REVIEW

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A Comparative Analysis and Scoping Review of Soft–Rigid and Industrial Parallel Rigid Grippers

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In this research, it is aimed to present a comparative analysis of soft–rigid industrial parallel rigid grippers to compare their technical capabilities and assess the potential for soft–rigid grippers to address the challenge of grasping fragile objects with various shapes and sizes. In this research, 24 soft–rigid grippers are first identified through a scoping review using the Web of Science database, capturing their technical features and performance. Providing a variable stiffness grasp ($n = 9$, 37.5%) and a limited grasp capability ($n = 8$, 33.3%) is the most common advantage and challenge, respectively, of soft–rigid grippers. Pneumatic actuators ($n = 12$, 50.0%), followed by tendon-driven electric rotary actuators ($n = 9$, 37.5%), are the predominant actuators used for soft–rigid grippers. Soft–rigid grippers are found to have a lower output force-to-weight ratio ($n = 9$, median $(\tilde{x}) = 13.62$, standard deviation $(\sigma) = 15.17$) in comparison to industrial parallel rigid grippers ($n = 63$, $\tilde{x} = 76.53$, $\sigma = 35.53$), but can provide a larger range of motion ($n = 20$, $\tilde{x} = 110.00$ mm, $\sigma = 42.97$ mm). This is the first quantitative comparative analysis between industrial parallel rigid and soft–rigid grippers, enhancing the understanding of their status and prospects in industrial applications. Herein, a common approach is proposed to standardize reporting to facilitate benchmarking between research-based and industrial grippers and highlight controlling soft–rigid grippers is an underexplored area that can enhance the technology's performance.

1. Introduction

1.1. Industrial Need

The rigid industrial gripper is a well-developed technology that has been widely adopted in industries since 1961 when the first industrial parallel gripper was introduced.[1] Current industrial grippers are highly advanced and diversified providing a large number of sizes and shapes.[2] The industrial gripper's capability to perform repetitive activities with a high level of repeatability, such as "Pick-and-Place" (PAP) operations, makes them the popular choice in industries like agriculture, manufacturing, and food processing.[3–5]

The robotic grippers excluding vacuum suction cups have been categorized as "rigid," "soft," and "soft-rigid" grippers.[4] In this research, vacuum suction cups are not included as a type of gripper, because it is not considered to have "fingers". With irregular, compliant, or fragile objects, the material stiffness of the gripper plays an essential role. Wang et al. and Hernandez et al.[3,6] identified the risk of damage to fragile and/or compliant objects from rigid grippers due to their hard surfaces. Long et al. Zhang et al. and Tai et al.[1,4,5] identified the lower flexibility and limited degree of freedom (DOF) of rigid grippers as a barrier to grasping a more diverse range of objects. To address this problem, industry and researchers started replacing the purely rigid grippers with soft grippers. Unlike rigid-body robots, soft robots are mainly made from elastic materials (e.g., silicone and rubber), which allow for a lower gripper mass, more flexibility, and increased safety around humans in close proximity allowing for collaborative working.[7]

However, Cheng et al. and Park et al.[8,9] highlighted that current soft grippers cannot support high payloads with high stability due to their materials and structure. Thus, purely soft or rigid grippers are insufficient for practical applications in industrial manufacturing.[10,11] Soft–rigid systems combine the flexibility and adaptability of soft materials with the stability and strength of rigid components.[9] This combination can allow for grippers to exhibit the advantages of both rigid grippers (high object mass, repeatability) and soft grippers (high object diversity, fragile objects). However, there is no quantitative comparative analysis between soft–rigid and industrial rigid parallel grippers. Additionally, none of these reviews have focused on the potential of soft–rigid grippers for meeting industrial requirements and PAP applications.

This research aims to present a comparative analysis of soft–rigid gripper technologies and industrial parallel rigid grippers to

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compare and contrast their technical capabilities and assess the potential for soft–rigid grippers to address the challenge of grasping fragile objects with various shapes and sizes. The results of this research shall provide a comprehensive quantitative comparative analysis between rigid parallel and soft–rigid grippers. The rest of this research is organized as follows: the methodology is described in Section 2; Section 3 presents the main results and discussion while Section 4 summarizes the conclusions including the contribution of this research.

2. Methodology

This research was carried out in two stages. In the first stage, a scoping review was conducted to identify the state of the art of current soft–rigid grippers. In this research, we define "soft-rigid" as grippers that contain both rigid and soft/flexible components. In stage two, a non-systematic search was conducted to compare the capability of soft–rigid and other grippers. A comparison of technical parameters between the identified soft–rigid grippers and industrial parallel rigid grippers was then undertaken to determine whether the current soft–rigid grippers can meet industrial needs.

2.1. Stage 1: Scoping Review

2.1.1. Search Strategy and Study Selection

The search "Soft-Rigid AND Pick AND Place OR Grasping OR Manipulation OR Gripper OR Arm*" was used to search all Web of Science online databases. The title, abstract, and full text were screened for studies which met the following selection criteria: 1) studies published before 30/04/2024; 2) studies related to the design or application of soft or soft–rigid manipulators and/or grippers, including both industry- and research-based applications; 3) studies that used the gripper to pick up objects; and 4) studies written in English.

This research followed the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses – Extension for Scoping Reviews* (PRISMA-ScR).

Studies that only picked up objects were included, as limiting the selection process to publications examining a full PAP operation would have overly limited the scope of the review.

In total, 111 studies were identified from Web of Science database. **Figure 1** illustrates the study selection process. After excluding studies deemed irrelevant during the screening of titles and abstracts, and removing studies that did not pick up objects or did not include a gripper, a total of 24 studies were considered suitable for inclusion in the final review.

2.1.2. Data Extraction

Key information including patterns, trends, inconsistencies, and gaps of identified soft–rigid grippers were summarized and synthesized. The technical parameters used for industrial grippers (type, design, application, payload, size, workspace, control strategy, advantages, and limitations)[12] were systematically extracted from the selected studies.

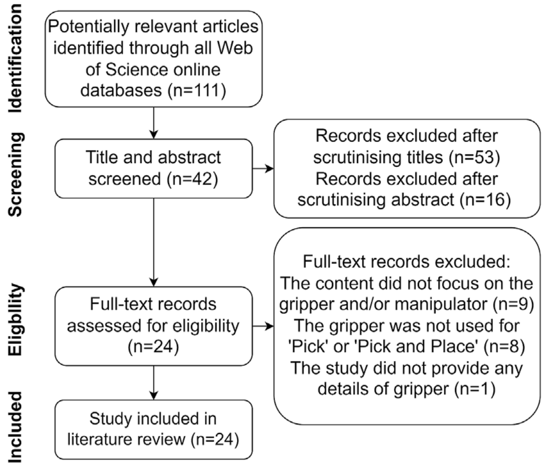

Figure 1. PRISMA-ScR of literature search and selection.

2.2. Stage 2: Comparison between Soft–Rigid and Industrial Parallel Rigid Grippers

A technical comparison between soft–rigid and industrial parallel rigid grippers was conducted to identify the capability gap between them. Industrial parallel rigid grippers were screened using the following criteria: 1) the industrial parallel rigid gripper is commercially available with details of technical performance; 2) the industrial parallel rigid gripper has an output force of $\leq$210 N, which is the maximum output force found for a soft–rigid gripper from the literature.

Figure 2 illustrates the technical parameters used for describing the industrial parallel rigid grippers and soft–rigid grippers identified in this research.

The common parameters that were used for comparison were: 1) range of motion (in millimeters, the distance between gripper fingers, which is the maximum diameter of the objects that can be grasped); 2) output force (in Newtons, the maximum force of each gripper finger); 3) payload (in Newtons, the maximum weight of object the gripper can grasp); 4) gripper weight (in Newtons); 5) output force to weight ratio; 6) finger length (in millimeters, the distance between the gripper palm and fingertip); and 7) response time (in seconds).

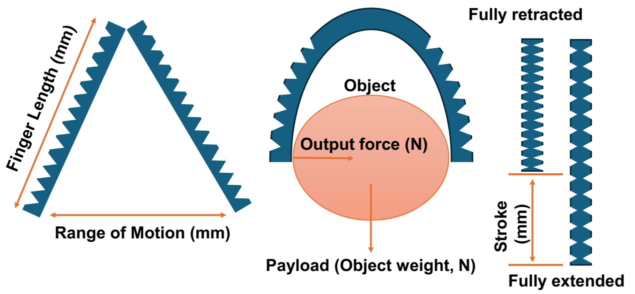

Figure 2. Illustration of the technical parameters used for comparison between manipulator types.

3. Results and Discussion

3.1. Results of Stage 1: Scoping Review

3.1.1. Motivation for Developing Soft–Rigid Grippers

Table 1 illustrates the general advantages and challenges for industrial parallel rigid grippers, research-based soft grippers and research-based soft–rigid grippers. Soft–rigid grippers have been designed to overcome the challenges faced by purely soft grippers, namely lower payload capacity, less stable grip, and jerky movement.[8,9,13,14] They have also been designed to overcome the challenges of purely rigid grippers, namely adaptability compliance, and high gripping pressure; increasing the likelihood of successfully gripping objects of various sizes, shapes, and constructions.[14–16] For purely soft grippers, generating sufficient gripping force to handle heavy objects can be challenging. Conversely, purely rigid grippers often generate high object pressures, which precludes the manipulation of fragile items (S1, Supporting Information).

Figure 3 illustrates the payload capabilities against "payload diversity" and the maximum payload mass of different grippers. The grasping capability for each gripper type described in this study incorporates both the payload maximum mass and diversity. Payload diversity is defined here as the number of distinct payloads each study used for experimental validation, to compare different grippers. When only a category of objects is documented, each category counts as one payload for scoring purposes. The maximum payload mass is defined as the maximum object mass the gripper can grasp. Object type was categorized into three types, "rigid" objects which would not deform or break easily when gripped with rigid grippers, "fragile" objects which would only deform or break under excessive pressure from rigid grippers, and "soft" objects which would easily deform or break under typical pressure from rigid grippers. One method to realize the soft–rigid grippers is to use variable stiffness. This would allow for soft, light objects or solid, heavy objects to be gripped by adjusting the stiffness of the gripper. Studies did not quantify the difference between soft and solid objects but used subjective categorization, much like in this publication.

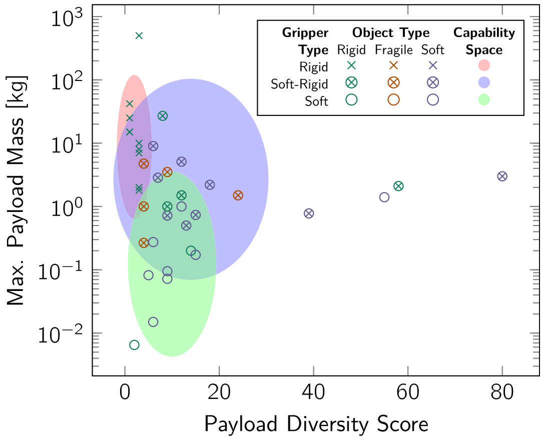

Figure 3. Maximum payload mass (in kg) versus payload diversity score in publications (Diversity scores from soft,[6,77–84] soft–rigid,[8,10,11,15,17–36] and rigid grippers[85–90] were determined based on the variety of objects used in experiments and product specifications. Capability spaces are shown with colored ellipses excluding outliers. Orange, purple, and green ellipses are the grasping capability for rigid, soft–rigid, and soft grippers respectively.).

Figure 3 indicates the soft–rigid grippers have the highest payload diversity score (maximum = 80, $\tilde{x} = 10.5$) compared with soft (maximum = 55, $\tilde{x} = 9.0$) and rigid grippers (maximum = 3, $\tilde{x} = 3.0$). Although rigid grippers have the largest payload (up to 500 kg), the soft–rigid grippers show a higher grasping capability considering the combination of object diversity and maximum payload.

3.1.2. Patterns: Design Types of Soft–rigid Grippers

We categorized the identified soft–rigid grippers into six main categories based on the design type. Type 1: soft gripper fingers with a rigid exoskeleton or rigid gripper fingers with a soft shell;[17–22] Type 2: modular rigid part connected to soft joints/tendons to achieve gripper flexibility and strength;[11,23–30] Type 3: changing gripper material stiffness to achieve the

Table 1. Summary of the general advantages and challenges for industrial parallel rigid, research-based soft, and research-based soft–rigid grippers.

Type of grippers	General advantages	General challenges
Industrial parallel rigid grippers	Stable and accurate performance.[14,46] High payload capability.[16] High working efficiency (e.g., lower response time).[91]	Risk of damaging fragile objects (e.g., fruits)[3,5] Lack of dexterity due to a larger size and weight[3] Lack of adaptability due to rigid construction (e.g., metal). Lower flexibility due to limited DOF.
Research-based soft grippers	Lightweight and high flexibility grippers.[7] Greater grasping adaptability to object size and shape.[16]	Lack of continuous smooth movement. Low maximum payload due to materials and construction.[8,9,13] Complexity of control due to infinite DOF, which causes less stable and less repeatable performance.[14] Longer response time.
Research-based soft–rigid grippers	A combination of soft and rigid components can provide both flexibility and stiffness.[15] Grippers are more dexterous.[16] Greater adaptability to object size and shape. Greater payload capacity in comparison to soft grippers.[14]	Stiffness adjustment systems may require longer response time (e.g., system uses thermoplastic polyurethane [TPU]).[31] Difficult to find a balance between flexibility and stiffness.[19,20] A more complex control algorithm is required.[17,29,36]

soft–rigid transformation;[10,31] Type 4: changing the rigid section structure to provide flexibility;[32] Type 5: soft actuator driving a rigid or soft part;[8,15,33] and Type 6: rigid gripper with a soft fingertip.[34–36]

Figure 4–6 illustrate the materials, design pattern, and performance comparison among the six identified soft–rigid gripper types. The full data extraction can be found in S2, Supporting Information. The following sections will discuss each design type in detail.

Type 1: Rigid Exoskeleton and Soft Shell: Six out of 24 (25.0%) of this type of soft–rigid grippers were identified through the literature review. This type of design achieved the largest payload capability (27 kg).[21] However, as the exterior is rigid, it offers none of the advantages of gripper compliance that allow for diverse and soft objects to be gripped and effectively act like a rigid gripper. Additionally, the manufacturing of this design is more complex compared to other soft–rigid grippers.

Type 2: Modular Design: Merging Rigid Parts with Soft Joints: Modular designed grippers use modular soft and rigid parts to construct complex grippers, which is the most common design for soft–rigid and soft robot grippers (9 out of 24, 37.5%) due to their high adaptability, high robustness, and low cost.[37] There are two main types of modular design in soft–rigid grippers: 1) merging rigid parts with soft joints[11,24,27,30]; 2) merging rigid and flexible parts with tendons.[11,23,25,26,28,29] By connecting the rigid link with soft bellows, this gripper provides more stable gripping than soft grippers.

Instead of using the bellows structure as a soft joint, Gafer et al.[23] designed a soft–rigid gripper for food handling with 3D-printed flexible joints. A similar design was observed by Hussain et al. in 2020.[29] They used interpenetrating phase composites to create the soft joint with varying stiffness through the structure by adjusting the infill density. This approach reduces the complexity of the manufacturing process, by allowing 3D printing to be used for both rigid and soft modules. Additionally, the modular design also provides higher customizability[8,30] and allows users to assemble the gripper based on their own needs. In an industrial or manufacturing setting a single robotic system with a modular design could be more cost effective as one robotic system could perform multiple tasks. Although a modular design in soft–rigid grippers shows great working efficiency and capability, there are still challenges during the manufacturing, particularly for the connection between the soft and rigid part.

Type 3: Material Stiffness Adjustment for Soft–rigid Transformation: Manipulating material characteristics to achieve a stiffness change is another method for soft–rigid gripper manufacturing (2 out of 24, 8.3%). The most common way is to change the temperature at a specific position (e.g., gripper finger joint) to change

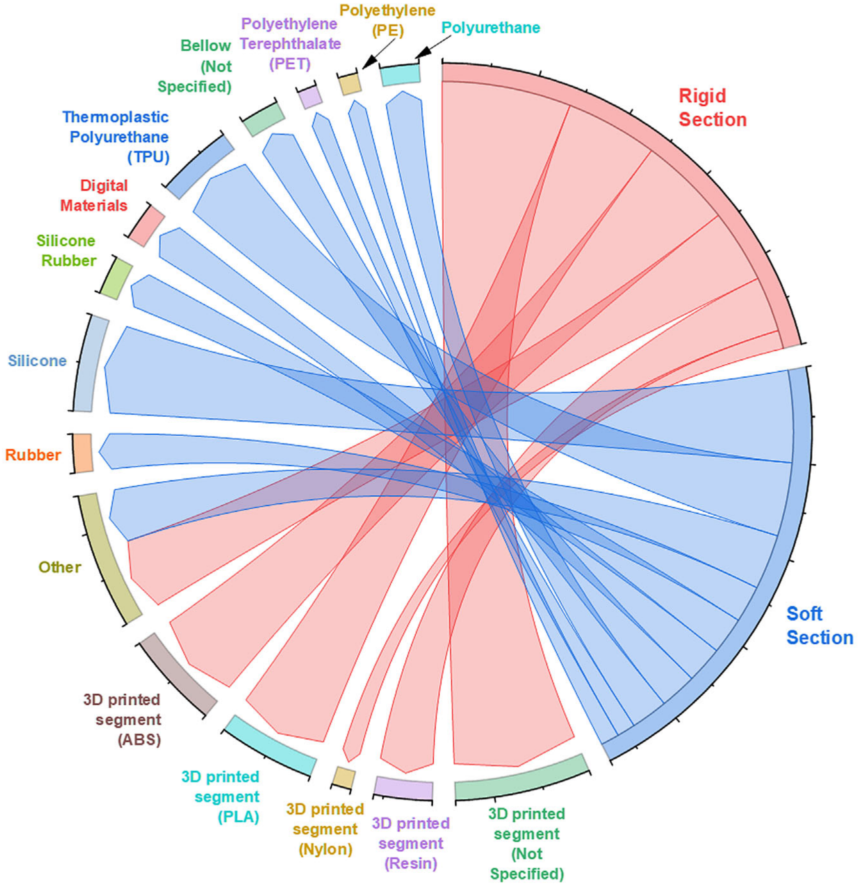

Figure 4. The materials used in identified soft–rigid grippers (The red section represents rigid components; the blue section represents soft components; "Other" represents there was not enough information; and the width of each material represents the occurring frequency through the 24 identified soft–rigid grippers.).

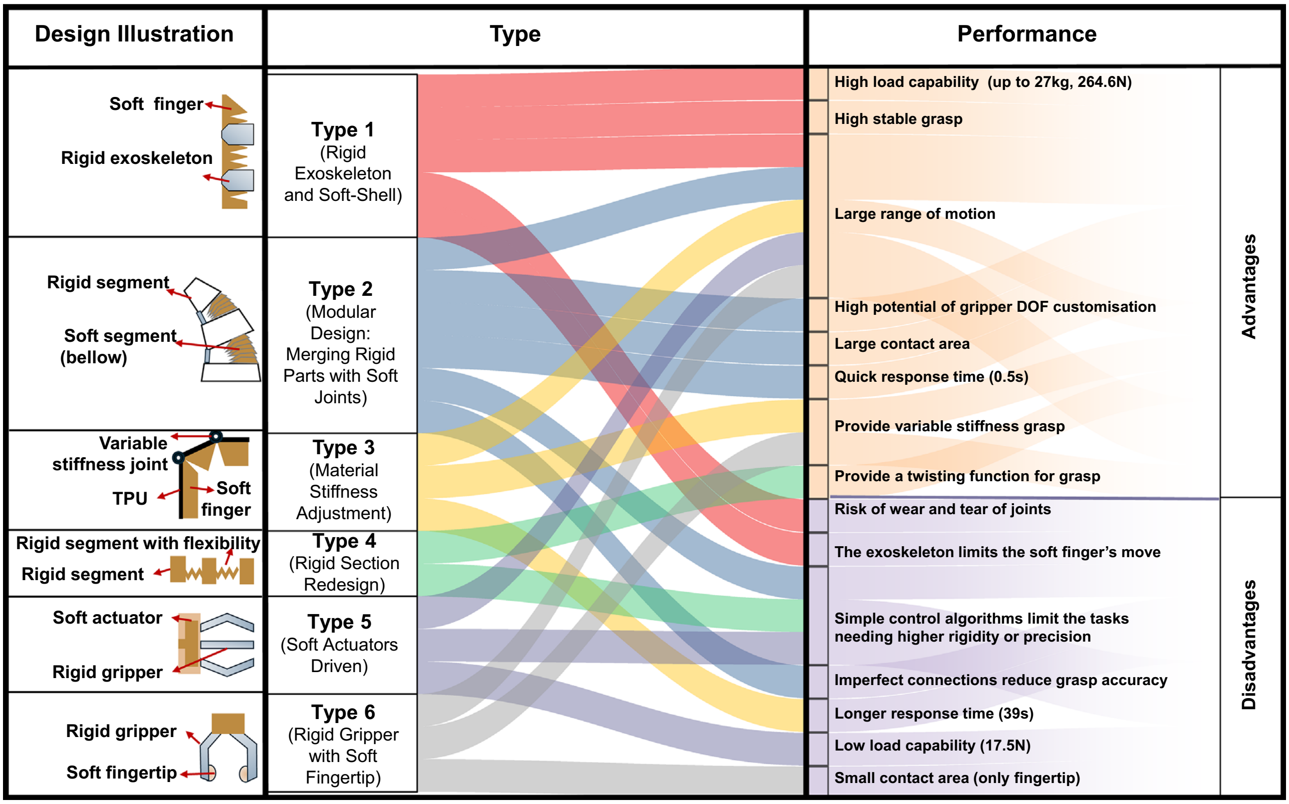

Figure 5. Sankey diagram of performance attributes for the six types of soft–rigid grippers shown with design illustrations, separated into rows of advantages and disadvantages. In the middle column, the different colors represent characteristics of different soft–rigid grippers, with each color corresponding to a type of soft–rigid gripper (Types 1–6); in the last column, orange and purple represent the advantages and disadvantages of the identified soft–rigid grippers, respectively. The height of each row represents the overall ratio of advantages to disadvantages.

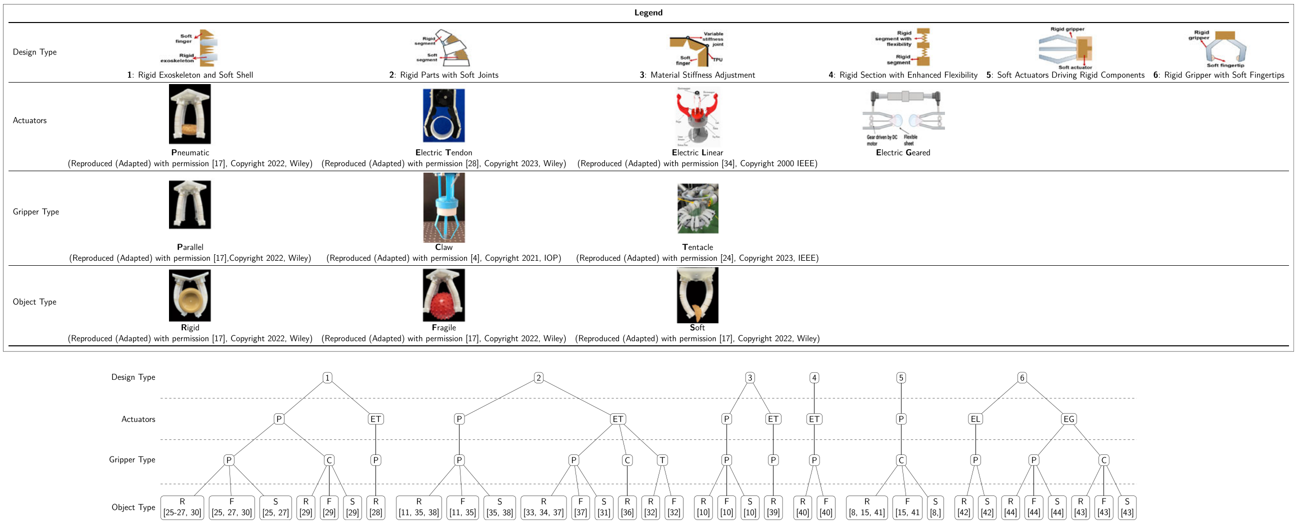

Figure 6. Tree diagram categorizing each unique gripper from the selected literature, classified by design type, actuation method, gripper type, and payloads used in experiments with the gripper. Design types are Type 1: rigid exoskeleton and soft shell; Type 2: modular design: merging rigid parts with soft joints; Type 3: material stiffness adjustment for soft–rigid transformation; Type 4: rigid section redesign for enhanced flexibility; Type 5: soft actuators driving rigid/soft components; and Type 6: rigid gripper with soft fingertip integration. Example illustrations of each type of actuators (pneumatic [P], electric tendon [ET], electric linear [EL], and electric geared [EG] actuators), grippers (parallel [P], claw [C], and tentacle [T] grippers) and objects (rigid [R], fragile [F], and soft [S] objects) are provided in the legend.

the material stiffness. Goh et al.[31] achieved this by increasing the temperature of conductive PLA, which softened it. Additionally, their novel design can be fabricated entirely through 3D printing. Li et al.[10] designed a soft–rigid gripper by combing pneumatic actuation with a heating circuit and water-cooling system to provide different stiffnesses. It can grip different shaped objects, with or without adjusting the gripper finger's PLA-based variable stiffness module. In addition, the upper rigid retractable structure can adjust the total workspace, increasing the adaptability of the gripper. However, this kind of design is highly restricted by the working environment as the materials are more sensitive to environmental factors, such as temperature. Additionally, an extra heating or cooling system is required for practical applications, which increases the response time, around 39 s for the stiffness change in ref. [10], ≈13 times greater than without stiffness adjustment (3 s). Therefore, optimizing the response time is essential in designing soft–rigid grippers of this type.

Type 4: Rigid Section Redesign for Enhanced Flexibility: A new approach introduced by Dragusanu et al.[32] is to replace the traditional flexible materials, such as elastomers, with a wave-shaped flexible joint using stiff materials, for example, acrylonitrile butadiene styrene (ABS). This design can provide both stiffness and flexibility without using multiple materials and complex manufacturing. Both rigid and flexible sections can be produced using additive manufacturing (AM) from one material, reducing the manufacturing time and cost. However, this specific flexible joint design is only suitable for tendon driven electric actuators due to the power transmission. The z-axis anisotropy and increased fatigue risk of 3D printed polymers is another main challenge for its fabrication.[38]

Type 5: Soft Actuators Driving Rigid/Soft Components: Integrating soft actuators with a combination of rigid and soft components represents another design approach for soft–rigid grippers (3 out of 24, 12.5%). Cheng et al.[8] designed a cylinder linear extension soft pneumatic actuator to drive a traditional rigid claw gripper. By changing the air pressure, the soft–rigid gripper can adjust its gripping force with a high degree of precision, allowing fragile objects to be gripped. In the same year, Cheng et al.[33] also developed another soft–rigid gripper by modifying a soft pneumatic actuator into a cylindrical soft vacuum actuator, which provides a more accurate model as part of this research. However, the grasping force is low and currently can be only used for lightweight objects. Wang et al.[15] addressed this problem by using an adjustable rigid palm skeleton, driven by a soft pneumatic spring to provide soft fingers with robust support, an expansive workspace, and a broad range for force adjustment. Additionally, they developed a gesture algorithm to adapt to irregular objects. However, a more complex optimization algorithm is required for better working performance.

Type 6: Rigid Gripper with Soft Fingertip Integration: Another type attaches a soft fingertip onto a traditional rigid gripper to provide lower gripping pressure and higher compliance (3 out of 24, 12.5%). Zhu et al.[35] introduced a novel approach, using flexible sheets of polyethylene terephthalate (PET) as the fingertip. By changing the PET sheet size and thickness, the gripper can grip a payload up to 5.1 kg. However, the design can only grip from a vertical orientation. The soft–rigid gripper for handling clothes designed by Marullo et al.[34] uses thermoplastic polyurethane (TPU) as the fingertip material to provide a more compliant interaction with the cloth. By aligning the electromagnet to the metal tags attached to the cloth, the precision and maximum payload is increased. However, the application of the gripper's magnetic field must be carefully controlled to prevent interference with other equipment.

Shape memory alloys (SMAs) are widely used in experimental soft actuators due to their ability to return to a predetermined shape when heated, allowing significant reversible deformation upon cooling.[39] This feature allows for the control of actuator movement and positioning without the need for complex mechanical components.[40] Although precise actuation has improved over the last two decades, achieving precise motion and force control remains challenging.[40] The inherent flexibility and the ability to withstand large strains make SMAs particularly suitable for soft robotics, where adaptability and elastic materials are critical for interacting with variable and dynamic environments which enhance the functionality and efficiency of soft actuators in various applications.[41] While soft grippers have used this technology,[42] none of the identified soft–rigid grippers used this technique. The reason for this may be due to the complexity of positioning SMA wires, the need of Joule heating system, high current requirements, slow actuation time, and lower grasping force.[41,42] The combination of SMAs and rigid components might be a solution to overcome these limitations and provide soft–rigid grippers with improved grasp performance.

3.1.3. Materials Used in Soft–rigid Grippers

The materials used in a soft–rigid gripper can be categorized into two parts, materials in the soft section and materials used in the rigid section. Figure 4 Illustrates the materials used in 24 identified soft–rigid grippers. The red section represents rigid components; the blue section represents soft components; the "Other" represents there was insufficient materials information; the width of each material represents the occurring frequency through the 24 identified soft–rigid grippers.

To meet the necessary flexibility and durability requirements, elastic materials such as silicone (occurrence $n = 5$),[19–22] rubber ($n = 2$)[17,36] and rubberlike materials (silicone rubber [$n = 2$][30,33] and TPU [$n = 4$][23,25,31,34]) were widely adopted in identified soft–rigid grippers.

Compared with silicone and rubber, silicone rubber offers similar performance but provides better thermal and chemical resistance, which expands the soft–rigid gripper working environment. Consideration of the ability to operate in extreme environments, such as exposure to high levels of chemicals or radiation, is a key factor for the next generation of robotics applications. While, for the 24 identified soft–rigid grippers, none of them explored the potential of adopting in extreme environments. The reason is that most soft–rigid grippers are in the research stage and are hard to transfer to commercialized products for industrial use.

In addition to the typical elastic materials, PET, polyethylene, and polyurethane were also used in identified soft–rigid grippers, although with lesser frequency. Additionally, due to the rapid development of PolyJet 3D printing technology, digital materials (e.g., Agilus or Tango) can provide rubberlike properties by combining two or more photopolymers in varying ratios to achieve specific mechanical properties, including flexibility and softness. Wang et al.[28] utilized PolyJet 3D printing technology to fabricate a soft–rigid structure directly using Vero PureWhite for the rigid finger backbone and Agilus 30 for the soft sections. Although various advanced materials have been used in soft–rigid gripper fabrication, the primary criterion for selecting soft materials is their ability to meet specific flexibility for better industrial adoption.

It is also worth noting that most soft–rigid grippers ($n = 20$) identified in this research use AM techniques for direct production and rapid tooling to cast parts, especially for the rigid components. Most identified soft–rigid grippers used famous materials such as ABS[23,25,32–34] and PLA,[8,10,20,24,31] and none of them used polycarbonate which has similar density but higher strength and stiffness or combined continuous fiber-reinforced thermoplastic composites such as continuous carbon fiber (CCR). Especially for fused deposition modeling (FDM), using CCR as the reinforcement layer has been widely used in AM since 2014.[43] Matsuzaki et al. showcased an innovative FDM technique where CCR were embedded within a PLA matrix during the printing process. The use of CCR enhanced the specimens' strength up to 185.2 (±24.6) MPa, which was 435% of that of PLA.[44]

It is worth noticing that the AM has been widely used for soft–rigid gripper fabrication, common issues with 3D printing, such as nonuniform shrinkage of materials and inefficiency of mass production still need to be addressed.[45]

3.1.4. Industrial Applications of Soft–Rigid Grippers

Among the identified soft–rigid grippers, only a few studies (5 out of 24) considered what the industrial applications of their design might be. These were fruit and vegetables,[23,25] textiles (e.g., cloth),[34] and consumer goods (e.g., plastic bottles or computer mice).[11,27] Most studies (19 out of 24) mainly focused on the gripper design and evaluated their performance by grasping different-sized objects rather than investigating their actual application to PAP activities. However, when transferring research-based grippers to industrial use, the primary consideration is their application suitability, including factors such as the types of tasks, compatibility with existing systems, and adaptability to PAP diverse materials.

Results from the literature review also indicate that most soft–rigid grippers (21 out of 24) are evaluated predominantly on their pick or grasp function. Among 24 soft–rigid grippers, only three considered the specific place function.[10,11,23] Specific place function is the orientation and designated location of the object at the end of the place function during the evaluation stage. Zhu et al.[11] demonstrated the performance of the soft–rigid gripper by performing a complete sequence of movements, including picking up a cup and pouring water into another cup, as well as performing a complete pipeline to grasp and then fold a towel. They considered not only the grasping function but also the orientation and location of objects after grasping. Another way to perform a place function is revering a pick function; however, it is not always so straightforward. Testing and evaluating the place function are essential to improve the practical adoption of soft–rigid grippers in the industry.

3.1.5. Actuators of Soft–Rigid Manipulators

As the traditional actuation method for soft robots, pneumatic actuation is still the dominant approach for soft–rigid grippers ($n = 12$, 50.0%), especially those fabricated with soft materials (e.g., silicone). The explanation for this is that a pneumatic actuation has an inherent compliance toward protecting delicate objects. To address the issue of control accuracy when using pneumatics to actuate soft materials, some researchers used the tendon-driven electric rotary actuator ($n = 9$, 37.5%), especially for the soft–rigid gripper fabricated with modular components or purely rigid materials.

Pneumatic Actuator: Due to the quick response time, lightweight, and easy implementation, pneumatic actuators remain a leading technology in soft and soft–rigid robotics[37,46] providing the desired movement through extension, retracting, bending, and twisting.[47,48] For the soft–rigid gripper, the pneumatic actuation is mainly used for controlling soft joints to provide flexibility to the whole system. Although pneumatic control has been successfully used in soft–rigid gripper applications, the actuation noise, relatively low repeatability, lower reproducibility, and complex modeling required to characterize the behavior of soft actuators are still limitations.[47] To overcome the limited precision control of soft pneumatic actuators, force, vision, or location sensors are always used for closed-loop feedback. Zhu et al.[11] designed a soft–rigid gripper controlled by a pneumatic actuator with stereoscopic vision to determine the actuator shape. Gong et al.[17] combined pneumatic control with a flexible mechanoreceptive sensor to measure the curvature of the actuator.

Electric Rotary Actuator (Tendon Driven): Tendon-driven actuation is where the grippers fingers are driven by the rotation of a motor to pull a tendon or cable.[49] Almost 40% identified soft–rigid grippers used a tendon-driven system, which indicates a trend toward using tendon-driven mechanisms as a replacement or adjunct for purely pneumatic-driven systems in soft–rigid grippers. Compared to pneumatic-driven systems, tendon-driven systems can offer superior precision, a more compact drive system, reduced response times, and heightened compatibility with other electronic components.[37,50] Hussain et al. and Wang et al.[25,28] developed tendon-driven soft–rigid grippers. However, manufacturing can be a challenge since this design is less tolerant of material defects or alignment errors.

Electric Linear Actuator: Although the electric linear actuator is not a common actuation method for soft or soft–rigid grippers, there were still some studies ($n = 2$, 8.3%) using an electric linear actuator, especially for those which only have soft fingertips. They provide the gripper movement through rigid mechanisms.

Figure 7 illustrates the combination of the design and actuation strategies of soft–rigid grippers identified through the literature review. Type 2 design (modular design) with tendon-driven is the most common combination for a soft–rigid gripper ($n = 6$, 25.0%), followed by Type 1 designs (rigid exoskeleton or soft shell) with the pneumatic actuator ($n = 5$, 20.8%).

3.1.6. Soft–Rigid Gripper Control Strategies

Most of the aforementioned research on soft–rigid grippers emphasizes the design and mechanical properties, leaving the

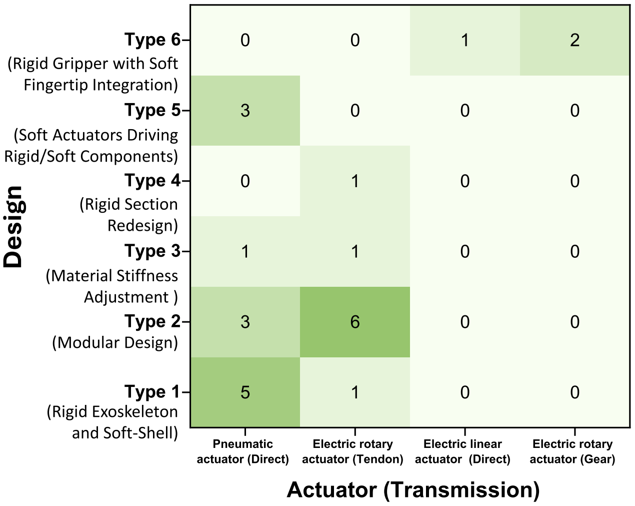

Figure 7. Frequency of the combination between design and actuator (transmission) for the 24 identified soft–rigid grippers.

aspect of control strategies relatively underexplored. Specifically, 20 out of 24 identified soft–rigid grippers addressed control to the extent of selecting the type of actuation, but only four of them provided a detailed control strategy.[8,11,15,30]

Most identified studies used open loop and especially on–off (bang-bang) controllers to control soft–rigid grippers.[21,22,24,26,27,34] This approach works well for predictable environments and simple tasks. In this method, grasping can be achieved with constant pressure at different levels, the value of which is determined at the beginning, regardless of the object. Bang-bang control is the simplest form of open-loop control, suitable for actuators with only two states (fully on or fully off). This method is effective for some basic grasping tasks but lacks the flexibility for complex manipulations.

Although various control methods exist, as these grippers gain traction in various applications such as delicate object manipulation and human–robot interaction, the need for more effective control strategies becomes increasingly apparent. Rough continuous movement and relatively large measurement and movement errors are the main disadvantages of soft–rigid grippers, which lead to the need of more complex control methods. Hussain et al.[29] acknowledged that lack of precise control over deformations in different directions was the main limitation of their design. Additionally, there is the need for accurate closed-loop feedback, as highlighted by Nishimura et al.[36] This emphasizes the importance of the development of sensors for soft–rigid grippers to meet industry accuracy requirements. Closed-loop control utilizes sensor feedback to fine-tune the actuation of the gripper in real time. This allows for adjustments based on the physical interaction between the gripper and the object being grasped, leading to more accurate, robust, and adaptable grasping.

Research related to the development of control methodologies that are tailored specifically for soft–rigid grippers should consider their unique compliance characteristics and adaptability. The control strategies for soft–rigid grippers, although an underexplored area, are often addressed with respect to “what” the type of actuation is instead of “how” best to actuate to achieve the desired performance (i.e., how to generate the desired control signal). Potential solutions include exploring model-based control approaches that account for the deformable nature of the gripper, as well as integrating machine-learning techniques to enhance grasp stability and object manipulation capabilities.[51–53]

Despite significant progress, challenges remain in the development of soft–rigid gripper control strategies. These include 1) ensuring seamless integration and communication between the soft and rigid components that will allow for smooth and precise manipulation and can adapt to variable environments; 2) developing control algorithms that can adapt to changes in object shape, size, weight, and environmental conditions; 3) including enhanced sensing and feedback to provide more accurate and detailed feedback for better control, robustness, and reliability; and 4) ensuring the control strategies are robust and reliable across a wide range of tasks and operating conditions.

Regardless of whether the grippers are soft and/or rigid, high-level control strategies of force/position will be important for practical implementation. Here, we aim to provide useful insights of potential advanced control strategies for soft–rigid grippers, based on specific case studies or examples of successful implementations (**Table 2**). For example, Types 1, 2, and 5 soft–rigid grippers often employ pneumatic actuators which introduce nonlinear air flow dynamics. One may consider adaptive control[54–56] or sliding mode control[57–59] to effectively account for strong nonlinearities. Researchers can identify the full potential of soft–rigid grippers, paving the way for advancements in robotic manipulation and interaction, by bridging the gap between design and control.

3.2. Results of Stage 2: Comparison between Soft–Rigid and Industrial Parallel Rigid Grippers

3.2.1. Non-Systematic Search

Considering that most review papers related to industrial parallel grippers did not provide specific technical parameters.[1,2,5,60] Thus, industrial parallel grippers collated in the review[12] were used.

In total, 63 industrial parallel rigid grippers were selected for the final analysis based on the inclusion criteria, of which 34 were from SCHUNK, 14 were from Festo, 8 were from SOMMER AUTOM, 3 were from IPR, and 4 were from AFAG. None of them was selected from PHD because no clear technical data was available. The analysis was conducted to enable a comparison of performance between industrial and state-of-the-art research soft–rigid grippers.

The results showed that current soft–rigid gripper technologies have the potential to meet industrial parallel rigid gripper needs in terms of range of motion, finger length, and output force. However, there are still some challenges for soft–rigid grippers to meet specific industrial requirements, such as the appropriate response time and output force to weight ratio. However, the lack of standardization limits the ability of soft–rigid grippers to be assessed for their applicability in realistic industrial and manufacturing activities. **Figure 8** shows the comparison analysis results of technical parameters from industrial parallel rigid grippers and soft–rigid grippers in this research (full analysis result is in S3, Supporting Information).

Table 2. List of control strategies that can be applied to soft–rigid grippers.

Control strategies	General advantages	General challenges
Proportional–integral–derivative control[92,93]	Simple structure and easy implementation. Effective for linear systems.	Difficult to handle nonlinearities (e.g., due to chamber air flow or mechanical friction). Suboptimal performance due to manual parameter tuning.
Adaptive control (adjusts parameters continuously to accommodate system dynamic changes or external disturbances, optimizing performance under varying conditions)[54–56]	Effective in handling of system variation and uncertainty, especially parametric uncertainty. Wide application range.	Complex implementation. Model-based method that requires at least partial system knowledge.
Model predictive control (MPC) (uses system models to predict future behavior and optimize control actions within limited time horizon).[94–96]	Effective in handling constraints, e.g., constraints of the actuator. Allowing current timeslot to be optimized, while keeping future timeslots in account.	High computational demand. Requires model knowledge.
Sliding mode control (nonlinear control method, forcing the system state to reach, and then slide along a predetermined surface).[57–59]	Robust to parameter variations. Effective for nonlinear systems.	Easy to cause rapid oscillations or fluctuations. Requires high operational frequencies (challenging for common gripper actuation).
H_∞ control (minimizing the worst-case gain from disturbance to output, providing an optimal performance).[97]	Robust to system uncertainty and external disturbance. Considers the worst-case performance.	Complex design. Difficult to handle nonlinearities (e.g., due to chamber air flow or mechanical friction).
Optimal control (a mathematical approach to determining a control policy)[98–100]	Optimal performance, e.g., suitable to save energy. Effective in handling constraints.	Requires precise model knowledge. Computationally demanding.
Machine-learning-based control.[101]	Data-driven method, great potential for systems that are difficult to model. Adaptive and scalable.	Requires a large amount of data for training. Black-box nature makes interpretation difficult.

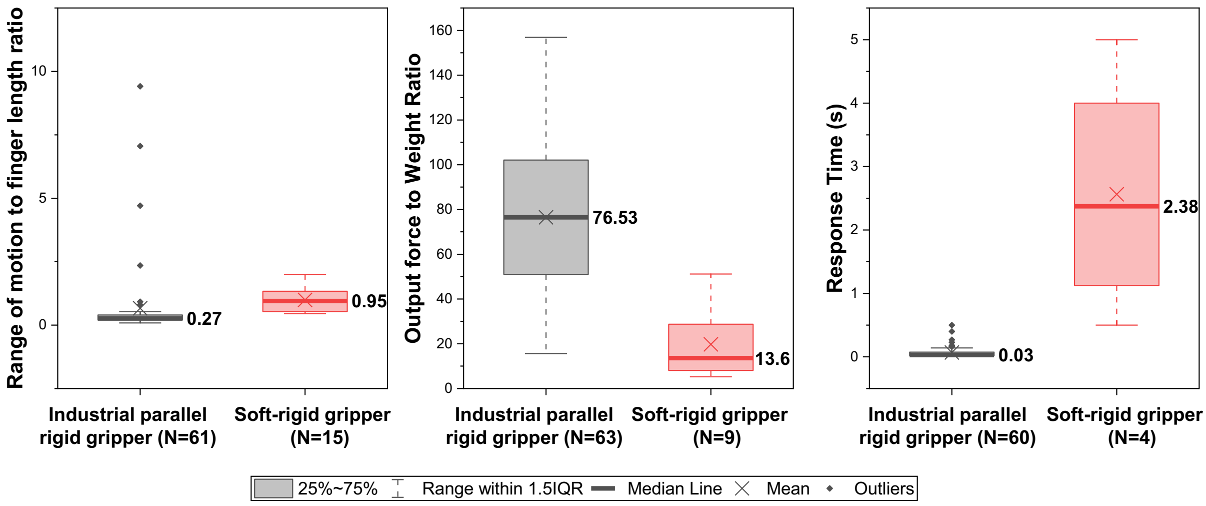

Figure 8. Comparison results of technical parameters of industrial parallel rigid and identified soft–rigid grippers (the label is median value).

3.2.2. Range of Motion to Finger Length Ratio

Range of Motion: The largest range of motion was 160 mm for industrial parallel rigid grippers and 180 mm for soft–rigid grippers Compared with industrial parallel rigid grippers (mean $\bar{x} = 17.43$ mm, $\tilde{x} = 8.00$ mm, $\sigma = 27.60$ mm), soft–rigid grippers had a generally larger range of motion ($\bar{x} = 113.99$ mm, $\tilde{x} = 110$ mm, $\sigma = 42.97$ mm), almost 6.5 and 13.75 times larger when comparing the mean and median. Which, in conjunction with soft–rigid capabilities, facilitates a more secure grasp of objects as the contact surface area will be larger and the object is more likely to be grasped around its center of gravity.

Finger Length: The finger length of the soft–rigid grippers was significantly greater; on mean 3.3 times larger (128.71 mm), compared to that of industrial parallel rigid grippers (38.93 mm). This is expected for such designs which offer a larger range of motion and improved secure grasping. As emphasized by Birglen and Schlich,[12] the finger length of industrial parallel rigid grippers is limited by the gripper's holding torque, which can affect its service life or cause mechanical failure. This limitation can be overcome by using soft–rigid grippers, as the soft section of the gripper (especially the soft fingertip) can adapt to the shape of the objects,[35,36] distributing the force over a larger contact area. Subsequently, the torque required to maintain grasping is reduced.

Range of Motion to Finger Length Ratio: The range of motion to finger length ratio of the identified soft–rigid grippers ($\overline{x} = 0.99$, $\tilde{x} = 0.95$, $\sigma = 0.48$) was superior, averaging 1.5 times greater than that of industrial parallel rigid grippers ($\overline{x} = 0.66$, $\tilde{x} = 0.27$, $\sigma = 1.56$). A larger range of motion to finger length ratio enhances the gripper's dexterity, flexibility, and better adaptability to grasp various objects.[61] As tested by Hao et al.[62] for the same gripper, different finger lengths did not significantly affect the maximum pull-off force. However, the longer the effective finger length, the easier it is to grasp objects larger than the gripper itself. This finding suggests that soft–rigid grippers can offer substantially broader grasping capabilities compared to their industrial rigid counterparts, enhancing their versatility in various applications. Thus, future research should focus on enhancing the range of motion to finger length ratio through innovative structural designs and materials, which could provide more effective and versatile soft–rigid grippers in complex applications.

3.2.3. Output Force to Weight Ratio

Output Force: Sixteen out of 24 identified soft–rigid grippers in this research mentioned gripper output force, which varied from 5 to 210.74 N. Compared with industrial parallel rigid grippers ($\overline{x} = 77.26$ N, $\tilde{x} = 63.63$ N, $\sigma = 53.48$ N), soft–rigid grippers identified in this research had a smaller output force ($\overline{x} = 38.68$ N, $\tilde{x} = 19.23$ N, $\sigma = 51.11$ N). However, the industrial and soft–rigid grippers had a similar maximum output force, which were 200 and 210.74 N respectively.

Gripper Weight: The weight of the grippers is another property of significant importance for robotic gripper applications in industry, as it directly impacts the total payload that the robot arm can manipulate and, therefore, industries prefer a light gripper.[12] For comparison with parameters measured in the same unit, the gripper weight in this research is expressed in newtons (N). For soft–rigid grippers, the lightest and heaviest soft–rigid grippers were 1.57 and 4.7 N respectively. For industrial parallel rigid grippers, the range is much larger with the lightest at less than 0.1 N, and the heaviest at 8.72 N, almost twice as heavy as the heaviest soft–rigid gripper. Compared with rigid industrial parallel rigid grippers, soft–rigid grippers tend to be significantly lighter, which increases the payload that can be carried for a given robot arm.

Output Force to Weight Ratio: The output force to weight ratio had a mean of 3.9 times greater for the industrial parallel grippers ($\overline{x} = 76.52$, $\tilde{x} = 76.53$, $\sigma = 35.53$) in comparison to the soft–rigid grippers ($\overline{x} = 19.76$, $\tilde{x} = 13.61$, $\sigma = 15.17$). We noted that the significant difference between the mean (19.76) and median (13.61) for the soft–rigid grippers. This means that the soft–rigid grippers are, on mean, significantly less efficient than their rigid counterparts. However, their greater compliance and flexibility may compensate for this limitation.

The lower output force to weight ratio is mainly due to the difference in material properties,[14] force transmission,[63] compliance trade-off,[63] actuation mechanisms,[11] design priorities,[14] and force distribution.[64] Unlike rigid grippers made of stiff materials (e.g., metal or hard plastic), which allow higher force transmission without deformation, "soft" sections in the soft–rigid gripper can deform and have the potential to reduce the output force. Rigid grippers can directly transfer the force provided by actuators, however, the "soft" sections in soft–rigid grippers may absorb some energy due to the material deformation resulting in a lower output force compared to rigid grippers.[65] Maximizing the output force to weight ratio should be one of the main design considerations of soft–rigid grippers applied in industry.

The obvious methods to improve the output force to weight ratio of a soft–rigid gripper, are to either increase the output force or reduce the mass of the gripper. Using high-power actuators or rigid mechanical lock structures are some of the simplest ways to increase the output force of soft–rigid grippers. Li et al. increased the gripper output force up to 1960 N by using a rigid locking mechanism between fingers.[66] Tang et al. showed that the output force of the gripper can be increased using higher inner air pressure in soft fingers.[67] Additionally, changing the finger stiffness, such as filling particle jamming in the fingertip or using stiffer materials can also improve the gripper output force.[68] For weight reduction, using lightweight materials can be an option. Particularly for the "soft" section in soft–rigid gripper, low-density silicone/rubber or PET plastic can be considered to reduce weight. Additionally, topology optimization can be employed during the design stage to reduce the weight of grippers.[69] As shown in the gripper designed by Sun et al. which achieved an output force-to-weight ratio of 49 using a topology-optimization-based design.[69]

Additionally, AM is commonly used in the fabrication of soft–rigid grippers, which can improve the force-to-weight ratio. Apart from using more advanced materials and a CCR reinforcement layer to increase component mechanical performance discussed in Section 3.1.3, printer toolpath optimization is another solution to increase the output force to weight ratio of soft–rigid grippers, using the following techniques. 1) Layer orientation optimization: for the models experiencing complex 3D stress distribution under loads, traditional planar-layer-based deposition results in anisotropy, which provides insufficient reinforcement in the Z axis, because the fiber orientation is limited to the $X-Y$ plane. Multiaxis AM can provide better orientation control of 3D printed components for better mechanical performance. Fang et al. proposed a nonplanar volume slicing algorithm and demonstrated that aligning nonplanar layers with stress lines can increase the strength of printed parts by more than six times.[70] 2) Fiber reinforcement path optimization: this strategy controls the placement and orientation of fibers within the thermoplastic matrix to align with the load path. By optimizing the 3D toolpath to follow the maximal stress direction, Fang et al. achieved a 644% increase in failure load and 240% stiffness improvement compared with planar-layer-based printing components.[71] Huang et al. developed an algorithm that minimized energy at turning angles and ensured efficient fiber deposition, leading to a toolpath that has a 46% improvement in enhanced structure strength.[72] 3) Infill pattern and density optimization: the proper selection of infill pattern (e.g., honeycomb, grid, and gyroid) can improve the components' mechanical performance. Birosz, Ledenyak, and Ando found that the honeycomb and gyroid pattern significantly increased the strength and stiffness of the components at the same infill rate.[73]

Although these optimization methods have been explored and reported for AM, their adoption of soft–rigid grippers is still small. Therefore, future research should prioritize the development of advanced materials, AM toolpath optimization, design optimization, and actuation mechanisms which can maximize the output force to weight ratio, leading to more powerful soft–rigid grippers suitable for a wider range of applications.

3.2.4. Response Time

Response time is defined as the quickest closing time of gripper fingers in this research. This is an important parameter for work performance evaluation of industrial parallel rigid grippers, as a reduction in response time is highly valued in industrial manufacturing activities, leading to higher work efficiency and lower production costs. Response time was significantly quicker for the industrial parallel rigid grippers ($\overline{x} = 0.07\,\text{s}$, $\tilde{x} = 0.03\,\text{s}$, $\sigma = 0.09\,\text{s}$) in comparison to the soft–rigid ones ($\overline{x} = 2.57\,\text{s}$, $\tilde{x} = 2.38\,\text{s}$, $\sigma = 1.91\,\text{s}$), with a mean of 37 times faster. This may be a significant limiting factor for robotic PAP tasks where speed is important. Due to the differences in the description of technical parameters between publications, it is difficult to extract the response time with a large sample size. The sample size of soft–rigid grippers for this parameter was $n = 4$, so further research is needed to conclude whether the findings are significant enough to make robust conclusions.

The different material properties are still the main reason for the lower response time of soft–rigid grippers. The stiff materials used in rigid grippers can respond to actuator forces instantaneously. In contrast, the compliant materials used in soft–rigid grippers have a delayed response due to deformation caused by the viscoelastic behavior of soft materials such as silicone[74,75] or rubber.[76] This behavior also means they absorb some energy (damping) provided by the actuators. Integrating advanced materials could be a solution to overcome this challenge, such as shape memory polymer and dielectric elastomers which have fast response time. Adding extra rigid support could reduce system damping and increase speed, especially for using electrical or hydraulic actuators.[14] Park et al. reduced their gripper's response time by 30% by coupling rigid supports to soft fingers.[9] Furthermore, the complex designs of the integration of soft and rigid sections may cause mechanical delays of the whole system's response.

For Type 2 soft–rigid grippers, the bonding between two materials is usually an adhesive connection.[18,19,33] However, the adhesion between the two materials may not be perfect, potentially leading to mechanical weaknesses or failures at the junction due to insufficient bonding strength. Apart from using better adhesive materials, the integration of AM materials might also be a promising solution. Multi-material 3D printing can print multiple materials with different stiffness at the same time to provide better coupling.[14] Using a mechanical connection, such as bolting, can improve the system linkage thereby providing a quicker response.[20,22,25] This is the most common connection method used for Type 2 soft–rigid gripper design, and the one providing the lowest response time (0.5 s).[25] By overcoming these challenges with some of these aforementioned suitable soft–rigid coupling or structure design, the gripper's capability can improve to be able to meet industrial needs and standards.

Hence, future research should focus on optimizing actuation systems and control algorithms to achieve faster and more reliable responses, enabling soft–rigid grippers to perform effectively in dynamic environments.

3.2.5. Harmonization of Performance Parameters between Research and Industrial Grippers

The 24 identified soft–rigid grippers were evaluated in different ways and use different technical parameters to describe their gripper's performance. The variety of different sets of technical parameters used among the identified soft–rigid grippers leads to significant complexity in benchmarking, which becomes even more challenging when comparing them with industrial parallel rigid grippers. For example, for industrial pneumatic driven grippers, stroke length is used to describe the range of motion. However, for soft–rigid grippers, distance between fingers is more commonly used to describe range of motion.

These findings highlight the need for a standardized set of technical parameters to describe robotic gripper performance and capabilities for comprehensive benchmarking. The comparison ensures a thorough assessment of the contributions and limitations of each study within the context of robotics research, thereby contributing to a better understanding of the current status and future directions of the field. Instead of performing PAP experiments with a variety of diverse objects, evaluating grippers using standard technical parameters is a simpler and more convenient way forward for soft–rigid gripper design and development. The gripper weight, finger length, response time, payload, and output force are suggested by the authors as some of the technical parameters that could be used as a standard for future soft–rigid gripper design and evaluation research.

Limitations of This Research: We identified 24 unique soft–rigid grippers and compared their performance to 63 industrial parallel rigid grippers, the results are indicative of the current state of the art. As further research is undertaken, statistical techniques can be utilized to provide a deeper insight. The reporting of technical soft–rigid gripper parameters is not standardized and differs across studies, this has limited our comparison of all studies.

4. Conclusion

This research reviewed 24 identified soft–rigid grippers and determined their potential to meet industrial needs through a scoping literature review, illustrating the potential of performance benchmarking between soft–rigid and industrial parallel rigid grippers. It highlights the potential of soft–rigid grippers to overcome the disadvantages of both soft and rigid grippers. Based on this research, soft–rigid grippers show high potential to meet industrial requirements for commercial use in novel applications, with the ability to grip a diverse range of both light and heavy objects without causing damage to soft or fragile objects. However, a better force to weight ratio, quicker response time, and more precise and stable control methods are required for current soft–rigid grippers to have widespread commercial use.

These improvements can be achieved through advancements in structure design, material selection, fabrication strategy, and control algorithms. In terms of soft–rigid gripper structure design, the innovations should aim to maximize flexibility and adaptability while maintaining the strength and durability required for various grasping techniques. This could involve exploring new geometries, joint mechanisms, and modular designs, which allow for customization and scalable gripper configurations. For the material selection, future research should investigate advanced composites, smart materials, and lightweight alloys that improve the soft–rigid gripper's overall efficiency while maintaining the required mechanical properties. In terms of the fabrication strategy, especially for the grippers manufactured by AM. The toolpath optimization including layer orientation, fiber reinforcement path, and improvement in infill pattern and density could be the priority option.

For the control strategy, future research could delve into the development of control methodologies tailored specifically for soft–rigid grippers, considering their unique compliance characteristics and adaptability. Potential avenues include exploring model-based control approaches that account for the deformable nature of the gripper, as well as integrating machine-learning techniques to enhance grasp stability and object manipulation capabilities. By bridging the gap between design and control, researchers can unlock the full potential of soft–rigid grippers, paving the way for advancements in robotic manipulation and interaction. Moreover, this research also highlights the need for research to produce a set of harmonized technical parameters for each gripper, and a detailed description of control methods to allow them to be adequately compared and evaluated for commercial use, which provides guidance for future research in the field. This research presents the first quantitative comparative analysis between soft–rigid and industrial parallel rigid grippers, enhancing the understanding of their status and prospects in industrial applications. The findings of this research contribute significantly to the body of research that examines soft–rigid grippers' potential for industrial use.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Lutong Li: Data Curation (lead); Visualization (lead); and Writing—Original Draft (lead). **Damian Crosby**: Data Curation (lead); Visualization (equal); and Writing—Original Draft (equal). **Matthew Shuttleworth**: Writing—Review and Editing (equal). **Omer Faruk Argin**: Writing—Review and Editing (equal). **Anthony Siming Chen**: Writing—Review and Editing (equal). **Guido Herrmann**: Project Administration (equal); Supervision (equal); and Writing—Review and Editing (supporting). **Robert Kay**: Project administration (equal); Supervision (equal); and Writing—Review and Editing (supporting). **Andrew Weightman**: Funding Acquisition (lead); Project Administration (lead); Supervision (equal); and Writing—Review and Editing (supporting).

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grippers, industrials, picks and places, requirements, softs–rigids

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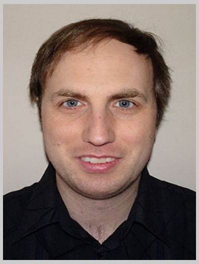

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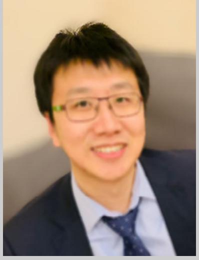

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