Actuated Palms for Soft Robotic Hands: Review and Perspectives

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Actuated Palms for Soft Robotic Hands: Review and Perspectives

Maria Pozzi, *Member, IEEE*, Monica Malvezzi, *Member, IEEE*, Domenico Prattichizzo, *Fellow, IEEE*, and Gionata Salvietti, *Senior Member, IEEE*

***Abstract*—The hand palm plays a crucial, active role in human grasping and manipulation tasks. However, in many of the currently available robotic hands, the palm is just a passive support holding the fingers. Most of the efforts in the literature focused on the design of dexterous fingers, while less attention has been put on the motion of the palm itself. Soft technologies opened up new opportunities in the design and actuation of multifingered robotic grippers, and led to a whole new set of devices. An increasing number of them features an actuated palm, i.e., a mechanism which contains actuated degrees of freedom that play an active role in grasping tasks. Motivated by such a trend, this article classifies and analyzes the prototypes of soft hands having an actuated palm, and delineates possible future perspectives related to the design of these devices.**

***Index Terms*—Design, grasping and manipulation, mechanisms, modeling and control, soft robotics systems.**

I. Introduction

THE mechatronic design of multifingered robotic hands poses several well known challenges, from the study of the kinematic structure and materials to adopt, to the choice of the sensing and actuation systems. Differently from other survey papers, which usually analyze the design of the entire hand [1], [2], possibly restricting the scope of the article to a particular application [3], this work focuses on the design of a specific part of robotic hands, i.e., the palm. While extensive research has been conducted on building robotic fingers with different shapes and functions, only a few works expressly tackle the design and actuation of robotic palms. Typically, the palm is conceived as a unique fixed part which supports the fingers and embeds their actuation system, both in nonanthropomorphic grippers [4], and in anthropomorphic hands [5], [6]. Nonetheless, despite having a passive palm, many of the anthropomorphic hands presented in the previous works achieve a certain level of thumb opposition. This is usually achieved by activating purposefully designed joint(s) at the base of the thumb, as in [7], not by explicitly moving the palm itself, as, for example, in [8] and [9].

However, endowing robotic grippers with some degree of actuation in the palm can add or enhance useful functions, independently from their level of anthropomorphism. This applies above all to devices in which fingers are underactuated, and thus less dexterous, as in soft hands [10].

This article reviews and classifies actuated robotic palms developed for soft multifingered robotic hands, i.e., hands with

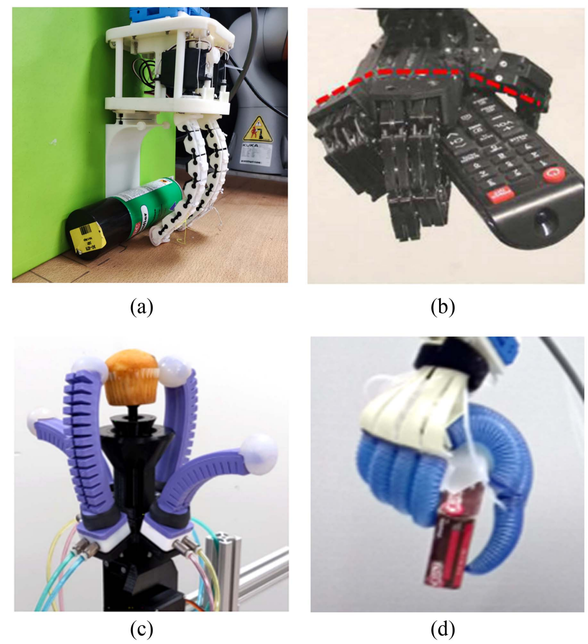

Fig. 1. Examples of multifingered soft robotic hands with actuated palms having different usages. (a) Soft ScoopGripper having a rigid actuated structure enabling new grasping strategies [11]. (b) Pisa/IIT SoftHand with a flexible palm for enveloping objects copy; © [2020] IEEE Reprinted, with permission, from [12]. (c) Soft gripper with a telescopic palm for in-hand manipulation © [2021] IEEE Reprinted, with permission, from [13]. (d) RBO Hand 2 having a pneumatic soft palm for thumb opposition [8].

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Monica Malvezzi is with the Department of Information Engineering and Mathematics, University of Siena, 53100 Siena, Italy (e-mail: monica.malvezzi@unisi.it).

Maria Pozzi, Domenico Prattichizzo, and Gionata Salvietti are with the Department of Information Engineering and Mathematics, University of Siena, 53100 Siena, Italy, and also with the Humanoids and Human Centered Mechatronics Research Line, Istituto Italiano di Tecnologia, 16163 Genoa, Italy (e-mail: maria.pozzi@unisi.it; domenico.prattichizzo@unisi.it; gionata.salvietti@unisi.it).

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two or more fingers having "purposefully designed compliant elements embedded into their mechanical structure" [14]. Thus, we do not include rigid grippers, nor prehensile end-effectors which do not have fingers, like suction cups, jamming-based grippers, or vacuum grippers. Many state-of-the-art soft hands have a passive palm, typically covered by a material that increases friction [6] or compliance [15], or even mimics the human skin [16]. In this review, instead, we focus on actuated palms, i.e., structures moved by different actuation sources (e.g., electric, pneumatic), which have an active role in grasping and manipulation tasks. Even though we focus on palms designed for *soft* hands, we include both, soft and rigid palms. Some representative examples are shown in Fig. 1.

The main purpose of this review is to inspire and inform the future development of actuated robotic palms, presenting the state-of-the-art technological solutions adopted in the literature to build and actuate these devices. The idea, in particular, is to study the added functions that an actuated palm can provide to different types of soft hands, showing the main advantages of such a structure. The conducted literature review shows that in anthropomorphic hands, the palm actuation typically allows thumb opposition and the envelopment of the object [8], [17], whereas in nonanthropomorphic grippers it is mainly used for other purposes, including the reconfiguration of fingers [18] and the execution of specific grasping strategies or in-hand manipulation tasks [11], [13].

The rest of this article is organized as follows. The anatomy of the human palm is briefly presented in Section II. In Section III, the criteria adopted to select the papers to be included in this review are described, whereas in Sections IV and V actuated palms developed for articulated and continuous soft hands are analyzed, respectively. In Section VI, the results of the literature review are discussed. Finally, Section VII concludes the article.

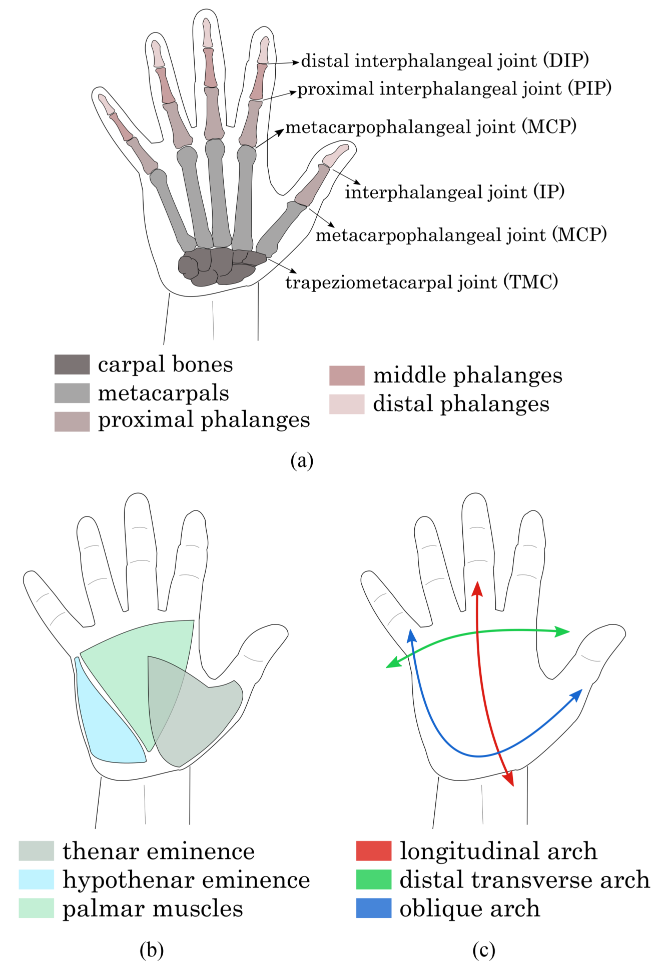

Fig. 2. Schemes showing (a) the bones and joints of the hand, (b) the hand muscles groups, and (c) the hand arches.

II. Palm of the Human Hand

The human hand is the result of a complex evolutionary process and is our interface with the external world, having a fundamental role in both, action (manipulation) and perception (sense of touch), i.e, a *dual role* [19], [20], [21]. The hand palm is highly involved in both processes as it contains all the muscles of the hand, and it is covered by skin, presenting, in the palmar side (glabrous skin), a tactile innervation density lower than in fingers, but higher with respect to most of the other body parts [22], [23], [24].

As shown in this article, the crucial role the palm has in the functioning of the human hand has inspired the design of anthropomorphic and nonanthropomorphic robotic grippers in which the possibility of actively controlling additional degrees of freedom in the palm allows to wrap around objects or to manipulate them in a controlled and deliberate way.

In this section, the bones, articulations, and muscles of the human hand are briefly described, as palm movements derive from the complex interplay of all these components. Thanks to its structure, the palm can bend along three main arches, achieving motions that are fundamental in manipulation tasks. The features of the human palm are shown in Fig. 2. The skeletal structure of the palm is the metacarpus, composed of five bones, the metacarpals, connecting the palm to the wrist on one side, and the palm to the fingers on the other side [Fig. 2(a)] [25]. The base of the first metacarpal (thumb) articulates with the trapezium bone, constituting the trapeziometacarpal (or carpometacarpal) joint, that allows thumb opposition. The bases of the second to fifth metacarpals articulate with the carpal bones, whereas their heads articulate with the base of the proximal phalanges, defining the metacarpophalangeal joints, which allow flexion/extension and adduction/abduction of the fingers.

The hand muscles can be divided into the following three main groups: 1) thenar eminence, 2) hypothenar eminence, and 3) palmar muscles [23]. The first group includes muscles dedicated to the thumb motion (flexion, abduction/adduction, and opposition), the second is in charge of furrowing the hypothenar eminence skin and of moving the little finger (flexion and abduction/adduction), the third contributes to the motion of the index, middle, ring, and little fingers. A sketch showing the approximate locations of the hand muscles groups is reported in Fig. 2(b).

Thanks to the hand muscles, the palm can bend and assume a concave shape, which is crucial to wrap around objects in prehensile tasks. The bending is achieved along three main arches [Fig. 2(c)]: longitudinal, distal transverse, and oblique [26]. The first extends from the crease of the wrist to the tip of either the middle or the index finger, the second forms a concave curvature at the metacarpal heads of the index, middle, ring, and little fingers, and the third is a concavity formed by the opposable thumb with the other fingers.

Not only the possible motions but also its conformation and consistency make the palm particularly suitable for grasping and enveloping objects. As described in [22], while the dorsal skin is thin, loose, and quite mobile, the palmar skin is thicker, presents soft pads due to fatty subcutaneous tissue, and is less mobile as it is attached to the palmar aponeurosis, that is a band of connective tissue which covers and protects the deep tissues of the palm and fingers.

The fundamental role of the human palm is evident when inspecting the main taxonomies that were developed to categorize human grasping and manipulation tasks [27], [28], [29], [30], [31]. One of the most well-known is probably the GRASP Taxonomy by Feix et al. [27], which classifies 33 ways in which the hand can be shaped to perform different types of grasps. The palm works as an opposition surface whenever large contact patches are needed (i.e., power-palm and power-pad grasps), whereas the muscles of the thenar eminence are used in all grasp types for moving the thumb. As detailed in [28], the human hand not only is capable of executing prehensile tasks with no object motion (e.g., holding an object still), but can also manipulate objects in-hand (prehensile task with object motion) and perform nonprehensile actions. While in holding tasks the hand muscles are mainly used for the thumb motion, in manipulation tasks the palm structure is fundamental to establish large contact areas with objects. This function is also widely exploited to perform prehensile and nonprehensile interactions with the environment (e.g., holding or sliding a large object against a table [29], [32]).

In [29], the authors also discussed no contact manipulation actions, which are performed when the hand *preshapes* while approaching the object, either according to the object geometry [33], or according to the task to be performed right after the grasp [34]. Palm motions play an important role also in hand preshaping as they allow to bend the fingers along the different hand arches.

III. Methodology

The literature search was conducted in Scopus and followed two main paths. On the one hand, we searched for *("robotic hand" AND "palm")* in the title, abstract and keywords until the end of 2022 and we found 150 results, of which only 17 documents were deemed relevant for our review according to the criteria stated in Section I. On the other hand, we searched for *[("robotic gripper" OR "robotic hand") AND "review"]* in the title, abstract and keywords, limiting the search to papers published between 2018 and 2022. This second search gave 53 results within which we selected three documents [2], [35], [36], discarding unrelated works and works dealing with planning and control aspects and not design. For the sake of simplicity we also did not consider works analyzing only rigid grippers [4] or grippers for very specific applications (e.g., assistance [37], food-handling [38], agriculture [39]). From the three reviews we found two papers that matched with the criteria of our review. To deepen the search, we also checked all papers cited by and citing the initial pool of 17+2 papers. As a result, a total of 39 papers were included in this review.

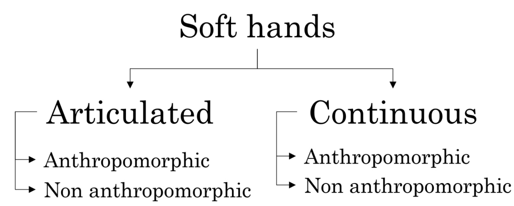

Fig. 3. Adopted classification of soft hands.

In [40], the authors presented a classification of robotic hands in five classes, based on finger structure and palm design, recognizing the importance of the latter. The focus of that classification is on the design of the entire hand, not only on the palm, and both passive and actuated palms are included. In addition, mainly rigid anthropomorphic hands are considered, and only a few prototypes of soft hands and nonanthropomorphic grippers are described.

In the following, we will classify actuated palms that we found through our literature review according to the type of soft hand they are attached to. According to the classification proposed by Della Santina et al. [14], we will consider two types of soft hands: articulated and continuous. The first have compliance at the joints, whereas the second present a finger structure that is continuously deformable. Within each of the two hand categories, we distinguished between nonanthropomorphic and anthropomorphic designs. The latter include hands with a clear bio-inspired design that typically have five fingers. The adopted classification is shown in Fig. 3.

Analyzed palms are listed, ordered by date, in Tables I, II, and III, and discussed in the next sections. The tables report information on the type of actuation system used to move the palm (electric, tendon-driven, pneumatic), the number of degrees of actuation (DoAs) of the palm, its main functions, the type of design of the hand (anthropomorphic or nonanthropomorphic), and the material(s) used to build the palm (rigid, soft, or a combination of the two). Examples of actuated palms for nonanthropomorphic grippers and anthropomorphic hands are shown in Figs. 4 and 5, respectively.

IV. Actuated Palms for Articulated Soft Hands

The prototypes of articulated soft hands with actuated palms that were analyzed in this review are reported in Table I.

A. Nonanthropomorphic Grippers

Most of the papers presenting actuated palms for nonanthropomorphic articulated grippers introduce mechanisms which allow to translate and rotate the fingers in different ways. Wei

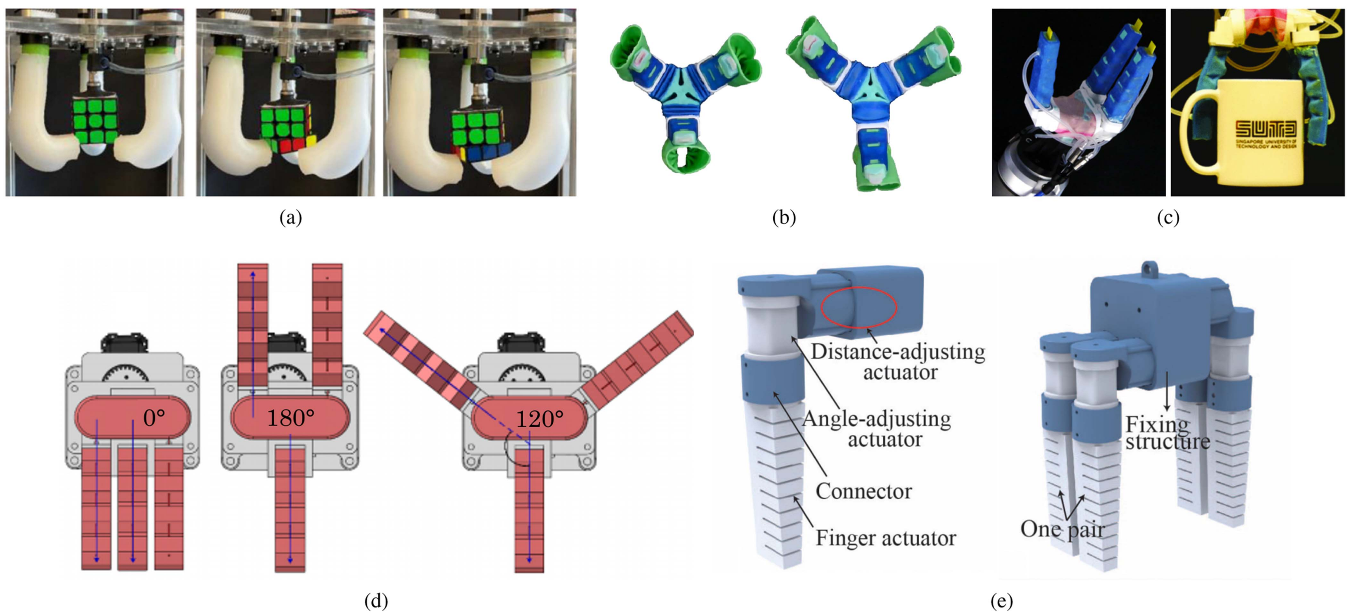

Fig. 4. Actuated palms for nonanthropomorphic grippers with different functions. (a) In-hand manipulation © [2021] IEEE Reprinted, with permission, from [41]. (b)–(c) Enveloping grasp with variable workspace Reproduced from [42] (Supplementary Movie S2) CC BY-NC 4.0 (http://creativecommons.org/licenses/by-nc/4.0/) and larger contact areas © [2020] IEEE Reprinted, with permission, from [43]. (d)–(e) Reconfiguration of the fingers through rotation © [2021] IEEE Reprinted, with permission, from [44] or rotation and translation © [2021] IEEE Reprinted, with permission, from [18].

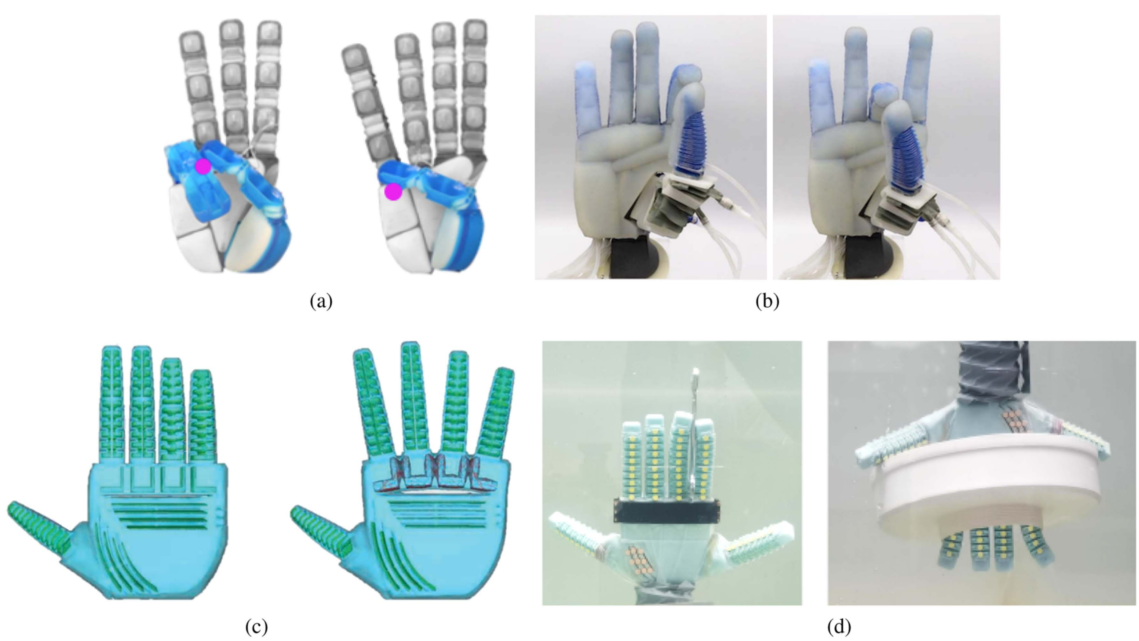

Fig. 5. Actuated palms for anthropomorphic hands with different functions. (a)–(b) Thumb opposition © [2022] IEEE Reprinted, with permission, from [9], Reproduced from [55] CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/). (c) Splaying of the fingers Reproduced from [56] CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/). (d) Enveloping grasp © [2022] IEEE Reprinted, with permission, from [57].

et al. [45] designed a gear mechanism in the palm that can rotate the fingers using a single electric motor. This allows to obtain spherical or cylindrical grasps. Wang et al. [46] introduced a palm mechanism that allows to coordinate three underactuated tendon-driven fingers in in-hand manipulation tasks. The mechanism is composed of a five-bar linkage that is moved through two electric servomotors. The developed gripper has been extensively tested in grasping and dexterous manipulation tasks [49]. The devices proposed by Kim et al. [47] and by Yamano et al. [48] have three underactuated fingers embedding rigid and compliant elements and a palm that allows the rotation of the two side fingers, like in the Barret Hand [50]. The reconfiguration of the fingers enables different grasp types, making the grippers very versatile. In the device presented in [47], it is

TABLE I
TABLE REPORTING THE ANALYZED ACTUATED PALMS FOR SOFT ARTICULATED ROBOTIC HANDS

Reference	Actuation system	# of DoAs	Functionality	Design	Material
Wei at al. (2018) [45]	Electric	1	Fingers reconfiguration	Non anthropomorphic	Rigid
Salvietti et al. (2019) [11]	Electric actuation, tendon-driven	1	New grasping strategies, enveloping grasp	Non anthropomorphic	Soft-rigid
Capsi et al. (2020) [12]	Electric actuation, tendon-driven	1	Enveloping grasp, thumb opposition	Anthropomorphic	Soft-rigid
Wang et al. (2020) [46]	Electric actuation, tendon-driven	2	In-hand manipulation, fingers reconfiguration	Non anthropomorphic	Rigid
Kim et al. (2020) [47]	Electric actuation	1	Fingers reconfiguration	Non anthropomorphic	Rigid
Yamano et al. (2021) [48]	Electric actuation	2	Fingers reconfiguration	Non anthropomorphic	Rigid
Shorthose et al. (2022) [9]	Pneumatic	1	Thumb opposition, enveloping grasp	Anthropomorphic	Soft

also possible to fully fold the central finger and move the other two to obtain a two-fingered parallel gripper.

Salvietti et al. [11] proposed an actuated palm with a different objective: a soft-rigid, movable structure was added to the hand palm, enabling new grasping strategies involving environmental constraint exploitation [51]. The developed gripper prototype has two tendon-driven fingers with rigid phalanges and compliant joints, and a scoop-like structure which is attached through a flexible hinge to the structure that supports the fingers [Fig. 1(a)]. The scoop is actuated through a servomotor that pulls two tendons attached to it. The use of the scoop during grasping tasks allows to perform the so-called *scoop grasp* strategy, in which the scoop slides between an object and the surface it is lying on, and then the fingers close and envelop the object [52]. Different scoop prototypes have been proposed in [53] and an automated procedure to design scoop-like structures to be added to different robotic grippers has been introduced in [54].

B. Anthropomorphic Hands

Capsi et al. [12] studied how to make the palm of the anthropomorphic Pisa/IIT SoftHand [6] concave and thus more adaptable to different objects [Fig. 1(b)]. The developed palm has two elastic rolling-contact palmar joints which allow it to bend along the following two axes: 1) between the index and thumb, and 2) between the middle and the ring. It is actuated through the same motor that closes the fingers thanks to a suitably designed tendon routing. A quantitative analysis of the newly introduced palm showed that the mobility of fingertips increases (Cartesian manipulability ellipsoids with a larger volume), with respect to that obtained with a fixed palm. From a qualitative point of view, the use of the articulated palm results in more enveloping and adaptive grasps.

Shorthose et al. [9] designed a five-fingered soft-rigid hand with a highly anthropomorphic palm made of different materials. It consists of four pneumatic sensing areas, a pneumatic actuator that allows the thumb adduction/abduction [Fig. 5(a)], and a passively compliant region which conforms to the grasped objects.

TABLE II
TABLE REPORTING THE ANALYZED ACTUATED PALMS FOR SOFT CONTINUOUS NON ANTHROPOMORPHIC ROBOTIC GRIPPERS

Reference	Actuation system	# of DoAs	Functionality	Material
Tawk et al. (2019) [58]	Vacuum	1	New grasping strategies, enveloping grasp	Soft-rigid
Zhong et al. (2019) [59]	Pneumatic and Vacuum	2	New grasping strategies	Soft-rigid
Subramaniam et al. (2020) [64], Jain et al. (2020) [43]	Vacuum	1	Enveloping grasp	Soft
Sun et al. (2020) [68]	Electric	6	Fingers reconfiguration	Rigid
Shao et al. (2020) [63]	Pneumatic	1	Fingers reconfiguration	Soft
Mathew et al. (2021) [44]	Electric	1	Fingers reconfiguration	Rigid
Pagoli et al. (2021) [41]	Vacuum, Electric	2	In-hand manipulation, Enveloping grasp	Soft-rigid
Teeple et al. (2021) [13]	Electric	1	In-hand manipulation	Rigid
Cui et al. (2021) [18]	Pneumatic	8	Fingers reconfiguration	Soft-rigid
Low et al. (2021) [69]	Electric	3	Fingers reconfiguration	Rigid
Shin et al. (2021) [67]	Electric	1	Fingers reconfiguration	Rigid
Cheng et al. (2022) [72]	Pneumatic	5	Fingers reconfiguration	Soft-rigid
Gai et al. (2022) [73]	Pneumatic/ Vacuum	1	Fingers reconfiguration	Soft
Gai et al. (2022) [61]	Pneumatic	4	Enveloping grasp	Soft-rigid
Teeple et al. (2022) [65]	Pneumatic	1	In-hand manipulation	Soft
Jain et al. (2022) [42]	Pneumatic	1	Enveloping grasp	Soft
Washio et al. (2022) [62]	Vacuum	2	Enveloping grasp, new grasping strategies	Soft
Cheng et al. (2022) [70] and Ye et al. (2022) [71]	Electric	1	Fingers reconfiguration	Rigid

V. ACTUATED PALMS FOR CONTINUOUS SOFT HANDS

In this section, actuated palms built for continuous soft hands are analyzed. The considered nonanthropomorphic grippers and anthropomorphic hands are listed in Tables II and III, respectively.

TABLE III
TABLE REPORTING THE ANALYZED ACTUATED PALMS FOR SOFT CONTINUOUS ANTHROPOMORPHIC ROBOTIC HANDS

Reference	Actuation system	# of DoAs	Functionality	Material
Yamaguchi et al. (2012) [74]	Electro-conjugate fluid (ECF) jet	2	Thumb opposition, enveloping grasp	Soft
Deimel et al. (2016) [8]	Pneumatic	2	Thumb opposition, enveloping grasp	Soft
Zhou et al. (2018) [76]	Pneumatic	1	Thumb opposition, enveloping grasp	Soft
Li et al. (2019) [17]	Pneumatic and vacuum	2	Enveloping grasp	Soft
Zhou et al. (2019) [77]	Pneumatic	3	Thumb opposition, enveloping grasp	Soft
Yang et al. (2020) [80]	Pneumatic	1	Enveloping grasp	Soft
Wang et al. (2021) [56]	Pneumatic	6	Thumb opposition, enveloping grasp, fingers reconfiguration (adduction/abduction)	Soft
Hao et al. (2021) [78]	Pneumatic	1	Thumb opposition, enveloping grasp	Soft
Firth et al. (2022) [81]	Pneumatic	3	Thumb opposition, enveloping grasp, fingers reconfiguration (index motion)	Soft
Puhlmann et al. (2022) [55]	Pneumatic	1	Enveloping grasp	Soft
Wang et al. (2022) [57]	Pneumatic	3	Enveloping grasp, thumb opposition	Soft
Zhang et al. (2022) [79]	Pneumatic	1	Enveloping grasp, thumb opposition	Soft

A. Nonanthropomorphic Grippers

The authors in [41], [58], and [59] proposed to endow the palm of their continuous soft grippers with an additional grasping tool based on vacuum. The first two used a suction cup, whereas the third designed a versatile palm to which either a suction cup or a granular particles gripper can be attached. While the suction cup used in [58] is fixed to the gripper at a predefined vertical distance from the fingers' bases, in the other two works the sucker can move up or down driven by a pneumatic cylinder [59] or using an electrically actuated mechanism [41]. In [41] and [58], the palm mechanism was activated together with the fingers or separately. This versatility allows to pick and place objects with different shapes and weights using a multimodal grasping approach. The additional translational DoF used in [41] also allows the gripper to have enhanced in-hand manipulation capabilities [Fig. 4(a)].

Similarly to [41], [58], and [60], Gai et al. [61] proposed a gripper capable of multimodal grasping. The designed gripper has two fingers to which suction cups can be added, and a palm to which a soft wrapper can be magnetically attached. The wrapper is made of four pneumatic pads attached on the lateral surfaces of a cube structure. By inflating the pads, it is possible to envelop small objects, or constrain protruding parts of larger objects in a more effective way than by using the fingers alone.

Multimodal grippers with bioinspired designs were presented in [42] and [62]. The first is inspired by a flower and has a rather complex structure in which an actuated palm supports three fingers equipped with nails and surrounded by large petals. The second is inspired by the elephant nose and is made of two soft pneumatic fingers covered by a silicone membrane which works as a sort of actuated palm. Jain et al. [42] equipped the gripper with a multimaterial inflatable palm that allows to reconfigure the workspace of the gripper by separating or moving closer the fingers [Fig. 4(b)]. Washio et al. [62] designed a palm membrane connected to two vacuum sources: one allows to use the gripper as a suction cup and the other one is connected to a particle jamming chamber which can be used to change the stiffness of the gripper. In both works, the resulting hybrid gripper is very versatile and can exploit different grasping strategies depending on the object to grasp.

Similarly to [42], Shao et al. [63] proposed to embed a pneumatic actuator in the palm of a three-fingered soft gripper to change the gripper workspace. The actuator is connected to a mechanism which moves the fingers outward upon inflation and inward upon deflation.

Subramaniam et al. [64] proposed a soft gripper with three fingers and an actuated palm. Similarly to the fingers, the palm structure is composed of stiff silicone wedges separated by hollow sections and covered by a thin soft skin. When vacuum is applied in the gaps, the palm bends. Experiments conducted by the authors showed that having an actuated palm increases the gripper workspace and payload, and allows to obtain larger contact areas. More recently, the gripper has been equipped with retractable nails [43] [Fig. 4(c)].

Teeple et al. [13], [65] presented different types of actuated palms for a continuous soft gripper with four fingers [66]. In [13], a 1-DoF rigid telescoping mechanism which moves along the direction perpendicular to the fingers' bases was introduced [Fig. 1(c)]. The palm actuation allows to change its diameter and height simultaneously and on-the-fly, providing an extra support to objects of different sizes during mid-air in-hand manipulation tasks. In [65], two different palm designs aimed at changing the friction force at the contact between the palm and the object are presented. The first one allows to vary the friction coefficient, whereas the second one allows to vary the preload normal force. Both palms exploit a 1-DoF pneumatic actuator. When inflated, in the first case, the actuator presses a soft high-friction membrane against a perforated rigid low-friction surface, thus increasing the friction coefficient of the palm. In the second case, instead, pneumatic actuation is used to inflate/deflate a foam-filled pouch, modulating the normal force exerted on grasped objects. Experiments showed that the actuated palms give an enhanced dexterity to the gripper, as the same finger motion can be used to perform sliding or tipping motions, depending on the palm actuation. In addition, the actuated palm can play a crucial role in the grasp stability.

As for most of the analyzed articulated grippers in Section IV-A, robotic palms can also be exploited to embed mechanisms for the reconfiguration of the fingers. Inspired by

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the design of the Barret Hand [50], Mathew et al. [44] [Fig. 4(d)] and Shin et al. [67] proposed three-fingered soft grippers in which two of the fingers can be reoriented symmetrically around the palm through a gear mechanism actuated by an electric motor. Also, Sun et al. [68] and Low et al. [69] designed grippers with soft continuous fingers and a rigid palm structure which can reposition and reorient the fingers. This allows to adjust the grasping range of the gripper based on the target object. The authors in [70] and [71] proposed two similar gear mechanisms which allow to reconfigure the fingers obtaining different pre-grasp poses. In both cases, the mechanism is actuated by a single stepper motor.

While previously cited papers used electric motors to reconfigure fingers and change the gripper workspace, other works adopted pneumatic actuators for the same purpose [18], [72], [73]. The authors in [18] and [72] proposed two similar grippers in which pneumatic actuators in the palm move the fingers' bases allowing their rotation and translation. In [18], the gripper has four fingers whose configuration can be changed using distance-adjusting actuators and angle-adjusting actuators. The first can be used to move the fingers closer or further from the palm in the horizontal direction, whereas the second can change the finger orientation with respect to the palm [Fig. 4(e)]. In the gripper presented in [72], the fingers are three and arranged in a circle around the palm. Here, each finger is connected to a pneumatic actuator that allows to change the distance between the fingers and the palm (extension). Two of the fingers also have an actuator that allows the rotation of the finger around its main axis. Gai et al. [73] proposed a two-fingered soft gripper endowed with a special "bracket structure," which is a soft pneumatic actuator connecting two soft fingers. The bracket works as an actuated palm and can be bent in two directions depending on whether it is inflated or vacuum is applied. By bending the bracket, the distance between the two fingers can be adjusted.

B. Anthropomorphic Hands

One of the first soft continuous hands with an actuated palm is the ECF hand presented in [74]. The authors added two actuators in the hand palm to execute thumb opposition and flexion/extension of the metacarpal. The actuators are made of silicone rubber balloons which are pressurized through an electro-conjugate fluid (ECF) jet.

The RBO Hand 2 [8] is one of the most popular continuous soft hands. It presents an actuated palm made of two pneumatic actuators that are twice as stiff as the fingers to better support grasped objects. They can be either inflated together or separately to generate different thumb opposition motions. The motion of the palm also allows the hand to better wrap around objects. Although we can consider the RBO Hand 2 anthropomorphic as it has five fingers and a human-like size, still its movements are not completely similar to the human ones [Fig. 1(d)]. The design of its successor, the RBO Hand 3, instead, has been fully bio-inspired, and lead to a device with 16 degrees of actuation [Fig. 5(b)] [55]. The palm of the RBO Hand 3 supports the fingers and the thumb and has an actuated degree of freedom which allows "palm hollowing", i.e., the flexion of the palm which brings the ring and the little fingers towards the thumb. The adopted actuator is a pneumatic bellow. The palm actuation was found to be fundamental for the hand to succeed in the Kapandji test [75].

The BCL-13 and BCL-26 hands proposed by Zhou et al. [76], [77] share some similarities with the RBO Hand 3, as they are pneumatic, bio-inspired, and present several degrees of freedom: 13 and 26, respectively. They both have actuated palms. The BCL-13 has only 1 DoA in the palm, which allows to rotate the thumb and better envelop objects. The palm of the BCL-26 hand, instead, contains 11 actuators, of which we can say that only three strictly pertain to the palm, as the other eight actually move the fingers. One of the three palm actuators is devoted to the thumb opposition, whereas the other two allow to bend the palm to bring the ring and little fingers closer to the thumb.

Similarly to [76], the authors in [78] and [79] provided their soft anthropomorphic hand with a pneumatic actuator in the palm for bending the thumb and better oppose it to fingers while enveloping objects.

In [80] and [81], two different pneumatic, bioinspired, monolithic palms for achieving enveloping power grasps with anthropomorphic hands were presented. They are made of a single piece of soft material (thermoplastic elastomer [80], silicone rubber [81]) endowed with air chambers arranged to reproduce motions along the hand arches [Fig. 2(c)]. Yang et al. [80] implemented the longitudinal and the distal transverse arches, whereas Firth at al. [81] focused on the longitudinal and the oblique ones.

Wang et al. [56] endowed their soft continuous hand with a palm composed of two parts, one for extending the distance between fingers and enlarging the grasping scope [Fig. 5(c)], and one for palm bending and thumb adduction/abduction. The palm is pneumatically actuated, as is the whole hand. The authors extended their work to build another hand with an actuated palm for bidirectional grasping in underwater scenarios [57] [Fig. 5(d)]. The new version of the hand has two thumbs, four fingers, and an actuated palm. The palm is reinforced by elastic fibers and is made of three pneumatic actuators as follows: 1) one for bending forward the fingers, and 2) the other two for the opposition of the two thumbs, which close in opposite directions.

Although placed in an anthropomorphic hand, the palm designed by Li et al. [17] does not perform bio-inspired motions, but achieves the goal of better stabilizing the grasped object. The proposed actuated palm has two layers: one made of silicone rubber, and the other one containing particles. The first one is pneumatically actuated and pushes the second one towards the object. To envelop the object, particle jamming can be activated by applying vacuum to the second layer.

VI. Discussion

Different aspects of the papers collected in this review have been analyzed in detail, and the results are summarized in Figs. 6–8.

Soft robotic hands and grippers usually have compliant structures with a limited number of actuators. Adding one or more DoAs to the palm enhances grasp stability and/or dexterity in an efficient, robust, and safe way. Actuating the palm can be simpler, from the mechanical perspective, than endowing the

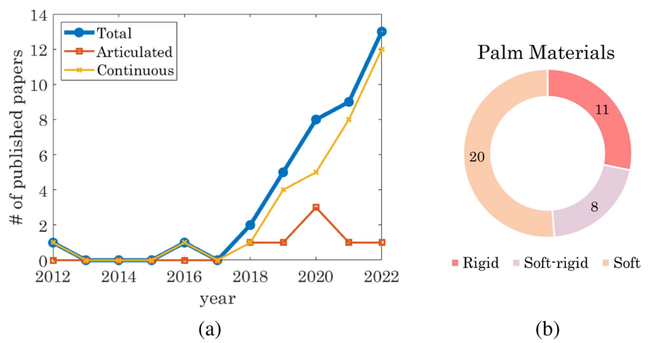

Fig. 6. Number of published papers describing soft robotic grippers or hands with an actuated palm with respect to (a) the publication date, and (b) the type of materials used to build the proposed palm.

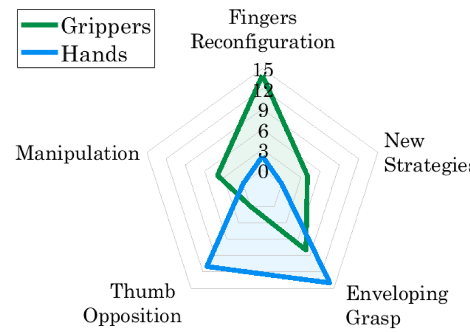

Fig. 7. Palm Functions: comparison between nonanthropomorphic grippers (green) and anthropomorphic hands (blue).

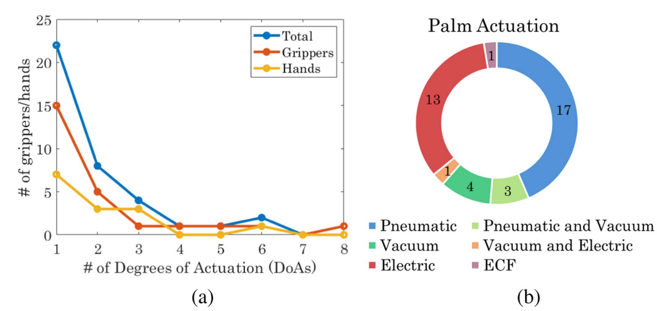

Fig. 8. Number of grippers included in the review with respect to (a) the number of degrees of actuation of their palms, and (b) the type of adopted actuation system for the palm.

fingers with more DoAs, due to the larger available space for actuators, and to the possibility of having them distant from the manipulation area. These are probably the reasons for the increased interest in building actuated palms for soft hands that stems from the total number of related publications in the last three years [Fig. 6(a)]. We found a prevalence of actuated palms in soft continuous hands with respect to articulated ones and their diffusion has become particularly evident in recent years. The reasons for this are difficult to state in a conclusive way, but one of them could be related to the fact that the adoption of continuously deformable structures in the design of robotic hands is a relatively recent trend, and thus the investigation of new fabrication processes and materials has led to several new studies and prototypes [35].

Regarding adopted materials [Fig. 6(b)], more than the 70% of the considered devices features a palm that is at least in part soft. Indeed, the high diversity in actuation technologies that are available for soft devices allows building palms having different structures and capabilities, ranging from grippers endowed with suction cups [41] to anthropomorphic hands with suitably designed air chambers in the palm to bend along directions that mimic the human hand arches [56]. Rigid palms are used only in nonanthropomorphic grippers and most of the time are designed to allow the reconfiguration of fingers.

From the analysis of the actuated palm solutions available in the literature for nonanthropomorphic grippers and anthropomorphic hands, some similarities and some differences can be observed. More specifically, concerning the palm functions, we identified five main usages of the actuated palms as follows: 1) fingers reconfiguration, 2) new grasping strategies, 3) enveloping grasp, 4) thumb opposition, and 5) in-hand manipulation. These are the functions of the human palm as well (see Section II), but are implemented in different ways depending on the level of anthropomorphism of the gripper. While in anthropomorphic hands researchers explicitly tried to reproduce the human hand arches' shape and motion, in nonanthropomorphic grippers the focus was more on reproducing the function itself, without mimicking the exact structure of the human palm. In Fig. 7, the implemented functions with respect to the type device are reported.

Both grippers and hands frequently present actuated palms to obtain more enveloping grasps, i.e., grasps with extended contact patches that result to be more robust. In anthropomorphic hands, this function is usually implemented together with thumb opposition. This latter feature is present only in anthropomorphic hands and is frequently tested using the Kapandji test [75]. Another typical benchmark used in the analyzed works for validating the capabilities of anthropomorphic hands is the implementation of all grasps from a taxonomy like the one proposed by Feix et al. [27].

In nonanthropomorphic grippers, the palm actuation is mainly used for finger reconfiguration, which consists in the possibility of repositioning the fingers around the palm to change the gripper workspace and the grasp type [Fig. 4(d), (e)]. The mechanisms adopted in this case can be considered as actuated palms since they provide the hand with additional degrees of freedom which allow it to change the pose of the fingers' bases with respect to the palm. In other words, palm actuators move mechanical parts to which the fingers are attached and these parts are considered as moving elements of the palm itself, not of the fingers, whose actuators are designed only for closing/opening motions. Fingers reconfiguration is usually not needed (or desired) in anthropomorphic hands as it might lead to rather nonanthropomorphic motions, unless, for example, splaying of the four fingers is considered [Fig. 5(c)].

In many prototypes of underactuated nonanthropomorphic grippers, additional DoAs are embedded in the palm to implement in-hand manipulation motions [Figs. 1(c) and 4(a)] and new grasp strategies [Fig. 1(a)] that would otherwise be impossible with a limited number of actuators placed only in the fingers.

An overview of the number and type of actuators present in the studied grippers and hands is available in Fig. 8(a) and (b), respectively. Actuated palms typically have a limited number of DoAs, 1 or 2 in most of the cases [Fig. 8(a)], both in grippers and in anthropomorphic hands. The actuation is more frequently achieved using pneumatic or electric systems [Fig. 8(b)].

VII. Conclusion and Perspectives

Most of the efforts in the relatively young field of soft hands design have been devoted to creating soft structures able to replicate flexion/extension capabilities of the human fingers. For this reason, passive supports have been used as palms with the aim of spatially distributing the fingers to obtain their relative opposition. The use of a passive palm has the advantage of simplifying the hand design, control and reliability, and reducing the number of actuators and of moving mechanisms. However, as shown in the devices presented in this review, adding degrees of actuation in the palm can unlock new grasping and manipulation capabilities unfeasible with underactuated fingers. As a future perspective, the active control of additional DoFs in the palm, combined with an increased sensing capability, could enable interactive perception strategies [82] in which, for example, the gripper actively collects tactile information on the shape of objects and exploits it to wrap around them in a controlled and intentional way.

New actuators, materials, technologies and structures developed in particular in the soft robotics community offer a wide range of possibilities for the future design of actuated palms. The palm could, for example, embed enveloping structures as the net-like one presented in [83] or exploit soft pneumatic plates to perform manipulation tasks using patterns of inflation/deflation of specific air chambers [84], [85]. As also shown in one of the papers that we included in the review [65], actuated palms can be used to achieve particular surface properties like compliance or friction and this could be implemented using, for example, microstructured controllable adhesives [86], or exploiting specific mechanical behaviours like bistability [87].

A relevant direction in soft robotics is represented by bioinspiration [88]. In this perspective, in grasping and manipulation tasks, the human hand represents the main reference, above all in the design of prostheses [12], [89]. As highlighted in Section II, the palm has an important role in human grasping and thus a promising research direction is in the design of palm structures that mimic human anatomy and/or capabilities (e.g., thumb opposition motion, concavity adaptation).

As shown in this review, however, the use of nonanthropomorphic structures gives more freedom to the designer and can lead to grippers capable of nonanthropomorphic manipulation strategies able to solve problems like grasping in cluttered environments or in-hand manipulation with a lower number of actuators and simpler structures with respect to anthropomorphic hands.

The literature review conducted in this article showed that there is a growing trend of expressly considering also the palm in the design and actuation of soft robotic hands. The combination of the adaptability of soft hands with the dexterity brought in by the use of active palms will contribute to the development of the next generation of robotic hands that could eventually bridge the gap between human and robotic manipulation.

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Maria Pozzi (Member, IEEE) received the B.S. degree in computer and information engineering, the M.S. degree in computer and automation engineering, and the Ph.D. degree in information engineering and science, all cum laude, from the University of Siena, Siena, Italy, in 2013, 2015, and 2019, respectively.

She is currently an Assistant Professor of Mechanics with the Department of Information Engineering and Mathematics, University of Siena and an Affiliated Researcher with the Italian Institute of Technology (IIT) of Genoa, Italy. In 2021, she was selected as one of the RSS Pioneers and she was an invited speaker at the IFRR Global Robotics Colloquium on The Future of Robotic Manipulation. Her main research interests include robotic grasping, simulation and modeling of soft robots, haptic interfaces for human–robot collaboration, and educational robotics.

Dr. Pozzi is an Associate Editor for *IEEE Robotics and Automation Magazine* and *IEEE Robotics and Automation Letters*, since 2018. She was the recipient of the RAS Haptics Grant promoted by IEEE RAS Technical Committee on Haptics.

Monica Malvezzi (Member, IEEE) received the Ph.D. degree in applied mechanics from the University of Bologna, Bologna, Italy, in 2003.

From 2002 to 2008, she was a Researcher with the University of Florence, Florence, Italy. From 2008 to 2018, she was an Assistant Professor with the University of Siena, Siena, Italy. From 2015 to 2019, she was a Visiting Scientist with the Department of Advanced Robotics, Istituto Italiano di Tecnologia, Genova, Italy. She is currently an Associate Professor of mechanics and mechanism theory with the Department of Information Engineering and Mathematics, University of Siena. She was a PI for the UNISI unit in the H2020 project “INBOTS - Inclusive Robotics for a better Society” and in the ERASMUS+ project BEREADY. She has authored or coauthored several publications in journals, international conferences, and book chapters. Her research interests include the control of mechanical and mechatronic systems, robotics, haptics, multibody dynamics, grasping, and dexterous manipulation.

Dr. Malvezzi serves as a Member of the editorial/organizing board of international conferences and journals.

Domenico Prattichizzo (Fellow, IEEE) was the General Coordinator of the FP7 IP collaborative project “WEARHAP: WEARable HAPtics for Humans and Robots from 2013 to 2017.” He is a Full Professor of robotics with the Department of Information Engineering and Mathematics, University of Siena, Siena, Italy, and a Senior Scientist with the Italian Institute of Technology, Genoa, Italy. He is currently the Coordinator of the Horizon Europe project “HARIA: Human-Robot Sensorimotor Augmentation–Wearable Sensorimotor Interfaces and Supernumerary Robotic Limbs for Humans with Upper-limb Disabilities.” His research interests include human and robotic hands, along with haptic perception and the art of manipulating objects which is increasingly oriented towards highly wearable robotics and wearable haptics.

Prof. Prattichizzo is the Editor-in-Chief of IEEE TRANSACTIONS ON HAPTICS, President of Eurohaptics society, and Co-founder of WEART, and the Italian Institute of Robotics and Intelligent Machines. He was invited as a Plenary Speaker, to IEEE Haptic Symposium in 2018, AsiaHaptics and IEEE International Conference on Robotics and Automation (ICRA) in 2016.

Gionata Salvietti (Senior Member, IEEE) received the master’s degree in computer engineering and the Ph.D. degree in information engineering from the University of Siena, Siena, Italy, in 2009 and 2012, respectively.

In 2012, he was a Visiting Researcher with the DLR Institute of Robotics and Mechatronics, Weblling, Germany, and with the University of Hamburg, Hamburg, Germany, in 2008. From 2012 to 2015, he was a Postdoctoral Researcher with the Italian Institute of Technology, Genoa, Italy. From 2020 to 2023, he was the PI for the University of Siena unit in the EU ERASMUS+ project “AUGMENTEDWEAREDU.” Since 2023, he is the PI for the PRIN project “ARTIS” financed by the Italian Ministry of Research and of the EU Erasmus+ project “ImmersiveSurgicalEd.” He is currently an Associate Professor of industrial robotics and control with the Department of Information Engineering and Mathematics, University of Siena, and an Affiliated Researcher with the Italian Institute of Technology. His research interests include collaborative robotics, assistive devices, and haptics.

Dr. Salvietti is an Associate Editor for IEEE TRANSACTIONS ON ROBOTICS since 2022, IEEE TRANSACTIONS ON HAPTICS, and *IEEE Robotics and Automation Letters* since 2020.