grippers for crops testing on a certain number of individual specimens of one type of crop; see the discrete binned, logarithmic horizontal axis. From this figure, It can be seen that most analyzed grippers only test on one or two exemplar(s) of a type of crop. If a gripper was tested on multiple crops, the largest sample size within a type of crop is used, as in all papers analyzed, the performance metrics were based on that pool of specimens.

Regarding the used material in the production of the soft gripper, the heavy presence of silicone rubber and TPU is quickly identifiable from Table 5. These soft materials are often used with molding and direct 3D printing, respectively. These two methods allow for complex shapes and textures of the soft gripper, and the production is relatively low-cost [114]. Only a few papers show testing with a range of similar materials with different hardnesses to optimize the soft gripper performance. Furthermore, none of the analyzed grippers used complex composites, e.g. a gradient of materials, probably because this method is harder to model in CAD, harder to test in FEM, and requires more involved manufacturing methods.

Fig. 10 presented a multitude of actuators, but among the 78 analyzed papers, only one mentioned power usage [89]. This is an important metric in the development of field robotics, as it, for example, allows to calculate operation time with a certain amount of stored energy. Most authors likely tried to optimize other performance metrics for their gripper, such as grip success rate at this stage of the design process instead of (also) measuring and minimizing energy consumption.

Fig. 14 shows that 47 of the 78 grippers were only tested on one or two exemplar(s) per type of crop, whilst crops are known for their shape, size, weight, and firmness variability even within a single type of crop. For example, strawberries vary widely in shape from long-conic to oblate [115], in weight from at least about 12 up to 40 g, and in firmness from at least 60 to 135 g/m^2 [116]. Moreover, most of these grippers employed simple pick and place grasping procedures and did not delve into detachment from the plant or damage to the plant or crop. This group of papers often started from the onset of developing a novel gripper without a specific use case in mind, and probably did not focus on extensively evaluating agricultural applications because of that. This approach limits the extent to which comparisons with extensively tested agricultural grippers could be made, see also Table 9, where only 15 grippers could be included, the applications of which were also differing. The number of grippers with the same

TABLE 9. **Performance metrics of soft grippers for crops.a)**

	(Soft) technology	Reference	Tested crop	Sample size	Grip success rate	Detachment success rate	Crop damage
Unit	N/A	N/A	N/A	#	%	%	%
	Fluidic elastomer actuators	[86]	Mushroom	30	-	100	0
	Vacuum cup	[43]	Strawberry	590 (suction) & 187 (no suction)	-	79.2 (suction) & 79.7 (no suction)	-
	Vacuum cup	[40]	Mushroom	2975	-	81.6	1.88 (C) c)
	Vacuum cup	[33]	Mushroom	689	-	67.5	-
	Passive structure with an external actuator	[96]	Blackberry	240	-	77.92 – 95.24	0 – 16
	Fluidic elastomer actuators	[36]	Tomato	124	-	81 (C) c)	-
	Fluidic elastomer actuators	[79]	Cucumber (5 in parallel)	50	98	-	-
	Fluidic elastomer actuators	[75]	Apple	172	70	67	-
	Fluidic elastomer actuators + vacuum cup(s)	[44]	Eggplant	40	-	62.5	12.5 (C) c)
	Passive structure with an external actuator	[37]	Apple	150	90.7 (C) c)	84.6	0
	Passive structure with an external actuator +	[38]	Tomato	25	92	92	0
	Passive structure with an external actuator	[45]	Bell pepper	UC: 47 & SC: 47 b)	UC: 80 & SC: 95 b)	UC: 12 & SC: 27 b)	UC: 26 & SC: 28 b)
	Vacuum cup with cutter		Bell pepper	UC: 43 & SC: 39 b)	UC: 52 & SC: 60 b)	UC: 4 & SC: 46 b)	UC: 21 & SC: 20 b)
	Vacuum cup	[46]	Cucumber	225	-	80	-
	Passive structure with an external actuator +	[59]	Strawberry	237	-	90.3	12.5

a) Performance metrics of analyzed grippers that did more than ten tests on crops and provided grip and/or detachment success rates. b) Note how Bac et al. tested two different grippers in two conditions: an unmodified crop (UC) and a simplified crop (SC) scenario. I.e., with or without removal of leaves and fruit clusters that could hinder their prototype. c) The letter "(C)" after a value indicates that it was calculated from the data present in the referenced paper instead of being directly mentioned by the authors.

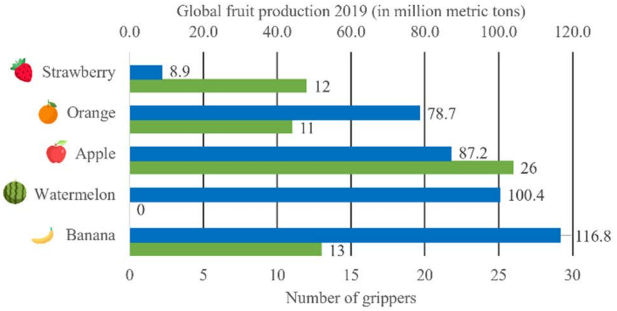

FIGURE 15. **In blue bars and top horizontal axis, the global fruit production per fruit in million metric tons (Shahbandeh, 2021), and in green bars and bottom horizontal axis, the number of grippers that tested on these fruits. One can see that for bananas, apples, and oranges both the production and testing is high, but for strawberries, the production is relatively low and for the watermelons, testing with soft grippers is absent. Crop icons: flaticon.com.**

application was thus limited, making it impossible to compare all the found grippers on a same scale, as the results of a cucumber gripper cannot be fairly compared to a strawberry gripper.

On the other end of the graph of Fig. 14, one can see that three papers tested their grippers on more than 400 individual exemplars within a type of crop. These papers have in common that the large sample sizes were not manually tested by humans, nor were they employed to improve the statistical significance of, for example, their grasping success rates [33], [40], [43]. Rather, these grippers were used in realistic, diverse harvest scenarios in which automatic detection, positioning, and removal were tested. Explaining both the need and feasibility of such large sample sizes.

Currently, it is difficult to compare the cycle time and the lifetime of the evaluated grippers. The cycle time is measured in different ways which made comparing them infeasible. For example, in some cases, the measured duration included manipulator movement, or even recognition processing time, whereas others reported the closing time of the gripper. The differences between these times can be large, e.g. the eggplant gripper by Hayashi *et al.* could grasp in 9.2 s, but localization, grasp, and release took 64.1 s [44]. The same problem arises with measuring the lifetime, ten grippers measured some indicator, such as the number of gripping cycles tested, number of cycles until failure, or the number of cycles of just the actuator. In both cases, a standardized test would be needed to enable a fair comparison.

Looking beyond the results of this paper, some requirements from [32] for pick and place robots in horticulture are not explicitly addressed by the analyzed literature. Examples are low maintenance, approval for contact with food, and ease of cleaning [32]. These factors can make or break the deployment of a gripper on an industrial level. It is, however, hard to measure these features quantitatively.

V. CONCLUSION

This study provided an analysis of the state-of-the-art of soft grippers for crop handling and harvesting and reported their quantitative and qualitative characteristics. We retrieved seventy-eight grippers from the academic literature and compared them with each other in terms of, amongst others, their design and reported performance. For example, we classified the grippers' designs into 13 distinct soft grasping technologies, where it has been found that not all possible (combinations of) technologies are explored in this field. Furthermore, we found that a small subset of agricultural soft grippers tests on selectively harvesting crops using a large sample size. We provided an overview of grip and detachment success rates and crop damage of this pool in Table 9. Additionally, we analyzed, amongst others, the grasping and detachment methods, materials used, payload to weight ratio, degree of actuation, degree of freedom, type of actuators and sensors employed, and the control of the gripping procedure.

Table 9 shows that the current performance of soft grippers for crops is inadequate to immediately fill in the labor gaps in the industry. Improvements on old grippers or entirely new designs are needed to improve detachment and damage rates. Improvements on old grippers or totally new designs are needed to improve detachment and damage rates. Future researchers could use the results and overview this paper gives to develop and test new soft grippers. For example, the gaps in Table 4 could be explored to research new (combinations of) grasping technologies for agricultural use cases. Future studies could also focus on designing standardized tests for soft grippers in agricultural applications, as most testing procedures found in this review were quite differing. For example, Fig. 5 shows that most researchers picked a couple of real crops from a wide range of options for testing, which has as a consequence that other researchers must compare the performances of grippers between literal tests on apples and oranges. In our opinion, this cannot be solved by using existing objects sets such as the Yale-CMU-Berkeley (YCB), as these consist of fake fruits, which have very different stiffnesses and weights compared to their real counterparts. They also lack the variability seen within a single type of crop, which makes real crops harder to grasp [117]. Another interesting line of research could be to study the impact on performance of grippers depending on different detachment/grasping methods or approach directions within and between crop species, see also Table 2 and 3 and Fig. 3 and 4. Lastly, for each crop, the connection between contact forces, see also Fig. 13, and the amount of damage to the crop, can be researched to further inform the design of future grippers.

APPENDIX

Supplementary tables can be found at https://doi.org/10.4121/19361837

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JOHANNES F. ELFFERICH received the B.Sc. degree *(cum laude)* in mechanical engineering from the Delft University of Technology, Delft, in 2019, where he is currently pursuing the M.Sc. degree in mechanical engineering, track biomechanical design.

Since 2019, he has been a part-time Mechanical Design Engineer at Odd.Bot, Rotterdam, The Netherlands. His current research interest includes robotic grippers for agricultural purposes, such as mechanical weed control and harvesting procedures.

DIMITRA DODOU received the Ph.D. degree *(cum laude)* from the Delft University of Technology, in 2006.

In 2007, she was a Postdoctoral Researcher at the Max-Planck Institute for Metal Research, Stuttgart, Germany. After returning to the Delft University of Technology, she received a VENI grant on the topic of strong of gentle grip of soft biological objects. She is currently an Associate Professor at the Department of Biomechanical Engineering, Delft University of Technology. Her main research interests include interfaces between soft and living matter, measurement methods for human factors for automated systems, and methodology for human-subject research.

COSIMO DELLA SANTINA (Member, IEEE) received the Ph.D. degree *(cum laude)* in robotics from the University of Pisa, in 2019.

From 2017 to 2019, he was then a Visiting Ph.D. Student and a Postdoctoral Researcher at the Computer Science and Artificial Intelligence Laboratory (CSAIL), Massachusetts Institute of Technology (MIT). He also held a postdoctoral position at the Department of Mathematics and Informatics, Technical University of Munich (TUM), in 2020, where he became a Guest Lecturer, until 2021. Since 2020, he has been affiliated with the German Aerospace Centre (DLR), as an External Research Scientist. He is currently an Assistant Professor at the Cognitive Robotics (CoR), TU Delft. His main research interests include modeling for control and model-based control of soft robots, intelligent control systems with application to robotics, and soft hands and manipulation of deformable objects. He has been awarded euRobotics Georges Giralt Ph.D. Award (2020) and the "Fabrizio Flacco" Young Author Award of the RAS Italian Chapter (2019). He has been a Finalist of the European Embedded Control Institute Ph.D. Award (2020).

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