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Review Article

A Systematic Review of Soft Actuators in Agriculture

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Abstract: Industrial machines and robots use actuators to facilitate repetitive tasks. Conventionally, stiff actuators are used to enable precise position control in a high-pace system. They are usually placed in human-free environments because of safety concerns as they do not comply in a collision. On the other hand, there has been a growing interest in human-robot interactions that require robots to be placed alongside humans. These applications need a soft actuator. An example of a soft actuator is a pneumatic muscle actuator (PMA) which produces a one-way motion and force as a result of the muscle’s contraction under air pressure. In this paper, the aim is to present a systematic review covering the main published solutions of soft actuators including PMA in agricultural applications. This paper provides a useful foundation on the soft actuators, their main applications in agriculture, their challenges and opportunities, as well as supporting new research works in the soft actuators' field.

Keywords: agriculture; soft actuator; pneumatic muscle actuator

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1. Introduction

Actuators are used everywhere to facilitate movements where a human is either incapable or requires great effort to perform. For example, the actuators that are used in industrial machines and robots to facilitate repetitive tasks. There are many types of actuators with the most common ones being pneumatic, hydraulic and electrical actuators. The type of actuator used depends on various factors such as precision, speed, cost and safety. A lot of outdoor equipment uses hydraulic or pneumatic actuators because of their portable energy sources. Pneumatic actuators are also preferred where cost, safety or pollution is a concern, for example, in the food processing industry. On the other hand, electrical or hydraulic actuators are sometimes preferred over pneumatic actuators due to some of their undesirable characteristics. For example, air is compressible which makes it difficult to control and many air compressors that provide the pressured air are noisy, which makes them inconvenient to work with.

Conventionally, stiff actuators have been used in industry because they enable precise position control in high-pace systems. Nevertheless, they are unsafe to operate near humans because they do not comply in a collision. On the other hand, there has been a growing interest in applying soft and compliant actuators in human-robot interaction to enable safe applications. For example, Wakimoto *et al.* (2011) presented a single-tube, micro silicone rubber pneumatic actuator which was simple, easy to fabricate and had large displacement. It was nicknamed “Nematode Actuator” because of its nematode-like, large bending motion. Besides being lightweight and safe, it was also dexterous and compliant, hence could be applied as a robotic end effector requiring curling motion and soft grasp. Similarly, Nakajima *et al.* (2013) developed an octopus-inspired robotic arm with 15 actuated degrees of motion and 8 degrees of freedom. Deimel and Brock (2016) also developed a compliant, underactuated, robust and dexterous anthropomorphic hand using a novel pneumatic actuator called PneuFlex. In addition to being safe, compliant actuators are also preferred for highly unstructured environment applications, for example, legged robots in rough terrain (Spröwitz *et al.*, 2013) and human-friendly robots (Pratt *et al.*, 2002), because of their force-controlled behaviour.

1.1. Mechanisms and Designs of Compliant Actuators

Vanderborght *et al.* (2013) defined compliant actuators as actuators with variable mechanical impedance, or variable impedance actuator (VIA). The impedance of an actuator can be defined as the ability of the actuator to resist motion and reach its set position regardless of the external forces it encounters. According to this definition, conventional stiff actuators have high and fixed impedance as they do not comply in a collision.

A few categories of VIA are active impedance by control actuator (AICA) and inherent compliance actuator (ICA) (Vanderborght *et al.*, 2013). AICAs are actuators which do not have a passive compliant element and rely on the controller alone to imitate the compliant behaviour (Albu-Schäffer *et al.*, 2007). They were first used in DLR (Institute of Robotics and Mechatronics, Germany) robots and have been used in commercial robots such as Kuka. An advantage of the AIC actuator is that it can vary the impedance online. However, its controller is complex and requires an accurate model of the system.

Different to AIC actuators, ICAs contain passive compliant elements. They can be categorised according to how the impedance is varied. Actuators with fixed compliance vary the impedance using software control whereas actuators with adaptable compliance do so via mechanical reconfiguration.

The most well-known ICA is the series elastic actuator (SEA) which has fixed compliance. It uses the concept of storing and releasing energy using elastic elements such as spring with constant stiffness between the gear and the load. The earliest paper that discussed the concept was by Pratt and Williamson (1995). The authors argued that despite the advantages of the then conventional method of the stiff interface, reduced stiffness interface offered several advantages including the ability to store energy. From the initial concept, several modifications were done to improve the interface performance. For example, Mathijssen *et al.* (2013) showed that compared to SEA, series-parallel elastic actuation (SPEA) was able to reduce not only the motor’s power requirement but also its torque demand, and thus can produce a smaller-sized motor. On the other hand, Mooney and Herr (2013) proposed another concept called continuously variable series elastic actuation (CV-SEA) which had a similar aim of reducing both requirements. They showed that by implementing a continuously variable transmission between a motor and its series elastic element, CV-SEA required less energy than SEA when used in a knee prosthesis during level-ground walking. In addition, Rouse *et al.* (2013) added a clutch in parallel with the motor within the SEA and called it clutchable series elastic actuation (CSEA). By doing so, it was demonstrated that the CSEA knee was able to save 70 % of energy compared to the SEA in a simulation study. Further treatment on ICA was covered by Plooij *et al.* (2017) where a clutched elastic actuator, which is a variation of the SEA configuration was investigated.

The second class of ICA is known as variable stiffness actuator (VSA) which uses adaptable compliance strategy. It adjusts the stiffness by changing the pretension of the spring connected to the motor. Some of the methods to do so are by adding an additional moment arm and a motor to generate and control stiffness, using a spiral pulley with linear spring or changing the effective length of the spring. More recently, Roozing *et al.* (2016) proposed the concept of asymmetric antagonistic actuation which they argued produced substantial energy efficiency improvement compared to the earlier VSA designs. In addition, VSAs were reviewed by Ham *et al.* (2009) where they were divided into equilibrium-controlled stiffness, antagonistic-controlled stiffness, structure-controlled stiffness and mechanically controlled stiffness. The authors also compared them based on 10 characteristics such as the minimum number of springs required and the possibility to vary linearity of the stiffness curve. Wolf *et al.* further elaborated on the VSAs by giving detailed guidelines on how to design them such as how to select the motors, sensors and springs (Wolf *et al.*, 2016). Jafari *et al.* (2015) also presented a review of VSAs where the characteristics of three VSAs; AwAS, AwAS-II and CompACT VSA were compared. While the three were similar in that different motors were employed to control the position and stiffness, and a lever mechanism was used to regulate the stiffness, their mechanical realisation and thus stiffness characteristics were different.

1.2. Designs of Pneumatic Muscle Actuator

Whereas the previous section discusses a class of compliant actuators known as VIAs, this section focuses on another class, the pneumatic muscle actuator (PMA). PMA can be described as a contractile and linear motion engine powered by gas pressure (Daerden & Lefeber, 2002). Its main feature is a flexible reinforced closed membrane connected to fittings at both ends through which mechanical power is transferred to a load. It contracts and exerts a pulling force on its load when air pressure is applied, thus producing a linear and one-way motion and force. Its low weight and highly compliant characteristics have been much appreciated in the robotic community because of the need to save energy and improve safety in applications involving human-robot interaction. Moreover, it uses a cheap, safe and clean energy source which is air pressure. This fact may explain why there is an increasing interest in their applications, for example, in continuum manipulators (Mohamed *et al.*, 2020), serial robots (Anh, 2010), servo systems (Jouppila *et al.*, 2014; Shen, 2010) and parallel robot (Son *et al.*, 2017), just to name a few.

In Zhang and Philen (2012), different manufacturing materials and processes to produce PMA was discussed among others. For the McKibben muscle, its basic construction is an elastic bladder covered by a braided sleeving, terminated by a clamping piece at one end and an air interconnection at another end. An example of the material used to make the bladder is silicone rubber, whereas for the sleeve, nylon. The materials are available commercially, making it possible to self-fabricate a McKibben muscle. However, to get the desired performance, the materials have to be chosen carefully because the bladder's hardness, number of fibre braided sleeves and braiding angle affect the muscle's maximum contraction and force (Davis & Caldwell, 2006; Kurumaya *et al.*, 2017). Additionally, to ensure air tightness when self-fabricating, the termination needs to be done carefully. For example, Vocke *et al.* tested several methods before settling with the swage-and-epoxy termination method (Vocke *et al.*, 2012).

Besides the McKibben muscle, a few researchers have proposed alternative PMA designs to overcome the McKibben muscle's shortcomings that are inherent in its design. This includes loss in output force caused by material stretching (Daerden *et al.*, 2001). For example, Villegas *et al.* proposed a pleated membrane structure called pleated PAM (PPAM). The membrane has high tensile stiffness to avoid the strain commonly associated with rubber. It is folded together along the long axis so that when applied with pressure, the muscle contracts. By preventing material stretching, the muscle is able to operate at low pressure and produce larger maximum contraction (Villegas *et al.*, 2012). Similar designs have also been used in the researches performed by Ito *et al.* (2020) and Terryn *et al.* (2018).

Besides PPAM, another novel design is the fibre-reinforced origamic robotic actuator (FORA) (Yi *et al.*, 2018). Unlike PPAM, its construction is similar to a McKibben muscle where it contains a bladder covered by a sleeve. However, instead of straightened rubber, the bladder is made of thermoplastic polyurethane and folded like origami. The authors claimed a significant improvement over a McKibben muscle with a maximum contraction force of over 50 % at only 0.1 MPa. In addition to that, it can be fabricated just by using a 3D printer.

A key challenge in PMA is the need for an external pressure source such as an air compressor which limits its practicality in untethered applications. To answer the question, “Is it possible to use the same method to actuate PMA without actually supplying pressure to the muscle?”, Miriyev *et al.* (2017) have proposed a low-cost electrically driven artificial muscle. To enable pressure change inside the muscle, the muscle is filled with ethanol which produces extreme volume change when heated. The heating is controlled through the electrical wiring connected to the muscle. By replacing thick pneumatic hoses with thin electrical wirings, the muscle’s mobility is improved. However, despite the obvious advantage, the life cycle of the actuator and its reliability when mass-produced has not been proven yet.

There is also another class of PMA called miniature McKibben muscle or thin McKibben muscle (TMM). Ashwin and Ghosal (2018) define it as a PMA with an outer diameter of less than 5 mm. Because of its minimal size, it can be used in tight spaces. An example of the fabrication process of TMM is detailed out in De Volder *et al.* (2011) where a TMM using a self-fabricated clamping piece with air interconnection, an off-the-shelf bladder and sleeve was developed. Chakravarthy *et al.* (2014) went a step further by fabricating their own bladder and sleeve. In order to produce a TMM, a low-diameter bladder had to be used, but it came at the price of reduced contraction ratio and force capacity (Kothera *et al.*, 2009). Even though decreasing the bladder’s wall thickness can reduce the issues, there was a limit to how much it could be done before the bladder gave way to high pressure. Therefore, they had to tinker with the bladder diameter and wall thickness before finalising the bladder design.

Even though the previously cited self-fabricated muscles have shown good performances, they have not been proven in mass production. Lightweight TMM with an outer diameter as low as 1.8 mm and weighing as low as 1.3 g/m has been produced commercially in the last five years (Kurumaya *et al.*, 2017). The availability of the commercial TMM can be the catalyst for a wider adoption among the public.

There are also several studies aiming to improve the PMA's performance or aid their applications. For example, Xie *et al.* (2021) designed a contraction ratio amplification mechanism (CRAM) to increase the contraction ratio. In addition, Mansard (2021) demonstrated the possibility of a macroporous smart gel as the tubing PMA material to realise a large PMA with minimal actuation time. Aside from that, many researchers have developed self-sensing PMAs to precisely control PMA (Hitzmann *et al.*, 2021; Kanno *et al.*, 2021; Legrand *et al.*, 2020; Wakimoto *et al.*, 2016). Other novel designs include using variable recruitment to maximise the efficiency of bundled McKibben muscles (Robinson *et al.*, 2015).

1.3. Applications in Agriculture

In agriculture, soft actuators have been used mainly as end effectors for agricultural robots, offering solutions for tasks that require dexterity, gentleness, and adaptability. Xie *et al.*, (2022) provided a thorough review of some of the end-effector applications such as in clamping and absorption mechanisms. A few examples given include medium-sized horticultural harvester (Russo *et al.*, 2017), pumpkin picker (Roshanianfard & Noguchi, 2020) and tomato picker (Hou *et al.*, 2021).

2. Materials and Methods

Systematic review is "a review that uses explicit, systematic methods to collate and synthesise findings of studies that address a clearly formulated question" (Page *et al.*, 2021). Different to a normal review, a systematic review requires its author to detail out the methods used in compiling the review, thus enabling other researchers to conduct a similar review in the future. The transparent reporting also ensures that the review is trustworthy and reliable and therefore helps the researchers to make the best decision.

2.1. Literature Review Planning Protocol

The review process follows this methodology (Carvalho *et al.*, 2019):

Research questions:

Q1. What materials are the soft actuator made of?

Q2. What applications are the soft actuator used in?
Q3. What are the design requirements of the soft actuator?
Q4. How is the performance of the soft actuator measured?
Exclusion criteria:
E1. Works not related to soft actuators or agricultural application
E2. Works that do not result in any form of actual experimentation, for example, simulation
E3. Works in which it is not clear from the title and abstract that they match the topic surveyed
Data extraction fields:
D1. Materials the soft actuator is made of
D2. Applications of the soft actuator
D3. Design requirements
D4. Performance parameters

2.2. Execution

Web of Science Core Collection (http://apps.webofknowledge.com) has been chosen as the database for our literature survey. It is a curated collection containing more than 21,100 peer-reviewed, high-quality scientific journals published worldwide. The survey was performed on January 14th, 2023. The search is based on the “Topic” field whose string is “agriculture* AND ((McKibben OR soft) AND (actuator* OR muscle*) OR (pneumatic AND muscle* AND (actuator* OR artificial)))”. The “Topic” field has been chosen as the search would encompass papers’ title, abstract and author keywords. The timespan (year published) of the search was limited to 2012-2023. The search resulted in 42 papers of which 22 were rejected based on exclusion criteria E1, E2 and E3.

3. Results of the Literature Review

Figure 1 shows the bar chart on the number of articles published between 2012 and 2023 using the extraction criteria mentioned previously. It can be seen that before 2017 and in 2018, there was zero publication. This trend indicates that the interest started to solidify in 2019 and has been steadily increasing ever since. Moreover, the trend seems to coincide with the increasing trend in publications related to human-robot interaction (search string: “human-robot”), as shown in Figure 2. In addition, search query with both soft and human-robot (search string: “human-robot” AND “soft”) also shows an increasing trend, as shown in Figure 3. These facts suggest that increasing demand in human-robot applications has been the catalyst for the increasing development of soft actuators in agriculture.

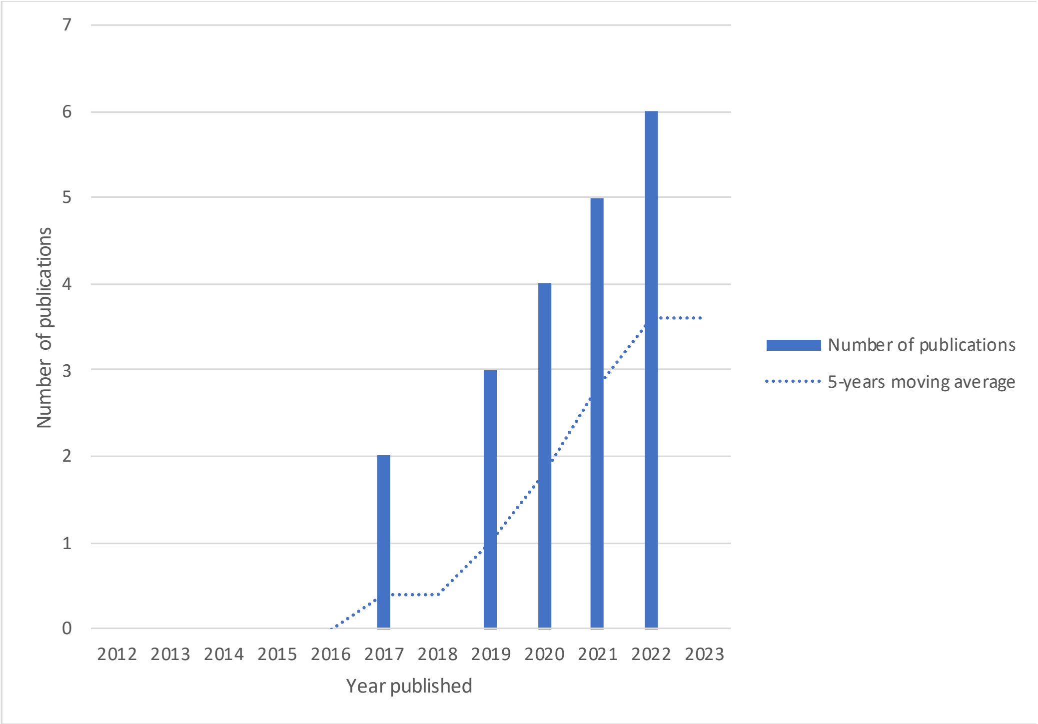

Figure 1. Number of publications for the last 10 years

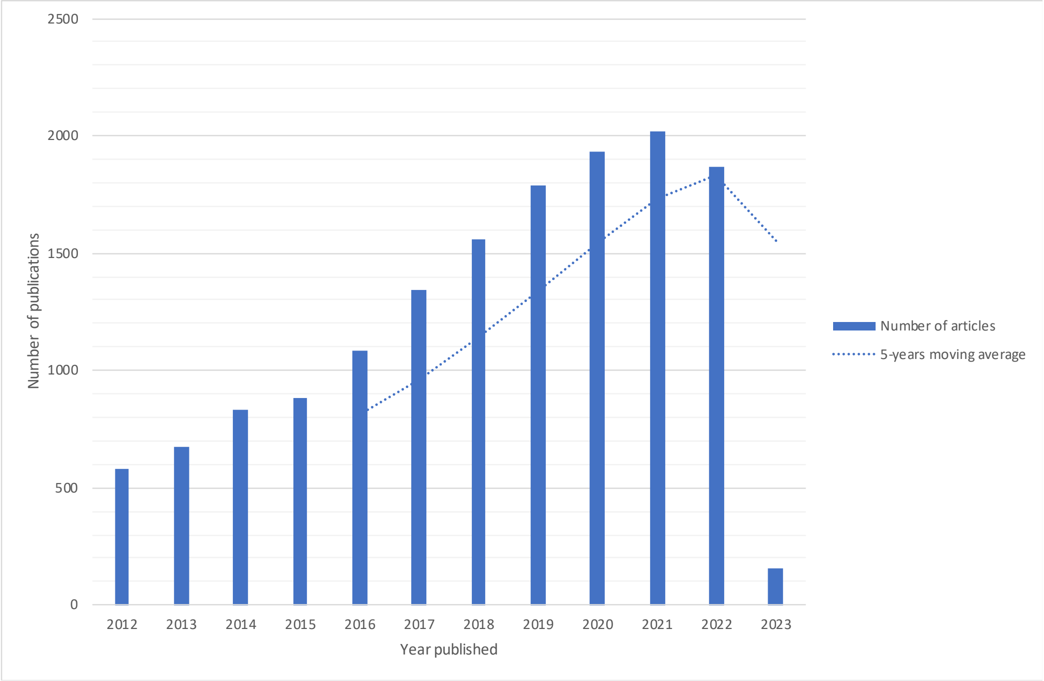

Figure 2. Number of publications related to human-robot interaction for the last 10 years

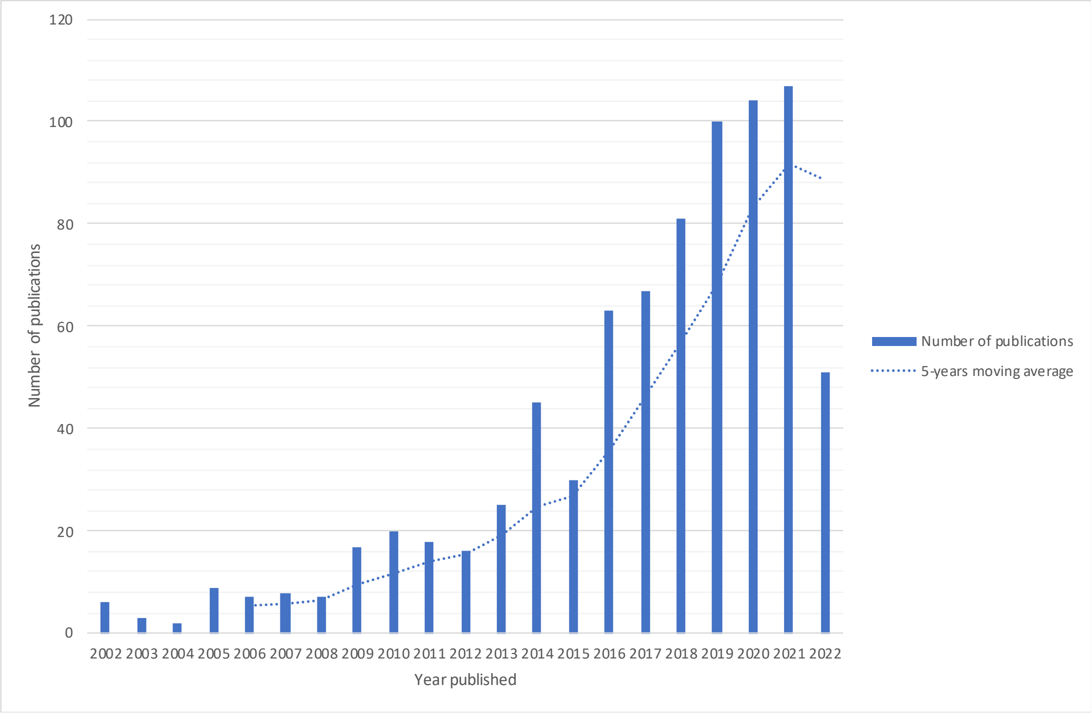

Figure 3. Number of publications related to soft actuator and human-robot interaction for the last 20 years

3.1. Publication Distribution Among Journals and Conferences

From the selected papers, 15 have been published in journals while five have been published in conferences. The journal papers belonged to 14 different journals, with the only journal with more than a single publication being Sensors and Actuators A: Physical. The other journals were, sorted alphabetically, ACS Applied Materials & Interfaces, Actuators, Advanced Materials Technologies, Agronomy-Basel, Bioinspiration & Biomimetics, Frontiers in Bioengineering and Biotechnology, IEEE Robotics and Automation Letters, IEEE Transactions on Automation Science and Engineering, International Journal of Agricultural and Biological Engineering, International Journal of Interactive Design and Manufacturing, Journal of Robotics and Mechatronics, MRS Bulletin and Soft Robotics.

On the other hand, the conference papers belong to five different conferences, all with a single publication. The conferences are, the oldest first, 2019 ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2019 Machines, Mechanism and Robotics (INaCoMM 2019), 2020 3rd IEEE International Conference on Soft Robotics (ROBOSOFT), 2021 Electroactive Polymer Actuators and Devices (EAPAD) XXIII, and 2022 Electroactive Polymer Actuators and Devices (EAPAD) XXIV.

3.2. Publication Distribution by Materials

Table 1 shows a summary of the number of publications related to the materials used. It can be seen that polymers such as elastomer or silicone rubber (Cao *et al.*, 2022; Chen *et al.*, 2021; Guanjun *et al.*, 2017; Navas *et al.*, 2021), dielectric elastomer (Hiruta *et al.*, 2021), electroactive polymer (Briggs *et al.*, 2021; Briggs *et al.*, 2022) and thermoplastic elastomer (TPE) (Cao *et al.*, 2022) have been the material most used with eight articles using them in their works.

Table 1. Summary of materials used and their number of publications

Material	Number of publications
Polymer	8
Thermoplastic polyurethane	4
McKibben muscle	2
Others (soft hydrogel, gelatine, carbon composite, engineered neuromuscular tissues)	6

3.3. Publication Distribution by Applications

Table 2 shows a summary of the number of publications related to their intended applications. It can be seen that most of the publications focus on fruit picker applications. This is probably due to the practicality of fruit picking for a soft actuator. Even though fruit picking is considered simple, selecting the right fruits which are ready to harvest remains a challenge.

Table 2. Summary of applications and their number of publications

Application	Number of publications
Fruit picker	14
Apple quality assessment	1
Bacteria detection	1
Cellular agriculture	1
Orthosis	1
Soil monitoring and exploration	1
Untethered digestible exploration	1

3.4. Citation Analysis

The number of times an article is cited represents the importance of the paper as it shows how relevant the paper is to other researchers. To perform the citation analysis, the Web of Science Core Collection portal has been used. Table 3 shows the most important articles which have citations of more than 10.

Table 3. Summary of top-cited articles

Title	Citations
A plant-inspired robot with soft differential bending capabilities (Sadeghi *et al.*, 2017)	46
A Soft Master-Slave Robot Mimicking Octopus Arm Structure Using Thin Artificial Muscles and Wire Encoders (Furukawa *et al.*, 2019)	16
Pose Characterisation and Analysis of Soft Continuum Robots With Modelling Uncertainties Based on Interval Arithmetic (Tan *et al.*, 2019)	16
Soft Robotic Manipulation System Capable of Stiffness Variation and Dexterous Operation for Safe Human-Machine Interactions (Chen *et al.*, 2021)	15
Design and implementation of variable inclined air pillow soft pneumatic actuator suitable for bioimpedance applications (Saleh *et al.*, 2020)	12

The paper with the highest number of citations is “A Plant-inspired Robot with Soft Differential Bending Capabilities” by Sadeghi *et al.* (2017), which has 46 citations. The paper presents a soft robot inspired by the movement of plants, which uses differential bending to achieve complex movements and tasks. The paper has likely received a high number of citations because it presents a novel approach to soft robotics that is inspired by nature. The use of differential bending to achieve complex movements is a unique and innovative idea that has attracted the attention of researchers in the field.

The second most cited paper is “A Soft Master-Slave Robot Mimicking Octopus Arm Structure Using Thin Artificial Muscles and Wire Encoders” by Furukawa *et al.* (2019) which has 16 citations. The paper presents a soft robot that mimics the structure and movement of an octopus arm using thin artificial muscles and wire encoders. Similar to the previous paper, the paper has likely received a high number of citations because it presents a novel approach to soft robotics that is inspired by nature.

The second joint most cited paper is “Pose Characterisation and Analysis of Soft Continuum Robots With Modelling Uncertainties Based on Interval Arithmetic” by Tan *et al.* (2019). The paper has likely received a high number of citations because it presents a novel approach to characterising and analysing the poses of soft continuum robots, which are a type of soft robot that can bend and twist in multiple directions. The paper provides a detailed analysis of the performance of the method, which makes it a valuable resource for researchers who are interested in developing similar methods for analysing soft continuum robots.

The similarity between the highest cited papers was that they have been published in a high-impact journal, which has likely contributed to their high citation count. The journals’ reputation and visibility have likely helped to increase the papers’ exposure and attract more citations from other researchers in the field. Overall, the papers’ innovative approach, detailed analysis, and publication in a high-impact journal have likely contributed to their high citation count.

4. Discussion

4.1. Soft or Hard?

Ahrary (2014) in his paper proposed that the mechanism of his robotic finger can be applied to realise a soft gripper. However, upon full paper inspection, it was concluded that this is probably not true. Besides the fact that it is not mentioned what material the gripper is made of, the inserted figures also show that the gripper is made of hard steel-like material. Moreover, the gripper has not been tested on soft objects such as a cherry or a leafy vegetable. Therefore, there is no reason to believe that the gripper is soft and therefore, it was rejected based on the E1 criterion.

4.2. Advantages of Soft Actuators

Soft actuators are more flexible than stiff actuators, which allows them to conform to irregular shapes and surfaces. This makes them ideal for applications where adaptability is important, such as in agriculture. In Wakimoto *et al.* (2011), a single-tube, micro silicone rubber pneumatic actuator was presented, which was simple, easy to fabricate and had large displacement. It was nicknamed “Nematode Actuator” because of its nematode-like, large bending motion. Besides being lightweight and safe, it was also dexterous and compliant, hence could be applied as a robotic end effector requiring curling motion and soft grasp. In addition, compliant actuators are also preferred for highly unstructured environment applications, for example, legged robots in rough terrain (Spröwitz *et al.*, 2013) and human-friendly robots (Pratt *et al.*, 2002), because of their force-controlled behaviour.

Soft actuators are also safer than stiff actuators because they are less likely to cause injury or damage in the event of a collision. This makes them suitable for applications where human-robot interactions are required. For example, Nakajima *et al.* (2013) developed an octopus-inspired robotic arm with 15 actuated degrees of motion and 8 degrees of freedom. Deimel and Brock (2016) also developed a compliant, underactuated, robust and dexterous anthropomorphic hand using a novel pneumatic actuator called PneuFlex.

4.3. Disadvantages of Soft Actuators

While soft actuators are generally more durable than stiff actuators, they can still be prone to wear and tear over time, especially when used in dynamic and repetitive motion applications. This is because they use materials that are more flexible and deformable, which can lead to fatigue and failure. In addition, over time, the materials may degrade, affecting their performance (Marchese *et al.,* 2015).

Besides that, soft actuators can be more difficult to control than stiff actuators because they are more flexible and deformable. This can make it challenging to achieve precise movements and positions, especially in high-precision applications. This complexity can make control algorithms more intricate (Mhd Yusoff *et al.*, 2022).

Soft actuators may also have limited force output compared to stiff actuators, which can limit their suitability for certain applications that require high force output. Because of this, they are often used in applications that don't require high-force output (Polygerinos *et al.*, 2017).

4.4. Future Directions

Soft actuators have the potential to revolutionise various aspects of agriculture by enabling more precise and adaptable control over agricultural processes and machinery. The integration of soft actuators into autonomous farming systems could improve the precision of agricultural tasks, such as planting, weeding, and harvesting. They can also provide gentle manipulation of crops and adapt to irregular terrains. Therefore, soft grippers and manipulators that can adapt to the shape and size of different fruits and handle them gently during harvesting could be developed (Banfi *et al.*, 2017).

Besides that, the advancement of soft robotic systems capable of harmonious collaboration with human labour in agricultural settings holds the potential to not only enhance overall efficiency but also elevate the skillsets and productivity of farm workers. As part of this transformative paradigm, the integration of soft wearable devices designed to assist with physically demanding tasks emerges as a particularly promising avenue. These wearable devices, built with compliant and adaptable materials, can seamlessly interface with the human body, providing support and amplification to a worker's physical capabilities, ultimately reducing fatigue and minimising the risk of injury. Such innovation represents a significant leap toward a more ergonomic, safe, and productive work environment within the agricultural sector, underscoring the evolving synergy between technology and human expertise (Della Santina *et al.*, 2020).

5. Conclusions

A systematic literature review has been carried out covering the main papers of soft actuators in agriculture and answering the research questions described in the literature review planning protocol. Soft actuators are used in many applications, and therefore various materials are used because of the different requirements for each application. The interest in this research area is consistent for the past five years as shown by the number of articles published yearly. The articles have also been published in a range of journals and conferences, which points to its wide audience. It is hoped that some insight can be gained on how to best apply soft actuators in agriculture. It is also hoped that future works could be focused on improving the applications' performance by investigating many different materials.

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