Review

Not peer-reviewed version

Stat of the Art in Wearable Wrist Exoskeletons Part II: A Review of Commercial and Research Devices

Roberto Francesco Pitzalis * , Daegeun Park , Darwin G. Caldwell , Giovanni Berselli , Jesús Ortiz

Posted Date: 14 November 2023

doi: 10.20944/preprints202311.0864.v1

Keywords: wrist exoskeletons; wearable devices; occupational sector; rehabilitation field; industrialization issues

Article

Stat of the Art in Wearable Wrist Exoskeletons Part II: A Review of Commercial and Research Devices

Roberto F. Pitzalis [1,2,*], Daegeun Park [1,*], Darwin G. Caldwell [1,*], Giovanni Berselli [1,2,*] and Jesús Ortiz [1,*]

[1] ADVR, Department of Advanced Robotics, Istituto Italiano di Tecnologia, Genoa 16163, Italy
[2] Department of Mechanical, Energy and Transportation Engineering (DIME), University of Genova, Via all'Opera Pia 15/A - 16145 Genova, Italy
* Correspondence: roberto.pitzalis@iit.it (R.F.P.); daegeun.park@iit.it (D.P.); darwin.caldwell@iit.it (D.G.C.); giovanni.berselli@unige.it (G.B.); jesus.ortiz@iit.it (J.O.)

Abstract: Manual handling tasks, both in daily activities and at work, require high dexterity and the ability to move objects of different shapes and sizes. However, musculoskeletal disorders that can arise due to aging, disabilities, overloading, or strenuous work can impact the natural capabilities of the hand with serious repercussions both in working and daily activities. To address this, researchers have been developing and proving the benefits of wrist exoskeleton., This paper, which is the part II of a study on wrist exoskeletons, presents and summarizes wearable wrist exoskeleton devices conceived for use in rehabilitation, assistance, and occupational fields. Exoskeletons considered within the study are those available either in a prototyping phase or on the market. They can support the human wrist by relieving pain or mitigating fatigue while allowing at least one movement. According to the requirements to be met, the majority have been designed active (80%) for higher force/torque transmission, and soft for better kinematic compliance, ergonomics, and safety (13 devices out of 24, more than 50%). Electric motors (11 devices out of 24, almost 50%) and cable transmission (9 devices out of 24, almost 40%) are the most common due to their simplicity, controllability, safety, power-to-weight ratio, and the possibility of remote actuation. As sensing technologies, position and force sensors are widely used in all devices (almost 90%). The control strategy depends mainly on the application domain: for rehabilitation, CPM (Control Passive Motion) is preferred (35% of the devices), while for assistance and occupational purposes AAN (Assistance-As-Needed) is more suitable (38% of the devices). What emerges from this analysis is that while rehabilitation and training are fields in which exoskeletons have been grown more easily and gained some user acceptance (almost 18 devices of which 4 are available on the market), relatively few devices have been designed for occupational aims (6 of which only 2 are available on the market) due to difficulties in meeting the acceptance and needs of users. In this perspective, as a result of the state-of-the-art analysis, the authors propose a conceptual idea of a portable soft wrist exoskeleton for occupational assistance.

Keywords: wrist exoskeletons; wearable devices; occupational sector; rehabilitation field; industrialization issues

1. Introduction

Manual handling tasks such as opening a jar, lifting a weight, and manipulating objects of different shapes and sizes, both in daily activities and at work, require high hand/wrist dexterity and the appliance of forces. These actions performed for a prolonged time, or where they are violent, irregular, repetitive, and/or involve awkward postures, play a role in the growth and aggravation of musculoskeletal discomforts of arms, wrists, and hands [1]. Musculoskeletal Disorders (MSD) affect joints, bones, muscles, tendons, or ligaments. They can progress from mild to severe and can lead to episodic or chronic diseases that alter the quality of life of people by reducing mobility and dexterity in activities of daily living (ADL). They can also arise as a result of aging, disabilities, and injuries.

Work-Related Musculoskeletal Disorders (WRMSD) have been known for a long time with early literature dating back to the work of Bernardino Ramazzini, an 18th Italian physician and scientist,

 doi:10.20944/preprints202311.0864.v1

who is considered the father of *occupational medicine* [2]. His studies on workers in Padova (Italy) identified more than 50 methods for preventing harm at work and pointed out that "workers' diseases" were attributable to the working environment, and prolonged, violent, irregular movements and postures [3–5].

Nowadays, as reported by the World Health Organization (WHO), approximately 1.71 billion people have WRMSD worldwide, most of which involve pain in the lower back and upper limbs [6]. In Italy, a report from the Italian Workers' Compensatory Authority (INAIL) [7] confirms this noting that 51.6 % of all Italian workers suffer from back pain problems, while 46.7 % have upper limb-related problems [8].

Fortunately, exoskeletons are increasingly being shown to provide benefits to the human body by transferring loads from the most vulnerable areas, and through the effective transfer of energy between the human and the robotic system. The number of projects involving these devices has increased dramatically since the 2000s and has involved different sectors such as military, medical, and industrial [9], although many of the very first examples were for military programs such as DARPA's "Exoskeleton for human performance augmentation". The key early developments were also focused on static devices for rehabilitation in clinical settings to help recover functionalities of the limb or reduce pain after injuries [10,11]. However, today the growing impact of WRMSD is placing more emphasis on Occupational Exoskeletons (OEs). *Crea et al.* in [12] produced a roadmap for the large-scale adoption of OEs that highlights the costs and benefits of these technologies in real-world scenarios, but only in the past 12 years commercial wearable solutions have entered the market to assist workers in burdensome and repetitive tasks [11]. Although this growth has been substantial, few have focused on the wrist, despite this being considered the fourth most common site for musculoskeletal pain in the upper limb [10–14]. This is due to design difficulties in the one-to-one correspondence with the human body. As presented and explained in the **Part I** of this work [15], these devices have to meet a variety of often *requirements* including: the bio-mechanics and pain factors of the human joint; the *application field*; the *kinematic compliance* with the human limbs and joints; the *dynamic compliance* according to the forces/torques required to perform certain tasks; the *rigidity* of the mechanism; the *ergonomics* and *safety* of the device, all of which must combine to ensure the system's adoption in real scenarios and its overall acceptance.

Different design structures have been explored by researchers and are still under development in the areas of rehabilitation and assistance [13,14,16–33], and occupational [11,34–36] exoskeletons. Those structures, as shown in the part I [15], can be classified according to the rigidity, actuation type, power source, power transmission methods, sensing and control strategy. Rigid devices [13,16–18,31,32], mostly made of hard and stiff materials (e.g., stiff linkages and gears), are preferred for better reliability in motion control and force/torque transmission. But soft or compliant structures are also seen to have benefits when there is a demand for more comfortable, lighter, safer devices that can overcome axis mismatches [11,14,19–30,33–38]. With respect to actuation type, a first and very critical distinction can be made between passive and active exoskeletons. Passive devices (which are by far the most common) are often driven by springs that store potential energy typically extracted from motion of the user [18,28,31,33,36]; while active units can use a variety of different sources of power: electrical [11, 13,14,16–19,23,29,30,32,35], pneumatic [20–22,34,37], and thermal [24–27,38]. Electrical motors are the most preferred due to their robust controllability, good power-to-weight ratio, and price. The type of power transmission influences the rigidity of the system. Various methods have been explored involving rigid structures (such as direct drive, rigid links, or gears) [13,16–18,27,31,32], tendons or Bowden cables [11,14,19,23,26,29,35,38], or compliant elements (such as springs, artificial muscles, or flexible joint-less structures) [20–22,24–26,28,30,33,34,36,37]. To function correctly, providing feedback for and to the human body, all wearable devices need sensing and control paradigms, and usually adopt more than one type of sensor and control strategy. In wrist exoskeletons, the key sensing parameters are position detected by encoders, potentiometers, IMU or flex sensors, force/torque measured using load cells, pressure sensors, or force resistive sensors (FSR), and bio-signals recorded using electromyography (EMG). Controllers can be designed to exert predefined trajectories and forces/torques based on a Control Passive Motion (CPM) strategy. This is mainly used in rehabilitation protocols for passive users. Or to provide Assistance-As-Needed (AAN) control, that guarantees a higher adaptability to the user needs. Furthermore, controllers can work in an active resistance mode by adjusting the stiffness of some springs to impose forces/torques that resist the motion of the subject and improve rehabilitation training.

In this **Part II** study, we review and describe in detail **wearable and portable wrist exoskeletons** designed since the 2000s. This paper differs from other reviews [10,12,39–45] through its focus on **wearable and portable wrist exoskeletons**, analysing their mechanical design, control, and functionalities, highlighting pros and cons, and providing suggestions on industrialising effective devices. This work draws a very clear distinction between hand and wrist, as they are very different from a clinical perspective [46].

The proposed review paper is organized as follows: in Section 2 there is the explanation and schematization of the materials and data selection protocol adopted. In Sections 3 and 4 there are detailed descriptions of wearable and portable wrist devices available, respectively, in a prototyping phase and in the market, and conceived for rehabilitation, assistance, or occupational purposes. As a result of the state-of-the-art analysis, in Section 5 the authors propose a conceptual idea of a novel portable soft wrist exoskeleton for occupational assistance. Finally, Section 6 summarises the most significant findings of the review paper and future trends of wrist exoskeletons. To simplify the gathering of information by the reader, a summary table is proposed in Appendix A (Table A1) reporting all devices took into account and their characteristics.

2. Materials and Methods

The methodological approach behind this review paper consists in searching on the market and in several databases (i.e., Google Scholar, MDPI, Scopus, Frontiers, Elsevier, ResearchGate, IEEE/ASME, ScienceDirect, Sage, Wiley and Taylor&Francis), looking for all technologies explored and implemented since 2000's about wrist exoskeletons.

The main keywords for conducting the research were *"Wrist exoskeletons"*, designed to be *"Wearable"* and *"Portable"*, for *"Rehabilitation"*, *"Assistance"*, or *"Occupational"* purposes. To ensure the results best reflects the goals of the study a set of specific inclusion and exclusion criteria were implemented to refine the search domain.

Inclusion criteria consist of:

- Upper limb exoskeletons which include the wrist in their design;
- Devices able to relieve pain or mitigate fatigue by supporting at least one wrist movement;
- Devices intended for rehabilitation, assistance and occupational purposes;
- Portable devices;
- All studies must be accessible by the authors in English.

Exclusion criteria consist of:

- Prosthesis or exoskeletons which do not allow free wrist movements;
- Military devices;
- Fixed/grounded devices;
- Studies in other languages or with insufficient information, which made the analysis unclear.

The methodological approach used, and shown in Figure 1, is similar to that of the part I [15], and focuses on describing, in detail, the design, control and assessment of the wearable and portable wrist exoskeletons.

 doi:10.20944/preprints202311.0864.v1

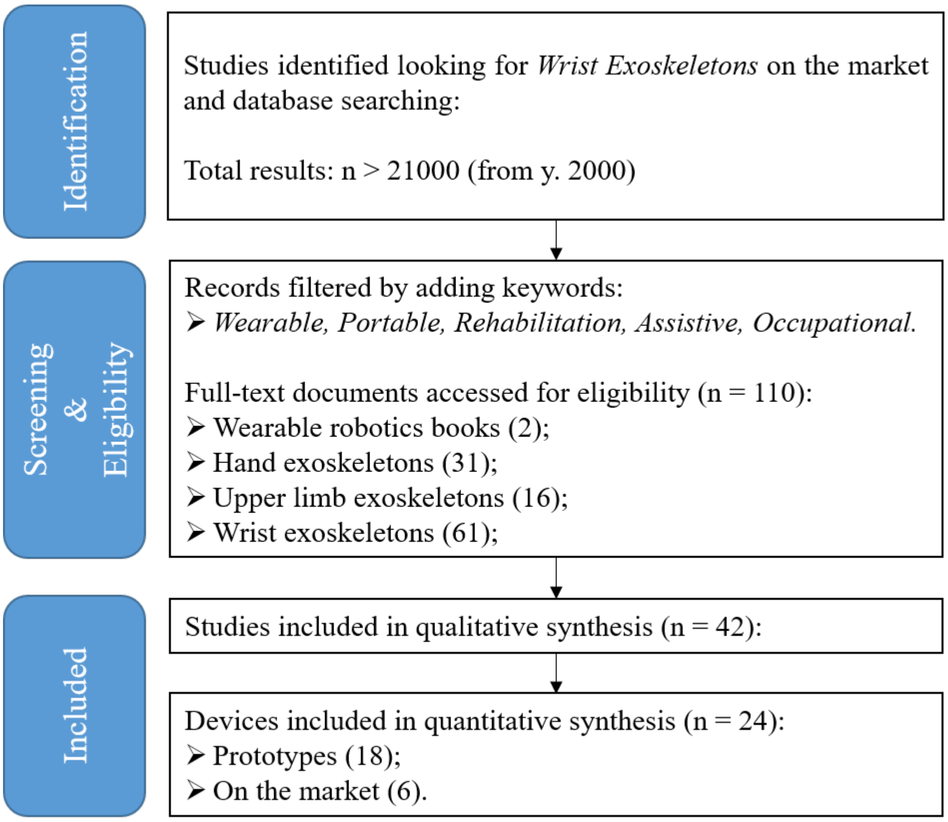


Figure 1. The flow chart methodology adopted to identify and screen all information available from online database and conduct our review.

3. Research and Pre-Commercial Devices

As with all developmental cycles, there is with exoskeletons an early phase of prototype design for research and pre-commercial testing. While the end goals for these devices may fully align with eventual commercial systems, they are often more complex in terms of hardware and software, may have unrealistic costs or may not fully conform to strict commercial mandatory regulations. Nonetheless these devices often form the basis for designs that will eventually become industry standards, and a full and comprehensive study and analysis of these systems is vital in any detailed review. The section provides a detailed study of wearable and portable wrist exoskeleton prototypes with, where appropriate, an assessment of the integrated actuation, electronics, control system and batteries, the ease of donning and doffing and the potential application scenarios. All devices are shown in Figure 2 and grouped according to structural rigidity criteria.

Based on the requirements proposed in [15], the schematic shown in Figure 3 provides relevant information about research and pre-commercial wrist exoskeletons.

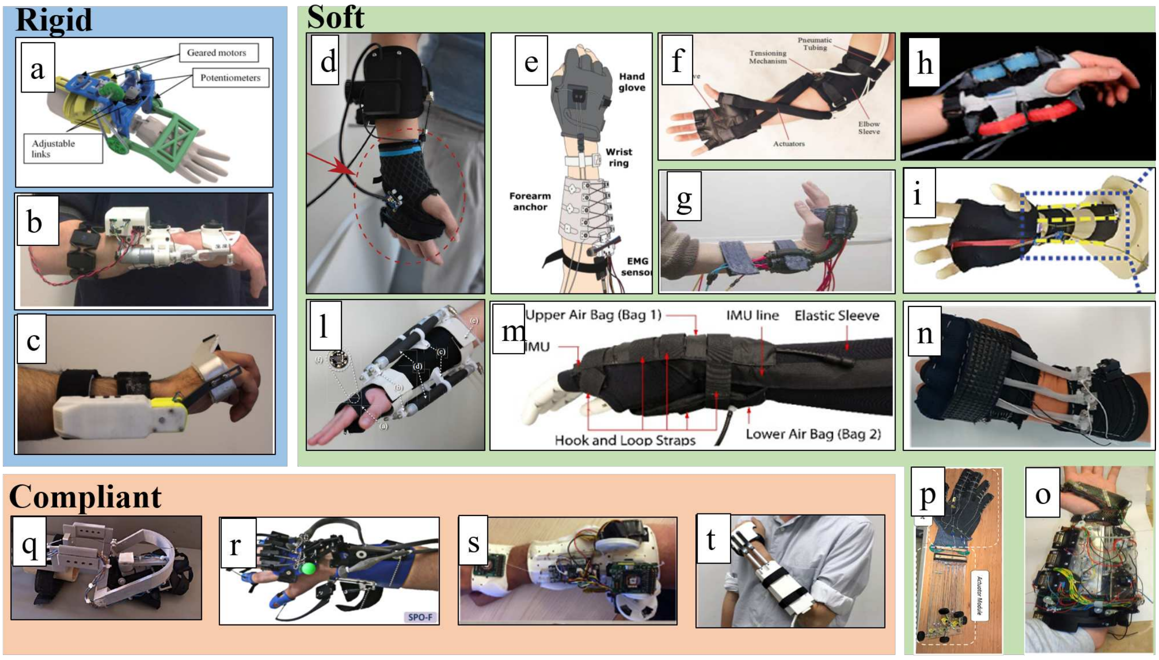


Figure 2. All wearable exoskeleton prototypes for wrist assistance. Devices are grouped by rigidity in: rigid (**a-c**), soft (**d-p**) and compliant (**q-t**). From from top left to bottom right it is possible to find: **a)** PWE designed by [16]; **b)** eWrist designed by [13,17];**c)** designed by [18]; **d)** exosuit designed by [11]; **e)** Exo-Wrist designed by [19]; **f)** soft orthosis designed by [20]; **g)** ASSIST designed by [21]; **h)** SOA-based wrist exoskeleton designed by [22]; **i)** a soft wrist exoskeleton designed by [23]; **l)** EXOWRIST designed by [37]; **m)** a soft robotic device designed by [34]; **n)** SWA - wrist designed by [24,25]; **o)**Wearable wrist and forearm exoskeleton developed by [26]; **p)** AST a SMA-based hand exoskeleton designed by [38]; **q)** SMA-based wrist exoskeleton designed by [27]; **r)** SCRIPT designed by [28]; **s)** a hand and wrist exoskeleton designed by [14,29]; **t)** a low profile wrist exoskeleton designed by [30].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

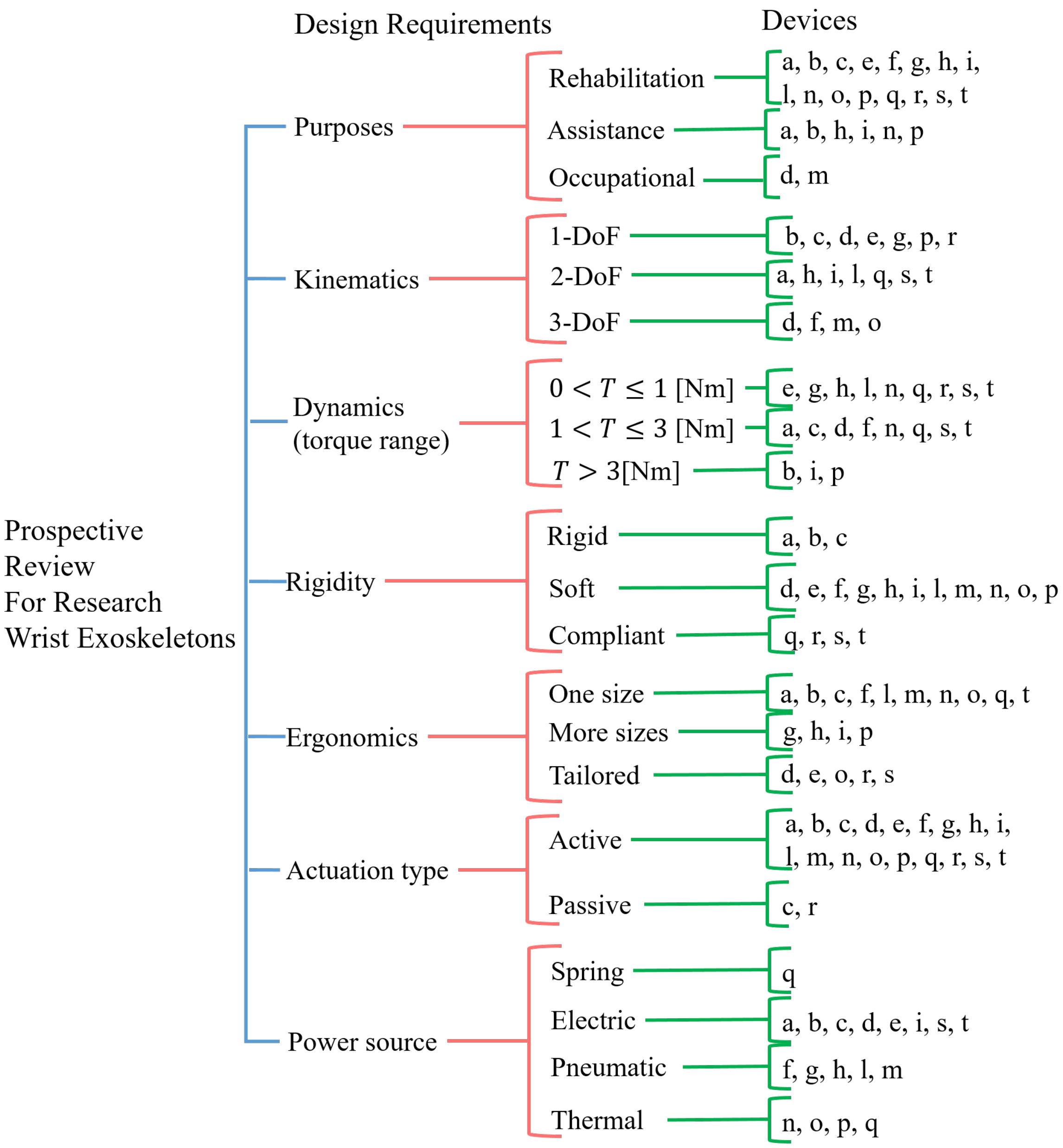


Figure 3. Schematic of research-wrist exoskeletons grouped by design requirements. Devices, named from a) to s), are the same as reported in Figure 2.

3.1. Rigid Devices

3.1.1. Development of a Portable Wrist Exoskeleton (PWE)

Xiao et al. in [16] investigated the design and control of a 2 DoF (flexion/extension and radial/ulnar deviation) portable, active and rigid wrist exoskeleton conceived for post-stroke rehabilitation at home, or used by workers to provide assistance in industrial settings. The Portable Wrist Exoskeleton (PWE) has a rigid kinematic chain made of ABS plastic and weighs 360 g. To avoid harm to the user, foam pads are inserted between the rigid parts and skin. To increase safety and prevent possible injuries, mechanical stoppers limit the RoM to $\pm 60°$ flexion/extension, and $\pm 25°$ radial/ulnar deviation. The power is transferred from the actuator (Pololu 298:1 micro DC geared motor), placed on the forearm brace, to the hand brace through gears and links. The maximum torque

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

generated are 2.3 Nm for flexion/extension, and 2.5 Nm for ulnar/radial deviation, which are enough for rehabilitation application, yet it may not be adequate for industrial use.

Two different control modalities have been implemented: position control for passive repetitive pre-programmed movements, suitable for rehabilitation application; and a torque control designed for torque amplification applications such as for workers' assistance. As control strategy, they investigated the feasibility of surface electromyography (sEMG) signal classification through neural network (NN) and support vector machine (SVM). By measuring the sEMG amplitude and torque exerted from the main wrist muscles of healthy subjects, the SVM predicted and followed the wrist movement in real time with the greatest accuracy (up to 80.44%), exerting different levels of torque depending on the wrist position.

This study suggests that machine learning techniques for motion prediction could be beneficial when performing highly dynamic tasks. However, the requirement for sEMG signals makes it hard to apply in industrial settings, where workers must wear them in contact with the skin.

3.1.2. The eWrist—A Wearable Wrist Exoskeleton

Lambelet et al. in [13,17] have presented *eWrist*, a portable and rigid 1-DoF wrist exoskeleton to support flexion/extension in rehabilitation and training. The device, shown in Figure 4, aims at enhancing wrist muscles activity in ADLs by measuring residual sEMG amplitude of stroke patients through a Myo armband: a commercially available sEMG device.

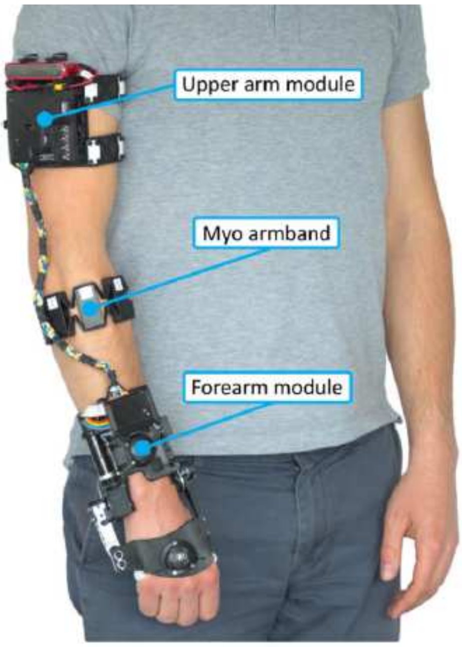


Figure 4. the eWrist: first attempt prototype of a wrist exoskeleton for rehabilitation and training designed by [13,17]. It is made of a rigid mechanism and powered by a rotary motor placed on a side of the forearm. It is conceived for wrist flexion/extension.

The whole device consists of a kinematic chain made of rigid and soft 3D printed parts, and weighs 556 g, including the battery (80 g) and the Myo armband [17]. A Boa Closure is used as tightening system and allows quick and easy one-handed placement. The actuation system incorporates a 12V DC brushless rotary motor (Maxon EC 16) with a total reduction ratio of 475:1, making it difficult to back-drive. Therefore, mechanical transparency is obtained through active control. A two-channel Hall effect sensor, integrated within the motor, determines joint angular velocity and position. A load cell, mounted between the bevel gear and the hand fixation, determines the torque.

A real-time PD-controller, integrated in a Raspberry Pi Zero, implements an *Assistance-As-Needed* (AAN) support strategy. This adjusts position and torque output based on several inputs: raw sEMG data from the Myo, force from the load cell, and the angular velocity. Two different dynamic behaviours, for different rehabilitation settings, are available: transparent or resistive. In transparency mode users can move freely and rapidly with low interaction torques (up to 0.34 Nm); in resistive modality, movements are constrained by higher torque values (up to 1.59 Nm).

The device has been characterized based on standardized metrics for rehabilitation devices and, subsequently, tested with healthy and stroke participants. Tests performed on healthy subjects showed that it can provide: a RoM of 154°, a maximum output torque of 3.7 Nm, a maximum output velocity close to 520°/s, and an average set-up time of 37.3 s. Observations from questionnaires of fifteen healthy subjects and two stroke survivors showed that the eWrist was positively received: it helped impaired subjects achieve a RoM comparable to that of healthy subjects; all participants were able to use it independently; the fixation systems were evaluated as being efficient, secure, and easy to handle.

However, some limitations still remain in terms of aesthetics, physical proportions and weight distribution: some subjects felt discomfort due to a wrong size, alignment mismatch between mechanical and biological joints, and skin pain caused by fixations.

3.1.3. Robotic Orthosis for Wrist Assistance

Sangha et al. in [18] have presented a wearable 1 DoF robotic orthosis to assist wrist flexion and extension in rehabilitation.

The device, shown in Figure 5, weighs 330 g and consists of a rigid aluminium kinematic chain, secured at the palm and forearm by C-shaped clamps and Velcro straps, and 3D printed ABS plastics which cover all the electronics. The actuator is a DC rotary motor with a custom gearbox with a high reduction ratio (1700:1). It provides a nominal torque of 1.12 Nm, and a stall torque of 8 Nm.

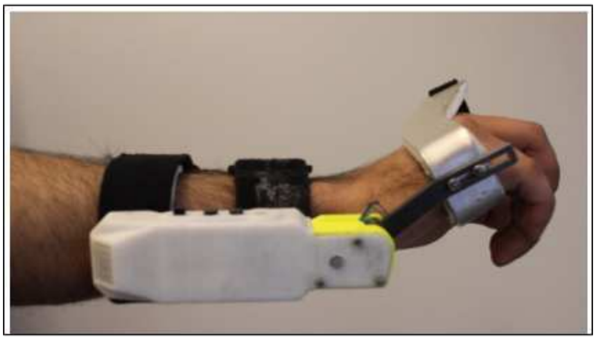


Figure 5. One DoF rigid wrist exoskeleton designed by [18].

The device can operate in three different modes according to the patient's impairment: passive, active resistive, and active assistive. Passive mode assists the wrist movements based on predefined parameters and the patient's RoM. It is useful for those with muscle weaknesses. Active modes assist wrist movements to augment brain plasticity and decrease muscles spasticity. Assistance is provided after detecting muscular effort with 8 force sensitive resistors (FSR) to record force-myography (FMG) signals from the forearm. A neural network (NN) is implemented in Arduino software to process the FMG signals and send the control command to the motor.

Tested on a healthy volunteer, it has: a RoM from 0° (full flexion) to 120° (full extension), a nominal torque of 1.12 Nm, and a battery life of 150 min.

Despite its interesting performances and features such as working modalities, compactness, lightweight, and cost, further investigations are required to test its efficacy in real scenarios with more subjects (both healthy and impaired).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

3.2. Soft devices

3.2.1. Soft Wrist Exosuit

Chiaradia et al. [11] have developed a novel 1-DoF wrist exosuit for assistance at work. It is made up of a soft wrist orthosis and two 3D printed ABS supports (one for the back and one for the palm), which help to distribute pressure on large areas, bear cable tension and sensors. The wearable parts, shown in Figure 6, weigh 300 g.

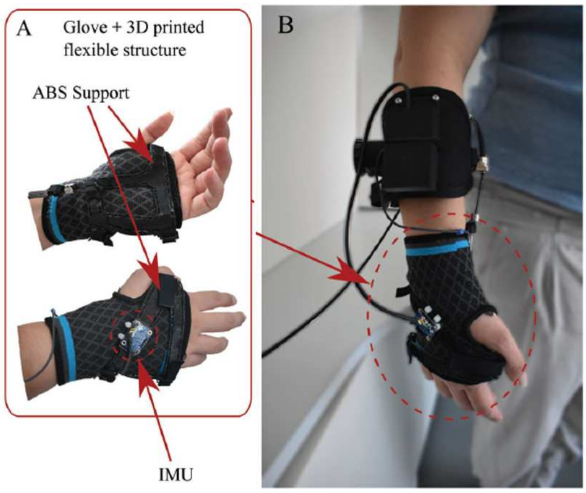


Figure 6. Soft wrist exosuit designed and developed by [11].

The system is actuated remotely using a bowden cable transmission and a Kollmorgen motor (AKM23F) with an Apex Dynamics planetary gear drive (PG II 040), and a gear ratio of 10:1. This helps reduce the weight on the human joint and the metabolic impact. A load cell measures cable tension, and 9 DoF inertial measurement units (IMUs) estimate wrist flexion: one on the back of the hand and one on the forearm.

The control strategy is based on admittance control for transparency and gravity compensation. The torque exerted on the wrist is compensated by evaluating an estimated torque, knowing the wrist angle and the cable force. The addition of a PID controller on the angular velocity gives the assistance faster by capturing the user motion intention.

The device enhances the wrist movement in a range of 150° (70° for flexion and 80° for extension) and can provide 3 Nm torque, sufficient to hold 3.0 kg. However, it adopts an external heavy DC motor which makes it difficult to wear, and the reduction in muscle activation seems lower than with other devices.

Despite its limitations, this prototype is worth attention due to its characteristics such as: industrial applications, softness because of the tendon-driven actuation, comfort and customization as the rigid parts are designed following a 3D scan of a human hand. Future developments may include full wearable actuation and control systems, improving the transmission efficiency with a control strategy for friction management and the comfort.

3.2.2. ExoWrist—A Soft Tendon-Driven Wrist Wearable Robot for Dart-Throwing Motion

Choi et al. in [19] presented a new soft wearable wrist robot called ExoWrist. The device is active and conceived to restore wrist functionalities of weakened upper limbs after injuries by focusing on the *Dart Throwing Motion* (DTM), the most natural wrist movement [47–50]. It is expected to be used both in or out-of-clinics.

The ExoWrist consists of a golf glove, a forearm active anchor and a wrist armlet. On the back of the glove, tendons are placed to transmit forces. The forearm anchoring consists of a truncated

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

cone shape made of soft and flexible materials. This compresses the forearm only when assistance is needed to reduce force losses through friction. The wrist armlet is a silicon-based 3D printed part and is customisable based on: wrist width, wrist height, and the DTM orientation plane. The use of soft materials and cables makes the whole device comfortable with an overall weight of 1 kg. The DTM plane and wrist kinematics of each individual have been measured by using 3D motion-capture sensors (Vicon) to define the tendons path to correctly apply assistive force.

The robot has been assessed on three healthy subjects by evaluating: the efficacy of the anchoring system, the motion tracking performance, and the ability not to hinder other movements. The results showed that without the active anchor the robot could not provide proper assistance. When the anchoring point is activated and properly tightened, the robot can assist more than 0.5 Nm, otherwise it cannot generate more than 0.2 Nm, less than required for ADLs (0.35 Nm). The robot can extend the wrist along the DTM plane for more than 50°, more than is needed for constraint-induced movement therapy (CIMT, 0°-20°), and it does not also affect movements at elbow, shoulder and fingers.

3.2.3. A Soft Robotic Orthosis for Wrist Rehabilitation

Bartlett et al. in [20] have proposed a home wrist rehabilitation soft device designed for patients suffering from hemiparesis after stroke. It is pneumatically actuated, portable, and soft, and weighs 2.26 kg. It consists of a glove, an elbow sleeve and a Boa ratchet tensioning mechanism, which facilitates donning and doffing with one hand and adaptation to different arm lengths. The actuation mechanism consists of pneumatic artificial muscles (McKibben actuators) anchored on both the palm and back of the hand. Their size is crucial: a tube diameter of 1/2 in. (approx. 12.5 mm) can exert a contractile force close to 120 N, at a pressure of 30 PSI (approx. 200 kPa), which is enough for rehabilitation. Their anchoring points determine the initial actuator length and thus affect contraction length, RoM and force direction.

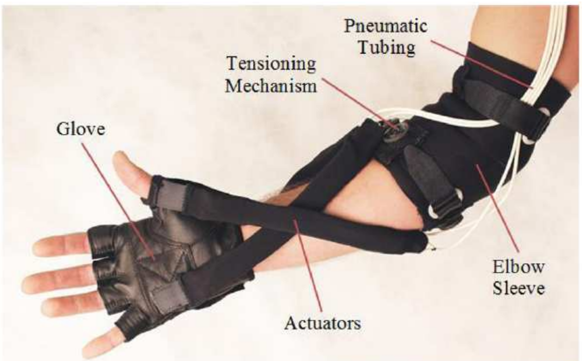


Figure 7. Soft robotic wrist orthosis [20].

The device works on agonist-antagonist principle: a single movement can be generated by activating a pair of actuators (e.g., the two in the palm for flexion, the two in the back for extension, etc.). The air pressure of each actuator is constantly monitored and modulated by a controller, which reads the status of pressure sensors and gives the input signal to a pump and relevant valves. The device can support all wrist DoFs by providing assistance over a range of 91° in flexion/extension, 78° in pronation/supination, and 32° in radial/ulnar deviation. Presented to a group of stroke patients, the participants gave positive feedback for its use in therapy.

3.2.4. Active Support Splint driven by Pneumatic Soft Actuator (ASSIST)

Sasaki et al. [21] have developed ASSIST, an active soft wrist splint to assist elderly or people in need of care, making them more independent. Two different types of ASSIST have been created: one for assistance in the whole RoM (type I), and the other for increasing muscular endurance (type II). They differ in the McKibben structure of artificial muscle actuators. Both devices consist of plastic interfaces,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

on the palm and back, to which two rotary soft pneumatic actuators are attached. Reinforcements at the ends allow the actuators to bend circumferentially, providing enough bending angle and torque for wrist assistance. The devices weighs almost 390 g. ASSIST is controlled by measuring the wrist angle with flex sensors and keeping the inner pressure constant. At 400 kPa pressure, type II provides almost 80° rotation and 1 Nm of torque; while type I allows the same bending angle with a lower torque (0.25 Nm). In contrast, the torque of type II decreases faster as the bending angle increases.

These devices were assessed on 5 subjects by measuring the amplitude of sEMG signals at the *flexor carpi ulnaris*. Results showed their suitability in correctly bending the wrist, and reducing muscular effort while lifting 3 kg.

Although the results are not statistically significant, these devices have promising capabilities also for industrial applications. However, there are drawbacks and further analysis and more data are needed to verify the benefits of prolonged use, make it fully wearable with a pressure tank and compressor above 400 kPa, assess reliability and control of the actuators' behaviour.

3.2.5. A soft robotic wrist brace with origami actuators

Liu S. et al. in [22] designed a low-profile, active and soft robotic (SR) wrist brace, that is pneumatically driven and has 2 DoF (flexion/extension and radial/ulnar deviation).

It consists of eight modular soft origami-patterned actuators (SOAs), a commercial wrist brace, and rigid anchors made of fabric to fix the actuators and transmit forces, as shown in Figure 8. Due to the inherent compliance of its materials, the SR brace enables safe interaction, has light-weight, compactness, comfort and adapts to various wrist sizes. The parts worn on the wrist weighs 214 g (each SOA weighs approximately 1.9 g), but the overall device weighs almost 1.76 kg, including the actuation system and batteries.

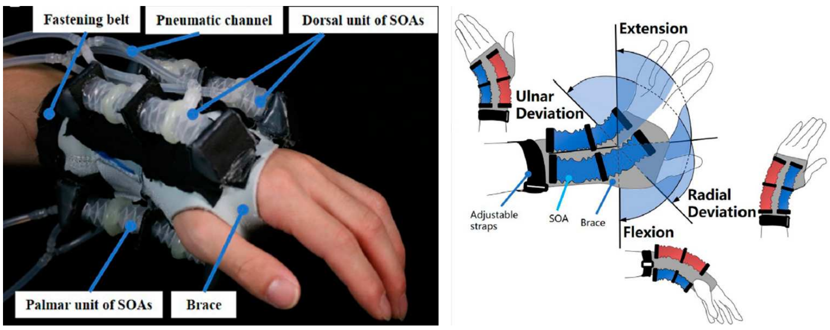


Figure 8. A robotic wrist brace with origami actuators developed by [22]. The actuators are placed on both the dorsal and palmar hand sides. Their elongation and contraction state are marked respectively as red and blue.

The actuation system include four identical two-SOAs units and two diaphragm air pumps. The device works by alternately contracting and expanding the actuators. For example, during flexion actuators on the dorsal side of the wrist elongate while those on the palmar contract. Their axial deformation exhibited when pressurized is converted into large bending due to anchoring constrains.

The control architecture consists of a high-level and a low-level control. The high-level controller estimates the wrist position depending on the pressure feedback from each actuator, and compares it with the desired motion. Thus, a pressure command is sent to the low-level controller to regulate the SOA pressure and elongation.

The device assessment was based on the RoM, output force, wearing position adaptivity, and performance. The RoM was measured without and with external loads (100, 200, 300 g). The maximum values, at $\Delta P = 160kPa$ pressure, were 30° in extension, 31° in flexion, 33° in radial deviation, and 22° in ulnar deviation. They decrease as the load increases. The force exerted achieved up to 7.5 N in flexion/extension, and 6 N in radial/ulnar deviation. The torque reached up to 0.76 Nm and met the functional requirement for rehabilitation therapy. The performance, assessed with IMU sensor, showed that the device consistently followed the planned flexion/extension, while it had less stability in ulnar/radial direction.

Although the results are promising and comparable with existing devices, future work will aim to optimize the design, improve compactness and portability, validate the effectiveness and side effects of specific rehabilitation therapies.

3.2.6. Bioinspired Musculoskeletal Model-based Soft Wrist Exoskeleton

Ning Li et al. in [23] describe a novel soft wrist exoskeleton for stroke rehabilitation and ADLs, shown in Figure 9.

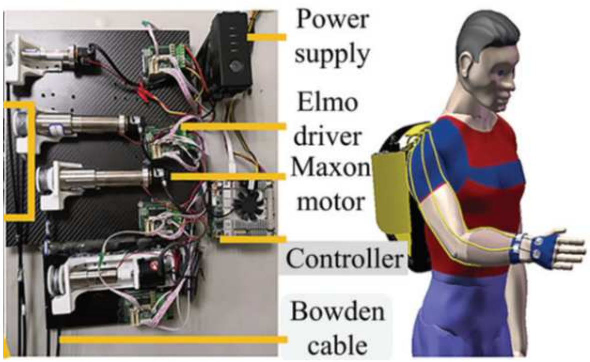


Figure 9. A soft wrist exoskeleton developed by [23]. The model shown comes from OpenSim simulation software.

They used commercially available components (motors, commercial body protectors, sensors, power supply) and investigated the distribution of muscle tension lines to identify the most efficacy path along which artificial tendons should be placed to correctly move the wrist. They analysed the kinematics of wrist muscles and simplified this to four main muscles: Extensor Carpi Radialis Longus (ECRL), Extensor Carpi Ulnaris (ECU), Flexor Carpi Radialis (FCR), and Flexor Carpi Ulnaris (FCU), which were arranged as to form a quadrilateral around the wrist. This design guarantees a more natural interaction with the user. To compare the exoskeleton movements with a real wrist, a Vicon tracking system was used to capture wrist trajectories of healthy subjects and those produced by the exoskeleton mounted on a hand mannequin.

The assessment was done in simulation (OpenSim software), and on healthy and impaired subjects. The device was able to cover the daily RoM requirements with a flexion/extension range of 115°, and a radial/ulnar deviation range of 70°. When tested on stroke patients, the device demonstrated an average 90.3% ability to recover healthy wrist motion. Moreover, by measuring the forearm sEMG signals from a healthy subject during 5 kg lift, the exo exhibited more than 40% reduction in muscle activation.

The overall results are consistent both in simulation and real scenarios, and pave the way for new and even better performing soft wrist exoskeletons. Although it is designed for rehabilitation and daily life assistance, the halving of muscle effort in lifting 5 kg is a great achievement and similar solutions could also be adopted in industry.

3.2.7. EXOWRIST: a wrist exoskeleton actuated by pneumatic muscle actuators

Andrikopoulos et al. in [37] developed a novel soft 2-DoF robotic wrist exoskeleton for rehabilitation, powered by pneumatic muscle actuators (Mckibben actuators).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

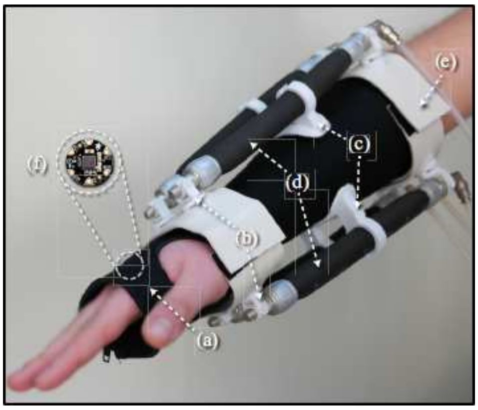


Figure 10. Soft wrist exoskeleton driven by pneumatic actuators and developed by [37].

The device, shown in Figure 10, consists of wearable elastic neoprene-based glove. It adopts four Pneumatic Muscle Actuators (PMAs), symmetrically distributed around the forearm, to function antagonistically and generate wrist flexion/extension and radial/ulnar deviation. PMA is like a tube, fixed to the glove with plastic supports, and it is characterized by a decrease in length when pressurized. The design uses few hard materials and enhances lightness, comfort and safety, with a total weight of approximately 430 g.

EXOWRIST's performance have been evaluated on a healthy, passive male volunteer. To achieve the maximum RoM, PMA should first be inflated to half its maximum stroke. Measured with an IMU placed on the back of the hand, the device can reach $\pm 30°$ in both flexion/extension and radial/ulnar deviation in less than 1 s. The pressure range is 0 to 8 bar, with a maximum operating pressure reaching 630 N of delivered force.

The control strategy adopts an Advanced Nonlinear PID (ANPID) algorithm which allows tracking of pre-defined sinusoidal motions with smooth, fast and accurate PMA responses. The safety was assessed by placing force sensors between PMA connections and the human's skin: the shear forces generated remain low, not exceeding 2.2 N.

The results prove that the EXOWRIST has potential in rehabilitation scenarios. However, there is a need for further improvements especially in the actuation system to make the device fully wearable, portable and safe, since high levels of pressure are required and must be supplied from a compressor or high pressure tank.

3.2.8. Carpal Tunnel Syndrome Soft Relief Device

Zhu et al. in [34] have proposed a novel device to alleviate Carpal Tunnel Syndrome (CTS) strains and pain by actively adjusting the wrist angle when operating in awkward postures for prolonged time, e.g., while typing on a keyboard.

The device, shown in Figure 11, consists of an elastic fabric sleeve that can be worn like a glove, and two thermoplastic (TPU) airbag actuators (eight-flanged bladders) sewn onto it. They are located at the lower and top part of the sleeve to extend and flex the wrist respectively by dynamically pressurizing and depressurizing them.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

Figure 11. Soft wrist exoskeleton designed by [34] to alleviate CTS: **a)** the whole device; **b)** the airbag actuators.

The performances were assessed on a hand mannequin by lifting the hand, with an external load of 200 g, to a height similar to that of a keyboard (1.9 cm). The device was able to lift the hand above 2 cm under a pressure of 31 kPa and from 0° to around 65° in 9 s under a maximum pressure of 62 kPa.

Although this device has interesting characteristics such as soft actuation, breathable materials, safety, easy and compact design, it needs further development to the design, control and experimental evaluation with subjects. CTS problems are highly topical and need special attention for the well-being of workers.

3.2.9. Wrist Assisting Soft Wearable Robot with integrated SMA Muscle

Jeong et al. in [24,25] proposed a novel shape memory alloy (SMA)-based wearable robot that assists 2-DoF (flexion/extension and radial/ulnar deviation) wrist motions in performing ADLs.

SMA actuators are metallic alloy that deform when heated above their transformation temperature and reduce their length between 3-5%, depending on the type and shape of the alloy chosen. SMA has potential properties as artificial muscles since it can produce high forces and can be fairly rapidly actuated via Joule heating. Furthermore, if shaped as a coil spring, it can produce forces up to 10 N, a contraction ratio of 40% and strains over 200%, achieving performances higher that than of SMA shaped as wires [27].

The device, shown in Figure 12, named Soft Wrist Assist (SWA), consists of: a finger-less glove, a forearm Velcro strap, and an elbow anchoring Velcro strap to adapt to different users' sizes, prevent and improve dislocation and slip [24]. Moreover, to transmit forces properly actuators are fixed on the glove with non-stretchable fabric. Five muscle-like actuators are attached at various positions: three to the back of the hand, and two on the palm. They are designed as coil springs, integrated into an active and stretchable coolant vessel, filled with mineral oil, for improved heating and cooling response. The wearable parts weigh 300 g, while the total mass, including the pump and radiator, is around 1.92 kg.

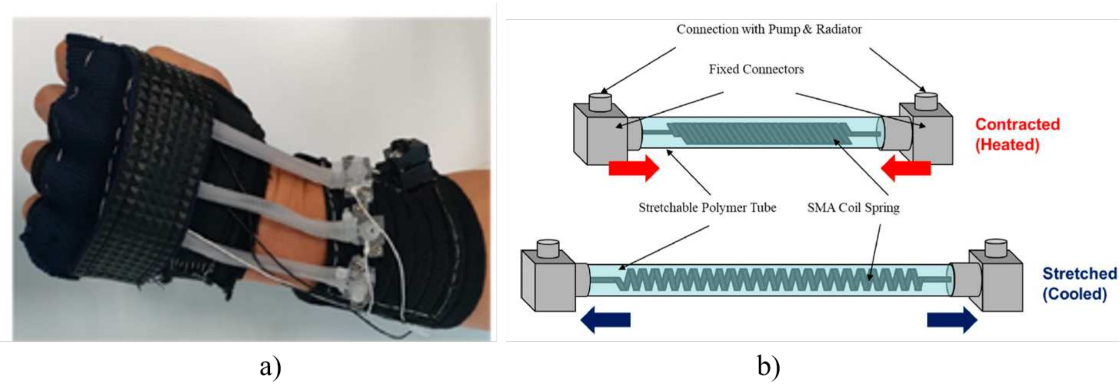


Figure 12. SMA-based wrist wearable robot developed by [24]: **a)** the real device; **b)** the SMA actuator design.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

The device can produce combined wrist movements such as radial-extension and ulnar-flexion by selectively activating the actuators. The overall RoM, torque, mechanical performances, wearability and set-up time have been assessed on five healthy subjects. The average RoM was 38°, 50°, 34°, and 35° respectively for flexion, extension, radial, and ulnar deviation. The maximum torques, measured on a 3D-printed arm mannequin, were 1.32 Nm during extension, while greater than 0.5 Nm for the other motions. Tests with external loads (1.5 kg and 3 kg) have shown that the torque assistance increased, on average, support by 62.81 %, 101.65 %, 58.11 %, and 44.23 % in flexion, extension, radial and ulnar deviation, respectively. The average wearing time was 87 s (if self-worn), and 75 s (if assisted by another person).

These performances are in line with rehabilitation targets. However,some issues have still to be solved: the anchoring system (Velcro straps) could not perfectly prevent dislocation and should be modified to ensure stronger fixation and faster locking. The robot size and shape should be optimized for all users, reducing discomfort due to actuator misalignments. Full wearability can be guaranteed by reducing weights and keeping working temperatures as low as possible to prevent burning of the user's skin.

3.2.10. Wearable SMA-Based Wrist and Forearm Exoskeleton

Hope and McDaid in [26] proposed a novel 3-DoF (flexion/extension, radial/ulnar deviation, pronation/supination) wearable and portable wrist-forearm SMA-actuated exoskeleton, for rehabilitation at home, or helping people perform ADLs.

The exoskeleton is active, soft, compact, low profile, lightweight (950 g) and low noise. It is attached to the user at three points: hand, wrist and forearm. Forces/torques are transferred from SMA actuators to the limb by tendon-pulley mechanisms which adopt wheels of different radii for force amplification, arranged around the forearm. Each DoF is controlled independently through a tendon module and a SMA actuator, for a total of six tendons and related mechanisms. This arrangement allows complex combinations of movements (e.g., DTM) based on agonist-antagonist principles by varying SMA length through Joule heating. The wire tension is released after cooling through conduction and forced convection heat transfer with fans. Tendon length is chosen to allow free movements covering the maximum RoM, and a potentiometer, fitted into the amplification wheel, measures SMA wire linear displacement. Six force sensors, arranged around the hand, provide information on flexion/extension and radial/ulnar deviation.

A variable stiffness model and active stiffness control of SMA actuators have been implemented. Stress and position of SMA wires are determined by potentiometer and force sensors. A closed loop PID controller modulates the duty cycle of the voltage applied to each actuator according to a target strain/position.

Two prototypes have been tested: one using a SMA actuator and a compensation spring, and another using SMA actuators in differential configuration. The assessment has been done by measuring tendon displacement while lifting a variable load and tracking different trajectories (step, sinusoidal and triangle waves). The expected displacement of the actuators in the spring-bias configuration covers 40 % of the expected RoM, while in the differential module covers the 65 %. In both cases the major issues are related to friction (especially at lower strain rates and duty cycle), tolerances in the mechanical components, and the uncontrolled pre-stress on the SMA wires.

Further potential improvements could include: a quantitative analysis of system friction to generate better and smoother control; a more effective cooling system rather than miniature fans, integration of sEMG sensors on the forearm cover as additional sensing method; redesign of each module to reduce the overall weight and fit different sizes.

3.2.11. ASR: A Wearable Glove for Hand Grasping

Hadi et al. in [38] have presented the ASR (Advanced Service Robots), a 5-fingered SMA-based hand exoskeleton for grasping rehabilitation and assistance, for use both in clinics and at home.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

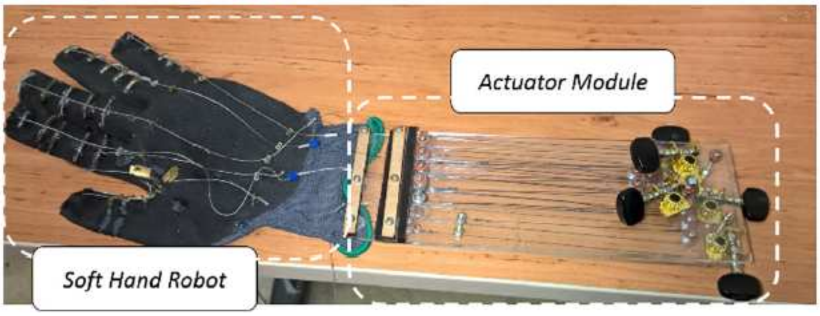


Figure 13. ASR: a SMA-based hand exoskeleton for grasping assistance [38].

ASR is active, portable, light (300 g without electronics and batteries), compact, and noiseless. Its actuation system consists of: two fishing wires for each finger (attached to the proximal and distal phalanges), a SMA actuator for each fishing wire (for a total of 10 SMA), and guides for connecting wires and transferring the force. The SMAs are fastened to a rigid platform on the forearm, and use 1 m FLEXINOL of 0.38 mm diameter, that can produce 22.5 N force. When the actuators are heated up with a current of 2.2 A, their tension force and length variation are transformed into phalanges motion and hand grasping.

A theoretical model which correlates tendon tension and grasping force have been developed and experimentally assessed by using two load cells to measure fingertip and tendon forces, a signal amplifier and Arduino Uno micro-controller to record data. Results show good agreement between theoretical and experimental values. The force exerted on the fingertip is 35% of the force produced by the SMA actuator. The total grasping force is more than 40 N, which is sufficient for typical ADLs (18 N). The overall speed of hand closure is 3 s, while it takes about 4 s to open by cooling down the actuators using air fans.

Although not directly conceived for wrist assistance, due to motion synergies between hand and wrist, problems at the wrist level reduce grasping ability, therefore this device could be considered a valuable wrist support.

Current drawbacks include: a lack of full wearability as integration of sensing and control systems is not yet implemented; no user trials; the high currents (2.2 A) needed which might be dangerous for real applications.

3.3. Compliant Devices

3.3.1. SMA Based Wrist Exoskeleton

Serrano et al. [27] have proposed a rehabilitation wearable wrist exoskeleton with 2-DoF (flexion/extension and radial/ulnar deviation) based on SMA actuators. The device, shown in Figure 14, is a hybrid because of a rigid kinematic chain around the joint actuated by flexible materials remotely placed.

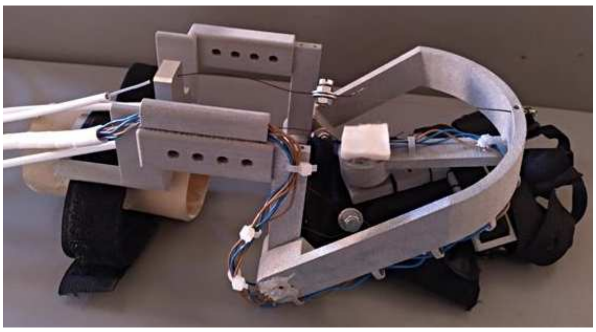


Figure 14. SMA wrist exoskeleton for rehabilitation developed by [27].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

Flexinol® is used as SMA actuator (0.51 mm of diameter), which can exert 35.6 N of force and more than 0.5 Nm of torque. One SMA wire is used for each movement, except flexion which is left under gravity.

The exoskeleton has made of simple and low cost parts through 3D-sintering polyamide with aluminum powder. The rigid interfaces are sewn on a glove to ease wearability. The device is symmetrical and can be worn both on right and left hands. The overall weight, considering the actuators, is less than 1 kg and the prize is approximatively 1060 $.

The feasibility of the system has been tested first on a simulator and then in real cases. Biomechanics of Bodies (BoB) software was used to select the proper actuation systems, evaluate human body biomechanics, mechanical designs and control algorithms. Then a pilot study was conducted on 3 healthy patients. Results showed the device allows a RoM between + 40° and -10° in flexion/extension; while between + 30° and -10° in radial/ulnar deviation. In both cases, the exoskeleton can follow a reference movement with small error. For a proper displacement of the wrist, 2.2 m long SMA wires are needed for extension, and 1.7 m for radial/ulnar deviation.

The main difficulty when controlling SMA actuators is their hysteresis which introduces non-linearity in the system. Thus, a BPID controller (a combination of a standard linear PID controller with a bi-linear compensator) has been used for a single SMA wire.

This device could be an alternative noiseless and low cost solution to current rehabilitation robots. Despite the inherent flexibility allows it to adapt easily to the body, the wearability is still an issue due to the encumbrance of long cables and the high temperature needed to activate the actuators.

3.3.2. SCRIPT: A Passive Orthosis

Ates et al. in [28] have developed a hand and wrist exoskeleton for post-stroke rehabilitation at home, which provides compliant and adaptable extension assistance during ADLs.

SCRIPT has been designed with either passive and active actuation. However, even if the active ones provide more benefits, their architecture results more complex, heavy (1.5 kg) and bulky. Thus, the authors focused on improving the passive mechanisms with dynamic interaction. The device in Figure 15 is called SPO-F, and represents the final achievement after 4 design architectures described in [28]. It is an hybrid solution involving a rigid kinematic chain with a soft actuation system (springs and cables). It provides assistance along 1-DoF: wrist and fingers extension to overcome the hyper-flexion problems and restore a more functional position. The finger mechanisms consists of 3D-printed stiff levers connected with digit caps via a Dyneema cable, and actuated via extension spring. The wrist mechanism is a 3D-printed double parallelogram which transfers torque to the hand plate thanks to an extension spring. Each spring force can be adjusted by individual ball-chains. As rigid interfaces, off-the-shelf ergonomic components from SaeboFlex [33] are used and available in different sizes (S, M, L, XL) to better fit on each subject.

Figure 15. SCRIPT passive orthosis. The SPO-F design developed by [28].

The device RoM has been assessed by using rotary position sensors (potentiometers), an Arduino Nano micro-controller and a visual marker on the hand plate for motion tracking. Results show the device can rotate up to 45° in flexion and 30° in extension.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

Assistance is proportional to hand flexion, spring stiffness (k), levers length, and their placement. The forces and torques are measured, via force sensors, for different stiffness values and different pre-tensioning forces at fixed k = 0.5 N/mm. In all cases, the minimum torque is higher than 0.5 Nm, while the maximum is 2 Nm at 60° of extension.

The first SPO orthosis was tested by 33 stroke patients in 3 different EU-countries. This has helped address the final design of SPO-F, which looks lighter (650 g), safer, more professional, comfortable, compliant, simple, easy to wear and able to satisfy rehabilitation requirements according to a stroke patient. Despite the great achievements obtained over the years, the design should be further improved in compactness due to its vertical profile. Furthermore, the extension force applied on the digits should be assessed with more patients because the compression applied might cause some fingers pain.

3.3.3. Hand and Wrist actuated Exoskeleton for Rehabilitation and Training

Dragusanu et al. [14,29] have developed a 2-DoF (flexion/extension and radial/ulnar deviation) active and hybrid exoskeleton to allow people with disabilities regain autonomy.

The device, shown in Figure 16, consists of a tendon-actuated mechanism with thermoplastic interfaces, which allows remote actuation and user's adaptation. All actuation and electronic components are placed on the forearm, and data are transmitted via Bluetooth. It is composed of two independent rigid parts tailored on the user: one on the hand and the other one on the forearm. Three tendons, wrapped around three pulleys, connect the motors on the forearm to the hand plate. Dynamixe XL-320 DC rotary motors are selected, with a stall torque up to 0.39 Nm at 7.4V, that is suitable for rehabilitation applications. The whole system weighs almost 300 g, and costs about 150 $.

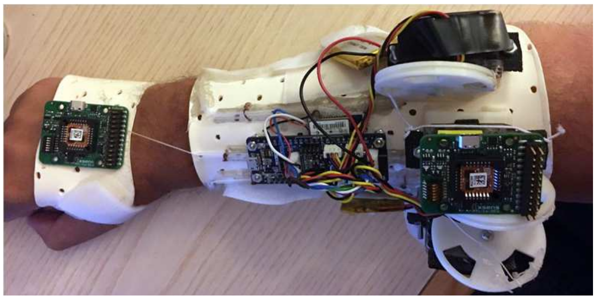


Figure 16. Exoskeleton for wrist rehabilitation developed by [29].

The control consists in tracking wrist movements by measuring the orientation of the hand with respect to the forearm using IMUs (on the hand and forearm). A Matlab GUI interface has been developed to guide the users during rehabilitation making the whole process easier to set and less boring.

This wrist exoskeleton has become a module of a full hand/wrist exoskeleton developed by the same authors [14]. This device, shown in Figure 17, can also actuate fingers flexion/extension, works for about 3 h, and has an overall weight of 500 g.

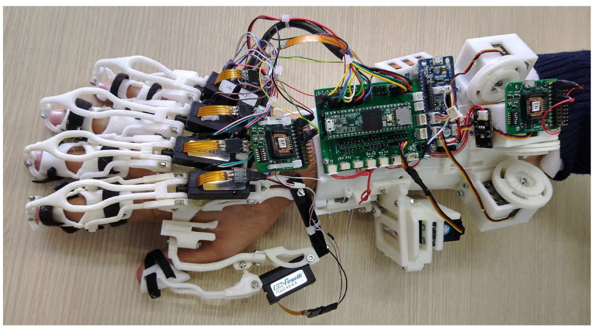


Figure 17. A rigid wearable hand/wrist exoskeleton developed by [14].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

The updated version of the wrist comes from users' feedback on wearability and anatomical adaptability. Subsequently, all rigid interfaces and the actuation module have been re-designed with a parametric approach: pulleys connected to the motor shafts are reduced in dimensions; an external support is added to wrap the excess wire; an automatic closure for the forearm module is designed to ease and halve the wearing time. The structure and control are developed to guarantee the use of hand and wrist modulus independently.

The device's performances has been assessed involving a patient in the execution of three exercises: flexion/extension, radial/ulnar deviation, and recording and reproducing a movement performed by a physiotherapist. Predefined set of movements are generated. Among 60 trials, the average root-mean-square (RMS) errors in following flexion/extension and radial/ulnar deviation movements are not normally distributed, and have statistically significant differences for different motor speeds (ω).

This device has interesting features and great potential for use in rehabilitation. It can assist all wrist movements, it is portable, wearable, cheap, lightweight, easy to control and manage autonomously, and has a TRL of 4. However, some improvements could be made to reduce the overall encumbrance, weight and improve the torque provided.

3.3.4. Low-Profile Two-DoF Wrist Exoskeleton

Higuma et al. in [30] have developed a 2-DoF rigid wrist exoskeleton for rehabilitation, which allows flexion/extension and radial/ulnar deviation movements. The mechanism consists of a hand back support, a forearm base where two linear actuators are placed, and two steel spring blades which connect the motors to the hand. The device is inherently flexible thanks to elastic elements which can deform during motion and adapt to the wrist centre of rotation while transmitting forces. Each linear actuator moves a spring blade independently, back and forth, allowing bi-directional force transmission.The device is made of 3D-printed resin, it is 310 mm in length and weighs 509.5 g.

Performances measured on a test bench showed a RoM in good agreement with Finite Element Analysis (FEA) results, which covers most of that of healthy subjects: 56.7° in flexion, 68.1° in extension, 39.5° in radial deviation and 13.8° in ulnar deviation. The constrains are mainly due to the limited stroke of the actuators.

The torque vary from 0.26 Nm (max flexion) to 2.47 Nm (max extension), with an average of almost 0.65 Nm for radial and ulnar deviation. The maximum load applied perpendicular to the wrist is 10.24 N for flexion/extension, with a shear force of 7.98 N; while for radial and ulnar deviation is 4.26 N, with a shear force of 4.14 N. Despite small interaction forces, a human evaluation is required to verify whether it harms the user.

Overall, it is a simple mechanism with a fairly soft structure which allows the wrist moving less overloaded. However, since linear actuators are not manually backdrivable, when turned off the fixed position of the blades may apply some shear force on user's skin. Moreover, the absence of a defined centre of rotation could make the springs deform in unwanted manners, increasing discomfort.

4. Commercial Devices

Searching online it is possible to notice how difficult is to find in the market devices conceived for workers' wrist assistance. Most of them are designed for rehabilitation and training, or are still prototypes unable to jump out from research labs and hit the market.

In 2020 Forbes published an article titled *"The Number Of Companies Making Industrial Exoskeletons Has Been Quietly Increasing For The Past Five Years"* [51]. One of the main contributors was Borislav Marinov, a founder of *ExR-ExoskeletonReport* website [52]. Borislav pointed out that still a comprehensive definition of what constitutes an "industrial exoskeleton" has to be defined [51]. The *Wearable Robotics Association* (WearRA) has estimated that the total number of businesses engaged with producing or distributing industrial exoskeletons has increased by 350% between 2015 and 2020,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

tallying an increase from 16 to 56 companies (as shown in Figure 18), and more than 700% up to now with almost 120 companies around the World [51,52].

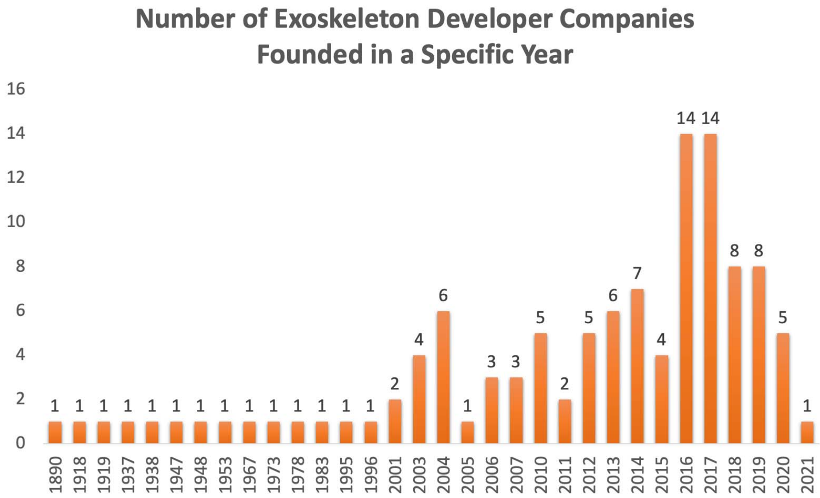


Figure 18. Statistics from resources available on *ExR-ExoskeletonReport* website [52].

A reason behind this increase may depend on a recent shift in the perception of the exoskeleton not as something which makes people either "superhuman" or "better", but rather as a specific tool, that could be worn and help workers complete physically repetitive tasks safer and more efficiently.

To get an idea of which are the exoskeletons that have been introduced onto the market over the last decade, the website *ExR-ExoskeletonReport* has taken on relevance. It could be considered the widest repository/catalog of exoskeleton devices for all application domains [52]. Looking into the *body area* section, it is possible to notice that there is a lack of devices conceived for wrist assistance. These deficiencies make the research and development phases more difficult since there is very little information. Hereafter, we propose a list of devices, already available on the market, which involve the wrist in their assisted segments. All devices taken into account, which will be described in the following sub-sections, are shown in Figure 19 and grouped according to structural rigidity criteria.

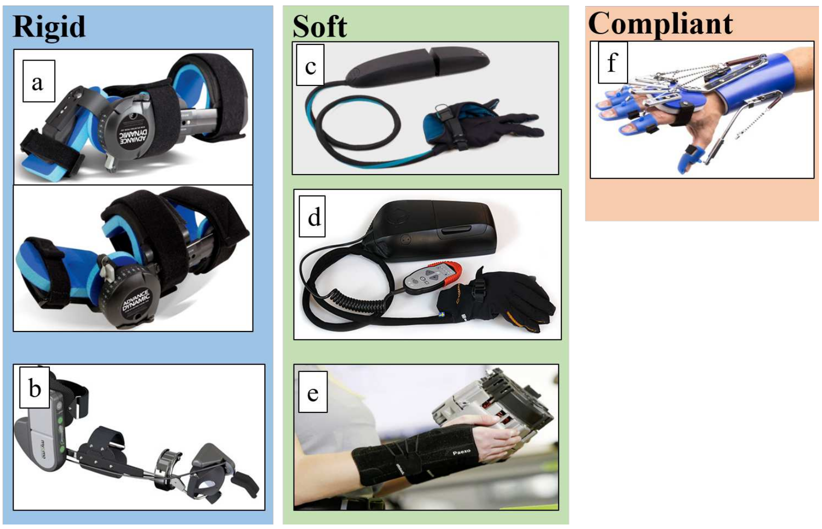


Figure 19. All commercial wearable exoskeleton for wrist assistance. Devices are grouped by rigidity in: rigid (**a**,**b**), soft (**c**-**e**) and compliant (**f**). From top left to bottom right it is possible to find: **a)** JAS wrists from Joint Active Systems [31]; **b)** Myopro designed by Myomo [32];**c)** CarbonHand designed by Bioservo [35]; **d)** IronHand designed by Bioservo [35]; **e)** Paexo wrist designed by Ottobock [36]; **f)** soft orthosis designed by Saebo [33].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

Based on the wrist exoskeleton requirements proposed in [15], the schematic shown in Figure 20 provides relevant information about commercial wrist exoskeletons.

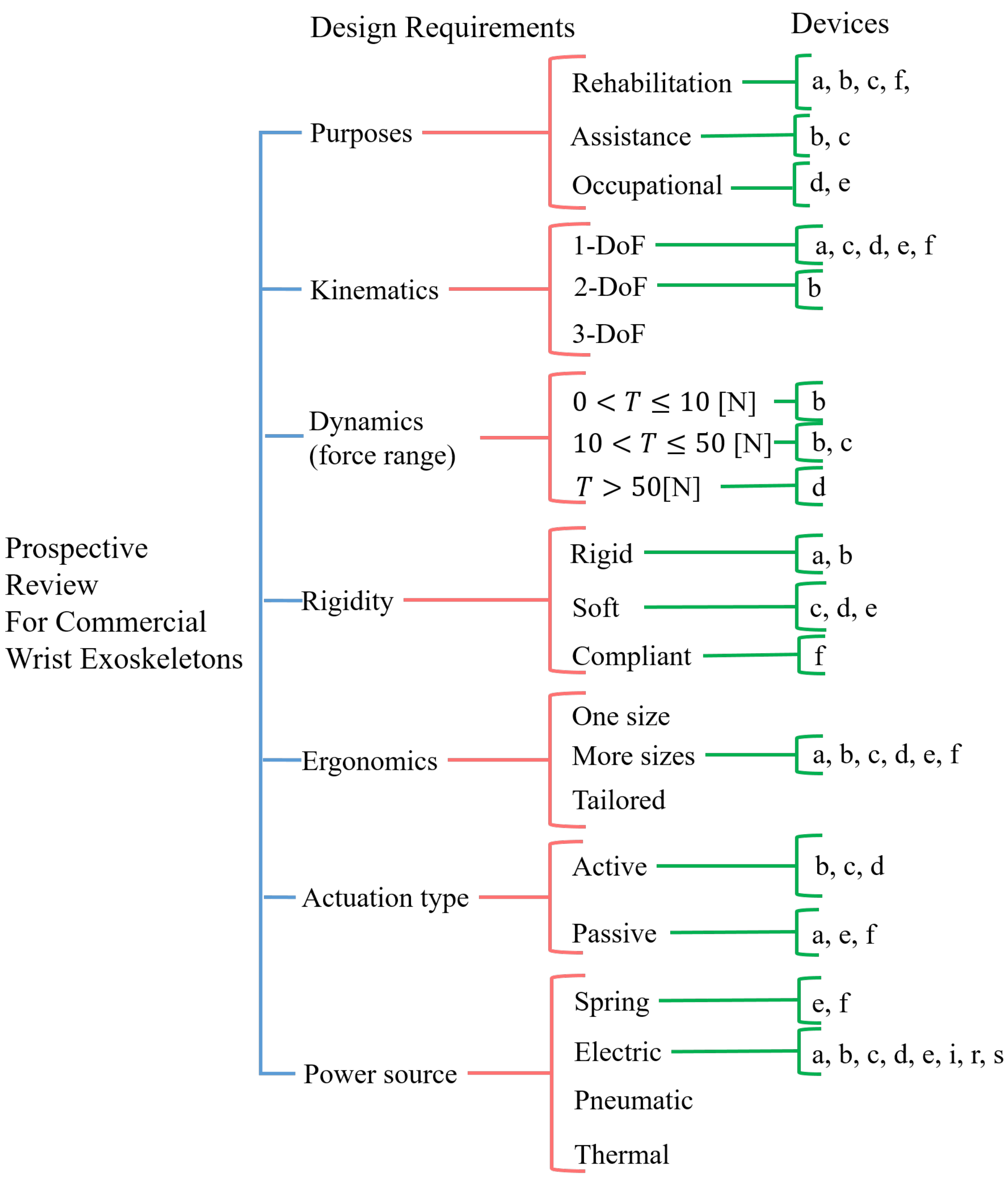


Figure 20. Schematic of commercial wrist exoskeletons grouped by design requirements. The devices, named from a) to f), are the same reported in Figure 19.

4.1. Rigid devices

4.1.1. JAS Wrists

These products are developed by *Joint Active Systems Inc.* (JAS), a leading company in the US for range-of-motion therapy for patients with motion losses. They provide a wide range of options, for assisting different limbs and joints, to meet the needs of each patient. Among all their products oriented to the wrist joint, we would like to focus more on the devices called *Advanced Dynamic Wrist Flexion* and *Extension* [31], shown in Figure 21 since they seem more practical and comfortable for use

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

outside clinics, at home to enhance therapy, while sleeping and resting to achieve permanent RoM gains. These devices are passive rehabilitation orthoses.

Figure 21. Dynamic Wrist orthosis for wrist flexion and extension recovery by JAS Inc. [31].

It is difficult to find open-source data/analyses on the effectiveness of these devices or to test them because they can only be purchased by proven patients. However, some articles described their safety, usefulness in the effective RoM increase and restoration for all levels of joint stiffness (e.g., wrist arthrofibrosis), and patient satisfaction [53].

4.1.2. MyoPro Orthosis

MyoPro Orthosis was born in 2006 thanks to the work done at MIT and Harvard Medical School, and then commercialized by the company Myomo Inc, Figure 22.

The product is a wearable active powered arm orthosis (including elbow-wrist-hand) designed to restore the function of paralysed or weakened arm for patients suffering from neuromuscular and neurological diseases or injuries (e.g., stroke arm paralysis, brachial plexus injury, cerebral palsy, multiple sclerosis). The MyoPro weighs approximately 1.8 kg, provides almost 0° to 130° of motion and 7 Nm of torque at the elbow, and 1 - 2.7 Nm torque for the fingers, ensuring the lifting of approximately 2.3 - 3.6 kg [54]. The device works by reading the faint nerve signals from the skin through sEMG, then amplifies them and activates motors to move the limb as the user intends, as shown in Figure 22. The wrist joint is conceived for improving dexterity and recovery muscle tones and functionalities. Several experiments have been done to evaluate its effects on in-clinic and at-home rehabilitation. Participants involved were able to perform bi-manual tasks for prolonged periods, increase their independence in ADLs, improve forces while grasping, lateral pinch strength, wrist RoM, and avoid emerging wrist ulnar and radial deviations [54,55].

 doi:10.20944/preprints202311.0864.v1

Figure 22. MyoPro device by Myomo Inc. [32].

4.2. *Soft devices*

4.2.1. Carbonhand®

Carbon-Hand is an assistive soft robotic glove for use outside of clinical settings, built on the Soft Extra Muscle (SEM™) technology [35,56]. It is sold by Bioservo for almost $7000.

Figure 23. Bioservo Carbonhand ® device and examples of related applications [35].

It is designed on a glove with pressure sensors in the fingertips to measure contact forces when interacting with objects or tools. Thus, power will be applied when the user initiates gripping to ensure a firm grip. So, it activates 1 DoF: the gripping (or finger flexion). It augments human capabilities by applying a force of up to 20 N per finger (involving only 3 fingers). The overall device weighs 685 g (glove + control unit), but since the control unit and the battery could be placed wherever preferred to the user's body, weight should not be an issue. Batteries are designed to last approximately 8 hours and the device is available in different sizes (XS, S, M, L, XL) for both right and left hands. The device

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

is conceived for rehabilitation and assistance-at-home by helping people with reduced hand functions perform ADLs independently [35,56].

This device goes under our attention because, due to motion synergies, hand dexterity is related to wrist motion and resistance capabilities: problems at the wrist level reduce grasping ability. Therefore, this device could be considered a valuable wrist support.

It has recently been assessed for six weeks in 63 participants with impaired hand functions [57]. Preliminary results have shown promising improvements in grip strength (+27%), pinch strength (+15%) and hand functionality (+12%). Since 2022, it has also been approved as a medical device according to the European Medical Device Regulation (EU-MDR).

4.2.2. Ironhand®

IronHand® is a soft active exoskeleton for grasping assistance and augmentation also built on the Soft Extra Muscle (SEM™). Initially, the development of the SEM™ technology was intended to rehabilitate patients with impaired hand function (e.g., CarbonHand®). Today, Bioservo Technologies is also focusing on prevention of injuries at work. The product has undergone long-term testing with various industrial partners, which have become key factors for its quick development since its first release in 2019 for almost $6,500 [35,58]. *IronHand 2.0*, shown in Figure 24, consists of a sensorised glove, a back-pack (with control and battery) and a hip-carry, everything designed in different sizes (S, M, L, XL) to better fit user's body. The whole system weighs almost 2,75 kg, of which 50 g the glove. The lithium battery in the back-pack is the sore point for the weight with a full-charge duration of almost 6-8 hours. The glove has force sensors (FSR) on the finger tips and the palm, and it is innervated by artificial tendons (e.g., bowden cables) which enhance fingers flexion and gripping thanks to the push-pull action of linear DC motors. Enabled when force sensors detect certain pressure levels, the tendon-driven system can generate a maximum force of 16 N per finger (80 N in total) [35,58], adjustable to adapt to different needs and applications, as shown in Figure 25.

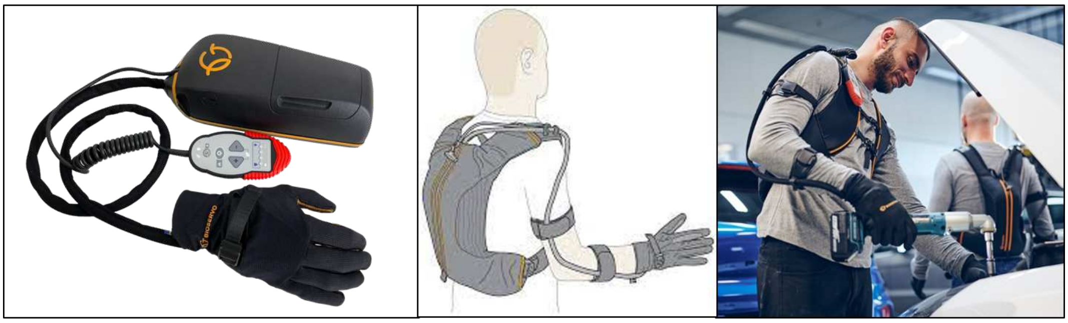


Figure 24. Bioservo IronHand® system and application [35,58].

The device can collect and share data through Bluetooth, 4G and Wi-Fi among different devices (e.g., tablet, control equipment), and save them in a local storage or in cloud (BioCloud™), Figure 25. The collected data also allow to assess the wearer's risk of developing injuries.

Even if it is a hand exoskeleton for grasping augmentation, again due to motion synergies, it is safe to assume that grip force and wrist fatigue are in a sense correlated. The strong the grasping the more compression will be transmitted to hand ligaments and wrist. Several clinical trials on the SEM technology over months [58–60], reported a significant improvement in gross hand grip strength, pinch strength and all hand functions in ADLs (e.g., grip, grasp, precise movements, writing, etc).

In spite of these promising results, in our opinion, this does not mean that reducing grasping fatigue it will guarantee the same reduction in wrist workload. Rather, it will reduce the probability to get injured, inflammations (such as CTS) and pain in the wrist joint.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

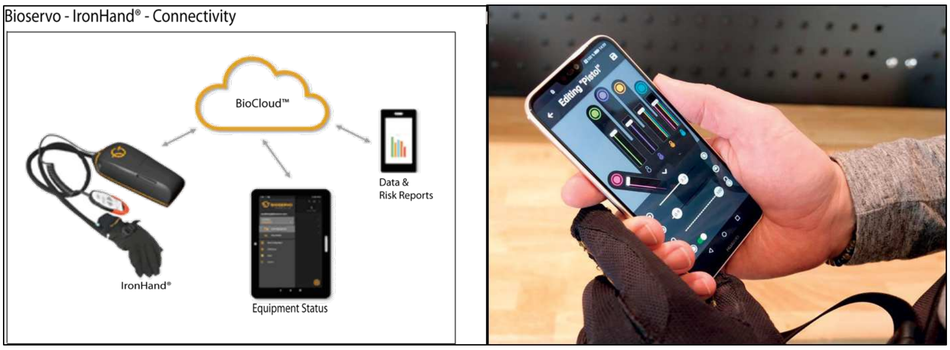


Figure 25. Bioservo IronHand® system control and connectivity [35,58].

4.2.3. Paexo Wrist®

Paexo Wrist is a commercial passive wrist exoskeleton developed and sold by Ottobock for almost 160$. In practice, it is an orthosis which aims at supporting the wrist while moving loads, and preventing injuries and inflammations. It can be used when holding a screwdriver, riveting tool or welding equipment, and carrying loads. By looking on the website *Paexo.com* and the user manual, the device adopts innovative solutions: materials for thermal regulation tested in space (provided by Outlast Material), a Pull-2-Lock mechanism for quick one-handed donning in few seconds, a metal splint inside the garment which fulfills the function of a flexible beam to absorb and transfer loads away from the wrist. For a better versatility, the device can fit both left and right hands and is available in different sizes (S, M, L) to satisfy different users. No sensors and control strategies have been implemented. The device and its application are shown in Figure 26.

Figure 26. The figure shows step-by-step the procedure of how to wear Paexo Wrist (pictures from **a** to **e**) and an example of use case (pictures from **f** to **m**). Images taken from Ottobock official website [36].

The company mentions that Paexo Wrist has been thought for relieving muscles and tendons when working for long periods with tools and in assembly, by stabilizing the wrist and ensuring an optimal distribution of the workload. Unfortunately we have found no more technical aspects or analyses about its positive effects on workers' health. So that, we cannot quantify its usefulness compared to other devices.

4.3. Compliant Devices

4.3.1. SaeboFlex

SaeboFlex, shown in Figure 27, is a custom-fabricated wrist, hand, finger orthosis [61], developed and sold by Saebo Inc. for almost $600 [33]. It is designed to improve mobility in individuals with hand/wrist weakness or spasticity due to neurological or orthopedic conditions.

 doi:10.20944/preprints202311.0864.v1

Figure 27. SaeboFlex device [33].

It is a passive device made of resistive springs and conceived for therapy both in clinics and at home. No sensors and control strategies have been implemented. The major goal is to position the impaired wrist and fingers into extension for proper functional grip and release training [61]. Optimum wrist angle is measured at 35° of extension, which is considered the position where maximum grip effort onset. This value can be modified according to the patient impairment. Pilot studies, conducted over months on patients who suffered from stroke [62,63], have proven that the device is safe, improves hand grip strength and dexterity moving objects, and increases wrist extension RoM by 5-6 degrees.

5. Design Proposal for a Portable Wrist Exoskeleton

Based on the literature and our experience, in this section, we propose a conceptual idea (TRL 1-2) of a technological device to assist all wrist movements, provide sufficient force support, and guarantee good user acceptance in industrial settings.

Softness, lightness, and customization are a must. Although obvious, these are factors that often emerge from user evaluation questionnaires [13,14,19,55]. Therefore, we will design a wrist exoskeleton on a glove to meet comfort requirements. We will customize the device to the user by taking anatomical measurements and utilizing 3D scanning technologies for the hand/wrist shape [11].

The device should allow the main movements of the wrist (flexion/extension and radial/ulnar deviation) and a combination of them in a controlled way. This would help during activities such as screwing, holding, hammering, and lifting. However, the RoM must be limited to avoid overstretching the human joint causing pain. This is in line with the safety requirements of a wearable device [15].

Gripping is also important, as the more the grasping, the more compression between the wrist ligaments, and the higher the probability of getting carpal tunnel inflammation.

To allow these movements, the idea is to use cable transmissions. Soft plastic supports/saddles (thick purple shapes in Figures 28 and 29) would be sewn on a glove to hold steel or fiber cables (tiny light blue lines in Figures 28 and 29) on the back, palm, lateral sides of the hand and fingers, as shown in Figures 28 and 29, where forces would be applied. The shape of cable supports would be designed starting from the 3D hand/wrist profile. The cables from the actuators should be routed around the hand, passing through Teflon sleeves (black in Figures 28 and 29) along the forearm to reduce friction. Care should be taken to avoid sharp edges or bending angles (e.g., 90° or more), as these cause friction losses along the cable's path. One cable would be used to actuate a single wrist movement, except for grasping, where all cables around the fingers would be actuated simultaneously.

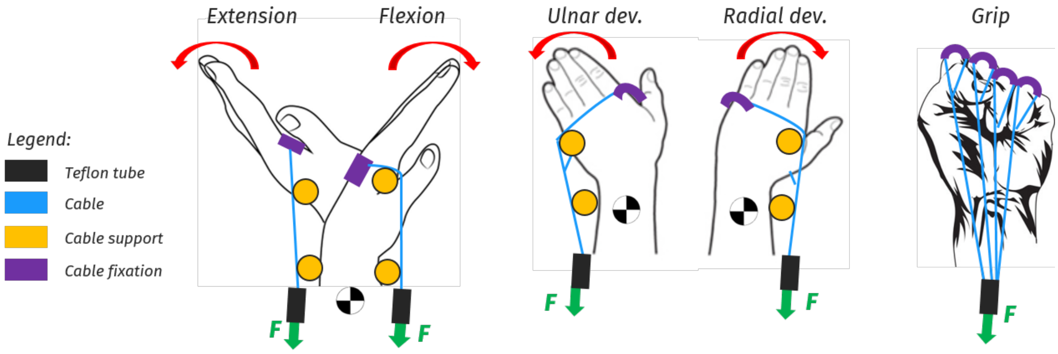


Figure 28. Hand and wrist movements to be assisted.

A rotary actuator, with a proper reduction transmission, would allow agonist and antagonist movements by pulling two cables (flexion/extension and radial/ulnar deviation), and would guarantee backdrivability. While for grasping a linear motor would be used to pull and close all fingers simultaneously. Forces (green arrow in Figure 28) would be applied through cables attached to actuators placed remotely, e.g., on a back-pack. This would help redistribute localized weights on the hand/wrist.

In terms of dynamic requirements [15], ideally, the device should guarantee to hold objects of 5 kg with almost no muscular effort. This could be beneficial both in rehabilitation and industrial sectors while handling loads. Actuators and transmissions have to be sized according to the weight to be handled. Consider a weight of 5 kg held on the palm, 10 cm from the wrist joint. It produces a force of almost 50 N and a torque of 5 Nm, which has to be compensated by the exoskeleton. Considering that standard normal-sized men's wrists have a 16-18 cm circumference, the wrist radius is between 2.5 - 2.8 cm. Therefore, the cable force to produce 5 Nm torque around the wrist should be almost 180 N. This can be improved with special supports by raising the cable and increasing the radius with respect to the wrist. These supports (orange in Figures 28 and 29) would also avoid cables unwinding, prevent the force vector from passing through the wrist CoR without producing effective torque, as shown in Figure 30, and reduce compression forces on the wrist.

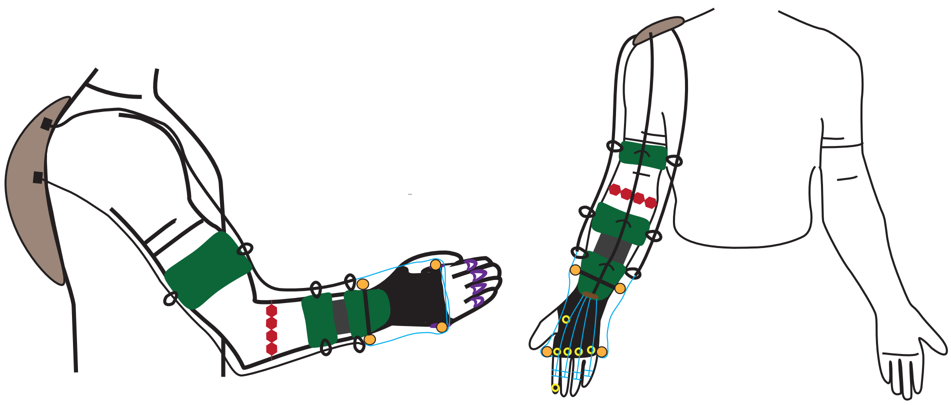


Figure 29. Conceptual idea of a portable wrist exoskeleton. Grey: backpack containing actuators and electronics; Green: webbings; Red: sEMG sensors; Black lines: Teflon tubes; Light blue lines: steel or fiber cables; Orange: rigid cable supports; Yellow: FSR sensors; Black: glove; Purple: soft plastic cable holders.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

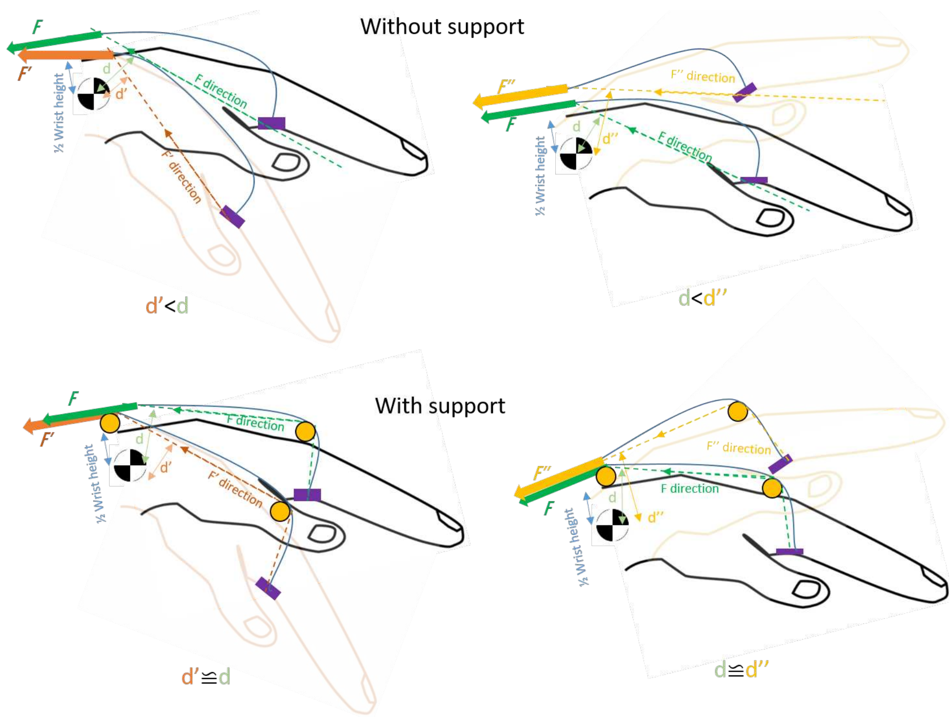


Figure 30. How the direction of the force changes when cable supports are present or not. On the left, the wrist goes from neutral to flexion, while on the right it goes from neutral to extension. Without cable supports, the cable may become loose during pulling, causing the force to be closer to the wrist's center of rotation, thus reducing the momentum and augmenting wrist compression (the distances d, d', and d'' represent the pulling force arm in the neutral, flexion, and extension positions, respectively). With cable supports (orange circles), the unwinding of the cable is limited, and there is always a minimum distance, similar to that in the neutral position, which ensures a minimum effective momentum even when the wrist is flexed (the worst position).

We would implement sEMG sensors (red in Figure 29) to detect electrical muscles spikes and muscle fatigue when the user moves its wrist. And FSR sensors (yellow in Figure 29) in the palm to detect when an object is grasped and measure the gripping pressure.

A control system would rely on machine learning strategies to anticipate hand/wrist movements according to the muscle activation, and on a PID controller to generate the required pulling forces on the cables. A low-level control loop would segment the EMG pattern to recognize which muscles are working and predict hand/wrist movement. The motors would then be activated according to the movement to assist, while the amplitude of the EMG signals and the grip force measurements would determine the amount of support to be given.

The objective is to design a device that supports user handling at least 5 kg without effort, as soft and light as possible (less than 1 kg), comfortable, portable, with a 6-8 hours battery, and an affordable and user-friendly command interface (UCI). We are inspired by existing commercial and research products with the most promising characteristics and well received by patients and workers. We aim to enrich research by creating a new wrist exoskeleton for occupational purposes, helping to support all wrist movements during activities that can be detrimental to its health.

6. Discussion and Conclusions

During the past few decades researchers have been working towards the development of exoskeletons with improved capabilities and "intelligence" levels to solve problems due to aging, disabilities, overload, strenuous works, which can prevent people from living a normal life, leading to marginalisation both on work and private life.

These devices are expected to play an important role in human health in the areas of rehabilitation, assistive technologies, and human power augmentation by transferring loads away from the human body while assisting in certain tasks. Some positive results and approvals have already been achieved in rehabilitation, while others need to be further investigated,such as for the occupational sector. The recent increase in disabilities caused by musculoskeletal disorders (with more than 1.7 billion cases worldwide) has frightened the European Commission and the WHO which have been leading awareness campaigns on this issue. Only in the last decade wearable commercial solutions have entered the market to assist workers in burdensome and repetitive tasks. However, has reported by *Tiboni et al.* in [43], relatively a few focus on the wrist despite being considered the fourth most common site of musculoskeletal pain in the upper limbs.

This paper review provides a comprehensive summary of several types of **wearable and portable wrist exoskeletons** available in both the market and research, as shown in Table A1 (see Appendix A). We have described and compared devices conceived for different applications (rehabilitation, assistance and occupational), by focusing on their technologies (hardware and control), their functions, their potential and limitations.

Macroscopic classifications of the wrist exoskeleton can be based on several aspects, as described in [15], including: purpose (rehabilitation, assistance or occupational), rigidity (rigid, soft, compliant), type of actuation, power source, power transmission, sensing, control strategies and technology readiness level (TRL), as shown in Figures 31 and 32.

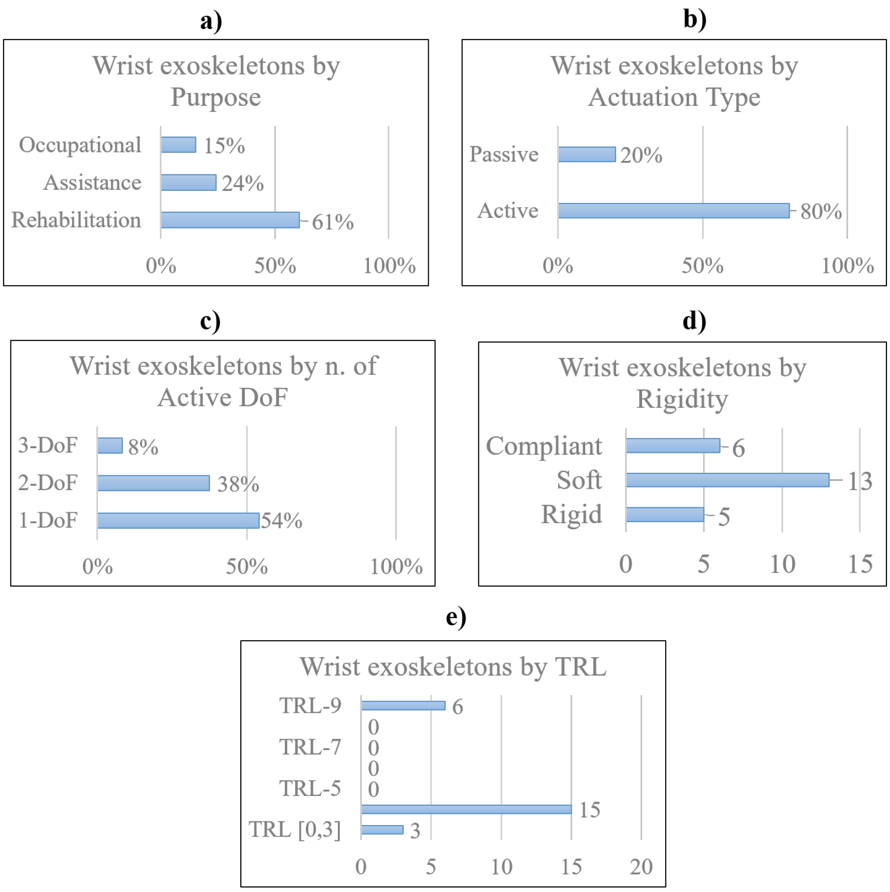


Figure 31. Different classifications by purpose (a), actuation type (b), number of active DoF (c), rigidity (d) and TRL (e), of wearable wrist exoskeleton took into consideration. The total amount of devices considered is 24. In some graphs, the percentage is preferred because some devices have been designed for more than one application or can be used both as passive or active. Only 6 devices out of 24 have passed conformity tests and entered the market.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

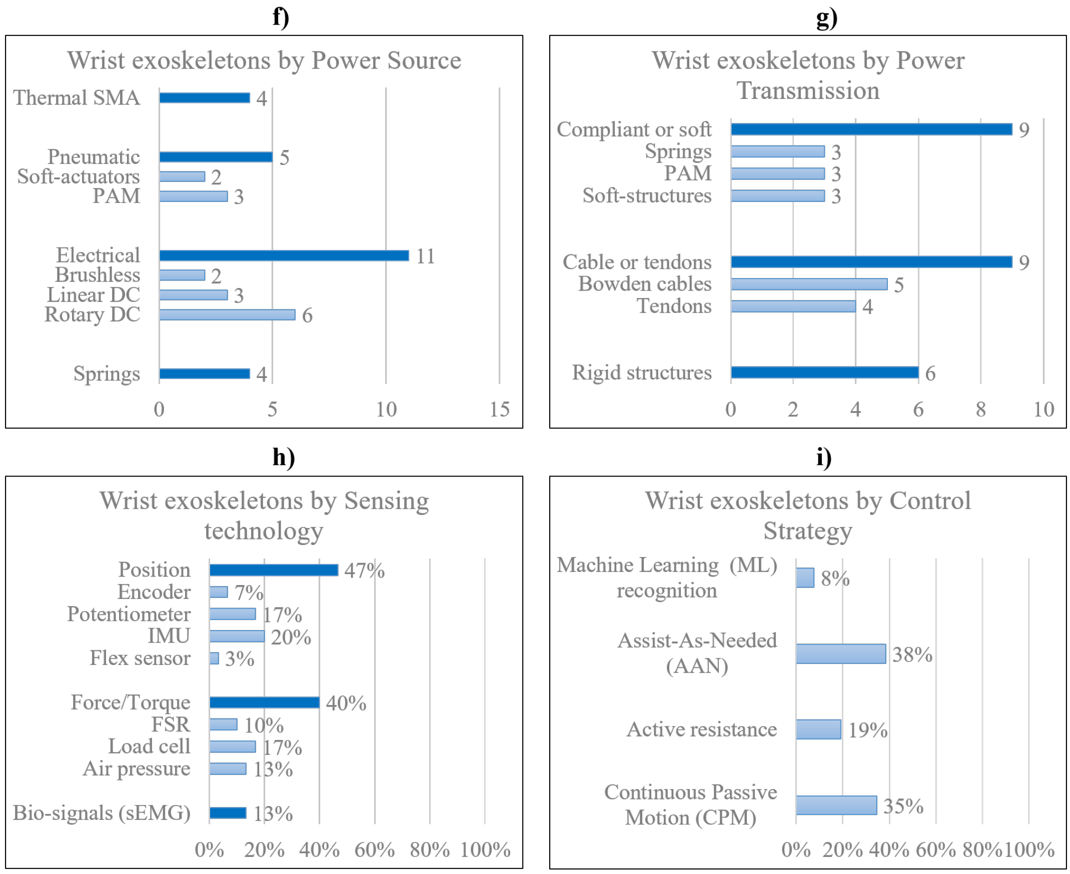


Figure 32. Different classifications by power source (f), power transmission (g), sensing technologies (h) and control strategies (i), of wearable wrist exoskeleton took into consideration. The total amount of devices considered is 24. In some graphs, the percentage is preferred because some devices adopts more than one sensing technology and control strategy.

A total of 24 **wearable and portable wrist exoskeletons** have been designed: almost 18 devices for rehabilitation and assistance, while 6 for occupational tasks, as shown in Figures 31 and 33.

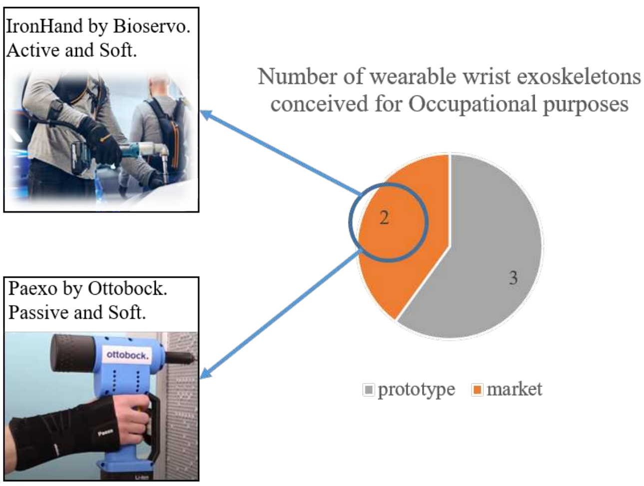


Figure 33. Classification by TRL of wearable wrist exoskeleton conceived for occupational purposes. Only two devices are available in the market: IronHand designed by Bioservo (active device), and Paexo wrist designed by Ottobock (passive device).

Looking at those data and Table A1, a strong prevalence of active devices emerged as they can provide greater forces/torques ensuring a wider range of applications. The most widespread actuation systems are electrical motors due to their robust controllability, great power-to-weight ratio, reliability, and price. For the power transmission, cables and tendons are preferred because of high force transmission, and remote actuation with a better redistribution of weight along the human body. However, they suffer from friction losses with non-linear behaviour, which make their control difficult. To ensure a better control of the device, lot of sensors are implemented. Position (encoder, potentiometer, IMU, flexible sensors) and force sensors (FSR, load cell, pressure gauge) are the most used. However, new control methods based on bio-feedback signals (e.g., sEMG) have also been tested. These sensors still have limitations in unstructured environments, as they must be attached directly to human skin and suffer from external noises. The main control strategies adopted are *Control Passive Motion* (CPM) and *Assistance-As-Needed* (AAN). The former consist in control the movement of the exoskeleton according to predefined trajectories; the latter evaluate the actual external load or muscle effort to modulate the assistance provided by the robotic device. AAN is strongly recommended in unstructured environments where the user could perform different activities. Moreover, new control techniques are being developed based on Machine Learning (ML) algorithms to predict user motion intention, and reduce the number of sensors adopted.

It is not easy to design wrist exoskeletons because of the complex anatomy of the joint: it can move in a 3D space while supporting high forces in a very compact size. This creates difficulties in reproducing and assisting such kinematics and dynamics, without hindering the human movements. Moreover, the requirements and specifications needed in certain applications lead to different design approaches.

The majority of the devices reviewed are still under development with promising practical outcomes, tested and used only in a laboratory setting. By looking at these, as presented in Section 5, the authors are working on the development of a novel portable wrist exoskeleton for occupational purposes. To facilitate user acceptance and accelerate the industrialisation phase, a soft device made on a glove would be the starting point. Tendon mechanisms, remotely actuated via DC motors, would first be tested as more reliable, robust, light, safe and cheap solutions. As sensing, position and force sensors would be distributed throughout the glove to detect wrist movements and forces/torques applied. As control strategies, advanced machine learning algorithms for the AAN would be adopted. They would detect motion intentions and provide assistance according to the position and overload of the wrist.

Like all products, including exoskeletons, technological and economic barriers, as well as communication biases, are open issues opposed to acceptance and industrialisation. The main obstacles could be identified in: the high costs and long-term research and development times, which are often incompatible with the views of stakeholders and consumers; lack of interest from stakeholders that makes it more difficult to justify the development; lack of market competitors makes it difficult to identify their pros and cons, and find more advanced solutions; need for CE or FDA or similar certifications. In view of emerging health and industrial needs, the authors expect an increase in demand for progress and development in the field of portable robotic wrist exoskeletons over the next decades.

Author Contributions: Conceptualization, R.F.P., D.P., G.B., J.O.; methodology, R.F.P., D.P., G.B., J.O.; formal analysis, R.F.P., D.P.; investigation, R.F.P.; resources, R.F.P.; writing—original draft preparation, R.F.P.; writing—review and editing, R.F.P., D.P., D.C., G.B., J.O.; visualization, D.P., D.C., G.B., J.O.; supervision, D.P., D.C., G.B., J.O.; project administration, D.C., J.O.; funding acquisition, D.C., J.O. All authors have read and agreed to the published version of the manuscript.

Funding: This work is funded by the Italian Workers' Compensation Authority (INAIL)

Institutional Review Board Statement: Ethical review and approval were waived for this study, due to the pure use of literature to obtain the results.

Informed Consent Statement: Not applicable since this study did not involve humans.

 doi:10.20944/preprints202311.0864.v1

Data Availability Statement: Data sharing is not applicable to this review paper. No new data were created in this study.

Acknowledgments: Our thanks go to INAIL (Italian Worker's Compensation Authority) for its ongoing support, collaboration and funding in the development of novel types of industrial exoskeletons, under the project Collaborative Exoskeletons-EC-2 in collaboration with Istituto Italiano di Tecnologia (IIT) and the University of Genoa.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

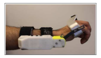
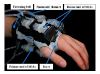
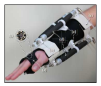
The following abbreviations are used in this manuscript:

MSD	Musculoskeletal Disorder
WRMSD	Work-Related Musculoskeletal Disorder
WHO	World Health Organization
INAIL	Italian's Workers Compensatory Authority
DARPA	Defense Advanced Research Projects Agency
OE	Occupational Exoskeletons
CTS	Carpal Tunnel Syndrome
DoF	Degree of Freedom
RoM	Range of Motion
CoR	Centre of Rotation
ADL	Activities of Daily Living
DTM	Dart Throwing Motion
TRL	Technology Readiness Level
ICR	Instantaneous Centre of Rotation
OA	Hand Osteoarthritis
OCRA	Occupational Repetitive Actions
HAL	Hand Activity Level
TR	Technical Report
IMU	Inertial Magnetic Unit
FSR	Force Resistive Sensor
sEMG	Surface Electromyography signals
CPM	Continuous Passive Motion
AAN	Assistance-As-Needed
ML	Machine Learning
WearRA	Wearable Robotics Association
SEM	Soft Extra Muscle
SCI	Spinal Cord Injury
EU-MDR	European Medical Device Regulation
JAS	Joint Active Systems Inc.
PWE	Portable Wrist Exoskeleton
NN	Neural Network
SVM	Support Vector Machine
FMG	Force-myography signal
CIMT	Constraint-Induced Movement Therapy
MVC	Maximum Voluntary Contraction
SOA	Soft Origami Actuator
PMA	Pneumatic Muscle Actuator
SMA	Shape Memory Alloy
SWA	Soft Wrist Assist
RMSE	Root Means Squared Error

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

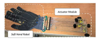
Appendix A

Table A1. Comparison of all wearable and portable wrist exoskeletons highlighting their characteristics.

Image	Reference	Device Name	Application Field	Actuation Type	Power Source	Power transmission	Force/Torque output [N][Nm]	Active DoF	Assisted motion	RoM	Sensing	Control	TRL	Weight	Price($)
	[16]	PWE	Rehab/Assistance Occupational	Active	DC motor	Links, gears	2.3 Nm 2.5 Nm	2	Flex/Extension Rad/Ulnar dev.	± 60° ± 25°	Potentiometer sEMG	CPM M.L.	**4	0.36 kg	-
	[13,17]	eWrist	Rehab/Assistance	Active	DC motor	Links, gears	up to 3.7 Nm	1	Flex/Extension	range 154°	sEMG, load cell, encoder	AAN	**4	0.56 kg	-
	[18]	*-	Rehabilitation	Passive Active	DC motor	Links, gears	up to 1.12 Nm	1	Flex/Extension	range 120°	Triggered Force (FSR)	CPM M.L.	**4	0.33 kg	*-
	[11]	Wrist exosuit	Occupational	Active	Brushless motor	Bowden cables	3 Nm	1	Flex/Extension	70°/80°	Load cell,IMU	AAN	**4	0.3 kg (hand)	-
	[19]	Exo-Wrist	Rehabilitation	Active	DC motor	Bowden cables	≥ 0.5 Nm	1	Extension	≥ 50°	sEMG	AAN	**4	1 kg	-
	[20]	*-	Rehabilitation	Active	Pneumatic	Artificial muscles	120 N	3	Flex/Extension Rad/Ulnar dev. Pron/supination	91° 32° 78°	Pressure	Triggered	**4	2.26 kg	-
	[21]	ASSIST	Rehabilitation	Active	Pneumatic	Artificial muscles	up to 1 Nm	1	Flex/Extension	80°	Flex sensor Pressure	AAN	**4	0.39 kg	-
	[22]	SOA-wrist	Rehab/Assistance	Active	Pneumatic	Flexible joint-less structures	up to 0.76 Nm	2	Flex/Extension Rad/Ulnar dev.	31°/30° 33°/22°	Pressure, IMU	AAN	**4	1.76 kg	-
	[23]	*-	Rehab/Assistance	Active	Brushless motors	Bowden cables	**≥ 5 Nm	2	Flex/Extension Rad/Ulnar dev.	range 115° range 70°	IMU	CPM	**4	0.65 kg	-
	[37]	EXOWRIST	Rehabilitation	Active	Pneumatic	Artificial muscles	630 N	2	Flex/Extension Rad/Ulnar dev.	±30° ±30°	IMU	CPM	**4	0.43 kg	-
	[34]	*-	Occupational	Active	Pneumatic	Flexible joint-less structure	*-	1	Flex/Extension	± 65°	IMU Pressure	AAN	**3	*-	-

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

Table A1. *Cont.*

Image	Reference	Device Name	Application Field	Actuation Type	Power Source	Power transmission	Force/Torque output [N][Nm]	Active DoF	Assisted motion	RoM	Sensing	Control	TRL	Weight	Price($)
	[24,25]	SWA	Rehab/Assistance	Active	Thermal SMA	Compliant	up to 1.32 Nm $\geq$ 0.6 Nm	2	Flex/Extension Rad/Ulnar dev.	38°/50° 34°/35°	Encoder Load cell	AAN	**4	1.9 kg	-
	[26]	*-	Rehabilitation	Active	Thermal SMA	Pulley-tendons	*-	3	Flex/Extension Rad/Ulnar dev. Pron/Supination	**up to 50°/48° **up to 16°/29° **up to 52°	Potentiometer Load cell	CPM	**3	0.95 kg	*-
	[38]	ASR	Rehab/Assistance	Active	Thermal SMA	Tendons	40 N	1	Gripping	-	Load cell	Triggered	**3	300 g	-
	[27]	SMA-wrist exo	Rehabilitation	Active	Thermal SMA	Linkages	$\geq$ 0.5 Nm	2	Flex/Extension Rad/Ulnar dev.	range 50° range 40°	Potentiometer	CPM	**4	1 kg	1060
	[28]	SCRIPT	Rehabilitation	Passive	Springs	Links, tendons	0.5-2 Nm	1	Flex/Extension	45°/30°	Potentiometer	-	**4	0.65 kg	-
	[14,29]	*-	Rehabilitation	Active	DC motor	Tendons	0.4 Nm	2	Flex/Extension Rad/Ulnar dev.	All	IMU	CPM	4	0.3 kg	160
	[30]	*-	Rehabilitation	Active	Linear DC motor	Leaf springs	0.26 to 2.47 Nm 0.65 Nm	2	Flex/Extension Rad/Ulnar dev.	57°/68 40°/14°	Potentiometer	CPM	**4	0.51 kg	-
	[31]	JAS wrist	Rehabilitation	Passive	**Springs	Links	-	1	Flex/Extension	up to 95°	-	-	9	*-	*-
	[32]	MyoPro orthosis	Rehab/Assistance	Active	DC motor	Likages	10 to 20 N	2	Flex/Extension Rad/Ulnar dev.	improve up to 35°	sEMG	AAN	9	1.8 kg	10000
	[35]	Carbonhand	Assistance	Active	DC motor	Bowden cables	**60 N	1	Gripping	All	Force (FSR)	AAN	9	0.7 kg	7000
	[35]	Ironhand	Occupational	Active	DC motor	Bowden cables	80 N	1	Gripping	All	Force (FSR)	AAN	9	2.5 kg	6500
	[36]	Paexo wrist	Occupational	Passive	Leaf spring	Elastic	-	*1	Holding	All	-	-	9	*-	160
	[33]	SaeboFlex	Rehabilitation	Passive	Springs	Links, elastics	-	1	Flex/Extension	improve up to 6°	-	-	9	1.6 kg	600

Note: * no information; ** hypotised according to its characteristics.

References

1. Gonçalves, H.; Cardoso, A.; Mattos, D.; Deola Borges, G.; Anacleto, P.; Colim, A.; Carneiro, P.; Arezes, P.M. Assessment of Work-Related Musculoskeletal Disorders by Observational Methods in Repetitive Tasks—A Systematic Review. *Occupational and Environmental Safety and Health III* **2022**, pp. 455–463. https://doi.org/10.1007/978-3-030-89617-1_41.
2. Ramazzini, B. De morbis artificum diatriba [diseases of workers]. *American journal of public health* **2001**, *91*, 1380–1382. https://doi.org/10.2105/AJPH.91.9.1380.
3. Armstrong, T.J.; Fine, L.J.; Goldstein, S.A.; Lifshitz, Y.R.; Silverstein, B.A. Ergonomics considerations in hand and wrist tendinitis. *The Journal of hand surgery* **1987**, *12*, 830–837. https://doi.org/10.1016/S0363-5023(87)80244-7.
4. Sluiter, J.K.; Rest, K.M.; Frings-Dresen, M.H. Criteria document for evaluating the work-relatedness of upper-extremity musculoskeletal disorders. *Scandinavian journal of work, environment & health* **2001**, pp. 1–102. http://www.jstor.org/stable/40967163.
5. Franco, G.; Franco, F. Bernardino Ramazzini: The father of occupational medicine. *American Journal of Public Health* **2001**, *91*, 1382–1382. https://doi.org/10.2105/AJPH.91.9.1382.
6. World Health Organization (WHO). Musculoskeletal conditions, Key facts. https://www.who.int/news-room/fact-sheets/detail/musculoskeletal-conditions, 2021.
7. INAIL-Italian Workers' Compensatory Authority). OCCUPATIONAL EXOSKELETONS:WEARABLE ROBOTIC DEVICES TO PREVENT WORK RELATED MUSCULOSKELETAL DISORDERS IN THE WORKPLACE OF THE FUTURE, 2020. Available online:http://www.osha.europa.eu.
8. European Agency for Safety and Health at Work (EU-OSHA). Work-related musculoskeletal disorders – Facts and figures. Standard, European Agency for Safety and Health at Work (EU-OSHA), Publications Office of the European Union, Luxembourg, 2020. https://doi.org/10.2802/443890.
9. Pons, J.L. *Wearable robots: Biomechatronic exoskeletons*; John Wiley & Sons, 2008. ISBN:9780470512944.
10. Du Plesis, T.; et al.. Review of Active Hand Exoskeletons for Rehabilitation and Assistance. *Robotics* **2021**, *10*, 1–42. https://doi.org/10.3390/robotics10010040.
11. Chiaradia, D.; Tiseni, L.; Xiloyannis, M.; Solazzi, M.; Masia, L.; Frisoli, A. An assistive soft wrist exosuit for flexion movements with an ergonomic reinforced glove. *Frontiers in Robotics and AI* **2021**, *7*, 595862. https://doi.org/10.3389/frobt.2020.595862.
12. Crea, S.; Beckerle, P.; De Looze, M.; De Pauw, K.; Grazi, L.; Kermavnar, T.; Masood, J.; O'Sullivan, L.W.; Pacifico, I.; Rodriguez-Guerrero, C.; et al. Occupational exoskeletons: A roadmap toward large-scale adoption. Methodology and challenges of bringing exoskeletons to workplaces. *Wearable Technologies* **2021**, *2*. https://doi.org/10.1017/wtc.2021.11.
13. Lambelet, C.; Temiraliuly, D.; Siegenthaler, M.; Wirth, M.; Woolley, D.G.; Lambercy, O.; Gassert, R.; Wenderoth, N. Characterization and wearability evaluation of a fully portable wrist exoskeleton for unsupervised training after stroke. *Journal of NeuroEngineering and Rehabilitation* **2020**, *17*, 1–16. https://doi.org/10.1186/s12984-020-00749-4.
14. Dragusanu, M.; Iqbal, M.Z.; Baldi, T.L.; Prattichizzo, D.; Malvezzi, M. Design, Development, and Control of a Hand/Wrist Exoskeleton for Rehabilitation and Training. *IEEE Transactions on Robotics* **2022**. https://doi.org/10.1109/TRO.2022.3172510.
15. Pitzalis, R.F.; Park, D.; Caldwell, D.G.; Berselli, G.; Ortiz, J. State of the Art in Wearable Wrist Exoskeletons Part I: Background Needs and Design Requirements. *Machines* **2023**, *11*, 458.
16. Xiao, Z.G.; Menon, C. Towards the development of a portable wrist exoskeleton. In Proceedings of the 2011 IEEE International Conference on Robotics and Biomimetics. IEEE, 2011, pp. 1884–1889. https://doi.org/10.1109/ROBIO.2011.6181565.
17. Lambelet, C.; Lyu, M.; Woolley, D.; Gassert, R.; Wenderoth, N. The eWrist—A wearable wrist exoskeleton with sEMG-based force control for stroke rehabilitation. In Proceedings of the 2017 International Conference on Rehabilitation Robotics (ICORR). IEEE, 2017, pp. 726–733. https://doi.org/10.1109/ICORR.2017.8009334.
18. Sangha, S.; Elnady, A.M.; Menon, C. A compact robotic orthosis for wrist assistance. In Proceedings of the 2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob). IEEE, 2016, pp. 1080–1085. https://doi.org/10.1109/BIOROB.2016.7523775.

19. Choi, H.; Kang, B.B.; Jung, B.K.; Cho, K.J. Exo-wrist: A soft tendon-driven wrist-wearable robot with active anchor for dart-throwing motion in hemiplegic patients. *IEEE Robotics and Automation Letters* **2019**, *4*, 4499–4506. https://doi.org/10.1109/LRA.2019.2931607.
20. Bartlett, N.W.; Lyau, V.; Raiford, W.A.; Holland, D.; Gafford, J.B.; Ellis, T.D.; Walsh, C.J. A soft robotic orthosis for wrist rehabilitation. *Journal of Medical Devices* **2015**, *9*. https://doi.org/doi.org/10.1115/1.4030554.
21. Sasaki, D.; Noritsugu, T.; Takaiwa, M. Development of active support splint driven by pneumatic soft actuator (ASSIST). In Proceedings of the Proceedings of the 2005 IEEE international conference on robotics and automation. IEEE, 2005, pp. 520–525. https://doi.org/10.1109/ROBOT.2005.1570171.
22. Liu, S.; Fang, Z.; Liu, J.; Tang, K.; Luo, J.; Yi, J.; Hu, X.; Wang, Z. A compact soft robotic wrist brace with origami actuators. *Frontiers in Robotics and AI* **2021**, p. 34. https://doi.org/10.3389/frobt.2021.614623.
23. Li, N.; Yang, T.; Yang, Y.; Yu, P.; Xue, X.; Zhao, X.; Song, G.; Elhajj, I.H.; Wang, W.; Xi, N.; et al. Bioinspired musculoskeletal model-based soft wrist exoskeleton for stroke rehabilitation. *Journal of Bionic Engineering* **2020**, *17*, 1163–1174. https://doi.org/10.1007/s42235-020-0101-9.
24. Jeong, J.; Yasir, I.B.; Han, J.; Park, C.H.; Bok, S.K.; Kyung, K.U. Design of shape memory alloy-based soft wearable robot for assisting wrist motion. *Applied Sciences* **2019**, *9*, 4025. https://doi.org/10.3390/app9194025.
25. Jeong, J.; Hyeon, K.; Han, J.; Park, C.H.; Ahn, S.Y.; Bok, S.K.; Kyung, K.U. Wrist assisting soft wearable robot with stretchable coolant vessel integrated SMA muscle. *IEEE/ASME Transactions on Mechatronics* **2021**, *27*, 1046–1058. https://doi.org/10.1109/TMECH.2021.3078472.
26. Hope, J.; McDaid, A. Development of wearable wrist and forearm exoskeleton with shape memory alloy actuators. *Journal of Intelligent & Robotic Systems* **2017**, *86*, 397. https://doi.org/10.1007/s10846-016-0456-7.
27. Serrano, D.; Copaci, D.S.; Moreno, L.; Blanco, D. SMA based wrist exoskeleton for rehabilitation therapy. In Proceedings of the 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2018, pp. 2318–2323. https://doi.org/10.1109/IROS.2018.8593987.
28. Ates, S.; Haarman, C.J.; Stienen, A.H. SCRIPT passive orthosis: Design of interactive hand and wrist exoskeleton for rehabilitation at home after stroke. *Autonomous Robots* **2017**, *41*, 711–723. https://doi.org/10.1007/s10514-016-9589-6.
29. Dragusanu, M.; Baldi, T.L.; Iqbal, Z.; Prattichizzo, D.; Malvezzi, M. Design, development, and control of a tendon-actuated exoskeleton for wrist rehabilitation and training. In Proceedings of the 2020 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2020, pp. 1749–1754. https://doi.org/10.1109/ICRA40945.2020.9197013.
30. Higuma, T.; Kiguchi, K.; Arata, J. Low-profile two-degree-of-freedom wrist exoskeleton device using multiple spring blades. *IEEE Robotics and Automation Letters* **2017**, *3*, 305–311. https://doi.org/10.1109/LRA.2017.2739802.
31. JAS-Joint Active Systems. JAS Wrist. https://www.jointactivesystems.com/products/areas/wrist, 2017. Online; accessed 5th of August 2022.
32. Myomo Inc.. MyoPro Orthosis. https://myomo.com/what-is-a-myopro-orthosis/, 2006. Online; accessed 8th of August 2022.
33. Saebo Inc.. SaeboFlex. https://www.saebo.com/shop/saeboflex/. Last accessed 30th of November 2022.
34. Zhu, M.; Adams, W.; Polygerinos, P. Carpal tunnel syndrome soft relief device for typing applications. In Proceedings of the Frontiers in Biomedical Devices. American Society of Mechanical Engineers, 2017, Vol. 40672, p. V001T03A003. https://doi.org/10.1115/DMD2017-3374.
35. Bioservo Technologies. Bioservo Strength for life - Professional and Healthcare. https://www.bioservo.com/. Last accessed 7th of September 2022.
36. Ottobock. Paexo Wrist Exoskeleton. https://paexo.com/paexo-wrist/?lang=it. Last accessed 5th of August 2022.
37. Andrikopoulos, G.; Nikolakopoulos, G.; Manesis, S. Motion control of a novel robotic wrist exoskeleton via pneumatic muscle actuators. In Proceedings of the 2015 IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA). IEEE, 2015, pp. 1–8. https://doi.org/10.1109/ETFA.2015.7301464.
38. Hadi, A.; Alipour, K.; Kazeminasab, S.; Elahinia, M. ASR glove: A wearable glove for hand assistance and rehabilitation using shape memory alloys. *Journal of Intelligent Material Systems and Structures* **2018**, *29*, 1575–1585.

39. Noronha, B.; Accoto, D. Exoskeletal devices for hand assistance and rehabilitation: A comprehensive analysis of state-of-the-art technologies. *IEEE Transactions on Medical Robotics and Bionics* **2021**, *3*, 525–538. https://doi.org/10.1109/TMRB.2021.3064412.
40. Gopura, R.; Kiguchi, K. Mechanical designs of active upper-limb exoskeleton robots: State-of-the-art and design difficulties. In Proceedings of the 2009 IEEE International Conference on Rehabilitation Robotics. IEEE, 2009, pp. 178–187. https://doi.org/10.1109/ICORR.2009.5209630.
41. Gopura, R.; Bandara, D.; Kiguchi, K.; Mann, G.K. Developments in hardware systems of active upper-limb exoskeleton robots: A review. *Robotics and Autonomous Systems* **2016**, *75*, 203–220. https://doi.org/10.1016/j.robot.2015.10.001.
42. Nikhil, G.; Yedukondalu, G.; Rao, S. Robotic exoskeletons: A review on development. *International Journal of Mechanical and Production Engineering Research and Development* **2019**, *9*, 529–542. https://archive.org/details/52.ijmperdaug201952.
43. Tiboni, M.; Borboni, A.; Vérité, F.; Bregoli, C.; Amici, C. Sensors and actuation technologies in exoskeletons: A review. *Sensors* **2022**, *22*, 884. https://doi.org/10.3390/s22030884.
44. Hussain, S.; Jamwal, P.K.; Van Vliet, P.; Ghayesh, M.H. State-of-the-art robotic devices for wrist rehabilitation: Design and control aspects. *IEEE Transactions on Human-Machine Systems* **2020**, *50*, 361–372. https://doi.org/10.1109/THMS.2020.2976905.
45. Cornejo, J.; Huamanchahua, D.; Huamán-Vizconde, S.; Terrazas-Rodas, D.; Sierra-Huertas, J.; Janampa-Espinoza, A.; Gonzáles, J.; Cardona, M. Mechatronic exoskeleton systems for supporting the biomechanics of shoulder-elbow-wrist: An innovative review. In Proceedings of the 2021 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS). IEEE, 2021, pp. 1–9. https://doi.org/10.1109/IEMTRONICS52119.2021.9422660.
46. Ferguson, R.; et al.. Wrist pain: A systematic review of prevalence and risk factors–what is the role of occupation and activity? *BMC Musculoskeletal Disorders* **2019**, *20*. https://doi.org/10.1186/s12891-019-2902-8.
47. Vardakastani, V.; Bell, H.; Mee, S.; Brigstocke, G.; Kedgley, A.E. Clinical measurement of the dart throwing motion of the wrist: variability, accuracy and correction. *Journal of Hand Surgery (European Volume)* **2018**, *43*, 723–731. https://doi.org/10.1177/1753193418773329.
48. Braidotti, F.; Atzei, A.; Fairplay, T. Dart-Splint: An innovative orthosis that can be integrated into a scapho-lunate and palmar midcarpal instability re-education protocol. *Journal of Hand Therapy* **2015**, *28*, 329–335. https://doi.org/10.1016/j.jht.2015.01.007.
49. Kaufman-Cohen, Y.; Friedman, J.; Levanon, Y.; Jacobi, G.; Doron, N.; Portnoy, S. Wrist plane of motion and range during daily activities. *The American Journal of Occupational Therapy* **2018**, *72*, 7206205080p1–7206205080p10. https://doi.org/10.5014/ajot.2018.026997.
50. Brigstocke, G.; Hearnden, A.; Holt, C.; Whatling, G. In-vivo confirmation of the use of the dart thrower's motion during activities of daily living. *Journal of Hand Surgery (European Volume)* **2014**, *39*, 373–378. https://doi.org/10.1177/1753193412460149.
51. Borislav, M. The Number Of Companies Making Industrial Exoskeletons Has Been Quietly Increasing For The Past Five Years. https://www.forbes.com/sites/borislavmarinov/2020/09/24/the-number-of-companies-making-industrial-exoskeletons-has-been-quietly-increasing-for-the-past-five-years/?sh=231b1c067bf4, 2020. Last accessed 5th of August 2022.
52. Borislav, M. Updated Directory of Exoskeleton Companies and Industry Statistics. https://exoskeletonreport.com/2021/12/updated-directory-of-exoskeleton-companies-and-industry-statistics/, 2021. Last accessed 5th of August 2022.
53. Schwartz, D.A. Static progressive orthoses for the upper extremity: A comprehensive literature review. *Hand* **2012**, *7*, 10–17. https://doi.org/10.1007/s11552-011-9380-2.
54. Dunaway, S.; Dezsi, D.B.; Perkins, J.; Tran, D.; Naft, J. Case report on the use of a custom myoelectric elbow–wrist–hand orthosis for the remediation of upper extremity paresis and loss of function in chronic stroke. *Military medicine* **2017**, *182*, e1963–e1968. https://doi.org/10.7205/MILMED-D-16-00399.
55. McCabe, J.P.; Henniger, D.; Perkins, J.; Skelly, M.; Tatsuoka, C.; Pundik, S. Feasibility and clinical experience of implementing a myoelectric upper limb orthosis in the rehabilitation of chronic stroke patients: A clinical case series report. *PloS one* **2019**, *14*, e0215311. https://doi.org/10.1371/journal.pone.0215311.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 November 2023 doi:10.20944/preprints202311.0864.v1

56. Nilsson, M.; Ingvast, J.; Wikander, J.; von Holst, H. The Soft Extra Muscle system for improving the grasping capability in neurological rehabilitation. In Proceedings of the 2012 IEEE-EMBS conference on biomedical engineering and sciences. IEEE, 2012, pp. 412–417. https://doi.org/10.1109/IECBES.2012.6498090.
57. Kottink, A.I.R.; Nikamp, C.D.; Bos, F.P.; van der Sluis, C.K.; van den Broek, M.; Onneweer, B.; Stolwijk-Swüste, J.M.; Brink, S.M.; Voet, N.B.; Buurke, J.B.; et al. Therapeutic Effect of a Soft Robotic Glove for Activities of Daily Living In People With Impaired Hand Strength: Protocol for a Multicenter Clinical Trial (iHand). *JMIR research protocols* **2022**, *11*, e34200. https://doi.org/10.2196/34200.
58. Hyttinge, M.; Einarsson, F. Bioservo Technologies. Technical report, Redeye, Equity Research and Investment Banking Company, 2021.
59. Osuagwu, B.A.; Timms, S.; Peachment, R.; Dowie, S.; Thrussell, H.; Cross, S.; Heywood, T.; Shirley, R.; Taylor, J. Clinical Trial of the Soft Extra Muscle Glove to Assess Orthotic and Long-Term Functional Gain Following Chronic Incomplete Tetraplegia: Preliminary Functional Results. In Proceedings of the International Conference on NeuroRehabilitation. Springer, 2018, pp. 385–389. https://doi.org/10.1007/978-3-030-01845-0_77.
60. Radder, B.; Prange-Lasonder, G.B.; Kottink, A.I.; Holmberg, J.; Sletta, K.; van Dijk, M.; Meyer, T.; Melendez-Calderon, A.; Buurke, J.H.; Rietman, J.S. Home rehabilitation supported by a wearable soft-robotic device for improving hand function in older adults: A pilot randomized controlled trial. *PloS one* **2019**, *14*, e0220544. https://doi.org/10.1371/journal.pone.0220544.
61. Hoffman, H.B.; Blakey, G.L. New design of dynamic orthoses for neurological conditions. *NeuroRehabilitation* **2011**, *28*, 55–61. https://doi.org/10.3233/NRE-2011-0632.
62. Barry, J.; Saabye, S.; Baker, D.; Fogarty, J.; Beck, K. Effects of the saeboflex® orthosis and a home exercise program on upper extremity recovery in individuals with chronic. *Journal of Neurologic Physical Therapy* **2006**, *30*, 207. https://doi.org/10.1097/01.NPT.0000281292.54130.1f.
63. Lannin, N.A.; Cusick, A.; Hills, C.; Kinnear, B.; Vogel, K.; Matthews, K.; Bowring, G. Upper limb motor training using a Saebo™ orthosis is feasible for increasing task-specific practice in hospital after stroke. *Australian occupational therapy journal* **2016**, *63*, 364–372. https://doi.org/10.1111/1440-1630.12330.