ABSTRACT Despite more than thirty-five years of research on wearable technologies to assist the upper-limb and a multitude of promising preliminary results, the goal of restoring pre-impairment quality of life of people with physical disabilities has not been fully reached yet. Whether it is for rehabilitation or for assistance, nowadays robotics is still only used in a few high-tech clinics and hospitals, limiting the access to a small amount of people. This work provides a description of the three major ''revolutions'' occurred in the field (*end-effector* robots, rigid *exoskeletons*, and soft *exosuits*), reviewing forty-eight systems for the upper-limb (excluding hand-only devices) used in eighty-nine studies enrolling a clinical population before June 2022. The review critically discusses the state of the art, analyzes the different technologies, and compares the clinical outcomes, with the goal of determine new potential directions to follow.

INDEX TERMS Assistance, end-effectors, exoskeletons, exosuits, rehabilitation, wearable robotics.

I. INTRODUCTION

In the field of assistive technology for the upper-limb, wearable robotics has been one of the main focus for several research groups in the last thirty-five years. From the pioneering promising results achieved in the nineties with end-effector robots, able to support the user's movements on a 2D plane [1], [2], the field has experienced at least two major ''revolutions''. First, starting from the mid-2000, more sophisticated rigid exoskeletons were designed [3], [4], a technology capable of controlling multiple degrees of freedom (DOFs) of the upper-limb along movements in a 3D workspace. In particular, these devices were able to act directly on the shoulder joint, only indirectly moved by end-effector robots. Then, from the beginning of 2010, the paradigm of soft robotics has been introduced and the so-called *exosuits* have been conceived [5], in a thrust towards portability and assistance to activities of daily living (ADLs). An illustrative overview of these systems is available in Figure 1.

By far, the two major applications for wearable robots have been stroke rehabilitation and injury prevention for workers in a factory setting [3], [9]. This emphasis is likely due to the large number of potential end-users (*e.g.* every year, in the US alone, there are 800,000 new instances of stroke [10], and work-related muscular-skeletal disorders accounts for nearly 70 million physician office visits [11]). Examples of less common applications for upper-limb wearable robots include (but are not limited to) understanding principles of human motor control [12], tremor suppression [13], assistance to people with disability [123], tele-operation [14], and interactions with virtual environments [15]. However, a strict

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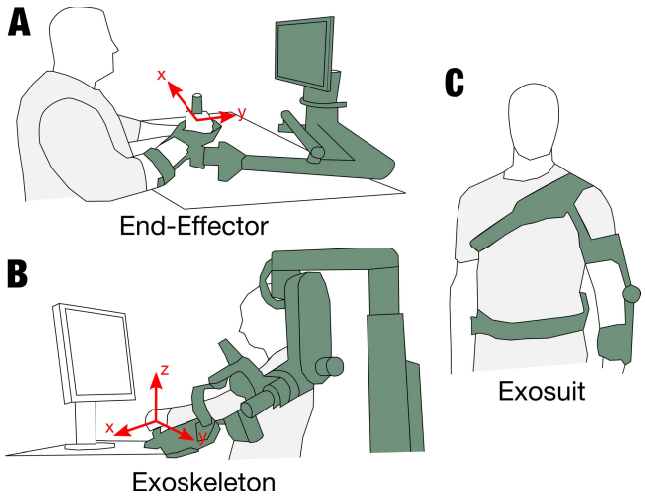

FIGURE 1. Evolution of wearable robotics for upper-limb assistance. A) Example of *end-effector robot*, image adapted from the MIT-Manus [1]. Such a device is supporting motions in a 2D plane, indirectly controlling the upper-limb – in particular shoulder and elbow – by having the user grasping an handle. Usually, the forearm is also strapped to the robot through a rigid cuff. B) Example of *exoskeleton robot*, image adapted from the Armeo Power [7]. An exoskeleton is made of multiple rigid frames and revolute joints directly attached to the biological upper-limb joints (any combinations of shoulder, elbow, wrist, and/or hand). This allows the robot to directly impose a torque to the controlled joint along a large range of movements in a 3D workspace. Usually multiple rigid cuffs are used to anchor the robot to the limb. The majority of these device are stationary machines, due to their not negligible weight, able to support the limb with very large amount of torque. C) Example of *exosuit robot*, image adapted from [8]. An exosuit is made of a combination of soft compliant textile and very few rigid elements. The actuation is usually pneumatic or cable-driven. Their main advantage is the lightweight nature, and thus a potential portability, at the cost of a complex anchoring and limited torque production.

categorization of devices by application is hard to determine, given that most of the available robots have been used for several different tasks.

It is instead simpler to discriminate devices by their *active* or powered *vs passive* or unpowered nature. Active devices can produce torque and transfer it to the limb. Most of the time the actuation system is electric, using DC motors, or pneumatic. Passive devices are instead using stored energy – more often through spring-loaded mechanism – to support motions, without requiring any active source. It is then up to the user to re-input energy into the system, and for this reason, more often these devices are used for application targeting healthy end-users (*e.g.* improving ergonomics to reduce injuries). Clearly, their main advantages are that they do not need to be charged thus working indefinitely, are inherently quiet, and are at least one order of magnitude less expensive than any active devices.

Despite a multitude of prototypes in universities and research centers, to date very few examples of wearable robots for the upper-limb are commercially available. Famous devices for rehabilitation purposes are the MIT-Manus, an end-effector robot commercialized under the name of *InMotion Arm* by Bionik, the ARMin, an active exoskeleton for the shoulder, elbow, and wrist, commercialized under the name of *Armeo Power* by Hocoma, and its passive version the *Armeo Spring*, the *MyoPro* by Myomo, a very unique active and portable exoskeleton for the elbow, wrist and hand grasping, the *Diego* by Tyromotion, an end-effector robot using cables to support bilaterally the forearms of the user, and the *ReoGo* by Motorika, a portable end-effector robot. Eight of the nine largest robot-assisted studies, involving more than 50 patients, were indeed performed with one of these robots ([16], [18], [20], [40], [70], [71], [92], [122]). From this count, assistive devices for hand and fingers are excluded: these robots represent a special case of wearable robots for the upper-limb, given that a larger number of active, rigid or soft solutions already exists on the market (*e.g. Amadeo* by Tyromotion, *CyberGrasp* by CyberGlove Systems LLC, *Hand of Hope* by Rehab-Robotics Comp. Ltd., *Maestro* by Gloreha).

When considering injury prevention instead, the vast majority of available devices is passive: famous examples are the *EVO* by Ekso Bionics, successfully tested in real factory settings by Ford and Boeing, the *AirFrame* by Levitate, adopted by Toyota, or the *Mate* by Iuvo, tested by the Fiat-Stellantis.

With this work, we provide the reader with an overview of the state of the art of wearable robotics for assistance of the upper-limb of an impaired population, using any of the available technologies *i.e.* end-effector robots, rigid exoskeletons or soft exosuits. The goal of this work is neither to provide a taxonomy of the field of wearable robotics, nor to analyze specific engineering aspects in detail. By discussing the main clinical results, we try to list the key challenges that are still faced by researchers and private companies in the field, in an effort to propose new ideas that could help the design and foster the clinical use of future generations of medical wearable robots.

A. REVIEW METHODOLOGY & INCLUSION CRITERIA

The review was carried out by searching among some of the main scientific databases (PubMed, ClinicalTrials, IEEE Xplore Digital Library, Science Direct, and Google Scholar) with different combinations of the following keywords: *wearable, robot, rehabilitation, assistance, support, exoskeleton, exosuit, soft, end-effector, manipulandum, upper-limb, shoulder, elbow, wrist, forearm, arm*. In addition, a free search for references listed in the keywords-based findings was also conducted.

Despite the above-mentioned different applications of wearable robotics, this review focuses on devices addressing assistance of individuals with a clinical condition (*e.g.* stroke, spinal cord injury). Robots aiming at reducing the rate of injuries in factory settings are thus excluded from the review. Robot assisting hand functions only are also excluded from the review. Please refer to [3], [5], [6], and [4] for state of the art papers with a wider scope and discussing wearable robots excluded by this work.

After a first round of research, 465 publications were retrieved. Given the clinical perspective of this work, preliminary proofs-of-concept studies (less than 5 patients),

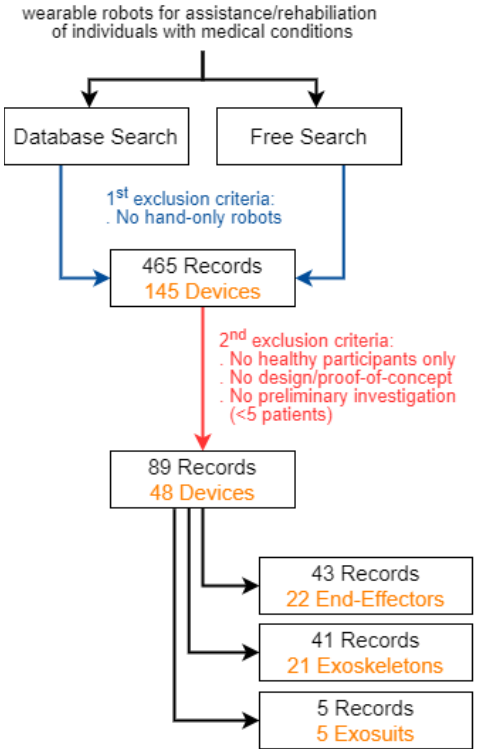

FIGURE 2. Literature search process flowchart. In total, 89 studies using 48 different wearable robots were reviewed.

manuscripts with a focus on hardware or software design only, and initial feasibility studies, in particular those including effects on healthy individuals only, were then excluded from the review.

As a result, 89 papers published before June 2022 were taken into consideration (see Figure 2).

B. LIST OF ABBREVIATION

1) STANDARD CLINICAL ASSESSMENT

Please refer to Table 1 for a list of clinical assessment abbreviations.

2) CLINICAL CONDITION

aS = Acute Stroke (< 1 month from stroke event), **sS** = Subacute Stroke (2 − 6 month from stroke event), **cS** = Chronic Stroke (> 6 month from stroke event), **S** = Stroke (mixed phases), **ND** = Neuromuscular Disorder (mixed populations), **ALS** = Amyotrophic Lateral Sclerosis, **AMC** = Arthrogryposis, **BI** = Acquired Brain Injury, **CP** = Cerebral Palsy, **DP** = Chronic Inflammatory Demyelinating Polyneuropathy, **ET** = Essential Tremor, **MD** = Muscular Dystrophy, **MS** = Multiple Sclerosis, **SCI** = Spinal Cord Injury, **SMA** = Spinal Muscular Atrophy, **T** = Traumatic Unilateral Brachial Plexus Injury.

II. WEARABLE ROBOTS FOR UPPER-LIMB ASSISTANCE

145 wearable robots for assisting the upper-limb – excluding hand only assisting devices – of people with clinical conditions are available in universities and research centers, at least in the stage of prototypes (see previous published state of the arts [3], [4], [5] for missing references after inclusion criteria of Section I-A). Of these, approximately one third of them (22 end-effector robots, 21 exoskeletons, and 5 exosuits) have been tested with a clinical population (N≥5 patients) and are the focus of this review. Among these 48 devices, thirteen are commercially available. Detailed description of these end-effector robots, exoskeletons, and exosuits, and corresponding testing protocols, are available in Table 2, Table 3, and Table 4 respectively.

TABLE 1. Standard clinical assessment abbreviations. The assessment are categorized by the International Classification of functioning, disability and health (ICF) domains [153].

Body Functions & Structure	
9HPT	Nine Hole Peg Test
DAS	Disability Assessment Scale
FMA	Fugl-Meyer Asmt.
MA	Motor Asmt. Scale
MAS	Modified Ashworth Scale
MI	Motricity Index
MPS	Motor Power Score
MRC	Medical Research Council Scale
MSS	Motor Status Score
RMA	Rivermead Motor Asmt.
Activity	
AMAT	Arm Motor Ability Test
ARAT	Action Research Arm Test
BBT	Box-and-Block Test
BI	Barthel Index
CAHAI	Chedoke Arm and Hand Activity Inventory
FAT	Frenchay Arm Test
FIM	Functional Independence Measure (Motor)
IPPA	Individually Prioritized Problem Assessment
JHFT	Jebsen Hand Function Test
MAL	Motor Activity Log
MAU	Melbourne Asmt. of Unilateral UL Function
PUL	Performance of Upper Limb Asmt.
TADL	Tremor in Activity of Daily Life
TMP	Upper Extremity Performance Test for the Elderly
WMFT	Wolf Motor Function Test
Participation	
COPM	Canadian Occupational Performance Measure
D-QUEST	Quebec User Evaluation of Satisfaction
FIM	Functional Independence Measure (Cognitive)
RLAS	Rancho Los Amigos Scale
SIS	Stroke Impact Scale

A. TECHNOLOGY OVERVIEW

The majority of the wearable robots are electrically actuated through standard DC motors directly moving the biological joints, with few exceptions using pneumatics (5 exoskeletons, 3 exosuits), cable-driven actuation (3 end-effectors, 2 exosuits), or being fully passive systems (2 end-effectors and 3 exoskeletons). Cable-driven robots are ultimately electrically actuated, but the limb is connected to the motors through cables, generating different interactions on-body and thus allowing for a different categorization. A recent trend is the combination of Neuro Muscular or Functional Electrical

TABLE 2. List of End-Effector robots involved in large clinical studies (>5 patients), gathered by device. DOFs & Actuation = XY (Z) → XY Degrees of Freedom and Z Actuation (X = number of DOFs at the Y joint; Y: S = Shoulder, E = Elbow, W = Wrist, H = Hand, F = Forearm; Z: E = Electrical, P = Pneumatic, N = None (i.e. passive mechanical device), F = Electrorheological Fluid, C = Cable-driven). Control = XY → X Type [4] and Y Input (X: P = Passive Control, T = Triggered Passive Control, A = Partially Assistive Control, R = Resistive; Y: K = Kinematics, F = Force). ⋆ EMG-triggered. Participants = XY → X number of participants, Y condition; Y: see Section I-B. Test: P = Preliminary, L = Longitudinal, H = Longitudinal at Home, CT = Controlled Trial. Duration (total hours and weeks) is only the time spent performing robot-assisted therapy. Improvement of standard clinical assessment: see Section I-B for list of abbreviations (not considering EMG activity, heart rate, kinematics i.e. ROM, speed, smoothness). In CT, * asterisk indicates improvement w.r.t. baseline and control group; no asterisk indicates improvement w.r.t. baseline only. Commercial robots: [1]InMotion Arm (Bionik), [2]Bi-Manu-Track (Reha Stim), [3]Haptic Master (Moog, Inc.), [4]ReoGo (Motorika), [5]deXtreme (BioXtreme), [6]Diego (Tyromotion), [7]Dynamic Arm Support Top/Help (Focal Meditech BV), [8]Ayura (Armon Products BV).

Reference	DOFs & Actuation	Control	Participants	Test	Duration	Improvement of standard clinical assessment		
						Body Functions	Activity	Participation
Cozens 1999 [27]	1E (E)	T (K)	5 cS, 5 MS	P	-	-	-	-
Cheng 2003 [26]	1E (E)	A (F⋆)	5 cS	P	-	-	-	-
Colombo 2007 [33]	1F/2F (E)	A (F)	20 cS	L	20h 5w	FMA, MPS	-	-
Colombo 2010 [41]	2F (E)		18 cS	L	10h 3w	FMA, MSS	-	-
Song 2007 [35]	1W (E)	A (F⋆)	5 cS	P	-	-	-	-
Hu 2007 [30]			7 cS	L	30h 7w	FMA, MSS, MAS	-	-
Hu 2008 [34]			15 cS	L	30h 7w	FMA, MAS	-	-
Hu 2009 [72]			27 cS	CT	30h 7w	FMA*, MAS*	-	-
Schoone 2007 [36]	5F (E)	A (K)	19 sS	L	2.6h 4w	FMA	-	-
Kahn 2006 [38]	3F (E)	A (K)	19 cS	CT	18h 8w	-	-	RLAS*
Chang 2007 [39]	1F (E)	A (F)	20 cS	L	18h 8w	FMA	-	-
Wu 2011 [130]		A (FES)	23 cS	CT	6h 3w	FMA	ARAT*	-
Volpe 2000 [40][1]	2F (E)	A (K)	56 aS	CT	25h 5w	FMA, MPS*, MSS*	FIM*	FIM
Fasoli 2008 [105][1]			12 CP	L	8h 8w	FMA, MAS	-	-
Frascarelli 2009 [107][1]			12 CP	L	18h 6w	FMA, MAS	-	-
Lo 2010 [16][1]	2F-1W (E)		127 cS	CT	36h 12w	FMA, MAS	WMFT	SIS
Miyasaka 2016 [118]		A (FES)	30 sS	CT	10h 2w	FMA	-	-
Rodgers 2019 [18][1]		A (K)	770 S	CT	29h 12w	FMA	ARAT, BI	SIS
Lum 2002 [42]	6F (E)	T (F)	27 cS	CT	24h 8w	FMA	BI	FIM*
Lum 2006 [43]			30 sS	CT	15h 4w	FMA, MSS, MAS*	-	FIM
Masiero 2007 [74]	3F (C)	P	35 aS	CT	20h 5w	FMA*, MRC*, MAS	FIM*	FIM*
Masiero 2011 [44]			21 aS	CT	20h 5w	FMA, MAS, MRC	BBT	-
Hesse 2003 [48][2]	1F-1W (E)	P, R (K)	12 cS	L	4h 3w	MAS, RMA	-	-
Hesse 2005 [47][2]			43 sS	CT	10h 6w	FMA*, MRC*	-	-
Ellis 2007 [37][3]	3F (E)	A (F)	6 cS	L	24h 8w	FMA	-	-
Coote 2008 [52][3]			20 cS	L	4.5h 3w	FMA, MAS	-	-
Fluet 2009 [53][3]			8 CP	L	9h 3w	-	MAU	-
Patel 2019 [54][3]	3F,1H (E)		13 aS	CT	8h 2w	FMA*	-	-
Beer 2008 [59]	6F (C)	A (F,K)	5 cS	L	20h 8w	-	-	-
Bovolenta 2011 [69][4]	2F (E)	P, A (K)	19 cS	L	15h 4w	FMA, MAS, MRC	BBT, FAT, FIM	-
Takahashi 2016 [70][4]			60 sS	CT	28h 6w	FMA*	-	-
Takebayashi 2022 [71][4]			119 cS	CT	30h 10w	FMA	-	-
Givon-Mayo 2014 [75][5]	2W (E)	R (K)	7 sS	CT	5h 5w	FMA, MA*	-	-
Keeling 2021 [83]	2F (E)	A,R (K)	19 sS	CT	10h 2w	FMA*	ARAT*, FIM*	-
Lamers 2019 [91][6]	3F (C)	A (K)	20 MS	CT	40h 8w	-	ARAT, BBT*	-
Aprile 2020 [92][6]			224 S	CT	22.5h 6w	FMA, MAS, MRC	ARAT, BI, FAT	-
Carpinella 2009 [108]	2F (E)	A (K)	7 MS	L	8h 2w	9HPT	-	-
Vergaro 2010 [109]		R (F)	8 MS	L	8h 4w	9HPT, Ataxia	TADL	-
Gilliaux 2015 [110]	1F (E)	A (F)	16 CP	CT	30h 8w	-	BBT*	-
van der Heide 2016 [124][7]	5F (N/E)	A (K)	20 ND	H	832w	-	-	-
Burgers 2015 [127][7]			8 MD	H	n.a. 12w	-	-	-
Lund 2009 [128][8]	5F (N/E)	A (K)	7 ND	H	n.a. 16w	-	IPPA	D-QUEST
Sivan 2014 [150]	2F (E)	A (K)	17 cS	H	n.a. 8w	FMA, MAS, MRC	ARAT, CAHAI	-

Stimulation (NMES or FES) with classical orthosis, powered or passive, accounting for 7 study protocols (8%).

All reviewed devices are wearable, *i.e.* worn around one part of the upper-limb, but a few examples are also portable,

TABLE 3. List of exoskeleton robots involved in large clinical studies (>5 patients), gathered by device. DOFs & Actuation = XY (Z) → XY Degrees of Freedom and Z Actuation (X = number of DOFs at the Y joint; Y: S = Shoulder, E = Elbow, W = Wrist, H = Hand, F = Forearm; Z: E = Electrical, P = Pneumatic, M = Magnetic, N = None i.e. passive mechanical device). † multi-robot system. Control = XY → X Type [4] and Y Input (X: P = Passive Control, A = Partially Assistive Control, C = Corrective; Y: K = Kinematics, F = Force, FES = Functional Electrical Stimulation). ⋆ EMG-triggered. Participants = XY → X number of participants, Y condition; Y: see Section I-B. Test: P = Preliminary, L = Longitudinal, H = Longitudinal at Home, CT = Controlled Trial. Duration (total hours and weeks) is only the time spent performing robot-assisted therapy. Improvement of standard clinical assessment: see Section I-B for list of abbreviations (not considering EMG activity, heart rate, kinematics i.e. ROM, speed, smoothness). In CT, * asterisk indicates improvement w.r.t. baseline and control group; no asterisk indicates improvement w.r.t. baseline only. Commercial robots: [1] MyoPro (Myomo), [2] Armeo Spring (Hocoma), [3] Armeo Power (Hocoma), [4] Motus Hand (Motus Nova), [5] HAL-SJ (Cyberdyne).

Reference	DOFs & Actuation	Control	Participants	Test	Duration	Improvement of standard clinical assessment		
						Body Functions	Activity	Participation
Stein 2007 [21][1]	1E (E)	A (K⋆)	6 cS	L	18h 6w	FMA, MAS	-	-
Page 2013 [77][1]			16 cS	CT	24h 8w	FMA	-	SIS*
Kim 2015 [32][1]			9 cS	H	23h 6w	FMA	MAL	-
Peters 2017 [28][1]	1E-1H (E)		18 cS	P	-	FMA	BBT	-
Sanchez 2004 [129][2]	3S-1E-1F (N)	A (K)	5 cS	P	-	FMA	-	-
Rahman 2007 [125][2]			17 ND	P	-	-	JHFT	-
Iwamuro 2008 [126][2]			10 cS	P	-	-	-	-
Housman 2009 [56][2]			28 cS	CT	24h 9w	FMA*	MAL	-
Gijbels 2011 [65][2]		A (FES)	10 MS	L	12h 8w	-	ARAT, TMP	-
Meadmore 2012 [117]			5 cS	L	18h n.a.	FMA	-	-
Estilow 2014 [104][2]			9 MD	P	-	-	-	-
Gunn 2016 [122][2]		A (K)	55 ND	H	n.a. 88w	-	-	-
Shank 2017 [123][2]			25 ND	H	n.a. 32w	-	-	COPM
Sehle 2021 [79][2]			30 sS	CT	11.3h 3w	FMA	-	-
Wolbrecht 2008 [55]	3S-1E (P)	A (K)	11 cS	P	-	-	-	
Reinkensmeyer 2012 [17]			26 cS	CT	24h 8w	FMA*	MAL, BBT*	-
Milot 2013 [84]	3S-1E-1F-1W (P)		20 cS	L	24h 8w	FMA	MAL, WMFT, BBT	-
Toth 2005 [46]	3S-2E† (E)	P	8 S	L	10h 4w	MAS, MRC	FIM, BI	FIM
Fazekas 2007 [45]			30 cS	CT	10h 4w	FMA, MAS, RMA	-	FIM
Pignolo 2012 [49]	3S-2E-1W (E)	P	14 sS	L	29h 7w	FMA	FIM	-
Frisoli 2008 [51]	3S-1E-1W (E)	A (F)	9 cS	L	18h 6w	FMA, MAS	-	-
Rocon 2007 [57]	2E-1W (E)	P	10 ET	P	-	-	-	-
Zhang 2011 [61]	2S-1E-1F-1W (P)	P	8 cS	L/H	9h 7w	-	-	-
K.-Marganska 2014 [20][3]	3S-2E-1W (E)	P, A (F-K)	73 cS	CT	18h 8w	FMA*	-	-
Mayr 2008 [66]	3S-2E-2W (E)	A (FES)	8 cS	L	n.a. 6w	-	-	-
Pedrocchi 2013 [68]	2S-1E (N)	A (FES)	5 ND	P	-	-	-	-
Ambrosini 2021 [116]			62 S	CT	27h 9w	MRC, MI	ARAT*, BBT*, MAL	-
Jackson 2007 [78]	3S-3W† (P)	P	6 cS	P	-	-	-	-
Culmer 2011 [50]			16 cS	P	-	-	-	-
Kim 2013 [85]	3S-1E-3W (E)	A (F-K)	15 cS	L	18h 6w	FMA	-	-
Crocher 2012 [86]	3S-1E (E)	C (K)	7 cS	P	-	-	-	-
Gandolla 2021 [87]	3S-1E (E)	P	14 MD	P	-	-	PUL	-
Kutner 2010 [88][4]	1W-1H (P)	P	17 sS	CT	60h 3w	-	-	SIS*
Cordo 2009 [89]	1W-1H (E)	A (F)	11 cS	H	60h 12w	-	-	SIS
Takahashi 2008 [90]	1W-2H (P)	A (K)	14 cS	CT	22.5h 3w	FMA*, MAS*	ARAT*, BBT*	SIS*
Rong 2017 [120]	1E-1W (E)	A (FES)	11 cS	L	30h 7w	FMA, MAS	ARAT, WMFT	-
Qian 2017 [119]			24 sS	CT	13.3h 5w	FMA, FIM, MAS*	ARAT	-
Chen 2018 [148]	3S-1E-1F (N)	A (K)	13 cS	P	-	-	-	-
Saita 2016 [152][5]	1E (E)	A (K⋆)	7 cS	L	20h 2w	FMA, DAS	MAL	-
Saita 2018 [151][5]			13 sS	P	-	-	-	-
Hyakutake 2019 [149][5]			10 cS	H	8h 4w	-	ARAT, MAL	-

meaning that after being worn, the patients can easily move them around the surrounding environment (the clinic, their house, etc.). Portable devices are usually fully untethered, *i.e.* standalone solutions, not requiring any external offboard controllers. Only 6 devices were categorized as portable: the *MyoPro* exoskeleton, the *HAL-SJ* exoskeleton, an exoskeleton for tremor suppression [57], a shoulder-elbow-wrist exoskeleton using modified McKibben pneumatic muscles [61], and two of the five reviewed exosuits [19], [25]. It is worth mentioning two other portable exoskeletons for tremor suppression [13], [29], excluded from the review because testing with less than five patients. For non-ambulant patients, mounting a wearable robot directly to the wheelchair is also a solution; this allows us to consider these robots portable:

TABLE 4. List of exosuit robots involved in large clinical studies (>5 patients), gathered by device. DOFs & Actuation = XY (Z) → XY Degrees of Freedom and Z Actuation (X = number of DOFs at the Y joint; Y: S = Shoulder, E = Elbow, W = Wrist, F = Forearm; Z: P = Pneumatic, C = Cable-driven). Control = XY → X Type [4] and Y Input (X: P = Passive Control, A = Partially Assistive Control; Y: FES = Functional Electrical Stimulation). Participants = XY → X number of participants, Y condition; Y: see Section I-B. Test: P = Preliminary, L = Longitudinal. Duration (total hours and weeks) is only the time spent performing robot-assisted therapy. Improvement of standard clinical assessment: see Section I-B for list of abbreviations (not considering EMG, heart rate, kinematics i.e. ROM, speed, smoothness).

Reference	DOFs & Actuation	Control	Participants	Test	Duration	Improvement of standard clinical assessment		
						Body Functions	Activity	Participation
Lessard 2018 [19]	2S-1E-1W (C)	P	9 n.a.	P	-	-	-	-
Simpson 2020 [24]	1S (P)	P	6 cS	P	-	-	-	-
Nam 2020 [25]	1E/1W (P)	A (FES)	15 cS	L	30h 7w	FMA, MAS	ARAT	-
O'Neill 2020 [93]	1S (P)	P	5 cS	P	-	-	-	-
Noronha 2022 [146]	1E-1H (C)	A (K)	10 cS	P	-	-	-	-

FIGURE 3. Examples of commercially available wearable robots. These robots are among the most tested device in literature, given that eight of the nine largest robot-assisted studies, involving more than 50 patients, were indeed performed with one of these robots ([16], [18], [20], [40], [70], [71], [92], [122]). End-effectors: InMotion, ReoGo and Diego. Exoskeletons: Armeo Power, Armeo Spring, MyoPro. Images retrieved without modifications from companies' websites. Copyrights of Hocoma, Bionik, Motorika, Myomo and Tyromotion.

it is the case of the passive robots *T-Wrex* (the father of the *Armeo Spring*), the *Dynamic Arm Support Top/Help* and the *Ayura*, and the one developed by Pedrocchi et al. [68] and Ambrosini et al. [116]. A modified portable eversion of the *T-Wrex*, designed for children, was mounted on a jacket by Gunn et al. [122].

Some end-effector robots were also designed as standalone solutions, movable around on a set of caster wheels, thus augmenting the possibility to easily transfer them into any unstructured environments: it is the case of the *ReoGo*, the *dExtreme*, and the *Armeo Spring*, all commercially available and weighing around 80kg, or the *NeReBot* prototype [44], [74], and the prototype by Sivan et al. [150]. As a reference, the *MyoPro* weighs around 2kg, while the *Armeo Power* more than 200kg. Clearly, we cannot consider these devices as portable by the above definition, but it is still important to notice how they could, in theory, adopted in an unstructured environment for unsupervised robot-assisted therapy.

From a control standpoint, partial assistance through impedance (position) or admittance (force) control is the most common solution, with the robot assisting as-needed the movement of the user along pre-defined trajectories. The level of assistance is usually based on a fixed manual tuning by a research team member. A few groups explored offline or online automatic strategies to adapt the robot assistance in order to reduce the risk of "slack" by the patients, *i.e.* the patient minimizing their effort and exploiting the robot support (*e.g.* [55], [98], [99]). Few groups used EMG in the control loop, either to trigger or modulate an admittance ([26], [30], [34], [35], [72]), an impedance (studies using the

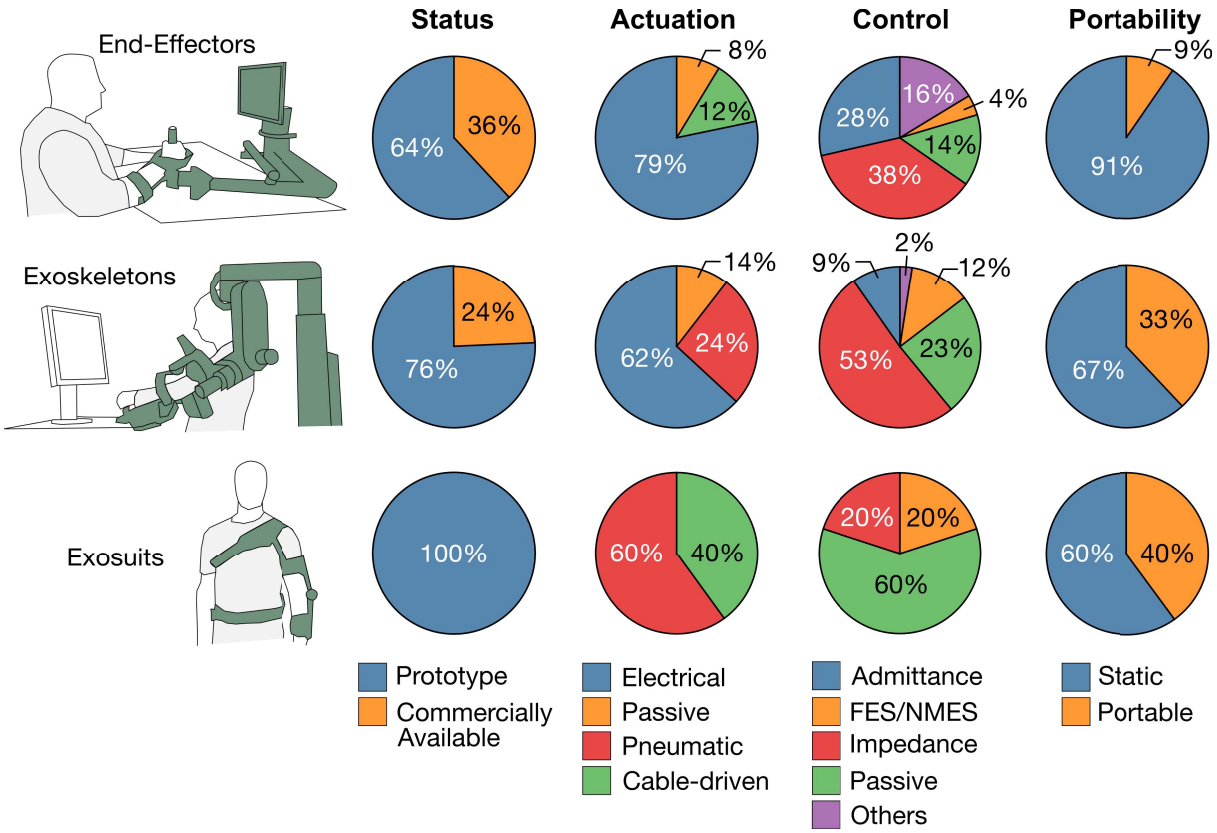

FIGURE 4. Overview of the main characteristics of the three types of systems – end-effectors, exoskeletons, exosuits – included in the review. Thirteen devices are commercially available, the majority of the robots are electrically driven, with any combination of partially assistive control (impedance or admittance). The vast majority of robots are static and cannot be easily transferred to any unstructured environment. A portable wearable robot is a device that after being worn, can be easily moved around the surrounding environment (the clinic, the house, etc.). FES/NMES = Functional/Neuro Muscular Electrical Stimulation.

MyoPro and the HAL-SJ) or a NMES strategy ([25], [66], [68], [116]). EMG-control is often the adopted solutions for actuating the elbow, given this joint simple 1-DOF nature and the feasible access to the biceps and triceps muscles. Except for Nam et al. [25] using an EMG-triggered NMES strategy to control the elbow or the wrist separately, and Noronha et al. [146] using an impedance control at the elbow, all the other soft exosuits have been tested on individuals with a clinical condition by adopting a passive strategy. Figure 4 provides an overview of the main characteristics of the three types of systems – end-effectors, exoskeletons, exosuits – after having performed the research within the above-mentioned databases.

B. CLINICAL OUTCOMES

When considering the study protocols, tests involving clinical populations are largely on post-stroke individuals (79%), with few occurrences on other conditions (*e.g.* multiple sclerosis, muscular dystrophy, cerebral palsy, spinal cord injury). Among post-stroke individuals, most of the studies involved chronic patients (56%-60%), that is individuals enrolled after at least 6 months from the stroke event. Exosuits clinical testing is almost absent, with only Nam et al. [25] testing on a population of more than 10 individuals. Figure 5 gives an overview of the clinical interventions.

The "gold standard" for assessing motor recovery after a stroke is the Fugl-Meyer Assessment, in the upper-extremity version (FMA-UE [94], 0-66 scale). The majority of the studies (69%, 82% if considering only studies enrolling stroke individuals) were able to show improvement in the FMA-UE score. From this analysis we excluded preliminary studies, usually consisting of a single testing session and thus hardly measuring any clinical assessment. Despite this large amount of studies showing improvements of FMA-UE, these gains are very often below the minimal clinically important difference (MCID = 5.25 [97] for chronic, 9-10 [95] or 12.4 [96] for sub-acute stroke survivors). When generalizing to all standard clinical assessments, gathered by ICF domains (see Table 1), 52 studies out of 69 (75%) reported improvements in Body Functions (most often FMA-UE, 69% of cases, MAS 32%, and MRC 11%), 31 (45%) improvements in Activity (ARAT 19%, BBT 12%, and WMFT 5%) and only 16 (23%) in Participation (SIS 9%, FIM cognitive 9%).

In controlled trials (randomized or not), when comparing against one or more control groups, the most common control intervention has been standard rehabilitation of similar

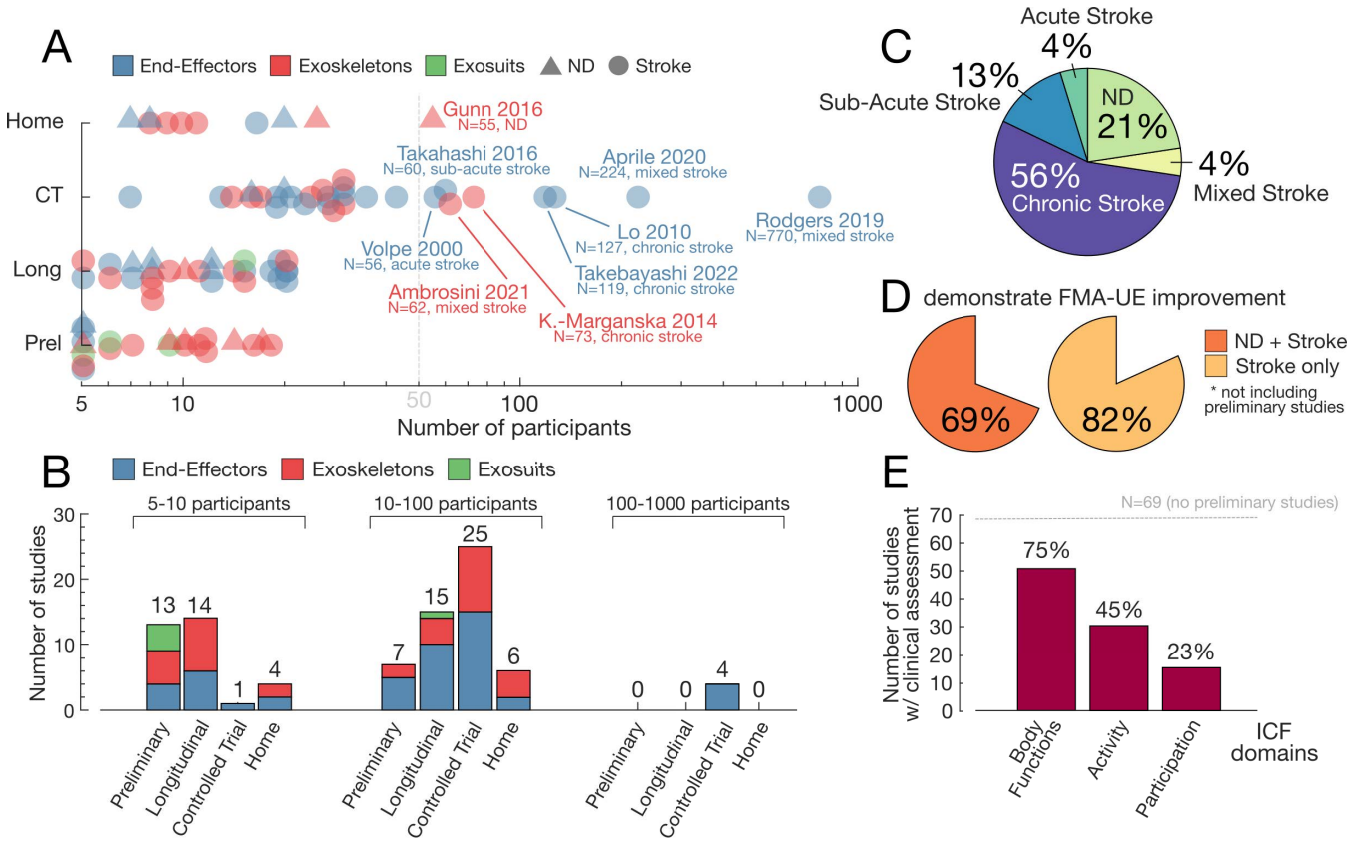

FIGURE 5. **Overview of the clinical interventions using a wearable robot for the upper-limb. A) Type of intervention *vs* number of enrolled participants. The largest studies (>50 patients) are reported. B) Number of studies *vs* type of intervention, grouped by number of participants. C) Most of the intervention focused on post-stroke rehabilitation (79%), and 56%-60% of these enrolled chronic stroke survivors (>6 months after the stroke onset). D) Among any longitudinal, controlled trial (CT), or home study, in 69% of the cases authors were able to claim improvement of the FMA-UE assessment (82% if limiting the analysis to studies enrolling stroke individuals only). However, in CT, rarely the improvement was significant with respect to the control group. E) Excluding preliminary protocols, 52 studies out of 69 (75%) reported improvements in Body Functions (most often FMA-UE, 69% of cases, MAS 32%, and MRC 11%), 31 (45%) improvements in Activity (ARAT 19%, BBT 12%, and WMFT 5%) and only 16 (23%) in Participation (SIS 9%, FIM cognitive 9%). ND = Neurodegenerative disease.**

dosage performed by the same team of therapists supervising the robot-assisted intervention. Only 5 studies reported a comparison against an intensive therapy protocol, with similar dosage and intensity, *i.e.* number of repetitions in the same amount of intervention time [16], [18], [42], [43], [118]. Less common comparisons were against passive mobilization by the robot [72], self-guided movement without any support [38], constraint-induced movement therapy [71], or therapy through an off-the-shelf electrostimulator [47].

Focusing on studies including a control group and enrolling stroke patients, the intervention effects were evaluated through the Standardized Mean Difference (SMD) based on Hedges' g, along with the 95% Confidence Interval (CI) of post-intervention values [147]. Two separate analyses were performed for end-effectors and exoskeletons and only studies which did not apply any type of robotic interventions in the control group were included. We can observe moderately positive effect of the robot assisted therapy in improvements of the body functions domain (Figure 6) and no difference in improvements of the activity domain (Figure 7). The analyses were performed using Review Manager 5.4 (RevMan, Cochrane).

III. DISCUSSION

Despite more than thirty-five years of research from a multitude of laboratories all over the world, the problem of assisting the upper-limb with a wearable robot is not solved yet. In particular when addressing the control of a complex joint such as the shoulder, considered one of the most mobile joint in the human body [111]. This is a challenging problem when dealing with healthy individuals: supporting people with physical impairments simply further increases the complexity. It is important to underline that this review focused only on devices that were utilized in testing protocols involving a clinical population. Passive exoskeletons for assisting workers in a factory line are starting to spread quickly among major private companies, above all in the automotive sector (*e.g.* Ford, Fiat, Toyota), increasing the interest in the field of assistive wearable robotics, but were excluded from the scope of this work.

By analyzing the outcome of the database search, it is noticeably that many systems never reached the market, staying in a phase of preliminary investigation as prototypes. The general flow followed by researchers is very often the following:

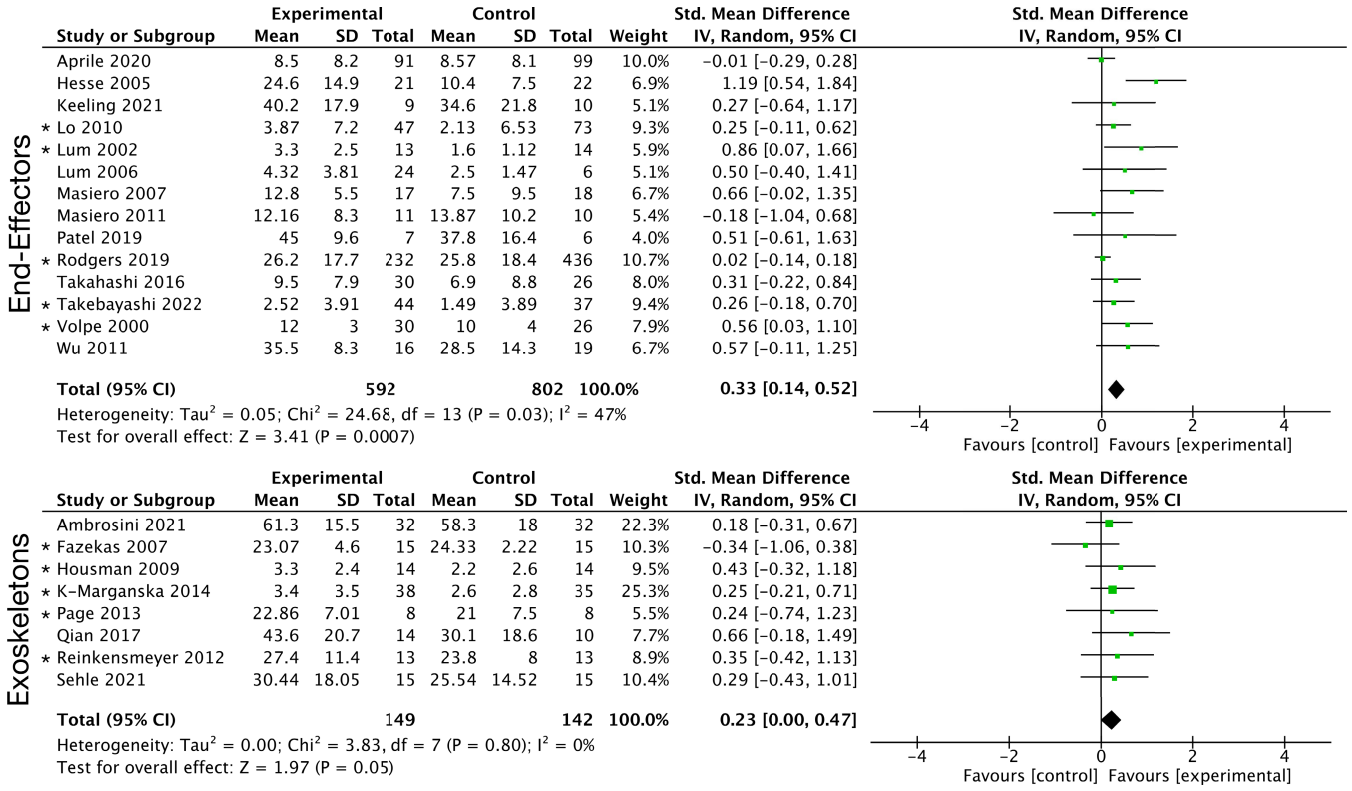

FIGURE 6. Meta-analysis of the effects on the Body Functions domain of a robotic intervention *vs* a non robot-assisted control group in CT enrolling stroke individuals. The robots are end-effectors (top) and exoskeletons (bottom). The metrics are always FMA-UE but in Ambrosini *et al.* 2021 [116] where MI is considered instead. A positive std. mean difference represents a result in favour of the experimental group. Results indicate a moderate positive effects of the usage of robots, especially for end-effectors involved in a larger number of studies and with a larger total pool of participants (over 1300 patients, versus less than 300 for exoskeletons). Mean is the absolute or relative gain at the end of the intervention, SD the standard deviation, Total the number of participant. * asterisk indicates studies enrolling chronic stroke individuals.

1) demonstrate improved passive range of motion, *i.e.* the robot passively moves the limb,
2) design an active control, involving participation of the patient at some level, and demonstrate improved arm kinematics (active range of motion, speed of task completion, smoothness, trajectory tracking),
3) assess the motor and/or functional recovery during a longitudinal study with one of the many available clinical metrics,
4) test against a control group and try to prove the greater results achievable by a robot-led therapy.

As a matter of fact, less than half of the reviewed wearable robots have been tested in a controlled trial, thus involving a comparison with a group of participants testing a different condition than the proposed robot-assisted therapy. And a large majority of the devices (97 out of 145 devices), outcome of the initial database screening, has never reached any of these stages with even as few as five impaired individuals. Actually, including any study with impaired individuals would add less than 20 studies and 10 devices to the list.

A different emphasis should be perhaps given to exosuits. Their development, above all for upper-limb assistance, is quite recent and there exist already some studies proving active control on healthy individuals, demonstrating ability to reduce assisted muscle activation through EMG, which may be running test involving clinical population as the next step [100], [101], [102], [103].

The reasons behind this lack of testing are multiple and not always easy to determine [154]. Obviously, reaching a level of technical maturity to allow for intensive testing of any device is a major engineering challenge. The bar is even higher for a wearable robot, designed to be in contact with the body of a person with physical impairments. However, even after this has been reached, if on one hand the technology is still having hard times demonstrating its ability to provide a meaningful improvement to the standard care [18], [20], [71], [92], on the other hand robots high cost (for both the initial investment and the maintenance) is a major barrier for public and private centers willing to start a robot-assisted clinical trial. At the same time, there is a clear mismatch between research and engineering community's needs and the clinical community attitude: even simpler and largely diffused technology (*e.g.* a stopwatch or a gaming console) which could provide benefit to the rehabilitation experience for the patients, in terms of objective data and quantitative feedback as well as increased engagement, are not generally diffused in standard clinics [136]. Ease of use needs to be central in the design of future wearable robots, but at the same time a shift towards the introduction of new technology in the

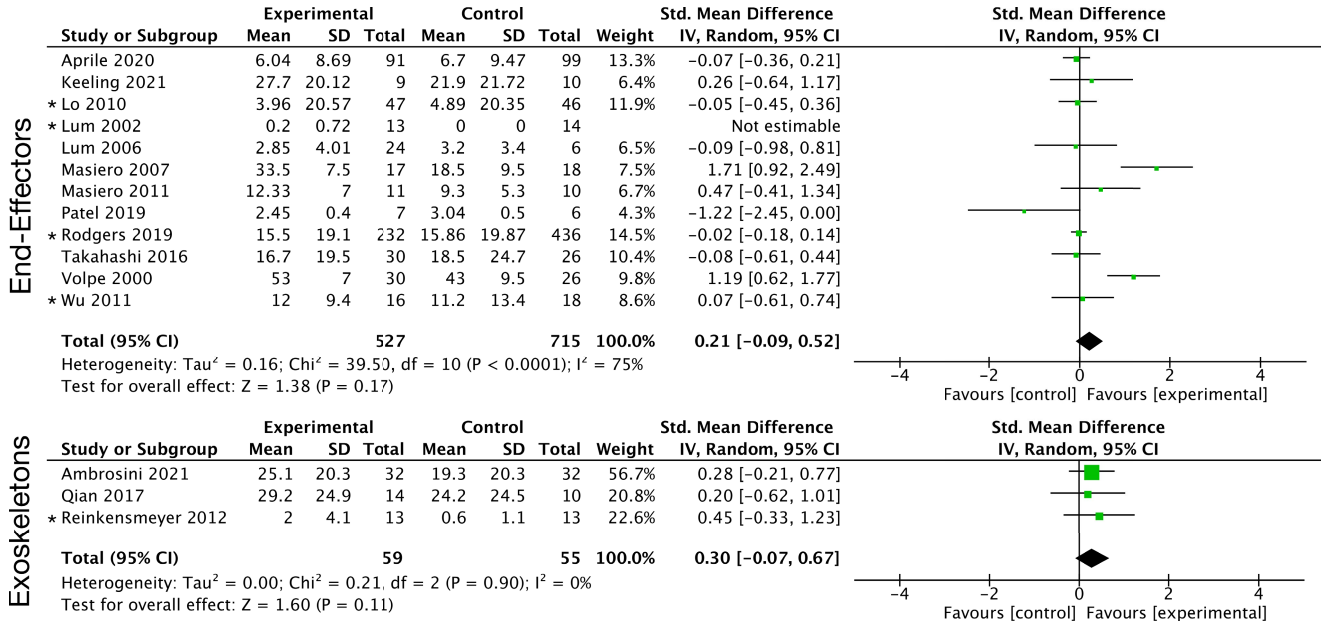

FIGURE 7. **Meta-analysis of the effects on the Activity domain of a robotic intervention *vs* a non robot-assisted control group in CT enrolling stroke individuals. The robots are end-effectors (top) and exoskeletons (bottom). The metrics are: 6 studies with ARAT, 3 with WMFT, 3 with FIM motor, 2 with BBT, and 1 with BI. A positive std. mean difference represents a result in favour of the experimental group. Results indicate no statistical difference in the effects of the usage of robots. Mean is the absolute or relative gain at the end of the intervention, SD the standard deviation, Total the number of participant. * asterisk indicates studies enrolling chronic stroke individuals.**

standard care, which clearly requires the necessity to master this technology, is desired.

A. STROKE VS OTHER CLINICAL CONDITIONS

79% of the studies involved stroke survivors, likely due to the major impact of this disease in the society, the high number of cases and a high survival rate, making this disease the third leading cause of disability worldwide [112]. Despite a common belief of the importance of anticipating the robot-intervention as soon as possible [132], [138], [142], more than half of the protocols enrolled chronic individuals, for whom the natural recovery "plateau" has already been reached [113] and therefore demonstrating any improvement becomes a much more complex task. Indeed, basically none of the available studies showed any improvement with respect to the MCID. However, targeting acute and sub-acute individuals raises the bar from a technological point of view, requiring devices to be seamlessly integrated in a more critical scenario (*e.g.* intensive care unit), ideally being used together with other medical equipment. Highly portable, less bulky and inherently safer exosuits (they cannot provide large torque, thus limiting the risk of accidentally hurting the user) may open up new possibilities to early testing, but the field is far from being ready to deploy devices to hospitals.

B. ROBOT FOR ASSISTANCE VS FOR REHABILITATION

Different conditions may require different treatment and robotic solutions [132]. Trivially, non-ambulatory patients can adopt slightly heavier hardware if mounted to the wheelchair (especially if motorized ones). For ambulatory patients instead, a wearable and portable solution is preferred, that is a robot that can be carried around without excessive effort (thus lightweight) and without paying too much attention to the surrounding environment (thus small and compact). Despite overlapping in many cases, assistance and rehabilitation do have different requirements and objectives.

A rehabilitative robot has the goal of making the patient reacquire pre-impairment physical conditions, ideally relearning pattern of coordination of the upper-limb, regaining full range of motion, strength and ability to perform activities of daily living (ADLs). During the therapy the robot should target maximum involvement of the user, reducing its support as much as possible, and reduce any potential pathological compensation that may arise (*e.g.* in stroke, bending the trunk to compensate the reduced ROM at the shoulder). Ideally, at the end of a therapy, the robot would not be used anymore.

An assistive robot, instead, has the goal of compensating for motor and functional losses of the patient that could be hardly reacquired with time, and actually may even increase. It is the case of neurodegenerative diseases (*e.g.* ALS) or permanent impairments, as for example with SCI individuals. Neither during, nor at the end of the therapy, the robot should be put aside. Instead, the patient should learn to improve their independence and quality of life through the use of this technology.

C. THE COMPLEXITY OF ASSESSING A ROBOTIC INTERVENTION

Objectively assessing the effectiveness of a robot-assisted therapy is not a straightforward task, in particular when considering the case of stroke rehabilitation. As said, for these it

is important to consider many factors as patient engagement, ability to generalize reacquired skills to a non-assisted context, retention in time.

A wearable technology can in theory collect information from the limb's motion that are hardly accessible during standard care. This pushed researchers to develop new data-driven metrics (*e.g.* using upper-limb synergies [31], see Schwarz et al. [131] for a review) which are however hard to spread through the medical community, mostly due to a hard time correlating these with standard metrics [145]. The cause of this complex correlation are multiple: standard metrics are usually too discrete to catch fine changes in patients' behaviour (*e.g.* FMA-UE, using a 3-point scale to score each task), are too categorical in assessing motor recovery (e.g. FMA-UE) *vs* functional recovery (e.g. ARAT), and they may not take in consideration compensations when assessing functional performance.

In controlled trials, different intervention for the control groups have been administrated. The majority tested against a standard therapist-led session, which guarantees for a similar duration of the therapy but does not guarantee a similar intensity, *i.e.* amount of movement repetitions in the same amount of time, potentially biasing the results towards a positive outcome of the robot-led therapy [133]. On the other hand, an intensive therapist-led session, matching the numbers achieved by an automatic robot, is not the standard for any individual undergoing rehabilitation nowadays, making the comparison ill-posed. Cost of therapy is also a factor in the general problem [121] and some have tried to assess the economical impact of the robot intervention, without positive results [16], [18].

FMA-UE is widely considered the ''gold standard'' for motor recovery in stroke and indeed many studies aim at improving this metrics. However, even when performing the robotic intervention on top of the standard care, thus clearly biasing the outcomes in favor of the robot therapy, FMA-UE improvements are rarely over the minimal clinically important difference and our meta-analysis showed very small positive effects of the usage of robot in the intervention (Figure 6). Similarly, advantages of the robot-therapy in terms of functional recovery are also unclear [121], [144] and our meta-analysis showed no difference between robot intervention *vs* standard care, see Figure 7, leaving the rehabilitation robotics approach questionable, at least with the current technology and control strategies.

In Masiero et al. [44], [74], a cable-driven robot, passively mobilizing the upper-limb of stroke individuals in the acute phase, improved the FMA-UE outcome compared to the standard care; despite the robot-therapy was performed for the intervention group in addition to the standard therapy, thus biasing the results, these are promising if a lightweight, cost-accessible, and compact device could be provided to individuals as soon as possible after the stroke onset, even performing such a simple strategy as passive mobilization.

In Hesse et al. [47], a 2-DOF end-effector robot was able to improve FMA-UE of 22 sub-acute stroke individuals significantly more than the 22 sub-acute stroke individuals enrolled in the control group. However, the control intervention was electrostimulation of their paretic wrist extensors: this discrepancy of intervention caused that *"with the robot, patients practiced a total of 24k repetitions, evenly divided between 4 different movement directions, whereas the control group practiced a total of 1800 to 2400 repetitions of wrist extension only"*. Moreover, the large increase of FMA-UE (+15 points at the end of the robotic intervention) may be in part due to a natural biological recovery: similar ranges are indeed appearing for other studies involving acute and/or sub-acute patients (e.g. [74], [79], [92]).

It is worth citing here three studies originally not included in the review [80], [81], [82] using a technology that is fully passive and commercially available (*ArmAssist* by Tecnalia). While other fully passive robot were included, given that these are mechanically reducing the effect of gravity on the upper-limb (*e.g. Armeo Spring*), *ArmAssist* is made of a linear rail that allows the arm to slide in a planar direction. Basically, this robot is a version of the common slide exercise, with the paretic arm on a towel on the table, very often implemented in standard care. The robot is however sold together with a software for remote monitoring and gaming. Tomic et al. [81] showed significant improvement of FMA-UE higher than the MCID (+18 points in FMA-UE) using this technology on 13 sub-acute stroke survivors *vs* a control group (N=13 sub-acute, +7.5 points). Engagement has been always considered crucial in the process of relearning [134], [139], and this result is a clear demonstration of the importance of making the therapy appealing to the patients.

Among the studies not directly assessing FMA-UE, it is worth mentioning Gunn et al. [122] and Ambrosini et al. [116], being two of the studies with the largest pool of participants. In [122], authors performed a survey with the families of 55 children with neurological impairments using a 3D printed version of the WREX exoskeleton (the precursor of the Armeo Spring, either mounted on a jacket or to the wheelchair) at home. Participants reported usage of the robot on average for 22 months and improvement of performance of a variety of ADLs (*e.g.* drinking from a glass, using a TV remote) when assisted by the passive robot, demonstrating the importance and the necessity of assisting technologies for daily use in unstructured environments. In [116], instead, authors were able to show greater statistically significant improvements (recovery of arm functions, ARAT, and dexterity, BBT) in a group of 31 acute/sub-acute stroke survivors using an EMG-triggered hybrid robotic system (*"Retrainer"*) with respect to a same size group of participants involved in an equally intensive conventional therapy, after 9 weeks of intervention. This result was not only due to pure increase in strength or reduced motor impairment, as both groups equally improved in MI, MRC, and MAL, but likely thanks to the possibility to perform personalized, intensive, and task-oriented training within an enriched multimodal sensory environment (visual, tactile, and proprioceptive, thanks to the use of EMG).

D. INCREASE THE EXPOSITION TO THE ROBOTIC ASSISTANCE

Being able to provide personalized and engaging assistance as soon as possible seems therefore to be a key to unleash the potential of wearable robotics. Videogames have the potential to increase the focus of the users and competing against peers can also be a factor to further increase participation [134], [139]. However, being able to assist the performance of real, individual-specific ADLs would likely be the request of every patient [134], [135]. In a recent review, Gandolla et al. [147] were able to demonstrate that upper-limb assistive devices significantly improve the performance of ADLs in people with neuromuscular diseases, despite reporting the problem of a low number of studies and participants.

Exosuits and soft wearable materials have the potential to allow the design of lightweight, unobtrusive, and cost-effective robots, thus ideally increasing the number of people who could benefit from such a technology. More than in the case of rigid bulky exoskeletons, these robots can ideally be worn for a long time during the day and can allow for interaction with an unstructured environment (*e.g.* a patient's house). Unfortunately, the length of table 4 is a clear demonstration that the technology is too ''young'' to claim any substantial finding but the direction seems promising.

E. RIGID VS SOFT: KEY DESIGN CHALLENGES

The non-negligible weight and volume of most of available end-effectors and exoskeletons is an issue for this technology, limiting exposition time and availability out of a high-tech clinical context. As a reference, the *Myopro*, one of the very few lightweight and portable exoskeletons, weighs approximately 2kg, over 80kg of an *Armeo Spring* and over 200kg of an *Armeo Power*.

Another typical design problem for classical rigid robots is the coupling between biological and robotic joints, which is often address by inserting redundant passive joint on the robot, above all around the shoulder [114], [115]. Clearly, the higher the number of DOFs to control, the harder and more complex is the control strategy that needs to be implemented. At the same time, the capability of being mechanically transparent, thus not limiting the user free movement, is crucial both for assessment purposes and, once the motor recovery has started, to reduce the assistance to maximize engagement [55], [140], [141]. However, this is harder to achieve if the mechanics and the control of the robot are complex.

Soft approaches, on the other hand, usually cannot achieve high torque values as their rigid counterpart and suffer from complex anchoring of the material to the biological joints [5]. Actuation systems tend to slide and move on the limb, requiring either more compression to the skin or anchoring through useful bony landmarks (*e.g. around the thumb, or the contralateral shoulder*), with the risk of quickly becoming uncomfortable. Precise positioning of the device during the donning is also less easy to achieve than with any end-effector or exoskeleton, thus requiring more robust solutions for sensing and control of the robots [143].

Common problems to both approaches do exist. Self-donnability seems to be out of most of the design scopes but should be addressed seriously in the near future to start considering further expansion into commercial applications. A full integrated system assisting both proximal (*i.e.* the shoulder) and distal (*i.e.* the hand) joints would be preferred given that both are fundamental to any ADLs. However, this raises the bar of the challenge of designing a single standalone portable and lightweight wearable device.

F. PERSPECTIVES

1) PATIENT, THERAPIST AND CAREGIVER ARE THE FOCUS

Very often the stroke patient is the only focus of the research effort. However, they are just one of the element of the rehabilitation process. In a preliminary study, O'Neill et al. [93] used a soft wearable robot to support the weight of the limb of five stroke survivors against gravity, but monitored the condition of an occupational therapist performing rehabilitation, demonstrating their reduced effort. Integrating the action of the therapist with the one of the patient and of the robot may be a key to open to novel solutions that indirectly affect positively the outcome of rehabilitation. Sensorizing the patient but also the therapist and perhaps the caregiver, can help enlightening new results and new needs that wearable technology can address.

2) THE PARADIGM OF CONTINUUM OF CARE

It seems clear that the field should move towards solutions that could guarantee a ''continuum of care'', meaning availability of support and rehabilitation not only in the clinical setting and thus only for few hours per week. Wearable robots should be able to extend the assisted-therapy to any environments, in particular the one of patients' houses, and ideally for most of the day. Because of this, researchers should focus on portability, lightweight design, assistance of ADLs. Soft exosuits have potential to achieve something along these lines, but may also fail due to fundamental issues (*e.g.* low torque production). A technology mixing the two approaches of rigid and soft could therefore be investigated: more rigid elements along a softer actuation chain could improve anchoring and torque delivery, resulting in a still lighter and much portable final design than standard exoskeletons and end-effectors.

3) UNSUPERVISED MONITORING

In a near future, thanks to the help of wearable robots, transiting from supervised to unsupervised at-home therapy could generate the need of better monitoring how the technology is used by the patient. At the moment, the only way therapists have to monitor what patients do when out of a clinical setting is the use of self-administrated activity log notebook, where patients write down performed activities, potential failures, at a very subjective level of detail [136]. Given the

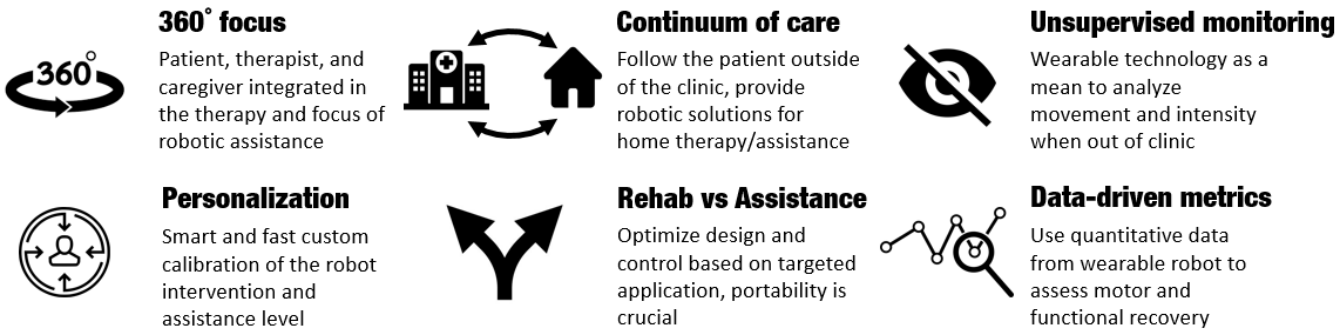

FIGURE 8. Directions to investigate. Six proposed directions of intervention for unleashing the potential of wearable robotics and foster widespread diffusion.

importance of engagement and intensity of movements, using the robot not only to support but also to monitor and retrieve quantitative data is desirable. Furthermore, when performing at-home therapy, attention monitoring solutions could also be used to inform the real intensity of performance of the patient, with the goal of better shape and customize the therapy to the real capabilities of the user.

4) PERSONALIZED INTERVENTION

It is widely accepted that personalizing the assistance is one of the key elements to more effectively induce neuroplasticity [134]. This should be kept in mind when designing a robot-assisted intervention. In most cases, the calibration step (if any) of the robot assistive parameters is absent or vaguely described, and likely the same ''default mode'' has been used for the whole pool of participants. Investigating smart, fast and customized strategies for optimize the behaviour of the robot to the specificity of the user is of interest and can help improve the final outcomes.

5) DIFFERENT REQUIREMENTS FOR REHABILITATION AND ASSISTANCE

Given the differences between assistive and rehabilitative robots, design requirements – mechanics, control, sensing – should also be different. For rehabilitation purposes, trying to develop robots that can assist on a large workspace to improve motor functions is necessary, but as already discussed, implementing solutions that are accessible early after a stroke is fundamental. Furthermore, designing one robot only to address every stage of recovery may over-complicate the requirements and thus the resulting technology. The concept of a ''robotic gym'', meaning a set of specific task-oriented devices, used gradually and accordingly to the physical recovery stage, can be considered to design more effective solutions. When considering assistive purposes instead, the design of novel wearable robots should likely be more focused on a target set of tasks to support. Portability is unavoidable and perhaps, a bottom-up design approach, starting from the definition of a limited number of activities that needs to be assisted by the robot, could lead the design to lighter devices, with optimal hardware and software requirements.

6) DATA-DRIVEN STANDARD METRICS

A new effort should also be made in the creation of new data-driven standard metrics, accepted by both the clinical and technical communities, to fairly assess the effect of the robotic intervention. A good number of automatic strategies have been developed to try to match quantitative data to the human evaluation, especially to estimate FMA-UE [137]. However, a push towards a better use of the large amount of data that modern wearable robots can collect is needed [145].

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