New Trends in Qualitative Research

Emerging trends in upper-limb embedded devices: A qualitative research study

ISSN: 2184-7770

Volume 16

Qualitative Research: Practices and Challenges

DOI: https://doi.org/10.36367/ntqr.16.2023.e796

Celina Pinto Leão, Vinicius Silva, Susana Pinto da Costa

Abstract: Framework This paper explores how a qualitative systematic literature review (SLR) can contribute to our understanding of the trends in upper-limb wearable devices. These devices are pieces of electronic equipment that can be worn as accessories, such as watches, or embedded in clothing, including gloves and sleeves, and could play an essential role in subjects' quality of life after any occurrence that affects their possibility to perform basic activities autonomously. Moreover, these devices can be used to improve manual performance tasks like surgical or precision tasks, and even more so when performed under extreme ambient temperature conditions. **Goals and Methods:** A SLR on upper-limb embedded devices was conducted based on scientific documents retrieved from the Scopus database. Two research questions were outlined: "How has this technology been evolving?" and "What is the trend according to the fields of application?". The combination of keywords (upper-limb* AND wearable* AND device*) was used in the title, abstract, and keywords fields. **Results:** A total of 555 documents were obtained. Descriptive statistical and bibliometric analyses were conducted, identifying trends, knowledge gaps, and the future direction of research. The free software VOSviewer was used to construct data visualization bibliometric maps of the co-authorship and co-citation network. A subset of 26 documents was considered for the critical qualitative synthesis. This step facilitated the visualization and exploration of the interconnectedness among authors and the citation patterns within the literature. Combining the information gathered enables addressing the extent and the emerging trends in upper-limb embedded devices' development according to the field they are applied. **Final considerations**: With this research, a starting point in developing a proof of concept of a novel device aimed at improving dexterity in challenging environments is established.

Keywords: Data Analysis; Interaction; Wearable Electronic Devices; Upper limb; Rehabilitation.

1.Introduction

Upper limb wearable devices are designed to be used or implanted on the arms, hands, or fingers. These devices can be used for various purposes, such as rehabilitation of people with movement disorders, as assistance with daily activities for people with physical disabilities, and as prosthetic devices for people who have lost the use of their limbs. These devices may use a combination of sensors, actuators, and control algorithms to assist or replace the function of the upper limb. These devices can be an external structural mechanism with joints and links corresponding to those of the human body (Rosen & Perry, 2007) or, more recently, be portable and flexible soft exoskeletons to assist the flexion of the upper limbs (Samper-Escudero et al., 2020b). Some research papers present review studies that go through particular aspects regarding upper limb devices, namely upper limb prostheses and rehabilitation technology (e.g., Bardi et al., 2022; Biddiss & Chau, 2007; Cordella et al., 2016; Lo & Xie, 2012; Walmsley et al., 2018; Wang et al., 2017).

Biddiss and Chau (2007) present a review of the acceptance and abandonment of upper limb prostheses from 1980 to the beginning of 2006, identifying the factors associated with abandonment and consumer dissatisfaction. Understanding and recognizing these factors is crucial for enhancing and refining the design of new devices, which is essential for optimizing the overall performance of these devices. They also highlight the significance of prioritizing participatory research and consumer satisfaction, which is crucial to ensure that the design of devices effectively closes the gap between the research lab and the clinic and between the clinic and the home.

Lo and Xie (2012) review and discuss using upper limb exoskeleton robots to rehabilitate patients with neuromuscular disorders, mainly to provide optimal rehabilitation therapy for stroke victims. Cordella et al. (2016) follow similar concerns regarding the limitations of current prosthetic solutions for people with limited autonomy and ability to perform daily living, working, and social activities. They propose a list of requirements for upper limb prostheses based on user needs to improve user satisfaction and reduce device abandonment. Walmsley et al. (2018) present and discuss the use of wearable sensors to calculate upper limb joint angle and their potential as viable instruments for measurement during active movement. Wang et al. (2017) listed and classified interactive wearable systems for movement and posture monitoring during upper body rehabilitation, regarding the sensing technology, system measurements, and feedback conditions and evaluating their wearability and clinical effectiveness. By doing this, they demonstrated that this area of research engages different backgrounds, not only from rehabilitation and biomedical sciences but also from computer science and engineering.

Burton (2020) discusses the various uses for exoskeletons and exosuits, including for rehabilitative care, industrial manufacturing, leisure activities, and military combat, highlighting that exoskeletons can be powered, passive, pseudo-passive, or active, and may be soft or rigid materials. The author also states that the substantial technological overlap between different uses allows for easy adaptation of exoskeletons and exosuits for various purposes. The ABLE 7-axes upper limb exoskeleton is an example of repurposing from stroke rehabilitation to industrial manufacturing. Exoskeletons can also be designed to reduce arm weight when carrying tools such as screw guns or paint guns. Elstub et al. (2021) define exoskeletons and exosuits (exos) as wearable devices that enhance physical activity, posture, and motion; devices that biomechanically assist with a variety of tasks, including bending, lifting, reaching, walking, running, and jumping, and are used in various applications, including clinical and occupational settings.

Pérez Vidal et al. (2021) discuss the characteristics and functionality of soft exoskeletons, analyzing investigations conducted over the past decade on upper and lower joints, including the shoulder, elbow, wrist, hand, hip, knee, and ankle. The authors examine factors such as degrees of freedom, force, actuators, power transmission methods, control systems, and sensors. Exoskeletons are designed to aid the movement of various joints in the body, with single or multiple degrees of freedom, depending on the complexity and physical capabilities of the device. The authors also classify exoskeletons based on their actuation devices, which can be electric, pneumatic, hydraulic, or hybrid.

More recently, Bardi et al. (2022) reviewed the current approaches in designing and producing soft robotic wearable devices, specifically upper limb exosuits, grouped according to actuation type. The authors conclude that while few devices are ready for market, exosuits show high potential for daily activity assistance, and clinical trials with shared evaluation metrics are needed to assess their effectiveness. Exosuits are a recent valid alternative for the disadvantages of exoskeletal structure devices in restoring human physical abilities and improving performance and quality of life. Exosuits, identified as soft robotic devices, are typically designed to be worn over the user's limbs, torso, or entire body and can provide not only assistance with activities of daily living and rehabilitation but also be used in military and industrial applications (Samper-Escudero et al., 2020b).

Indeed, upper limb wearable devices have a wide range of applications. However, most research seems to focus on medical applications, including rehabilitation, assistance with daily activities, and prosthetic devices. Although numerous reviews discuss these systems, none establish the linkage between concept clusters or trace their evolution over time. There is an intricate lexicon that may bring confusion regarding the significance of terms that may seem synonyms. Hence, the primary objective of the present study is to gain insights into the evolution of these devices in correlation with other concepts, thereby enhancing knowledge regarding their application trends and emerging areas within the field.

This research endeavors to shed light on the evolution of the technology, as mentioned earlier, through a systematic literature review (SLR) by posing two research questions (RQ):

RQ1: “How has this technology been evolving?”, and

RQ2: “What is the trend according to the fields of application?”.

RQ1 seeks to understand the trajectory of this technology, exploring its advancements and changes over time. By examining its evolution, the study aims to uncover the key developments, breakthroughs, and transformations that have shaped its current state.

RQ2 aims to investigate the trend of this technology within various fields of application. By analyzing its utilization across different domains, the study intends to identify emerging areas where the technology has gained prominence and ascertain the extent to which it has been adopted.

2.Methods

A Systematic literature review (SLR) was conducted, followed by descriptive statistical analysis. The free software VOSviewer (van Eck & Waltman, 2023) was used to construct and view bibliometric maps. As a research method, SLR includes comprehensive literature searches, well-defined inclusion and exclusion criteria, systematic quality assessment, and careful synthesis and interpretation of findings (Silva et al., 2022; Thomé et al., 2016). VOSviewer was selected because of its user-friendly graphical interface and ability to generate maps of co-authorship and co-citation networks, which are useful inputs for the analysis. The findings allowed for reducing the number of documents to 26 considered for the critical qualitative synthesis. Combining the information gathered enabled addressing the extent and emerging trends in the development of upper limb embedded devices according to the field in which they are applied.

2.1 Search Methods

The SLR was conducted based on all published studies on upper-limbed embedded devices and their application areas considering the Scopus database. The combination of keywords:

[upper-limb* AND wearable* AND device*]

was used in the title, abstract, and keywords fields. The character "*" allowed finding words with the same stem, that is, all possible characters after the last letter (e.g., plural of each word). Since the search is not case-sensitive, the hyphen is considered a space. So, the use of "upper-limb" is equal to the use of "upper limb”.

No restriction to the time frame was considered allowing us to verify the evolution of this topic over time and whenever a change is made. Only articles, conference papers, and book chapters were considered. The search, conducted in December 2022, yielded 555 documents. This number was obtained after excluding not available full documents.

2.2 Data collection and analysis

Considering all 555 documents, a descriptive analysis was performed, which facilitated a comprehensive understanding of the overall trends and patterns. The analysis helped refine and select the data results to answer this study's main research questions.

After conducting a search of the Scopus database, it was found that the earliest publications on this topic appeared in 2002. Beginning in 2015, a clear trend of a rapid increase in the number of documents published, which is almost exponential in nature. However, with the onset of the pandemic in 2020-2021, there was a noticeable decrease in the number of publications. As seen in Fig. 1, there has been a slight increase in the number of publications in 2022.

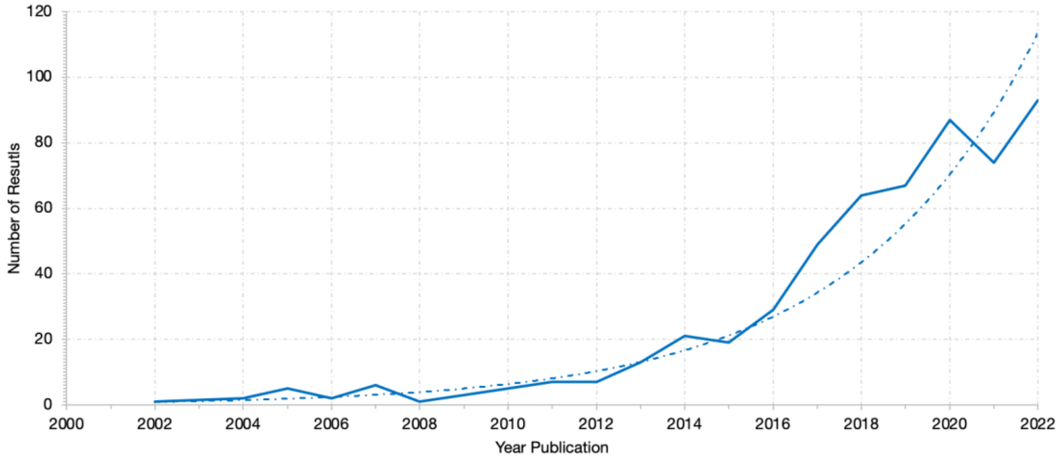

Figure 1. Number of documents by year of publication.

The majority of the publications (57%) were in the form of articles, followed by conference papers (39%) and book chapters (4%). In terms of subject areas, the majority of the publications (72.5%) fell into four major categories, with engineering being the most significant (29%), followed by computer sciences (22%), medicine (15%), and biochemistry, genetics, and molecular biology (6.5%). These findings are presented graphically in Fig. 2.

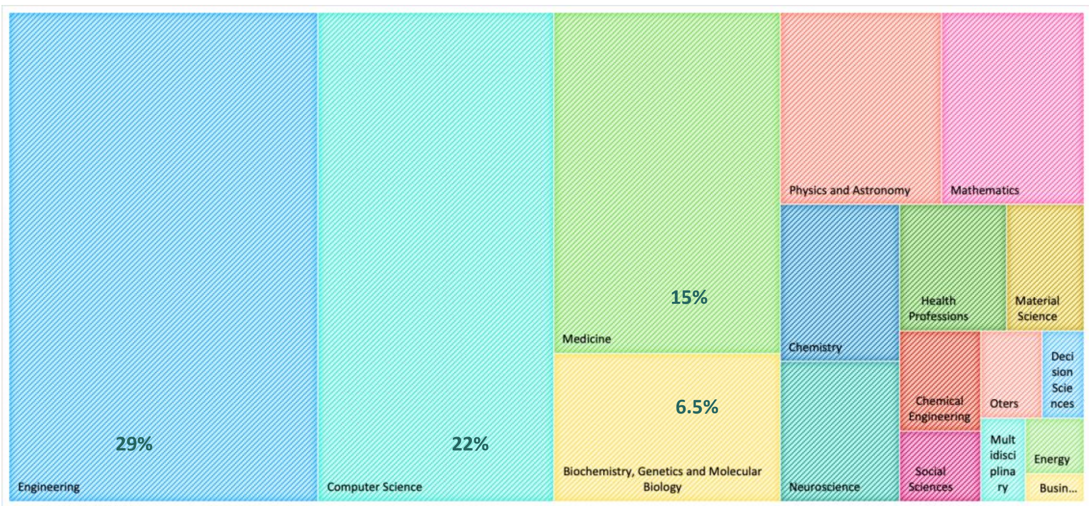

Figure 2. Documents by subject area.

Sixty countries were identified with at least one document. Table 1 lists the top 12 countries with their documents' frequencies in descending order of the total link strengths. The United States of America (USA) had the highest number of publications, with 115 (20.7%), and the highest total link strength value. Italy had the second-highest number of publications, with 90 (16.2%), followed by China with 74 (13.3%).

The UK and Japan had 45 publications each (8.1%), with the UK having a higher total link strength value (25) than Japan's 17. The total link strength is a measure of the overall strength of the citation links between a particular document and other documents.

Table 1. Top 12 countries' documents' frequencies, citations, and total link strengths.

Country	Documents	Citations	Total link strength
USA	115	2900	38
Italy	90	1595	27
China	74	872	24
UK	45	677	25
Japan	45	505	17
Canada	38	274	10
Switzerland	32	450	30
Germany	22	319	27
Singapore	19	269	11
Australia	19	105	9
France	11	68	8
Belgium	6	186	10

Fig. 3 displays the clusters defined in which each country is represented by a sphere whose size is proportional to the number of documents, and the color indicates the average number of citations.

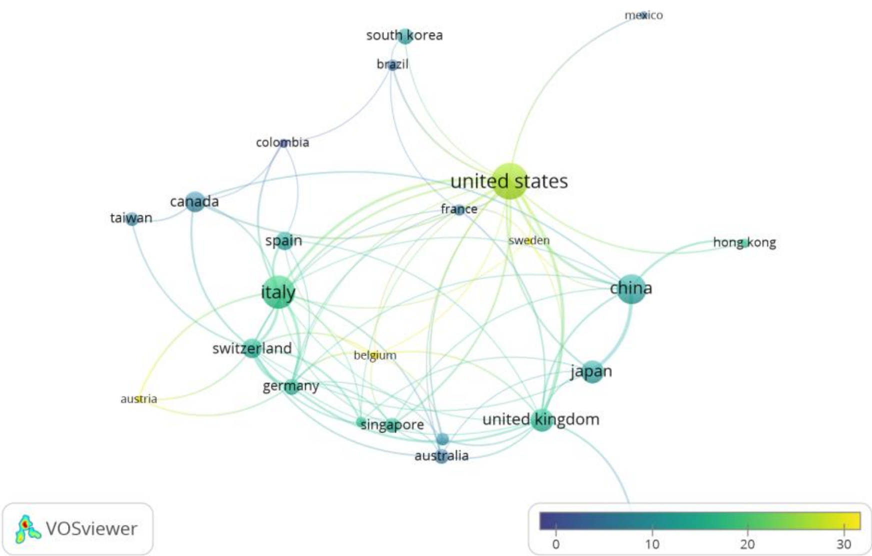

Figure 3. Co-authorship overlay visualization map of countries based on average citations.

Fig. 4 displays the average publication year for documents published between 2015 and 2022. Notably, the number of documents published on this topic has been steadily increasing over the years, and it is interesting to observe that European countries such as Germany and France have recently begun to publish research related to this topic, as indicated by the yellow-colored spheres in Fig. 4.

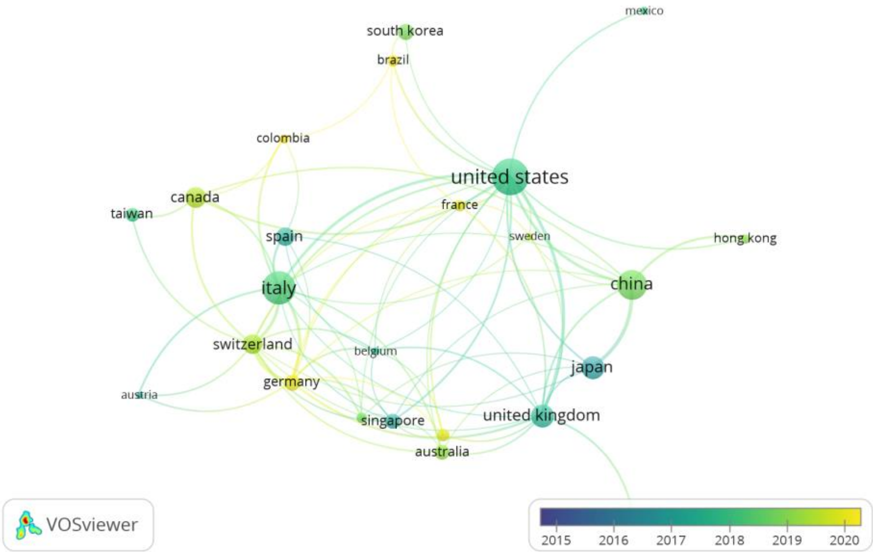

Figure 4. Co-authorship overlay visualization map of countries based on average publication year.

3.Results and Discussion

The results described in the previous section will help refine and select the data results to answer the research question RQ2, "What is the trend according to the fields of application?". Thus, two steps were taken. Firstly, a continuation of the descriptive analysis of the 555 documents was conducted, which included a citation analysis of relevant keywords. Secondly, the analysis was refined by identifying the most representative clusters of keywords, and then, the data were organized to identify different themes and the relationships between them.

3.1 Keyword Citation Analysis

A co-occurrence analysis was performed considering the keywords (indexed and author). A keyword is not only a word or phrase that summarizes the main topic of a document but also assists in classifying the information and streamlining the process of searching and retrieving information from a database or search engine. Therefore, analyzing the co-occurrence of keywords can help identify trends, which can be helpful for further development in a research domain.

Fig. 5 depicts the network that was generated from the bibliographic data for the keyword co-occurrence map. In the visualization, the distance between two keywords approximately indicates their relatedness in terms of co-occurrence links. Thus, the closer two keywords are located to each other, the stronger their relatedness is. This network was constructed based on 1316 keywords, subsequently reduced to 63 by defining a minimum occurrence threshold of 5 for each keyword. The seven clusters obtained are distinguishable by their colors: red for "wearable sensors", green for "wearable device", "exoskeletons", and "human-robot interaction", blue for "stroke" and "activities of daily living", yellow for "rehabilitation robotics" and "soft robotics", purple for "rehabilitation", light blue for "assistive devices" and "haptics", and orange for "exoskeleton" and "wearable robot". Notably, "exoskeletons" also appear in the green cluster alongside "exosuit" and "upper limbs".

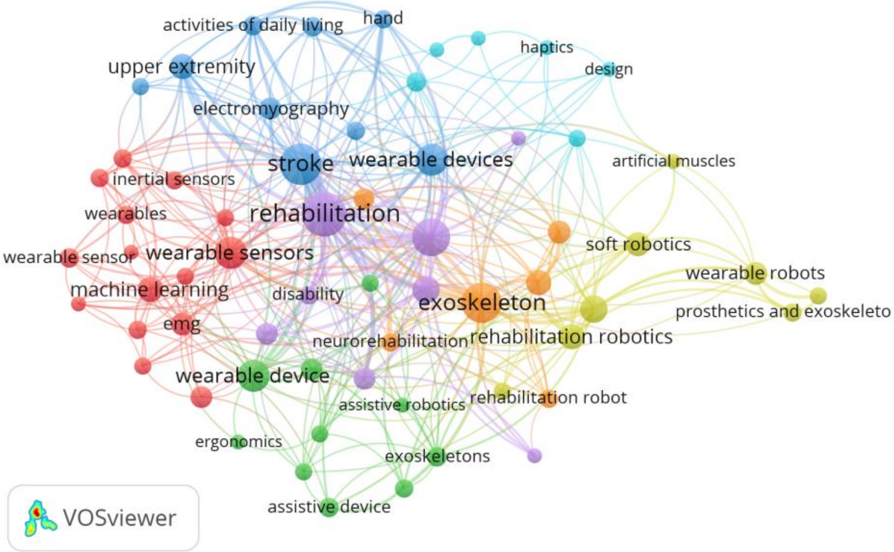

Figure 5. Co-occurrence network visualization map of keywords.

Furthermore, an analysis of the keywords by year was conducted, indicating that the adoption of the most recent keywords ("Exoskeletons", "exosuit", and "upper-limbs") occurred after 2020, as shown in Fig. 6. This figure was created based on the average occurrence score of the keywords per publication year.

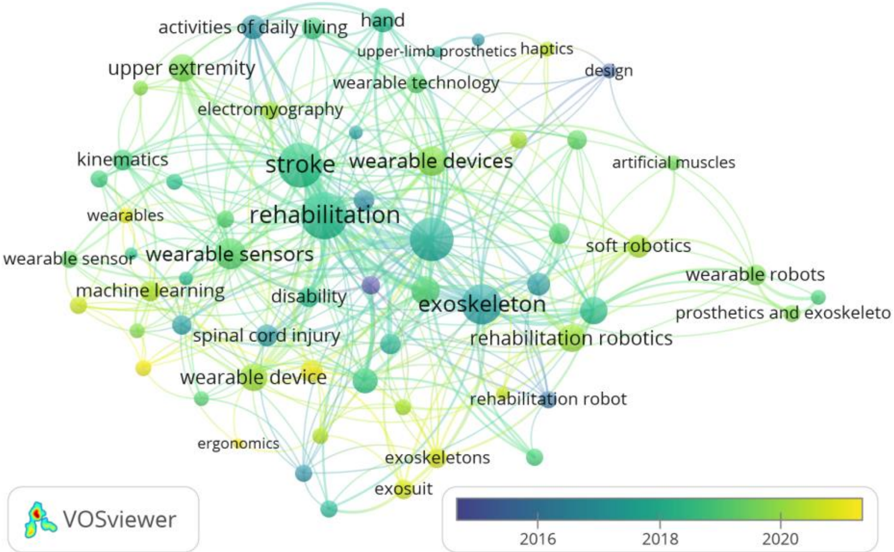

Figure 6. Co-occurrence overlay visualization map of keywords based on average publication year.

Examining Fig. 6 from left to right, one can observe the evolution in using keywords related to upper-limb embedded devices. In 2018, the keywords were primarily linked to "exoskeleton" and "activities of daily living", followed by "wearable device" and "soft robotics". Subsequently, around 2020-2021, new developments emerged, highlighting new areas of applications based on "exosuit" and the incorporation of machine learning. Machine Learning is used to interpret the sensor's signal in a personalized way according to the user.

Exoskeletons and exosuits are wearable devices that can enhance human capabilities, but they are designed for different purposes and have different features (Burton, 2020; Elstub et al., 2021; Pérez Vidal et al., 2021). As previously mentioned, exosuits, also known as exoskeleton suits, are more lightweight and flexible than exoskeletons and can also be used by healthy people to enhance their performance by assisting with industrial applications, as illustrated in Fig. 7 or daily living or surgical or precision tasks when performed under extreme ambient temperature conditions, among others (Fu et al., 2022). These two types of technological devices, exoskeletons, and exosuits, are still in the early stages of development, and technology is evolving rapidly.

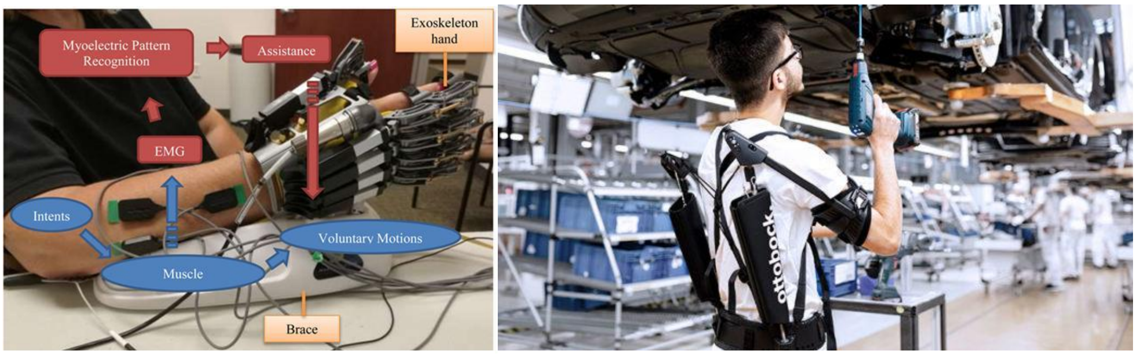

Figure 7. Examples of two types of Exoskeletons and exosuits devices that enhance human capabilities.

Combining the information gathered makes it possible to comprehend the driving force behind upper limb embedded systems and grasp how it has progressed to increasingly optimized systems, allowing to follow the second step refining the analysis considering the green cluster of keywords (see Fig. 5).

3.2 New Trends Analysis

As previously referred to, "exosuits" is a keyword that started to be used recently. So, of the 555 documents initially identified, 26 used "exosuits" as a keyword to summarize the main topic of the work developed, which were then selected for further critical analysis. The authors reviewed all papers individually and then together to compare and discuss their initial findings. Any disagreements were resolved through discussion and reached a shared consensus. During this process, the data were iteratively analyzed, identifying patterns or categories and classifying them into meaningful descriptions or codes, generating new insights, meaning, and significance of the data according to the objectives. The final codes yielded were: target population, activity, type of final product, and main results obtained. This set of codes was selected to facilitate the analysis to address and answer the research question RQ2 effectively. So, to identify the field of application, the codes target population, activity, and type of final product, which naturally seemed to be the most appropriate and easy to identify through the reading of the selected documents. The fourth code, the main results obtained, was also considered because it allows the identification of the final result of the scientific work described, reinforcing the current state of technological and scientific development of this topic. The authors' scientific backgrounds collectively contributed to the accomplishment of this stage, with each author's unique background and years of experience adding valuable perspectives and insights to the discussion. To emphasize knowledge and know-how in human factors in engineering and technology development in electronic and computer engineering.

Table 2 lists, by descending order of publication date, and summarizes the primary descriptions of these 26 documents according to the four considered codes.

Table 2. List and main descriptions of the 26 documents selected.

Citation	Target population	Activity	Type of final product	Main results obtained
Burchielli et al. (2022)	Patients suffering from neuromuscular diseases	Elbow flexion and extension	Physical Equipment	The feasibility of using exosuits in hybrid rehabilitation treatments of neuromuscular diseases in order to promote motion recovery.
Sambhav et al. (2022)	To augment, reinforce or even restore human performance (i.e., elderly generation, workers or soldiers, paraplegic patients)	Generalized simulation framework allowing incorporation of any advanced control strategy for upper limb assistive exosuit	Simulation platform	A Gravity Compensation (GC) controller has been implemented on the wearable device to decrease the joint moments, muscle activations, and metabolic costs during a simple repetitive load-lifting task with two different speeds.
Missiroli et al. (2022)	Occupational environment	To provide gravitational support to both shoulder and elbow flexion-extension in strenuous manual tasks	Physical equipment	An innovative concept of hybrid upper-limb occupational exoskeletons to extend the capability of the OEs to provide gravitational support to both shoulder and elbow flexion-extension in strenuous manual tasks.

Citation	Target population	Activity	Type of final product	Main results obtained
Samper-Escudero et al. (2022)	For bimanual assistance of ADLs and long-term usage.	Upper limb: shoulder and elbow	LUXBIT is a cable-driven flexible exoskeleton that combines fabrics and sewing patterns to promote anatomical adaptation.	The system presented and its textile interface with the user can become a valuable asset in repetitive tasks and the maintenance of a pose, thus preventing the development of musculoskeletal conditions.
Lotti et al. (2022)	Pilot - any (human wearers)	To match frequency ranges of biomechanics, but also in detecting and interpreting the human intention	A control framework for an upper limb exosuit which works using an EMG model-based myoprocessor module.	Using biosignal in the control loop for wearable robotics improves reliability and interaction between the device and its pilot.
Galofaro et al. (2022)	Impaired individuals (rehabilitation of patients with neuromuscular diseases)	Elbow flexion	A new device that combines NMES and an upper limb exosuit to assist elbow movement.	Hybrid controller allows users to complete repetitive tasks with extremely light exertion, resulting in accurate and precise movements.
Weston et al. (2022)	Workers performing overhead work	Upper limbs and lumbar spine exertion - support and comfort	Not applicable. The objective was to evaluate three passive upper-extremity exoskeletons relative to a control condition.	Exoskeletons offered virtually no benefit for the conditions tested, but the experimental task was not highly fatiguing to the subjects. Results may vary for tasks requiring constant arm elevation or higher force demands.
Pont-Esteban et al. (2022)	Impaired individuals (passive rehabilitation)	Shoulder and elbow articulation	Design of a robust motion (position and speed) control architecture (CPISDO) for an upper-limb cable-driven rehabilitation exosuit.	The proposed controller has outperformed the other two conventional candidates utterly: The tracking RMSE is the lowest in both articulations in all the performed movements; it offers a response without both oscillations and overshoot (contrary to the other two controllers). There is no need to tune the controllers' parameters specifically for each subject. Average RMSEs are lower than other state-of-the-art approaches.
Natividad et al. (2021)	Impaired subjects: Activities of daily living (ADLs) assistance	Shoulder articulation and humerus (abduction and adduction, horizontal flexion and extension, forward flexion and extension).	2-DOF soft robotic shoulder exosuit that uses modular soft actuators that are able to emulate the humerus' movement.	Up to 65% reduction in muscle activation when performing shoulder elevation and up to 34% when rotating the plane of elevation.
Sy et al. (2021)	Impaired subjects: ADLs assistance	Upper limb: shoulder, elbow, and wrist.	New robotic fabric sleeve for upper limb assistance based on fabric garments and hydraulic-driven soft artificial muscles with low hysteresis.	The assistive sleeve reduced the workload on the user's muscles.
Samper-Escudero et al. (2021)	General application: rehabilitation, demanding tasks and preventing unsafe movements, astronauts' workday, among others	Intended for bimanual assistance in daily living, being equipped with a backpack to this end	Physical prototype equipment called LUXBIT uses a textile backpack to promote outdoor application and freedom of movement around the workspace	Decrease muscle activity in the upper limbs' flexion allowing the user to hold tiring postures for an extended time; also, the exoskeletons can likewise improve the performance of astronauts by mitigating the effects of weightlessness conditions in the upper limbs' proprioception, dexterity, and force exertion.
Pont-Esteban et al. (2021)	Upper limb rehabilitation.	Upper limb: shoulder and elbow	Embedding of a position sensor in the elbow of the LUXBIT exosuit to control its position.	The control system is capable of following reference trajectories with enough precision for upper limb rehabilitation tasks.
Lotti et al. (2020)	Upper limb flexion assistance	Elbow flexion	Upper limb exosuit with focus on elbow flexion The assistance is provided by recovering the front cable during elbow flexion.	Comparative study of two different control approaches on the same robotic suit: a model-based myoelectric control (*myoprocessor*) and a dynamic-based control. Assistance from the exosuit resulted in a marked reduction in the effort of muscles working against gravity, with both control approaches achieving similar results.
Samper-Escudero et al. (2020b)	Upper limb rehabilitation	Elbow and shoulder flexion	An exosuit to assist the upper limbs flexion by using a design based on textiles	The exosuit can assist elbow flexion and partially assist the shoulder. It is a portable solution based on motors and electronics embedded in an ergonomic backpack. Additionally, it combines different layers of fabric to couple the exosuit and interface it with the user. The device reduces muscle activation by 26%. Additionally, an appropriate combination of fabrics increased cloth stiffness in the principal motion directions and reduced seams and shear forces.
Langard et al. (2020)	Upper limb rehabilitation	Analyzing the stresses generated by an exoskeleton on the shoulder.	It proposes a model of an exoskeleton that consists of a cable-driven mechanism attached to an elastic sleeve worn by the user.	The paper focuses on analyzing the stresses generated by the exoskeleton on the human arm, especially on the shoulder joint. The paper uses numerical simulations to investigate how different design parameters of the exoskeleton affect these stresses, such as the position and orientation of the cable anchor points and pulleys. Results showed that some design choices could reduce the stresses on the shoulder joint.
Pastor et al. (2019)	Upper limb assistance	A motion capture system for controlling an exoskeleton for the upper limb	A low-cost exoskeleton consists of an elastic sleeve mitten and a cable-driven mechanism that can assist the user in performing different arm and hand movements.	The paper proposes a sensor fusion algorithm that combines the IMUs and flex sensors data to estimate the shoulder, elbow, and wrist joint angles. It evaluates the performance of the motion capture system in terms of accuracy, latency, and robustness. The motion capture system can achieve an average error of fewer than 5 degrees for all joints and a latency that permits real-time teleoperation.
Kieran Little et al., (2019)	Upper limb	Exosuit to reduce the muscle effort of the user when flexing the elbow	A new algorithm that modulates the assistance level of the exosuit based on the	The paper argues that this algorithm can adapt to different shoulder positions and movements. In order to validate it, the authors measure the

Citation	Target population	Activity	Type of final product	Main results obtained
			orientation of the arm measured by an inertial measurement unit (IMU) attached to the upper arm.	muscular activity of the biceps brachii and triceps brachii using electromyography (EMG) sensors. The paper reports that the new algorithm reduced the muscular activity of both muscles by about 20% compared to no assistance, regardless of shoulder position and movement.
Georgaraki et al. (2019)	Upper extremity impairments muscular dystrophies, by stoke and typical aging	Daily life tasks	Model: analysis of interactions between movement directions in the upper extremity regarding daily living tasks for the development of a new design concept that can be used to simplify the design of exosuits	The interaction of movement directions during daily living tasks has not yet been comprehensively analyzed. By coupling humeral axial rotation and rotation in the plane of elevation to humeral elevation, the shoulder can be assisted on a one-degree-of-freedom support trajectory during a wide range of daily living tasks.
Chiaradia et al. (2019)	To augment human motor abilities or restore lost motor functions	The variety of hardware architectures for wearable robots that assist human joints requires an equally rich assortment of control schemes.	Systematization of Systems for physical human-robot interaction.	Identification of the strengths and weaknesses of each approach to serving as a tutorial for a growing number of engineers and research groups that are designing stiff and soft robots for human motion assistance and augmentation.
Lessard et al. (2018)	For stroke survivors and many other people with upper-extremity impairment	activities of daily living	Portable Equipment, CRUX, mimetic control algorithm, and mechanical functionality	Exosuit to address this challenge: Compliant Robotic Upper-extremity eXosuit (CRUX).
Kiml et al. (2018)	focused on industrial functionality	Soft exoskeletons, known as exosuit, reinforce workers in lifting heavy loads	Equipment, a voice-controlled upper limb exosuit designed to aid its user in lifting up to 10kg per arm.	A soft exosuit for industrial applications, with the potential to reduce the effort in the arms in lifting and holding tasks.
Xiloyannis et al (2018)	stroke survivors	for assisting elbow movements in activities of daily living (ADLs).	Equipment	the design, control, and evaluation of a cable-driven soft suit for assisting elbow movements in activities of daily living (ADLs).
Lessard et al. (2017)	rehabilitation patients and/or augmentation of human movements	could be useful in physical therapy and in extreme environments where users are expected to exert their bodies to the fullest extent.	Portable Equipment, CRUX, a compliant, robotic exosuit for upper extremities	CRUX provides a lightweight, compliant multi-joint upper-extremity solution for meaningful and useful augmentation of human movements without sacrificing flexibility.
Gaponov et al. (2017)	the patient that needs rehabilitation to perform tasks that involve trunk motions and overground movements	fully portable, lightweight exosuit-type device for shoulder and elbow to assist dynamic rehabilitation	Equipment, Auxilio, based on working principle and kinematics.	The exosuit, Auxilio, is a light, compact, and easily adjustable device that assists shoulder flexion, abduction, and elbow flexion.

Of the 26 articles analyzed, most describe the device (18) to be used in the rehabilitation of patients who have suffered some accident (impairments muscular dystrophies, by stoke) that made it impossible to use the upper limbs (approximately 6) and in everyday tasks, the rest to be used in an occupational environment as support and extension to manual tasks (2). Some articles do not explicitly refer to the population to which the device is suitable, referring to a general application in its application: in rehabilitation, either to help in the execution of tasks that require effort or to help in the tasks and movements of astronauts. The remaining 12 refer to the development of the models/algorithms and mechanisms that are attached to the device, the control platform, and the sensors needed to follow the movements of the upper limbs.

It is noteworthy that the identification of two teams that develop this type of device is visible. On the one hand, the Samper-Escudero team, with the description of the developments of LUXBIT, a cable-driven flexible exoskeleton that combines textiles and sewing patterns to anatomically adapt and promote freedom of movement in outdoor and workspace applications. On the other hand, Lessard's team with CRUX, portable equipment with a mimetic control algorithm and mechanical functionality, offers a lightweight, compliant upper-extremity solution to augment human movements while preserving flexibility.

4.Final Considerations

The systematic literature review (SLR) provides a comprehensive understanding of exoskeletons and exosuits, their differences, and how they function. Exoskeletons and exosuits are wearable devices projected to augment human capabilities in various applications. However, they differ in construction and weight: exoskeletons are often heavier and bulkier and started being developed for medical purposes to support and assist individuals with physical impairments and in industrial settings to reduce the risk of injury and fatigue among workers; exosuits are lighter and more flexible. Both exoskeletons and exosuits can also assist healthy individuals in enhancing their performance and reducing the risk of injury in sports and military settings. They have shown potential therapeutic benefits in rehabilitation and physical therapy by promoting muscle activation and improving gait patterns in individuals with mobility impairments. The versatility of exosuits makes them a promising area of research and development in wearable technology.

The evolution of these devices throughout the years is not surprising, given their role in the current industrial revolutions underway (4.0 and 5.0); the fourth industrial revolution (I4.0) started in 2011, with a focus on digitalization, marked by the use of cyber-physical systems on connected devices to automate the processes further. Industry 5.0 (I5.0), on the other hand, represents a new era of manufacturing that strongly emphasizes the importance of human involvement and collaboration with advanced technologies. Unlike its predecessors, which focused on automation and efficiency at the expense of human input, Industry 5.0 recognizes the unique skills and insights that humans bring to the production process (Sarfraz et al., 2021). By leveraging technologies such as artificial intelligence, robotics, and the Internet of Things, Industry 5.0 aims to empower workers and enable them to work alongside machines to achieve better outcomes. This shift towards a more human-centric approach has the potential to not only increase productivity and efficiency but also improve job satisfaction and working conditions for employees. Industry 5.0 is, thus, characterized by a focus on the human element in manufacturing, including integrating advanced technology with human workers to enhance productivity, safety, and job satisfaction. Exos are a prime example of this trend, as they are wearable devices that augment human capabilities and have potential applications in various industries, including manufacturing, healthcare, sports, and even in more disruptive activities, such as space exploration. Exoskeletons have been shown to augment their users' skills and physical abilities significantly. This technology has the potential to be particularly useful for astronauts during spacewalks, where the effects of microgravity can result in a significant loss of physical capabilities. In such scenarios, exoskeletons can provide the necessary support and assistance to allow astronauts to perform tasks more efficiently and precisely. Additionally, exoskeletons equipped with sensors and other advanced technologies can help monitor and regulate astronauts' vital signs and other health parameters, ensuring their safety and well-being during long space missions.

Although the analysis provides insights into the evolution and trends of exoskeletons and exosuits, as an SLR relies on existing literature, it may have inherent constraints and biases. It may not capture all aspects or address every research question comprehensively. The present work focused on the last decade, achieved through one selected database (Scopus). Documents without online publication versions available were not included. In further analysis, other databases, such as the Web of Science, could also be considered for broader searching. The search could be extended beyond the use of keywords by considering the iterative snowball backward and forward searches, which could help identify relevant literature that may have been missed and enhance the comprehensiveness of the SLR (Webster & Watson, 2002). Nevertheless, the findings offer a broad understanding of the development, differences, and applications of exoskeletons and exosuits, highlighting the importance of considering the human element in designing and implementing wearable technology. In short, by providing additional support, reducing fatigue and injury risk, and enhancing physical performance, exoskeletons and exosuits can improve human workers' quality of work and life. This progress aligns with the values of Industry 5.0, which seeks to optimize the relationship between technology and humans to benefit both. As a result, it is possible to observe an increasing focus on the development of exoskeletons and exosuits in recent years as the importance of the human element in manufacturing and other industries continues to be recognized.

The breakpoint observed in 2015 may also be an indicator of this transition between I4.0 and I5.0, as this year can be considered approximately the mid-term of the implementation of I4.0 and I5.0 (Sarfraz et al., 2021). As such, the next step in this research, among other things, involves considering the data divided into these two clusters (before and after I5.0 onset) regarding the publishing date, using 2015 as a breakpoint to understand better what may have caused the exponential trend afterward. A further step in this research would be to understand which areas have been tackled by some specific countries.

5.References

Bardi, E., Gandolla, M., Braghin, F., Resta, F., Pedrocchi, A. L. G., & Ambrosini, E. (2022). Upper limb soft robotic wearable devices: A systematic review. *Journal of NeuroEngineering and Rehabilitation, 19(*1), Article 87. https://doi.org/10.1186/s12984-022-01065-9

Biddiss, E., & Chau, T. (2007). Upper limb prosthesis use and abandonment: A survey of the last 25 years. *Prosthetics and Orthotics Internationa, 31*(3), 236–257. https://doi.org/10.1080/03093640600994581

Burchielli, D., Lotti, N., Missiroli, F., Bokranz, C., Pedrocchi, A., Ambrosini, E., & Masia, L. (2022). Adaptive hybrid FES-force controller for arm exosuit. *Proceedings of the IEEE International Conference on Rehabilitation Robotics,* 1-6. https://doi.org/10.1109/ICORR55369.2022.9896493

Burton, S. D. (2020). Responsible use of exoskeletons and exosuits: Ensuring domestic security in a European context. *Paladyn, 11*(1), 370–378. https://doi.org/10.1515/pjbr-2020-0015

Chiaradia, D., Xiloyannis, M., Solazzi, M., Masia, L., & Frisoli, A. (2019). Rigid versus soft exoskeletons: Interaction strategies for upper limb assistive technology. In J. Rosen & P. W. Ferguson (eds.), *Wearable robotics: Systems and applications,* (pp. 67–90). Elsevier. https://doi.org/10.1016/B978-0-12-814659-0.00004-7

Cordella, F., Ciancio, A. L., Sacchetti, R., Davalli, A., Cutti, A. G., Guglielmelli, E., & Zollo, L. (2016). Literature review on needs of upper limb prosthesis users. Frontiers in Neuroscience, 10, Article 209. Media S.A. https://doi.org/10.3389/fnins.2016.00209

Elstub, L. J., Fine, S. J., & Zelik, K. E. (2021). Exoskeletons and exosuits could benefit from mode-switching body interfaces that loosen/tighten to improve thermal comfort. *International Journal of Environmental Research and Public Health, 18*(24), 13115. https://doi.org/10.3390/ijerph182413115

Fu, J., Choudhury, R., Hosseini, S. M., Simpson, R., & Park, J. H. (2022). Myoelectric control systems for upper limb wearabler robotic exoskeletons and exosuits — A systematic review. *Sensors, 22*(21), 8134. https://doi.org/10.3390/s22218134

Galofaro, E., D'Antonio, E., Lotti, N., & Masia, L. (2022). A hybrid assistive paradigm based on neuromuscular electrical stimulation and force control for upper limb exosuits. *Proceedings of the IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, 1-6. https://doi.org/10.1109/BioRob52689.2022.9925466

Gaponov, I., Popov, D., Lee, S. J., & Ryu, J. H. (2017). Auxilio: A portable cable-driven exosuit for upper extremity assistance. *International Journal of Control, Automation and Systems, 15*(1), 73–84. https://doi.org/10.1007/s12555-016-0487-7

Georgarakis, A. M., Wolf, P., & Riener, R. (2019). Simplifying exosuits: Kinematic couplings in the upper extremity during daily living tasks. *Poceedings of the 2019 IEEE 16th International Conference on Rehabilitation Robotics*, 423-428. https://doi.org/10.1109/ICORR.2019.8779401

Kieran Little, C. W. A., Xiloyanis, M., de Noronha, B. A.P.S., Kim, Y. G., Masa, L., & Accoto, D. (2019). IMU-based assistance modulation in upper limb soft wearable exosuits. *Proceedings of the 2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*, 1197–1202. https://doi.org/ 10.1109/ICORR.2019.8779362

Kiml, Y. G., Xiloyannis, M., Accoto, D., & Masia, L. (2018). Development of a soft exosuit for industriale applications. *Proceedings of the 2018 7th IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics*, 324–329. https://doi.org/10.1109/BIOROB.2018.8487907

Langard, M., Aoustin, Y., Arakelian, V., & Chablat, D. (2020). Investigation of the stresses exerted by an exosuit of a human arm. *Mechanisms and Machine Science, 80*, 425–435. https://doi.org/10.1007/978-3-030-33491-8_50

Lessard, S., Pansodtee, P., Robbins, A., Baltaxe-Admony, L. B., Trombadore, J. M., Teodorescu, M., Agogino, A., & Kurniawan, S. (2017). CRUX: A compliant robotic upper-extremity exosuit for lightweight, portable, multi-joint muscular augmentation. *Proceedings of the 2017 IEEE International Conference on Rehabilitation Robotics*, 1633–1638. https://doi.org/10.1109/ICORR.2017.8009482

Lessard, S., Pansodtee, P., Robbins, A., Trombadore, J. M., Kurniawan, S., & Teodorescu, M. (2018). A soft exosuit for flexible upper-extremity rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 26*(8), 1604–1617. https://doi.org/10.1109/TNSRE.2018.2854219

Lo, H. S., & Xie, S. Q. (2012). Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects. *Medical Engineering and Physics, 34*(3), 261–268. https://doi.org/10.1016/j.medengphy.2011.10.004

Lotti, N., Xiloyannis, M., Missiroli, F., Chiaradia, D., Frisoli, A., Sanguineti, V., & Masia, L. (2020, November). Intention-detection strategies for upper limb exosuits: Model-based myoelectric vs dynamic-based control. In *2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)* (pp. 410-415). IEEE. https://doi.org/10.1109/BioRob49111.2020.9224284

Lotti, N., Missiroli, F., Xiloyannis, M., & Masia, L. (2022). A model-based control strategy for upper limb exosuits. In J. C. Moreno, J. Masood, U. Schneider, C. Maufroy, & J. L. Pons (Eds.)*, Wearable Robotics: Challenges and Trends* (pp. 339–343). Springer International Publishing. https://doi.org/10.1007/978-3-030-69547-7_55

Missiroli, F., Lotti, N., Tricomi, E., Bokranz, C., Alicea, R., Xiloyannis, M., Krzywinski, J., Crea, S., Vitiello, N., & Masia, L. (2022). Rigid, soft, passive, and active: A hybrid occupational exoskeleton for bimanual multijoint assistance. *IEEE Robotics and Automation Letters, 7*(2), 2557–2564. https://doi.org/10.1109/LRA.2022.3142447

Natividad, R. F., Miller-Jackson, T., & Chen-Hua, R. Y. (2021). A 2-DOF shoulder exosuit driven by modular, pneumatic, fabric actuators. *IEEE Transactions on Medical Robotics and Bionics, 3*(1), 166–178. https://doi.org/10.1109/TMRB.2020.3044115

Pastor, S. S., Rivera, C. T., Avilés, O. F., & Mauledoux, M. F. (2019). A real-time motion tracking wireless system for upper limb exosuit based on inertial measurement units and flex sensors. *International Journal of Engineering, Transactions B: Applications, 32*(6), 820–827. https://doi.org/10.5829/ije.2019.32.06c.04

Pérez Vidal, A. F., Rumbo Morales, J. Y., Ortiz Torres, G., Sorcia Vázquez, F. de J., Cruz Rojas, A., Brizuela Mendoza, J. A., & Rodríguez Cerda, J. C. (2021). Soft exoskeletons: Development, requirements, and challenges of the last decade. *Actuators, 10*(7), Article 166. https://doi.org/10.3390/act10070166

Pont-Esteban, D., Contreras-González, A. F., Samper-Escudero, J. L., Sáez-Sáez, F. J., Ferre, M., & Sánchez-Urán, M. (2021). Validation of an elbow position super-twisting sliding-mode controller for upper-limb exosuit using a soft position sensor. *Journal of Physics: Conference Series, 1828*(1), 012074. https://doi.org/10.1088/1742-6596/1828/1/012074

Pont-Esteban, D., Sanchez-Uran, M. A., & Ferre, M. (2022). Robust motion control architecture for an upper-limb rehabilitation exosuit. *IEEE Access, 10*, 113631–113648. https://doi.org/10.1109/ACCESS.2022.3217528

Rosen, J., & Perry, J. C. (2007). Upper limb powered exoskeleton. *International Journal of Humanoid Robotics, 4*(3), 529-548. https://doi.org/10.1142/S021984360700114X

Sambhav, R., Jena, S., Chatterjee, A., Bhasin, S., Santapuri, S., Kumar, L., Muthukrishnan, S. P., & Roy, S. (2022). An integrated dynamic closed loop simulation platform for elbow flexion augmentation using an upper limb exosuit model. *Frontiers in Robotics and AI, 9*, 768841. https://doi.org/10.3389/frobt.2022.768841

Samper-Escudero, J. L., Contreras-González, A. F., Ferre, M., Sánchez-Urán, M. A., & Pont-Esteban, D. (2020a). Efficient multiaxial shoulder-motion tracking based on flexible resistive sensors applied to exosuits. *Soft Robotics, 7*(3), 370–385. https://doi.org/10.1089/soro.2019.0040

Samper-Escudero, J. L., Gimenez-Fernandez, A., Sanchez-Uran, M. A., & Ferre, M. (2020b). A cable-driven exosuit for upper limb flexion based on fibres compliance. *IEEE Access, 8*, 153297–153310. https://doi.org/10.1109/ACCESS.2020.3018418

Samper-Escudero, J. L., Coloma, S., Olivares-Mendez, M. A., Sanchez-Uran, M. A., & Ferre, M. (2021). Assessment of a textile portable exoskeleton for the upper limbs' flexion. *Proceedings of the 2021 IEEE 2nd International Conference on Human-Machine Systems*, 1-6. https://doi.org/10.1109/ICHMS53169.2021.9582447

Samper-Escudero, J. L., Coloma, S., Olivares-Mendez, M.A., González, S. U., & Ferre, M. A. (2022). A compact and portable exoskeleton for shoulder and elbow assistance for workers and prospective use in space. *IEEE Transactions on Human-Machine Systems, 99,* 1-10. https://doi.org/10.1109/THMS.2022.3186874

Sarfraz, Z., Sarfraz, A., Iftikar, H. M., & Akhund, R. (2021). Is Covid-19 pushing us to the fifth industrial revolution (Society 5.0)? *Pakistan Journal of Medical Sciences, 37*(2), 1–4. https://doi.org/10.12669/pjms.37.2.3387

Silva, K. A. G., Costa, A. P., & Teixeira, N. P. (2022). Qualitative analysis of digital content curation models: Possibilities for use in CAQDAS. *New Trends in Qualitative Research, 12*, e630. https://publi.ludomedia.org/index.php/ntqr/article/view/630

Sy, L., Hoang, T. T., Bussu, M., Thai, M. T., Phan, P. T., Low, H., Tsai, D., Brodie, M. A., Lovell, N. H., & Do, T. N. (2021). M-SAM: Miniature and soft artificial muscle-driven wearable robotic fabric exosuit for upper limb augmentation. *Proceedings of the 2021 IEEE 4th International Conference on Soft Robotics*, 575-578. https://doi.org/10.1109/RoboSoft51838.2021.9479333

Thomé, A. M. T., Scavarda, L. F., & Scavarda, A. J. (2016). Conducting systematic literature review in operations management. *Production Planning & Control, 27*(5), 408-420. https://doi.org/10.1080/09537287.2015.1129464

van Eck, N. J., & Waltman, L. (2023). *VOSviewer Manual*. VOSviewer.

Walmsley, C. P., Williams, S. A., Grisbrook, T., Elliott, C., Imms, C., & Campbell, A. (2018). Measurement of upper limb range of motion using wearable sensors: A systematic review. *Sports Medicine – Open, 4*(1), Article 53 https://doi.org/10.1186/s40798-018-0167-7

Wang, Q., Markopoulos, P., Yu, B., Chen, W., & Timmermans, A. (2017). Interactive wearable systems for upper body rehabilitation: A systematic review. *Journal of NeuroEngineering and Rehabilitation, 14*(1), Article 20. https://doi.org/10.1186/s12984-017-0229-y

Webster, J., & Watson, R. T. (2002). Analyzing the past to prepare for the future: Writing a literature review. *MIS Quarterly, 26*(2), 13–23. https://www.jstor.org/stable/4132319

Weston, E. B., Alizadeh, M., Hani, H., Knapik, G. G., Souchereau, R. A., & Marras, W. S. (2022). A physiological and biomechanical investigation of three passive upper-extremity exoskeletons during simulated overhead work. *Ergonomics, 65*(1), 105–117. https://doi.org/10.1080/00140139.2021.1963490

Xiloyannis, M., Dhinh, K. B., Cappello, L., Antuvan, C. W., & Masia, L. (2018). A soft wearable elbow exosuit. In R. K.-Y. Tong. (ed.), *Wearable technology in medicine and health care* (pp. 193–214). Elsevier. https://doi.org/10.1016/B978-0-12-811810-8.00010-5

Celina Pinto Leão
Centro ALGORITMI, University of Minho, Guimarães, Portugal
https://orcid.org/0000-0003-3725-5771
cpl@dps.uminho.pt

Vinicius Silva
Centro ALGORITMI, University of Minho, Guimarães, Portugal
https://orcid.org/0000-0003-0082-343X
d7662@dei.uminho.pt

Susana Pinto da Costa
Centro ALGORITMI, University of Minho, Guimarães, Portugal
https://orcid.org/0000-0001-7440-8787
susana.costa@dps.uminho.pt

Submission date: March 2023
Review date: March 2023
Publication date: July 2023