Exoskeletal Devices for Hand Assistance and Rehabilitation: A Comprehensive Analysis of State-of-the-Art Technologies

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***Abstract*—Robots are effective tools for aiding in the restoration of hand function through rehabilitation programs or by providing in-task assistance. To date, a multitude of exoskeletal devices employing distinct technologies have been proposed, making navigating this field a challenging task. To this end, we propose a set of classification criteria to help categorize devices. In this review, a set of 97 publications representing 72 active exoskeletal devices for hand assistance and rehabilitation is analysed. Furthermore, the distribution over the years within each of the criteria is presented. Results show clear trends, such as preferring underactuated devices, electrical transducers with flexible transmission or the more recent uptake of soft technologies. Lastly, the readiness level of hand exoskeleton technology is presented in terms of the whole device and each of the identified sub-classifications. Most of the devices are still in laboratory testing phase, undergoing healthy subject trials or limited clinical trials, with very few having actually reached the market. We hope to provide researchers with a comprehensive analysis of currently employed design choices in hand exoskeletons, highlighting the most developed avenues of research and the latest emerging ones.**

***Index Terms*—Wearable robotics, exoskeletons, hand, assistance, rehabilitation.**

I. Introduction

One of the main ways for humans to interact with the surrounding environment is through movement. Simple actions, such as reaching and grasping a glass of water or brushing our teeth, seem easily feasible to most of us, and we could not imagine our life without them. However, people who have lost the movement of their hands or ability to properly control them cannot or have difficulty in performing such Activities of Daily Living (ADLs) [1]. The loss of hand function is often associated to neurological (e.g., stroke) or muskuloskeletal conditions (e.g., traumatic injuries or muscular disorders). Efforts have been made and are continuously increasing in providing rehabilitation and/or daily assistance to people that have a medical condition which diminishes their hand function ability.

From a neurorehabilitation point of view, it has been reported that the performance of functional tasks in a highly intensive, repetitive manner is beneficial to the patient [2]–[5]. The ability of robots to perform motions in a repetitive manner over long periods of time makes them a potentially beneficial tool for providing high-intensity treatment [6]. Furthermore, robots enable more independent training with lower supervision, allowing the patient to perform intensive therapy for longer [7]. In terms of daily life assistance, the use of robotic devices, namely exoskeletons, could greatly improve the independence of their users [8].

A hand exoskeleton is a complex system whose development requires a multi-disciplinary approach, creating many possible avenues of research. Although it is widely accepted that exoskeletons can be beneficial tools for helping users with hand mobility issues, there is currently no device or technology considered ideal to fully restore the user's lost function. A number of reviews on hand exoskeletons has been published already [9]–[21]. However, most present limitations which this paper attempts to address, such as: a lack of a systematic analysis of devices according to all their technical components [9], [11], [12], [19]; including devices that are not aimed at hand assistance, but rather upper limb in general [13], [18], [20], [22], [23] or including lower limb as well [21]; limiting the scope to a certain type of devices, e.g., limiting to soft devices [15] or cable-driven systems [18]; having a too broad scope, including end-effector devices as well [10], [11], [14], [24]. Some reviews are outdated [16]. The reviews by [14] and [24] provide an excellent analysis of developed hand exoskeletal technologies. However, after their publication, a great number of new devices have been published, which make up approximately half of the devices identified in this review. There have been very interesting developments in recent years, namely with the development of soft and hybrid devices (please refer to Section II-B3 for a detailed description), which complement the above-mentioned reviews. This literature review aims to complement the existing body of reviews in hand exoskeletons by proposing a new and intuitive classification system according to their technical characteristics. This system includes a measure of the maturity

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of current technologies employed in hand exoskeletons, which the authors hope can shed light into the state of the art in this field. Furthermore, a discrete distribution of the devices by their year of publication is here presented, which provides detailed insight into the evolution of technologies over the years.

The rest of this paper is organized as follows. In Section II, the search procedure is outlined, and the classification system is explained. In Section III, the results of the search of literature and organization of the devices according to the defined taxonomy are presented. An analysis of the distribution of the devices in each criterion and observed trends along the years is also performed in Section III. Finally, Section IV presents concluding remarks.

II. Methodology

A. Search Scope

The search was limited to scientific journals indexed in Scopus using the title/abstract/keyword search option. Only peer-reviewed literature from journals in the English language was considered. The search was limited to devices that provide some degree of assistance to the physical motion of the hand by applying forces/torques, i.e., active devices. Devices that provide only haptic information about the hand segments were not included. The keywords were the following: "hand AND (assistance OR assistive OR rehabilitation OR rehabilitative) AND (robot OR robotic OR glove OR exoskeleton)." In addition to papers collected through keyword search, further sources were added from references and citations of analysed papers. These sources were not limited to academic publications, but also included websites and documentation of commercial devices. Because there are often multiple publications for the same device that build upon each other, these were grouped under the same device, and all relevant information was retrieved from the most recent publication. In the case where a more recent article presents a radical change in any component of the device, publications were not grouped together. The exclusion criteria were: (1) Devices that are not exoskeleton-based (exoskeletons, active orthoses and glove-based systems), i.e., it is end-effector based; (2) Devices that are passive, i.e., do not actively support hand motion via an actuation system; (3) Devices whose publications are lacking fundamental information regarding the classification criteria "targeted area", "actuation level", "actuation system" or "motion intention", making it impossible to classify them according to these criteria.

B. Classification Criteria

For a better understanding of what is the technology used in the devices that have been developed, criteria for classifying and organizing them according to their technical characteristics were developed. In this way, one can more easily detect what is the leading approach within each category and draw conclusions regarding what is lacking in the state of the art. As such, seven different criteria were considered: *Targeted area*, *Actuation level*, *Rigidity*, *Actuation system*, *Motion intention*, *aTRL* and *Purpose*. All the characteristics of a device can be categorized according to one of the above-mentioned classes, allowing for a generalized description of the working principle of the system. These classes can be further separated in different sub-classes, completing the full characterization of the device (Figure 1). Below, a detailed description of each class and sub-class.

1) Targeted Area: The *targeted area* criterion describes which area of the hand is intended to be assisted. The areas considered in this classification are the *thumb*, the *fingers* (index, middle, ring and/or little fingers) and the *wrist*. These sub-divisions are not mutually exclusive, as a single device can actuate, for example, the thumb and the fingers at the same time.

2) Actuation Level: The *actuation level* criterion of a robotic device concerns whether a device is *fully-actuated* or *underactuated* [25]. Fully actuated devices have the same number of Degrees of Freedom (DOFs) and Degree of Actuation (DOAs), with one actuator per DOF, whereas underactuated devices have more DOFs than actuators. Under the latter sub-division, a device can be considered *non-continuum* if it has finite DOFs, or a *continuum* robot if it has infinite DOFs.

3) Rigidity: The *rigidity* criterion is related to the stiffness of the device and is the most closely associated to comfort. It can be divided in 3 sub-classes: *soft*, *rigid* or *hybrid*. Soft devices are defined as being composed of only soft, compliant materials at the interface between the robot and the user that do not limit the natural movement of joints (meaning hard components, like battery casings, can be placed remotely), and most torques/forces are borne by the user's skeletal structure. A device is defined as rigid if it is composed mostly of hard, stiff materials at the interface between the device and the user, and all torques and forces are borne by the device's mechanical structure. Hybrid devices combine one or more features of soft and rigid ones in the same component.

4) Actuation System: The *actuation system* of a device can be divided in two components: *transducer* and *transmission*.

The transducer converts energy to mechanical power, and can be classified in *electric*, *pneumatic*, *hydraulic* or *thermal*. An electric transducer has an electric motor as the component that transforms electricity into mechanical motion. A pneumatic transducer uses compressed air by regulating the amount of air that is being fed into the system, which in turn is translated in changes of shape or force of the actuating component. Hydraulic transducers have a similar working principle as the pneumatic ones, but instead of air, a liquid is used. Devices with thermal transducers all use Shape Memory Alloys (SMAs), which are alloys that can be deformed but return to their original shape once they are heated.

The transmission is then responsible for transmitting the resulting mechanical power to the load, and can be divided in: *flexible*, *fluidic* or *linkage*. Flexible transmission is one where the power of the transducer is transmitted via tendons (e.g., cables inside Bowden cables), wires or flexible shafts. Fluidic transmission is in the form of tubes that allow for a fluid to flow through, such as air or water. In a linkage transmission, forces/torques are transmitted to the load via non-flexible bars or other types of mechanisms.

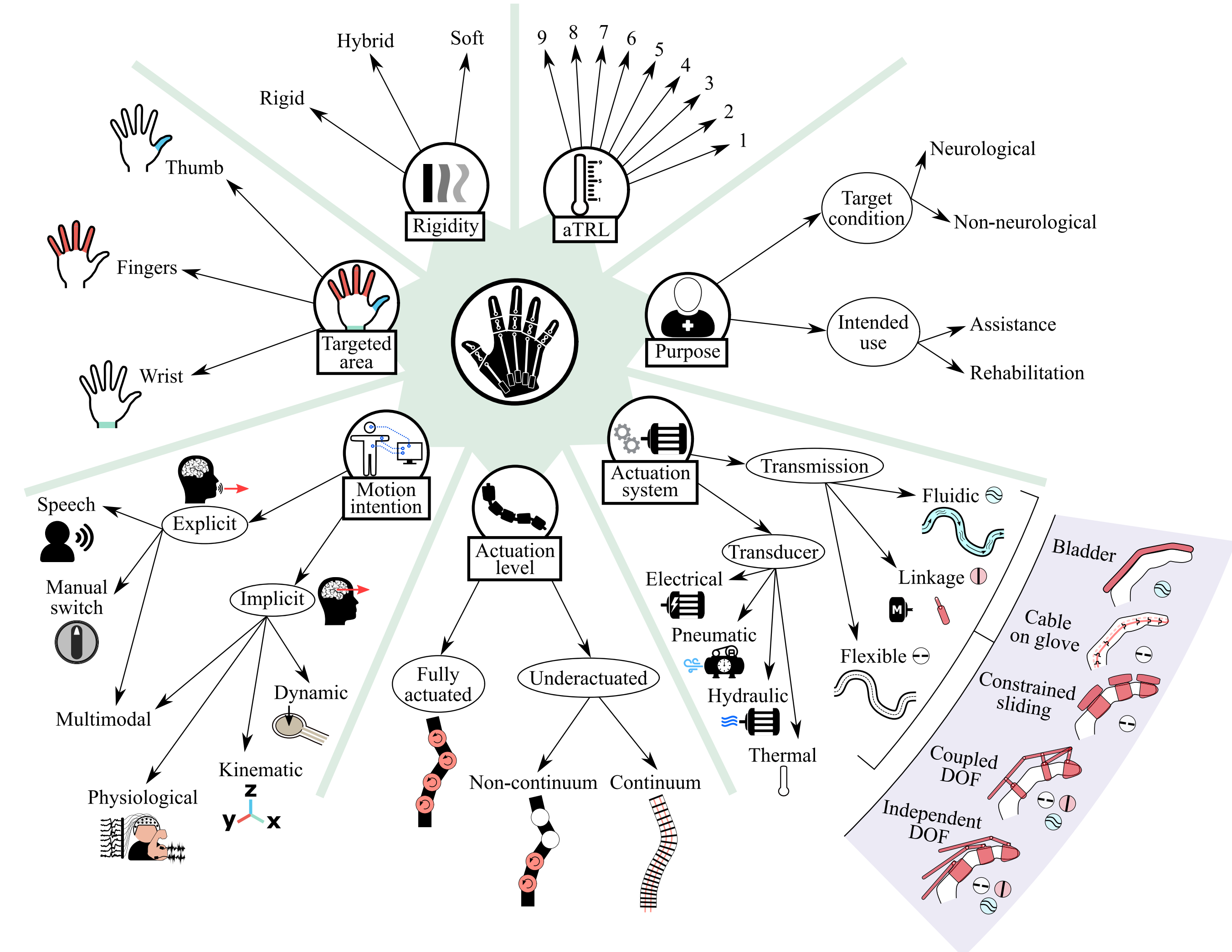

Fig. 1. Criteria for classification of the exoskeletal devices for hand assistance that were analysed. There are 7 criteria: *Targeted area*, *Actuation level*, *Rigidity*, *Actuation system*, *Motion intention*, *aTRL* and *Purpose*. Regarding the actuation system, the colour-and-pattern-coded circles establish the relation between types and sub-types of transmission. Regarding motion intention, multimodal signals can include any of the sub-classes of signals.

The types of transmission can be further divided in *cable on glove*, *constrained sliding*, *independent DOF*, *coupled DOF* or *bladder*. A cable on glove transmission is one where there are cables directly connected to the glove which are pulled depending on the output of the actuator. A constrained sliding transmission is one where a flexible type of transmission (like a stiff wire) is guided through a structure and is actuated in a push and/or pull fashion, with the structure constraining the possible movements. In an independent DOF transmission, each segment of the hand/fingers is operated independently with its own transducer. In a coupled DOF transmission, rigid links assembled together and connected to the target area transfer the torque generated by the transducer. A bladder transmission is one where a chamber is directly coupled to the target area such that when fluid travels to/from it, forces are generated and directly transmitted.

5) Motion Intention: The motion intention criterion is organized based on [14], [26]. It is categorized according to the signals input to the system, which can be of 2 forms: *explicit* or *implicit*. Explicit signals are used for commanding motion intention by using systems in parallel with the device, typically based on *speech* commands or the use of *manual switches* (these also include the use of user interfaces) to control actuation. Implicit signals are used for detecting motion intention using systems in series with the device, and most are based on *kinematic* (position or its derivatives), *dynamic* (force or torque) or *physiological* signals. There are also devices that use a multimodal approach, where multiple sensor inputs are used to predict motion intention. For the control method to be considered multimodal, data from two or more sensors must be used at the same time. This is to exclude devices where data from one sensor are used in one control mode and from another sensor in a different control mode.

6) Adapted Technology Readiness Levels (aTRL): The aTRL criterion measures at what stage of development the hand exoskeleton is. By measuring the readiness of a technology, one can infer how promising and effective it is, as the requirements for achieving higher aTRLs include testing both the performance and clinical outcomes. It has been adapted from [27], taking inspiration from [28], [29]. There are 9 levels

TABLE I

THE ADAPTED TECHNOLOGY READINESS LEVELS (aTRLS) DEFINED IN THIS PAPER. FOR THE SAME LEVEL, THE ORIGINAL DEFINITION BY NASA IS PRESENTED TOGETHER WITH THE PROPOSED ADAPTED DEFINITION. THE aTRLS CAN ALSO BE DESCRIBED BY THEIR SHORT FORM NAME (LAST COLUMN). ADAPTED FROM [27], [28]

Level	Original TRL definition	aTRL definition	Short form
1	Basic principles observed and reported	Published research identifying problem/possible technology.	Conceptualisation
2	Technology concept and/or application formulated	Publications of analytic studies. Supporting analyses providing scientific information and data to develop research proposals.	
3	Analytical and experimental critical function and/or characteristic proof-of concept	Proof of concept of individual elements of the device are tested in limited number of laboratory models, publication of results.	
4	Component and/or breadboard validation in laboratory environment	Proof of concept and safety demonstrated in laboratory environment.	Laboratory testing
5	Component and/or breadboard validation in relevant environment	Proof of concept and safety demonstrated in healthy human trials. Evidence of device being equivalent to predicate device (FDA 510 k) ready for clinical trials.	Clinical trials I
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	Clinical trials conducted in small number of impaired subjects (< 20) under controlled conditions for safety evaluation.	Clinical trials II
7	System prototype demonstration in a space environment	Clinical trials for effectiveness on large number of impaired subjects ($\geq$ 20) in operational environment for safety evaluation. Determination of short-term adverse events and risks associated with the device. Final design validated.	Clinical trials III
8	Actual system completed and "flight qualified" through test and demonstration (ground or space)	Device has been certified to work under operational environment and intended conditions. FDA 510(k) or equivalent approved.	Certification
9	Actual system "flight proven" through successful mission operations	The device is being marketed. Post-marketing studies.	Commercialisation

in total, with the lowest number corresponding to the earliest stages of development (Table I). For a device to obtain a determined aTRL, it must fully comply with the requirements for that same level.

7) Purpose: The purpose criterion refers to what is the objective of the device and who is it aimed for, as claimed by the device's authors. It can be divided in terms of the *targeted condition* that the device aims to help with, being either *neurological* conditions or *non-neurological*; and in terms of its *intended use*, which can be *assistance*, *rehabilitation* or both. Regarding the medical condition it targets, neurological ones include diseases, disorders or injuries related with the nervous system, such as a stroke or spinal cord injury, whereas non-neurological ones encompass a broader definition of conditions that are not directly related to the nervous system, such as traumatic injuries of the muscle or tendons, or muscular dystrophy.

III. DISCUSSION

There were 2577 sources identified as possible candidates to be included in the review. After screening, full-text analysis and selection of publications from other sources, the final number of publications analysed in this review comes to 97 publications that represent 72 devices (Figure 3). The classification of each device according to the defined criteria sorted by aTRL, with additional information, is presented in Table II (Supplementary Information). Figure 2 shows representative examples of devices.

A. Analysis of Devices and Current Trends

1) Targeted Area: The vast majority of devices actuate the fingers together with the thumb (72%) due to the nature of the function of the hand, which lies in grasping objects [39], [40] (Figure 4). However, some devices actuate only one finger together with the thumb [41], [42], allowing only for pinch grasps to be performed. Another approach is the support of the whole hand, i.e., fingers, thumb and wrist, although not a popular one (3%) [43], [44]. A few research groups have opted for devices (3%) with support only of the thumb, be it (a) because of its unique characteristics—such as large force, being opposable and having many DOFs—[45], (b) as a first step in an incremental process to eventually assist the fingers as well [46] or (c) as a platform for investigating control paradigms [47]. Only 7% of devices did not have support of the thumb, showing its importance.

2) Actuation Level: Underactuated devices are often the preferred alternative in terms of actuation level (82%) due to the easy solution of the joint misalignment problem they provide [24] (Figure 5). This also makes them a preferred alternative especially when developing devices for daily assistance. The use of a non-continuum mechanism (42%) [48], [49] seems to be of comparable popularity to the use of a continuum mechanism (43%) [34], [50], with the difference in preference relying mostly on the rigidity of the device: non-continuum devices are mostly rigid and continuum ones are mostly soft/hybrid. There are also reports of fully actuated devices, albeit fewer (18%) [51], [52]. They are used almost exclusively for rehabilitation, given that they allow for the investigation of a wide range of motion, speed and force control at the joint level, and therefore for the exploration of different training settings and paradigms [51]. However, because the hand has many DOFs, controlling each one requires a large amount of actuators, making the device heavier and requiring a more complex control scheme. As such, fully actuated devices are generally not suitable for assistance in the performance of ADLs. From Figure 5, one can see that the number of underactuated devices has been increasing over the years, whereas the

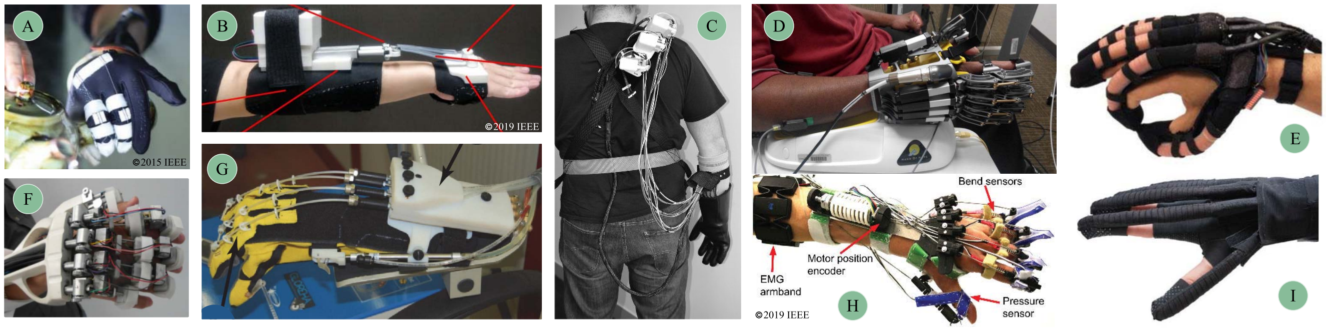

Fig. 2. Representative examples of different technologies employed in hand exoskeletal devices. (A) Electrically-actuated soft device with flexible, cable on glove transmission for actuation of the fingers and thumb [30]; (B) Electrically-actuated hybrid device with flexible, independent DOF transmission for actuation of the wrist [31]; (C) Thermally-actuated soft device with flexible, cable on glove transmission for actuation of the fingers and thumb [32]; (D) Electrically-actuated rigid device with linkages, coupled DOF transmission for actuation of the fingers and thumb [33]; (E) Hydraulically-actuated soft device with fluidic, bladder transmission for actuation of the fingers and thumb [34]; (F) Electrically-actuated rigid device with linkages, independent DOF transmission for actuation of the fingers and thumb [35]*; (G) Pneumatically-actuated hybrid device with flexible, constrained sliding transmission for actuation of the fingers and thumb [36]; (H) Electrically-actuated hybrid device with flexible, constrained sliding transmission for actuation of the fingers and thumb, with multimodal motion intention detection using physiological, kinematic and dynamic sensors [37]; (I) Pneumatically-actuated soft device with fluidic, bladder transmission for actuation of the fingers and thumb [38]*. *Image used under the creative commons licence CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

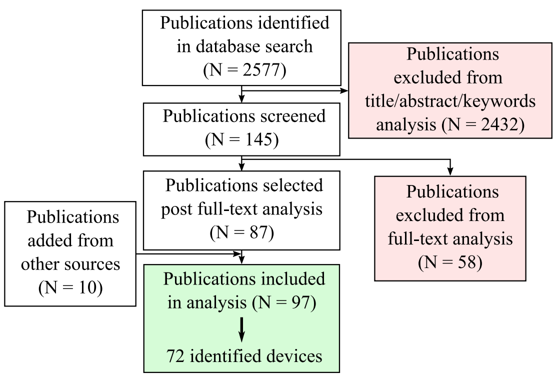

Fig. 3. Procedure for the literature search. Out of the 2577 sources found, 2432 were discarded after screening of title and abstract, then 58 were excluded during full-text screening, resulting in 87 articles. Ten more resources were added from other sources, resulting in a total of 97 publications representing 72 individual devices.

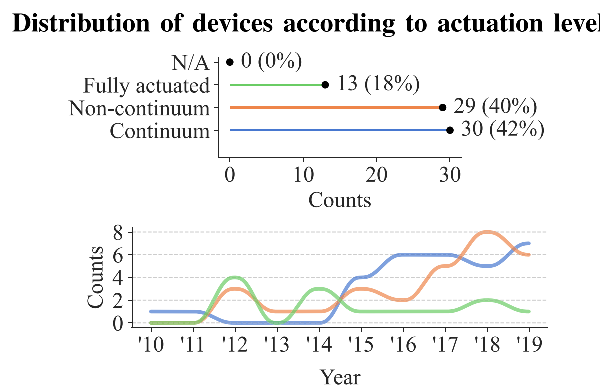

Fig. 5. Results of the literature review for the criterion Actuation level: number of devices (percentage of total devices) classified into each sub-class (top) and the progression of the numbers of each sub-class over the years (bottom).

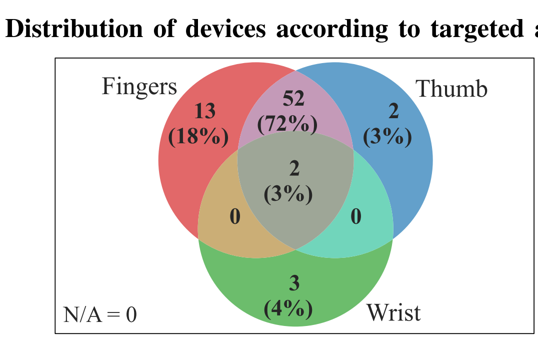

Fig. 4. Results of the literature review for the criterion Targeted area: number of devices classified into each sub-class (percentage of total devices).

opposite has happened for fully actuated ones. The downwards trend in the use of fully actuated mechanisms suggests that underactuated ones provide a better solution when it comes to actuation level.

3) Rigidity: Rigid devices have been the main option (50%) in the general paradigm of robotics due to their ability to deliver high power in a precise manner [51], [53]–[56] (Figure 6). Rigid devices have the advantage of allowing for more precise control due to their more easily modelled behavior, however, they are bulky, heavy and most do not properly account for a misalignment between the robot's and the user's joints [57]. Their presence in the field has always been large and does not seem to be waning, as can be observed from Figure 6. Soft devices are also a popular approach (35%) that has become more common in recent years. This is due to their soft properties that intrinsically solve the joint misalignment problem, be it in a pneumatically-actuated system with a fluidic [34], [50] or a flexible transmission [38], or in an electrically-actuated system with flexible transmission [30], [58]. They are generally lighter and less bulky than their rigid counterpart, but more difficult to control due to the compliant nature of the mechanism. Hybrid devices are not nearly as prevalent as soft or rigid ones (14%), but one can observe from Figure 6 that this is a growing field. They can be achieved in different ways: a non-continuum rigid structure that has many more DOFs than the

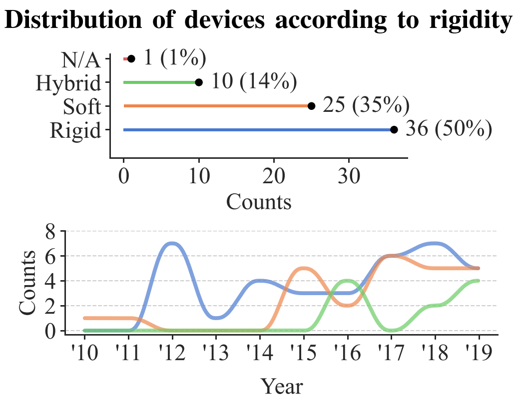

Fig. 6. Results of the literature review for the criterion Rigidity: number of devices (percentage of total devices) classified into each sub-class (top) and the progression of the numbers of each sub-class over the years (bottom).

ones needed, attached to a soft framework [59]–[61]; a mechanism that alternates between soft and rigid segments with a soft interface between it and the hand [62]; a soft actuator that is encased in a rigid segmented structure [63]; a system with a constrained sliding type of transmission [36], [64]. These devices are promising because they exhibit some advantages of both soft and rigid mechanisms: they have stiff parts that withstand the applied forces and improve safety, while at the same time having soft components that improve wearability.

4) Actuation System: An electric transducer is the most popular approach (70%) due to its ease of use, reliability, high precision and high power-to-weight ratio [24], [65], [66] (Figure 7). High torque outputs are obtained by coupling gearheads, which can increase the backlash of the system and decrease its backdrivability [14], [67], [68]. The most popular use of electric motors is in rigid devices, as all of them have electrical actuation, even though it is also a favored mode of actuation in soft and hybrid devices. Pneumatic actuators are also used—although not nearly as much as electrical ones (22%)—due to their low weight, high power-to-weight ratios and the inherent compliance of the actuator when used with a bladder transmission [50]. However, they are difficult to control [69] and typically need a large and bulky hardware to operate. Hydraulic transducers work in a way similar to pneumatic actuators, but are associated with more accurate control and higher stiffness due to the fluid used for transmission (liquid) being incompressible. However, the presence of liquid increases the weight of the device [50], and there is a safety hazard due to the possibility of leakage, which could be one of the reasons why only one device that uses hydraulic actuation was found [34]. Thermal transducers are implemented via the use of SMAs, and have been growing in popularity due to their small volume and weight and their high power-to-weight ratio [70], [71]. However, there are still many obstacles associated with their use: they provide small forces and take time to build up, are difficult to control and present a hazard due to the heat needed to actuate them [32], [72], [73]. Figure 7 shows that there has been an increasing trend in the use of electrical transducers, and a slightly less increasing tendency for using pneumatic transducers. Thermal transducers are clearly an emerging technology, with the few cases having all been proposed in the last 4 years.

The type of transmission is intricately related to the type of transducer used, where in most cases a flexible or linkage transmission is used with electrical or thermal transducers [65], [69], [74] and a fluidic one with pneumatic or hydraulic transducers [34], [75]. This partly explains why the flexible type is so popular (54%): the large number of devices using electrical transducers positively influences the amount of flexible transmissions. However, there are limitations to the use of this type of transmission. For example, the typical way to implement cable-driven actuators is using Bowden cables, which introduce friction in the transmission. This makes it difficult to model the output force of the actuator, requiring sensors at the distal end which further increase the bulkiness of the wearable component of the system. Linkage transmissions are only used with electrical transducers, and present an attractive approach due to the small loss of energy between the transducer and the plant, permitting precise control. Even though this transmission allows smaller and lighter transducers to be used, it comes at the cost of increasing the weight of the wearable part of the device, given that the actuation system is typically stored on the hand itself [76] or on the arm [64], also resulting in poorer wearability of the device. This explains why they are far less used when compared with flexible transmissions. Fluidic transmissions are also a commonly used type due to their typical implementation as inflatable bladders: fluid is pumped inside the bladder, and embedding it with strain-limiting layers allows for bending to occur in a desired direction. They are inherently compliant and safe to wear due to the use of soft materials, avoiding joint misalignment. A frequently reported drawback is the difficulty in accurately controlling the mechanical behavior of fluidic transmissions [69]. The first reported studies where such transmissions are used focused mostly on characterizing the capabilities of inflatable bladders rather than modelling their behavior [77], [78]. However, quickly new approaches were proposed, where for example changing the properties of the embedded strain-limiting layers results in desired motions [79], or changing the stiffness of the bladder itself achieves different bending angles at the joints [80], [81]. Still, this type of transmission is the less used of all, which is probably related to the low preference for pneumatic transducers as well. Nonetheless, it has observed an increase in preference over the last years due to the rise in popularity in soft robotics.

Regarding the sub-types of transmissions, the distribution of the numbers seems to be more uniform, with the exception of the coupled DOF sub-type: this is the most common one (35%) and it has been commonly used for almost a decade. This sub-type allows for underactuated systems, which are more easily controllable than other types of underactuated mechanisms [82], [83]. However, they can make the device very bulky [84], making their implementation in devices meant for daily assistance questionable. Nonetheless, their usefulness in a purely rehabilitative setting is apparent. The bladder, cable on glove and independent DOF sub-types all have similar presence in the scientific community (19%,18% and 17%,

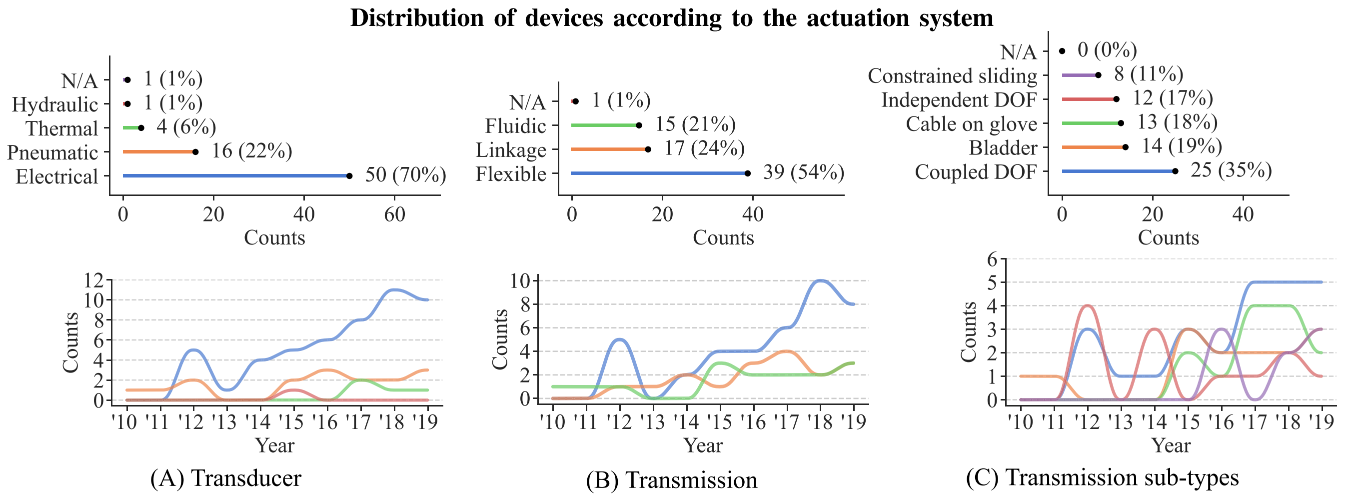

Fig. 7. Results of the literature review for the criterion Actuation system according to transducer (A), transmission (B) and transmission sub-types (C): in the first row, number of devices (percentage of total devices) classified into each sub-class; in the second row, the progression of the numbers over the years.

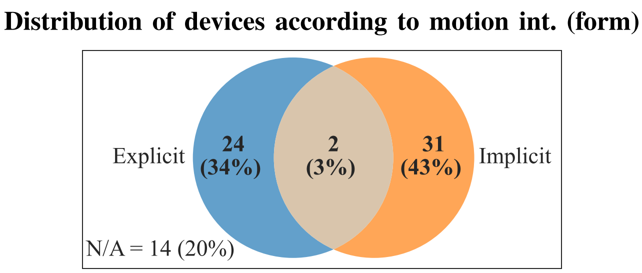

Fig. 8. Results of the literature review for the criterion Motion intention according to form of the signal: number of devices classified into each sub-class (percentage of total devices).

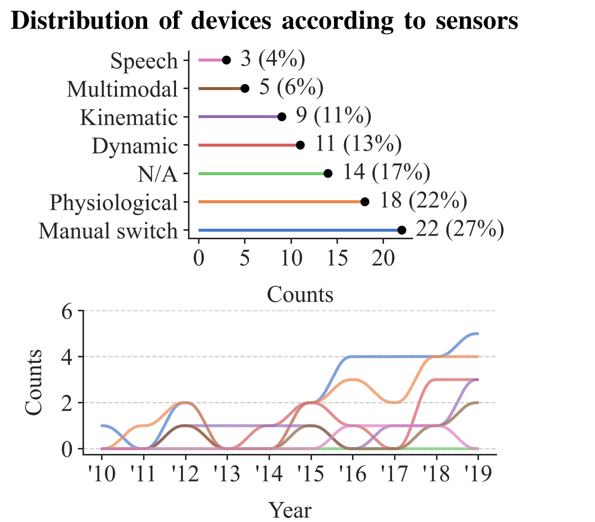

Fig. 9. Results of the literature review for the criterion Motion intention according to the sensor used: number of devices (percentage of total devices) classified into each sub-class (top), and the progression of the numbers of each sub-class over the years (bottom). The signal used in multimodal motion intention detection has also been included in its respective signal bar, e.g., if a device employs a multimodal technique via EMG and kinematic signals, these have also been accounted in their own bars in the chart. Note that the N/A plot (green line) remains at 0 because it was not deemed important to show these results, as it would clutter the plot unnecessarily.

respectively). A bladder sub-type of transmission is commonly used together with pneumatic actuation, as it imparts high compliance to the actuation system [81]. One can see that the rise in pneumatic transducers happens at the same time as the one in bladder mechanisms (Figure 7), showing these two are closely related. The mechanism that seems to have had the greatest increase over the years is the cable on glove one. A popular application of the cable on glove sub-type consists in using an electrical transducer for driving a single wire that is routed around multiple fingers, allowing for grasping that adapts to different shapes [30], [85], but it can also be used by having one single SMA actuator for each finger segment [73]. The use of this sub-type also seems to be quite promising for implementation in daily assistive devices, as the wearable part is often very slender, resulting in little interference during interaction with objects. An independent DOF sub-type allows for highly precise control of the fingers, yet it typically requires an actuator for each segment, which can make the device bulky and the control complicated [51], [52]. Constrained sliding sub-types of transmissions are a viable approach for achieving underactuation, as usually there is a single wire (or its equivalent) per finger [37], [39]. However, it can be difficult to control how the forces are transmitted to each phalanx, requiring extra care to prevent hyperextension [60], [64].

5) Motion Intention: Figures 8 and 9 show the distribution of the collected devices considering the motion intention criterion. There is a similar number of devices opting for using explicit (37%) or implicit (46%) signals, with the latter taking the upper hand. Only a handful (3%) of those employ both forms of signals, showing that it is preferred to opt for only one of them. One fifth of analysed devices did not report any type of motion intention, likely because they were still in a hardware development and testing phase.

The use of manual switches is very popular due to the simplicity and reliability they offer [38], [48]–[50]. Surprisingly, an increase of the use of manual switches over the years has been observed. Speech can be used as a direct interface to give commands to the device [64], but it is not a commonly used signal (4%). It provides intuitive task-based control and its main advantage lies in leaving the hands free (as opposed to manual switches), however it has a limited set of commands, acting often more as a state-machine. With the improvement of natural language processing algorithms, it is expected that the adoption of more speech-based motion intention detected will increase, as the set of commands would greatly expand, making the control interface more intuitive.

Of the implicit signals, physiological ones are the most common (22%). Electromyography (EMG) signals are electric signals that measure neuromuscular activity and are commonly used due to their easy implementation and feature extraction [33], [78]. Although they provide a reliable measurement of muscle activation, it is required that the subject has residual muscular activity, making it difficult to use in the case of highly impaired subjects [86]. Electroencefalography (EEG) signals measure the electrical activity of the brain, namely its sensorimotor rhythm. By accessing the signal responsible for motion at the source of the motor pathway, one avoids the signal degradation that is associated with signal acquisition at the distal end of the pathway, e.g., EMG [11]. However, typically surface electrodes are used, which limits the resolution of the signals and increases the susceptibility to recording artefacts [8]. Dynamic signals include force and torque signals which are read at the interface between the device and the hand or the device and the object. They are typically implemented in a system where motion intention is detected when the force exerted by the user exceeds a certain threshold [53], [87]. Kinematic signals can be detected by, e.g., flexion sensors [77], [88] or Inertial Measurement Units (IMUs) [67]. These signals can be employed to signal motion intention by, for example, using wrist flexion/extension [46] as the trigger signal, or by moving an unassisted finger [76]. Both dynamic and kinematic signals constitute a popular approach, as they typically require little hardware, and the motion intention detection method is direct and simple to implement. This presents advantages when compared to physiological signals, where more complex analysis and processing of signals is often required.

Only 5 (7%) devices integrating multimodal control in their motion intention detection strategy were identified [8], [37], [48], [49], [60], [89]–[91], showing that this is not a popular approach for detecting motion intention. All multimodal strategies include the use of physiological signals, either paired with other type of physiological signals (e.g., EEG and EMG), with kinematic or with dynamic signals. This suggests that physiological signals contain valuable information which can be complemented using other signals. For example, [37] implemented two multimodal control modalities, one targeted at subjects with difficulties in opening their hand and the other for subjects with difficulties in closing it. In the former, bend sensors are used to detect opening intention, and, in the latter, pressure sensors aid in detecting closing intention. This shows that integrating different signals can compensate for the drawbacks associated with each of them and can also provide targeted control. It should also be noted that all systems incorporating multimodal sensing used implicit signals. This is likely due to the requirement regarding the definition of multimodal sensing set in Section II-B5, which prevents systems using multiple signals non-concurrently from being classified as multimodal. For instance, in their device, [64] use voice recognition to change between states ("open", "hold" and "close") whereas EMG is used to give command for performing the movement. Although such few researchers opted to include multimodal systems, this is definitely a promising field (as can be seen from Figure 9), namely with the fast rise in popularity of data fusion techniques together with machine learning algorithms in identification of human motion [92] that is currently being observed. Furthermore, by integrating multiple sensors, one can compensate for eventual losses in one signal by using other signals, decreasing the possibility of insufficient detection of motion intention [37].

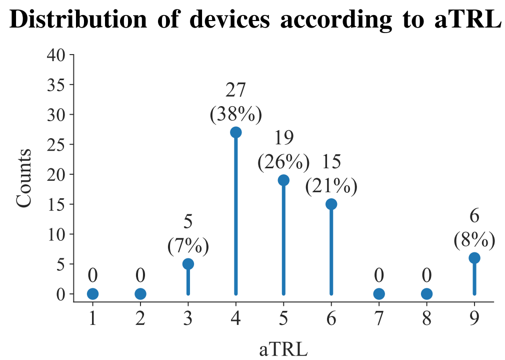

Fig. 10. Results of the literature review for the criterion aTRL: number of devices classified into each aTRL (percentage of total devices).

Out of all the publications reporting using implicit signals, only 11 also presented an evaluation of the performance of the motion intention detection algorithm. The outcome of this evaluation was in the form of either success rate in classification of human intention or in false positive rate, both presented as percentages. The average success rate when considering only implicit signals was 83%. This shows that even though explicit signals are generally preferred, algorithms using implicit signals perform very well and should be more often considered when developing hand exoskeletons.

6) aTRL: The results regarding the aTRL criterion can be seen in Figures 10 and 11. One can see that most devices are at development and laboratory testing phases, with 45% being at level 4 or below. However, many devices have undergone phase I (26%) or phase II (21%) clinical trials. It is evident that few devices reach the final stage of commercialization, with only 6 being on the market. Figure 11 shows the distribution of each sub-class of the criteria *actuation level*, *rigidity*, *actuation system* and *motion intention* in terms of the aTRL achieved by each device. From this plot, it is possible to analyse the readiness level of each type of technology. In terms of actuation level, it is clear that fully actuated technology is far from being widely implemented in the market, as the highest level it has reached is 6. Underactuated mechanisms are far more advanced, as only such devices have reached commercialization phase. Regarding rigidity, all types of technology seem to be equally advanced. As soft and rigid devices have

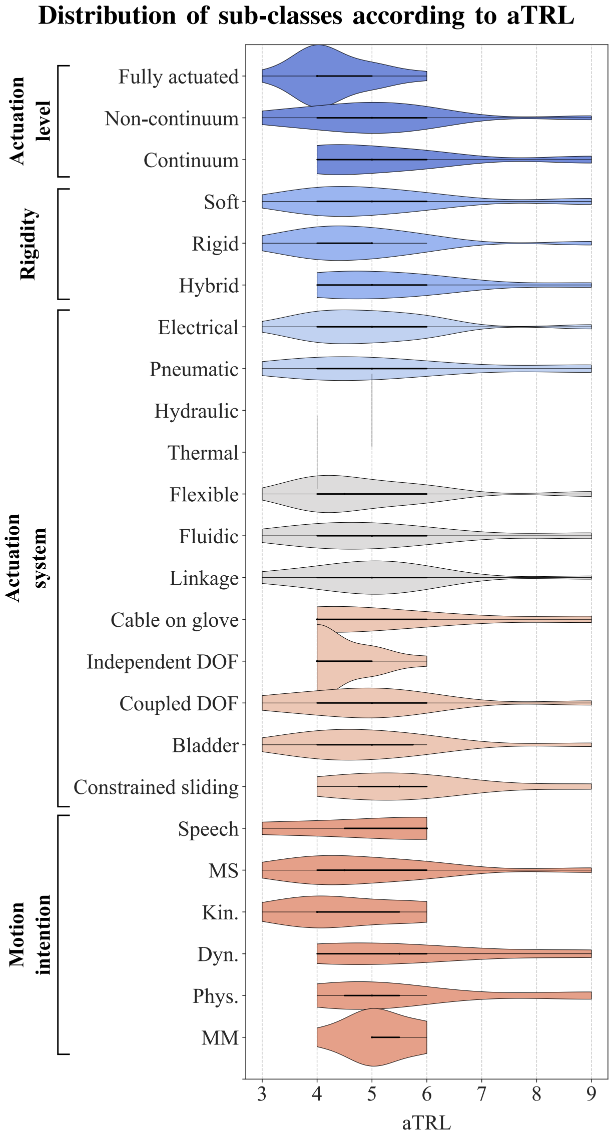

Fig. 11. Distribution of the devices for the criterion aTRL according to each one of the classification criteria.

been researched for longer, it is expected these will experience an advance in their readiness level in upcoming years. However, in the long term, we believe hybrid technologies hold more promise due to the high power output performance they exhibit coupled with high comfort, which is a defining trait in user acceptability. With respect to the actuation system, electrical and pneumatic transducers are the ones used in the systems with highest aTRL. These two types of technology have been used for a long time due to the well-known working principles that they are based on. This allows them to be easily implemented with different transmissions, which are typically the target of research and innovation. In other words, the transducer is merely used as a source of mechanical energy, and investigators working on hand exoskeletons usually focus their efforts on new transmissions. It is therefore expected that these transducers will continue to be implemented in future devices. Although the behavior of hydraulic systems is also well understood, the necessity for a liquid which increases the device's weight and the risk of spillage make them less preferred options as implementations of clinically useful devices, as there need to be more stringent safety testing for use with humans. Thermal transducers are still at an early aTRL stage, however, they have been considerably more investigated than hydraulic ones, especially in recent years. It is expected that the aTRL of devices with thermal transducers will advance in upcoming years, as SMA actuators become smaller, more efficient and have larger bandwidth. Concerning the types of transmission used, all 3 have a similar distribution, with linkage transmissions being slightly more developed on average than flexible and fluidic ones. Still, there is only one commercially available device using linkages (coupled DOF sub-type) [33], whereas, of the other 4 devices, 2 employ fluidic transmission with bladder [50] and coupled DOF [93] and 2 employ flexible transmission with cable on glove [94] and constrained sliding [36]. Among sub-types, however, there are clear differences. Independent DOF technology is still at lower readiness levels. Separately controlling the torque/position of each joint is a challenging task due to the nature of the fingers: one needs to assure proper kinematic compatibility with its natural and complex motions; and the finger segments are of small dimensions and have 4 DOFs. In independent DOF mechanisms, as they are not underactuated, the risk of joint misalignment is high, requiring more extensive safety measures, as seen in [52]'s device. This sub-type of transmission seems better suited at assisting a single target area at a time, as it is less intrusive for the user and easier to control for the developer. Although there are many systems with cable on glove transmissions, a great part are at level 4. Still, the use of cables can be very advantageous especially due to the possibility of using electric transducers—which are easy to control and have a high power-to-weight ratio—placed remotely for improved wearability. The greatest advantage lies in how slim and lightweight the system turns out, with most systems weighing around 200 g or less. Coupled DOF, bladder and constrained sliding sub-types are all very promising types of technology that present different methods of achieving highly underactuated systems. They have a similar distribution in terms of aTRL, where the main difference between them lies in the type of transmission used: coupled DOF uses mostly linkages, constrained sliding uses mostly flexible transmission and bladder only uses fluidic transmission. Coupled DOF transmission is a well-established technology that is the target of extensive research, as one can precisely control the movement of a single finger [95] or group of fingers [96] to follow a desired trajectory with the use of a single actuator. This presents an advantage when compared to constrained sliding, where the movement is harder to control. However, in this sub-type, the force transmitted to the hand does not impose a trajectory, which has the benefit of self-aligning with the user's hand. With regard to motion intention, technology is still not very advanced, as only manual switches and the use of dynamic and physiological signals have achieved aTRL 9. The use of kinematic signals seems to be still limited. This could be due to these signals requiring good motor skills to be preserved by the user, which is generally not the case with impaired users. Multimodal systems are also still not very

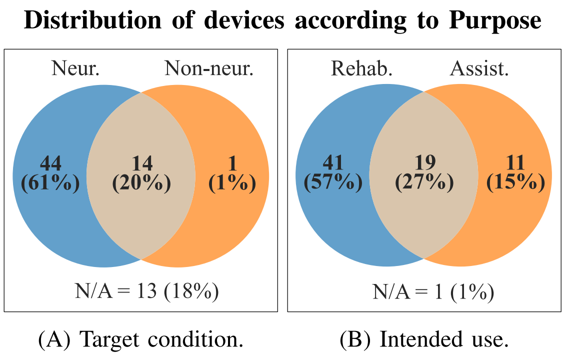

Fig. 12. Results of the literature review for the criterion Purpose according to (A) targeted condition and (B) intended use.

advanced, but the advent of data fusion and machine learning techniques is an indicator that we could see a fast rise in the readiness of this technology. Physiological and dynamic signals are, of the implicit signals, the ones that hold the most promise, but for different reasons: physiological-based motion intention detection is popular due to bypassing interaction with the environment, inferring motion directly from the biological signal that the human body creates; dynamic-based intention detection is very easy to implement by using force sensors on the fingertips.

7) Purpose: The large majority of the analysed devices are identified as being meant for aiding people with neurological diseases (81%), and there are some that are meant for muscular conditions (21%). Many devices are also meant for both types of disorders, however, only one is meant solely for muscular disorders, meaning this is not a popular type of condition to focus on. Surprisingly, 18% did not specify which condition they were targeting, which is a larger number than expected.

In terms of intended use, most devices are meant for rehabilitation (84%), there being twice as much as ones meant for assistance (42%). About one fourth of the total identified devices are meant for both types of uses, and only one did not specify what its intended use was.

B. Summary of Main Findings

It is clear that when it comes to the targeted area and the actuation level of a device, underactuated devices aiding the fingers and thumb are preferred. Such devices are light and simple to control and provide enough assistance to the hand to execute the necessary tasks during rehabilitation or ADLs.

The choice of a device's rigidity and actuation system is more nuanced, strongly dependent on the purpose of the device. Rigid devices with electrical transducers are an appropriate choice to use in a rehabilitation setting, where accurate control is necessary for exploring certain training paradigms. Comfort and low weight, areas where rigid devices are lacking, are not a priority in such a setting. On the other hand, soft devices are more appropriate for daily assistance, as they are safer to use and more lightweight. Pneumatic transducers allow for the use of bladders as transmission, which are efficient at distributing forces along the finger joints to achieve underactuated mechanisms that are comfortable and safe to wear. However, the necessity of bulky hardware such as air compressors limits their portability, which is fundamental in fully aiding with ADLs. There is a clear need for smaller pneumatic transducers that require low energy—enabling the use of batteries—but can achieve the necessary power output. At the moment, the use of electrical transducers with cable on glove transmissions seems the most promising technology to achieve portable devices that can help with daily activities: batteries are easily integrated with such devices, facilitating portability, and the transmission is extremely svelte, resulting in unobstructed interaction with objects and a comfortable device.

Most researchers have opted to implement manual switches to control their devices, preferring to focus on aspects other than implicit motion intention detection, such as actuation systems. Typically, developers prefer to develop hardware separately from software, therefore motion intention detection is not the focus of the testing of proposed devices, but rather performance. The choice of sensors, where to place them and how to transmit data (wired vs. wireless) have an impact both on hardware design and control strategies. Although the control interface might not be a top priority during initial stages of development, still it should inform the design of the sensory system from the initial stages of the design phase.

C. Open Challenges & Future Directions

The field of hand exoskeletal devices has seen a great development over the years, with the number of new publications steadily increasing. Nonetheless, there is still much to explore, as only very few devices have actually reached the market. It is clear that the greatest challenge is in the development of wearable robots that can be used for daily assistance rather than being limited to clinical settings. The reason why we consider this challenge with top priority is because the successful implementation of an exoskeletal device for daily assistance entails overcoming a series of obstacles. For example, most devices are not able to aid with multiple types of grasping, which is fundamental to a healthy use of the hand in daily life. The ones that attempt to do so require several actuators that confer a high degree of control to the device. However, this becomes troublesome when the target is to achieve a portable, lightweight and slim wearable system. Furthermore, the thumb is rarely actuated in the entire spectrum of its movement—often being limited to flexion/extension—even though it is its large freedom of movement that allows for a wide variety of grasp types [97]. The assistance of thumb abduction/adduction, resulting in its opposition, is often ignored when developing hand exoskeletons. The issues mentioned so far, namely portability, wearability or the ability to assist the execution of different grasp types (which requires active support of the wide range of thumb motion), are related to high-level functional challenges. The technical challenges, i.e., efforts to develop novel technologies, should serve the purpose of tackling such high-level requirements.

Another important topic to consider when developing devices intended for daily assistance is the human-robot interface. The main obstacle lies in the difficulty of implicitly detecting motion intention in an accurate way. The most promising type of implicit signal is the physiological one, namely the use of EEG signals in Brain-Computer Interfaces (BCIs). Unlike other signals, like EMG, dynamic or kinematic signals, which are directly affected by the degree of motor impairment, the integrity of EEG signals is independent of the motor ability of the patient [98]. The ability of the brain to imagine a motion, also known as motor imagery, has been shown to be highly useful in detecting motion intention, while at the same time stimulating neurorehabilitation [99]. Yet, few devices integrate EEG sensing in their intention detection techniques. It is unclear why this is the case, with the main reason likely being that focus is usually brought to the mechanical characteristics of the system first. Most researchers prefer to first explore the actuation system of the robot, and once a satisfying solution is found, they move on to investigate control techniques. The fact that many devices are in early development stages explains why including implicit motion intention detection in a device's control paradigm has not been a top priority. Nonetheless, promising developments have been made in BCIs, and their usefulness in the control of hand exoskeletons has been shown [31], [39].

IV. Conclusion

This review presents a comprehensive analysis of current literature on active exoskeletal devices for hand support. The reader can see that there is an extensive collection of devices who adopt very different approaches in their implementation. The reasons behind the choice of the approach when it comes to any of the criteria here established is, therefore, a complex one. Researchers must consider the trade-off between the advantages and disadvantages associated with each type of approach.

We hope that this paper will help in investigating technological implementations of hand exoskeletons, and to guide them through this complex, yet fascinating field.

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