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User Requirements and Involvement Methods in the Development of Hand Exoskeletons: A Review

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Current hand exoskeleton systems for assistive and rehabilitative purposes pose challenges due to weight, bulk, and size, thus negatively affecting user experience in terms of comfort and wearability. End-user involvement is vital during design and deployment to improve usefulness, usability and user acceptance. A scoping review was conducted to identify the currently prioritized user requirements and user-centered practices in the development of hand exoskeleton systems. Content analysis was used to identify the user-centered design criteria and user research methodologies in 124 articles. More studies aim for rehabilitation than assistance and the dominant form of assessment is system validation. Wearability, comfort, portability, adaptability, affordability and safety were the most frequently targeted user-centered criteria. Only 38 articles reported assessment with human subjects, the majority of them being functional tests, followed by usability tests. We offer user-centered design directions and methodological suggestions for user involvement to improve the usability and acceptability of the exoskeleton systems, and discuss the necessity for restructuring the engineering design strategy for better adaptability. This research has direct applications for the design and assessment of assistive and rehabilitative hand exoskeletons by offering user requirements. The findings and suggestions can have wider implications in the field of wearable robotics for developing, evaluating, and refining systems through a user-centered perspective.

Additional Keywords and Phrases: stroke; exoskeleton; assistive technologies; wearable robotics; user requirements

1 INTRODUCTION

An exoskeleton is a wearable robot which aims to assist users in recovering, substituting or amplifying sensorimotor functions. The use of this specific wearable technology has recently accelerated in military, industry and rehabilitation settings [1]. Higher life expectancy, an ageing society and an increased survival rate of strokes and injuries due to medical advancements give rise to the increased prevalence of such wearable systems for assistive and rehabilitative purposes, along with growing industrial and entertainment technology markets [2]. The use of wearable assistive technologies is expected to ease the medical burden of long-term care and labor shortages due to changing demographics [3]. Consequently, the assistive robotics market is expected to continue its global growth, most of which is occupied by exoskeleton systems and solutions for upper body extremities [4].

Robotic training in rehabilitation has proven effective in substantial recovery of motor function in conventional clinical settings [5], though home deployment is expected to provide better effectiveness as a result of higher frequency and duration in functional exercises [6]. Moving from clinical settings to end-user context brings additional challenges. Currently, exoskeletons are mainly employed in academic and clinical settings due to issues with pain, comfort and donning the skeleton, and further commercialization requires a

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better understanding of the needs of potential users [7]. As wearability means being in direct contact and interaction with the human body, compliance with user requirements to ensure usability is an important aspect of the exoskeleton technology [8].

The current exoskeleton systems pose limitations in terms of the device weight, bulk and size. This negatively affects comfort and portability [2,8,9], in addition to limitations in device capability to fit into the natural use context [8,10]. Such issues harm technology acceptance, hence leading to device abandonment [8,11–13]. Dealing with technical complexity and barriers to user acceptance of wearable robots requires multidisciplinary collaboration among diverse fields [2,14–16], and a multi-stakeholder system delivery approach [17].

In this study, we focus on the user requirements for assistive and rehabilitative hand exoskeletons. Hand exoskeletons embody all the state-of-the-art challenges brought by current assistive robotics technologies and more. Specifically, the kinematic complexity of the hand, the diversity of tasks that need to be supported, and the need for adaptability to these diverse combinations of movements and hand sizes are addressed [2,18,19]. The aforementioned difficulties were faced throughout the engineering design process while selecting mechatronics components and the synthesis of control systems and mechanisms. To actuate the exoskeletons, various actuators such as pneumatic, ultrasonic, and DC motors are used [20]. Higher torque and power requirements necessitate massive actuators or pneumatic actuation systems, resulting in increased hand inertia or control system design difficulties. Likewise, depending on the intended control performance, the exoskeleton should be equipped with a variety of sensors. Increased sensor number adversely affects the mechanical design and may increase the overall mass required to be carried on the hand. Excessive hand and finger inertia during rehabilitation will result in abnormal motor re-learning [21]. Rehabilitation after stroke strives for functional recovery rather than compensation. The goal of stroke rehabilitation is to achieve functional recovery through motor re-learning [22].

In recent years, the design of robotic rehabilitation has taken into account motor learning principles as well [23]. The control systems of exoskeletons play a significant role in the efficacy of robotic rehabilitation. The patient would suffer from slacking if the exoskeleton's control mechanism was entirely dictated [24,25]. The role of the control system in motor re-learning is currently under investigation and has not been properly articulated. Some of the most common control system techniques in the literature include assistive, corrective, resistive, and disruptive actions [26]. The control approach should be adopted and altered based on the patient's functional level. By promoting motor variability and exploration strategies, disruptive or resistive ways of control activities may give an advantage over assistive solutions [27,28]. In addition to the control system design, the synthesis of the exoskeleton mechanism includes challenges based on kinematic and kinetic constraints, as well as the desired motion characteristics. All these systemic complications make the design of robotic hand rehabilitation and assistance systems a considerably challenging field.

As seen, hand exoskeleton systems are technically challenging to engineer and assess. There are very few systems that are commercially available for end-users, e.g., Carbonhand by Bioservo Technologies [29], Neomano by Neofact [30], Vrehab by Vendra Medical [31], HandyRehab [32], and R-Touch by BTL Robotics [33]. These commercially accessible robotic systems exhibit different features, limitations, and perspectives concerning engineering design. Some systems are available for clinical use within specific rehabilitation programs, under professional supervision (e.g. Hand of Hope) [34]. Furthermore, only a few devices (such as HandyRehab) [32] provide versions appropriate for home therapy. Home based rehabilitation brings additional objectives, constraints, limitations and challenges. Technology Readiness Level (TRL) is often referred to describe the maturity level of wearable robots. TRL is a 9-level metric developed by NASA to assess the maturity level of various technologies [35]. Terrazas-Rodas et al. [36] conducted a survey with developers of wearable robotic devices, vast majority of which aim at assistance or rehabilitation. They identified that the TRL level for most devices are between 4-7, which corresponds to prototype level. A review study of lower-limb exoskeleton systems for rehabilitation and assistance found that most of them are at Level 5-6 [37]. Another study reviewing upper limb wearable robots identified that majority (75%) of the devices scored a TRL of 4-5, which means they are at validation stages [38].

Assistive technologies are complex product systems, the development of which require the participation of primary, secondary and tertiary users consisting of end-users who benefit directly from the technology, medical

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professionals, professional or non-professional caretakers and institutional stakeholders [8,14]. However, direct efforts to understand the primary user requirements have been somewhat limited in the scientific community [11], while the specification of end-user requirements is often delegated to the technical and clinical experts [10]. To ensure better usability, user satisfaction and technology acceptance, it is vital to involve end-users in the development of assistive technologies such as exoskeletons [1,15,39]. It is particularly useful to invite users to contribute to the decision-making process starting from the early design phases to identify design requirements from a user-centered perspective [14,40,41].

In addition to a strong focus on technology rather than user factors [10], limited user involvement, and lack of standards and rigor in user research are also underlined in the literature on assistive robotics. In their literature review of articles reporting user perspectives of exoskeleton technology, Hill et al. [11] found only three studies which directly involved end-users. Another review by Koumpouros et al. [42] shows that very few studies use reliable measures for the assessment of rehabilitation or assistive robot devices. They emphasize the lack of standards as the vast majority of the studies used non-validated instruments (93.9%) with tailor-made questionnaires being the most common tool (66.7%). A recent survey by Ármannsdóttir et al. [15] provides further evidence for the lack of standards in user involvement. Based on responses to a survey with professionals who take part in the development of lower limb exoskeletons, they found that many of them use "unspecified questionnaires" and "conversations with users" to assess issues such as comfort, satisfaction, usability and emotional responses. Consequently, current practices lack reliability in understanding, implementing and assessing positive user experience with assistive technologies [12].

Despite limited user-centered practices, issues such as comfort, portability and wearability of the exoskeletons are widely acknowledged in the literature [8,9,18,19,40,43,44]. However, subjective perceptions of users on these and other design requirements are rarely addressed. As robotic assistive devices are newly emerging, innovative technologies, it is important to go beyond conventional usability tests and understand user perceptions and reflections [45]. User perceptions of usability, usefulness and appearance are equally important for defining design requirements and accurate evaluation of the device [3,7,46–48]. Moreover, the mismatch between user expectations of the assistive technology and the experience the device currently offers might lead to dissatisfaction and device abandonment [11,49].

User studies conducted for the development of exoskeleton systems are rare but not absent. Very few studies focused on identifying user requirements [10,40,50] and usability assessment [18,44,51,52] of hand or arm exoskeletons. On the other hand, user studies for lower limb exoskeletons for mobility are more common [3,6,7,12,14,45,53–56]. To elicit user requirements and perceptions, interviews [10,14,45,57] and focus groups [6,40,54] are preferred. Examples of user evaluation techniques to assess usability, user satisfaction and acceptance of exoskeletons are System Usability Scale [12,44,51], Quebec User Evaluation with Assistive Technology [53], Tele-healthcare Satisfaction Questionnaire - Wearable Technology [44], Intrinsic Motivation Inventory [51,52], Credibility and Expectancy Questionnaire [52] and more commonly, custom-designed questionnaires and scales [3,7,12,18,45,56,58].

The fact that there are not many commercial/mature products means there are also not many studies available on longitudinal user research or evaluations, and little information about product adaptation, let alone opportunities for inquiring about reasons for device abandonment. However, it is still necessary to investigate technology acceptance and design requirements of hand exoskeletons from users' perspectives to develop solutions that are potentially useful, usable and satisfactory. In this sense, soft and rigid exoskeleton systems differ in terms of design and performance, which impact the user experience. For example, rigid exoskeletons offer better accuracy and functional performance but pose issues in terms of comfort, weight, bulkiness and appearance, whereas soft exoskeletons (also known as gloves) are lighter and safer but at the expense of device performance [2]. Furthermore, user-centered design requirements can be expected to differ for systems designed for assisting activities of daily living (AoDL), and for those developed for the recovery of motor functions in conventional rehabilitation settings.

A number of review studies attempted to present the state-of-the-art in exoskeleton designs. Some of these reviews focus on either lower-limb [59] or upper-limb devices [9,13,38]. These reviews mostly outline device characteristics, such as actuation type, mechanical design, technology readiness level, degrees of freedom or control strategy. One review study focused entirely on the factors affecting user experience with exoskeletons

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[60], though the review scope was wide to include all limbs and application areas including occupational, rehabilitation, military and sports purposes. Five reviews focused exclusively on hand exoskeletons. Review by Ferguson et al. [2] outline various types of mechanism, actuation, transmission, sensing method, and control; and introduces existing hand exoskeleton systems under the following categories: assistive, rehabilitation, augmentation and others. Heo et al. [61] classified existing hand exoskeleton systems based on actuator type and intention sensing method. Tran et al. [62] analyzed the reviewed systems based on actuation mechanism, degrees of freedom, range of motion, device weight, material, sensor type, portability and alike specifications. Shadid et al. [63] focused on soft hand exoskeletons based on their mechanical, electrical and functional attributes (actuation, force, degree of freedom, finger movement, range of motion, weight, purpose) and provides an overview of the recent trends in the soft robotic hand exoskeletons. Du Pleiss et al. [64] reviewed active hand exoskeletons in terms of type, purpose, design (actuation, sensing, control) and design requirements. Wearability and adaptability were further discussed for different design types. While these studies are extremely useful for identification of mechanical design strategies, they have little contribution to our understanding of user requirements and planning user-centred design methodologies in the design and development of hand exoskeletons.

The goal of this study is to identify and propose user-centered directions for the development and assessment of hand exoskeleton systems for assistive and rehabilitative purposes. We aim to answer the following research questions: (1) What are the common user-centered criteria considered when developing hand exoskeleton systems? (2) In which ways users are involved in the hand exoskeleton design process? For this purpose, we conducted a literature review to identify how and to what extent user factors are considered in the development of hand exoskeleton systems for assistive and rehabilitative purposes. We expect this review to demonstrate current trends and gaps in prevalent research practices to be able to discuss future user-centered directions that need to be taken when developing assistive and rehabilitative hand exoskeleton systems. The contribution of this study is twofold: First, by providing a comprehensive overview of user requirements, and the extent of user-centered practices in the development of hand exoskeletons, we aim to expand and complement the knowledge and perspective for mechanical design strategies. Second, we propose engineering design strategies for improved adaptability and overall usability of these systems. In the rest of the paper, we will present the methodology, analysis and discussions on the findings of the review.

2 METHODOLOGY

Collection of the data sources was conducted in two phases: initial search in March 2022, and complementary follow-up search in January 2024 to update the dataset. Continuously updating the systematic review is recommended in healthcare research as new data becomes available [65]. Although the analysis of our initial scoping review had not been published at the time, we decided to update the data sources given the rate at which the literature is emerging, and the extensive time spent for the initial, labor-intensive review and reporting process. This section outlines the methodology initial and updated search and analysis.

2.1 Search Strategy & Data Sources

In March 2022, three online databases, Web of Science, Scopus, and PubMed, were searched to find relevant sources. The scanning was done among journal papers and conference proceedings published until 31 December 2021, without limiting the start date. We deliberately included the conference proceedings in the review because we focus on the development process of the exoskeletons, which includes works in progress, likely to be reported in conferences. No exclusions were specified in the search strategy. However, the word "user" was added to eliminate purely clinical studies. A total of 711 records were identified at this stage. Creation of the coding scheme and the intercoder reliability calculations detailed in Data Analysis section were made based on this initial dataset.

Considering the time passed following the initial review, analysis and reporting process, an update to the search was made in January 2024 in order to include sources published in 2022 and 2023. The same search strategy was applied in the same databases and an additional 249 records were identified at this stage. The keywords and fields used in each database and the number of resulting records in each stage are given in Table 1.

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Table 1: Search strategy and the number of hits from the covered databases (S1: Search 1, S2: Search 2)

		Total
Web of Science	exoskeleton (All Fields) AND rehabilitation (All Fields) AND hand (All Fields) AND user (All Fields)	284 records *(S1:208 - S2:76)*
	exoskeleton (all fields) AND assist (all fields) AND hand (all fields) AND user (all fields)	168 records *(S1:121 - S2:47)*
Scopus	TITLE-ABS-KEY ((“hand”) AND (“exoskeleton”) AND (“rehabilitation”) AND (“user))	250 records *(S1:183 - S2:67)*
	TITLE-ABS-KEY ((“hand”) AND (“exoskeleton”) AND (“assist”) AND (“user))	109 records *(S1:77 - S2:32)*
Pubmed	All Fields=(hand) AND All Fields=(exoskeleton) AND All Fields=(rehabilitation) AND All Fields=(user)	81 records *(S1:64 - S2:17)*
	All Fields=(hand) AND All Fields=(exoskeleton) AND All Fields=(assist) AND All Fields=(user)	68 records *(S1:58 - S2:10)*

2.2 Study Selection

Studies were selected to be examined in this review if they include a design of an original hand exoskeleton device focusing on user assistance or rehabilitation purposes. Papers focusing on other upper-limb parts (wrist or arm extensions of exoskeletons) and special-purpose tools and apparatus were excluded. Studies were also excluded if (i) there was not a reported hand exoskeleton design, (ii) the reported exoskeleton design was not to be used for rehabilitation or assistive purposes, (iii) the study only focuses on the advancement of technical performance or partial improvement instead of mechanical design specifications (e.g., new materials for actuators or a new control method) and, (iv) the article was not written in English.

The initial database search resulted in 711 studies in total including 329 from Web of Science, 260 from Scopus, and 122 from PubMed. The authors gathered all 711 records with their titles, abstracts, authors, publication venues and years, and imported them into a Microsoft Excel spreadsheet. Following that, one author screened the titles and abstracts of the articles to exclude duplications (n=400). In this stage, 155 papers were deemed not eligible going through their titles and abstracts, since they either did not include a hand exoskeleton or were not written in English. For the remaining 156 studies, a full-text review was conducted by the authors to investigate further their eligibility based on the above-mentioned inclusion and exclusion criteria. Uncertainties about including some of the articles were resolved through discussion and reaching a consensus. As a result, 106 studies were included in the initial review. The updating review followed the same procedure, which resulted in the inclusion of additional 18 studies. Consequently, 124 studies were included in this scoping review. Details of this stage are reported in the PRISMA chart [66] (Figure 1).

2.3 Data Analysis

It is seen in the literature that user-centered methodology is not common among the studies including the development of hand exoskeleton systems. Thus, user-oriented design criteria and terminology might not be apparent at first glance. Therefore, in this scoping review, data is examined through content analysis [67]. We adopted an ‘emergent coding’ strategy where two researchers took part in the analysis to conduct a preliminary examination of the data and create a codebook, which was later used for main analysis. The analysis steps are explained in detail below.

Initially included 106 studies were analyzed with an inductive coding approach [68] by performing full-text screening to determine and categorize the user-centered design criteria, assessment types of the produced systems (system validation and/or user study), and purpose of exoskeleton designs (assistive and/or rehabilitative) as stated in the articles. The articles that reported a user study were further investigated in terms of their methodology (sampling and methods used). In the first stage, 20 random articles were examined in

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detail by two authors, and open coding was performed individually for initial identification of the recurring themes inductively. Afterwards, the results were discussed, and the initial coding frame was created based on consensus.

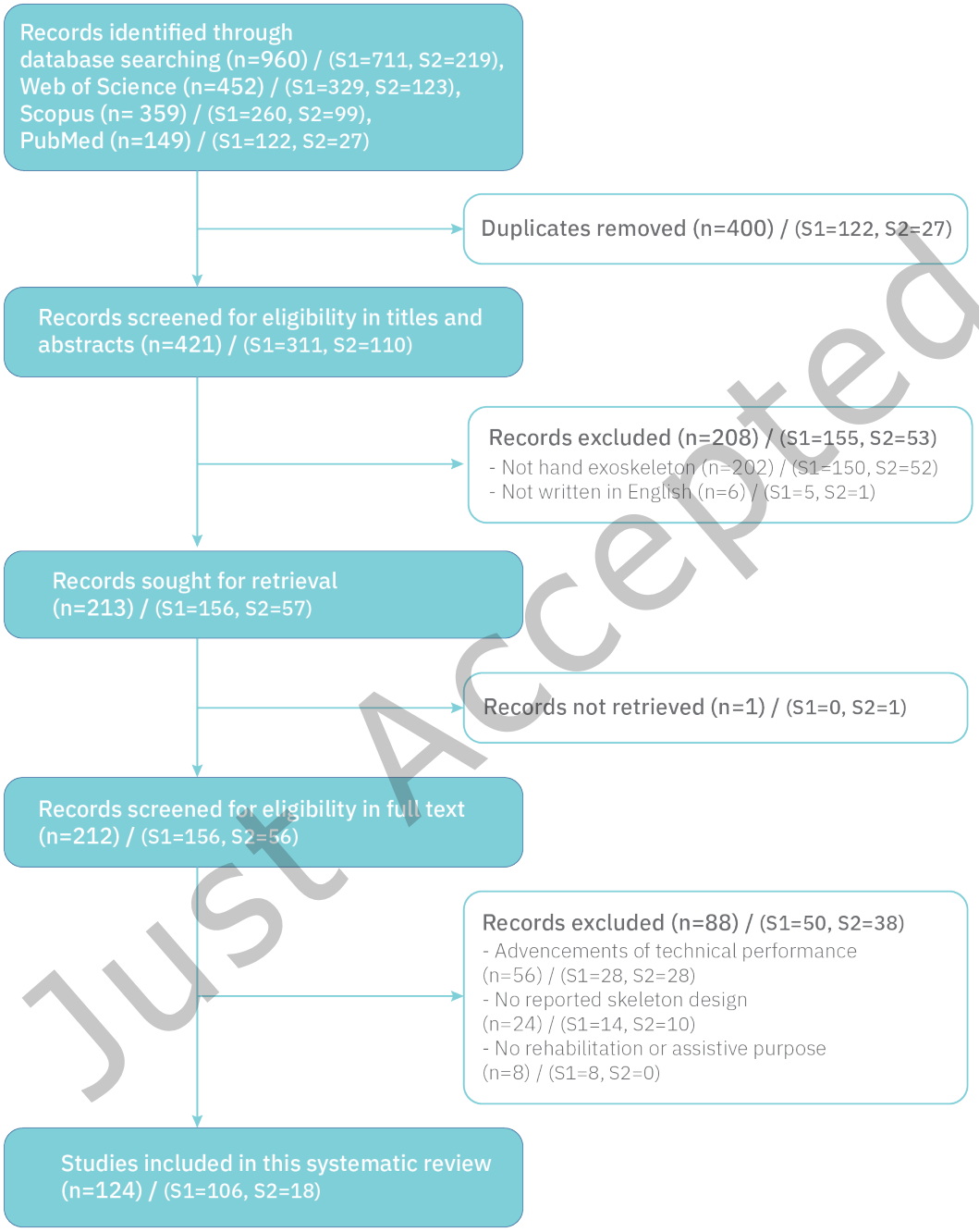

Figure 1: Identification of studies via databases and study selection process (n=124) (S1: Search 1, S2: Search 2)

According to this coding frame, 20 more random articles that were not included in the first analysis were selected and coded independently by both researchers. The results were compared to evaluate intercoder reliability [69]. Cohen's Kappa coefficient (κ) score was calculated as 0.77. Disagreements were solved through discussion and necessary updates were made to the initial coding frame to create the final coding frame.

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Following that, one researcher analyzed all 106 included articles in detail from scratch according to the final coding frame. Each user-centered criterion, the purpose of design and assessment type were coded for each article as 1-0 (1=present in the article, 0=absent in the article).

At the next stage, 20 (approx. 20%) more articles that were not screened in the previous stages were randomly selected and coded individually by the second researcher to calculate intercoder reliability. Through a comparison of the codes by both authors, Cohen's Kappa coefficient (κ) was calculated as 0.84. Since values above 0.8 are considered "very strong" agreement [70], the analysis of the first researcher was used as the final coding. Finally, the additional 18 records from the updated search were coded by the first researcher and included in the final analysis. The final coding sheet is shared as data in the supplement file.

After the final coding, papers that reported a user study were screened in full text by both researchers and discussed to identify the study purpose, sample size and characteristics, and tools and methods used in data collection, as is presented in the Results section.

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3 RESULTS

3.1 Purpose and Assessment of Designs

Of all the 124 articles included in the review, 53 of them are conference proceedings and 71 of them are journal articles. The first study that fits our inclusion criteria was published in 2006. Figure 2 shows the distribution of the number of articles grouped into three-year intervals. In the first three intervals, only 2, 7 and 9 studies were published respectively. A consistent increasing trend can be seen in the fourth (n=30) and fifth intervals (n=47). The trend took a downward trajectory in the last interval (n=30), which could be an indicator of the halted lab and human research due to social distancing measures during the pandemic. Another trend is seen in the breakout of published article types. In the first two intervals almost all the published articles were conference proceedings, while in the last two intervals, the number of journal articles surpassed the number of conference papers (Figure 3).

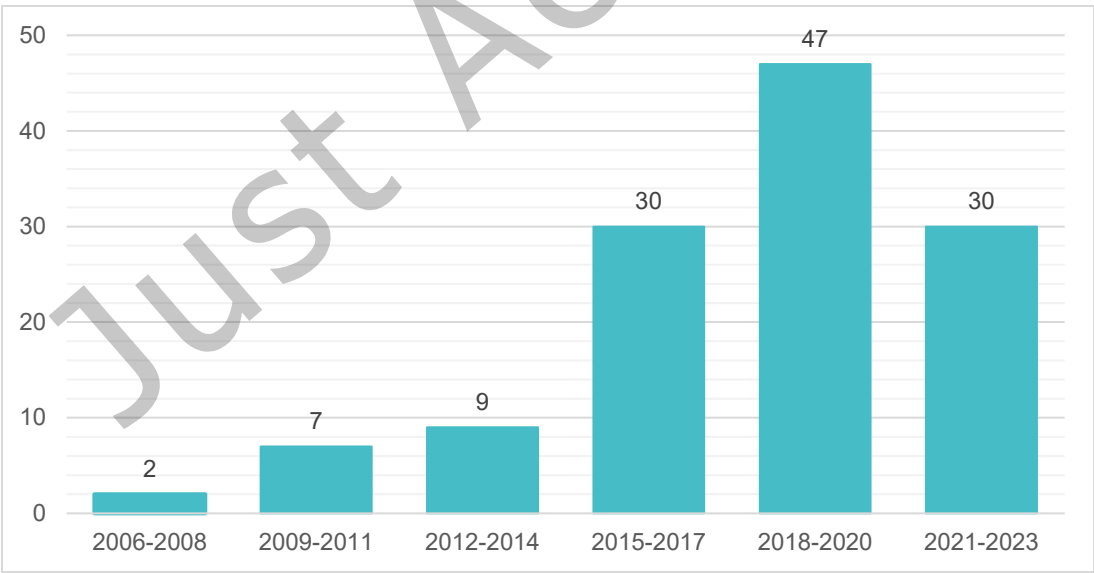

Figure 2: Yearly distribution of the number of articles

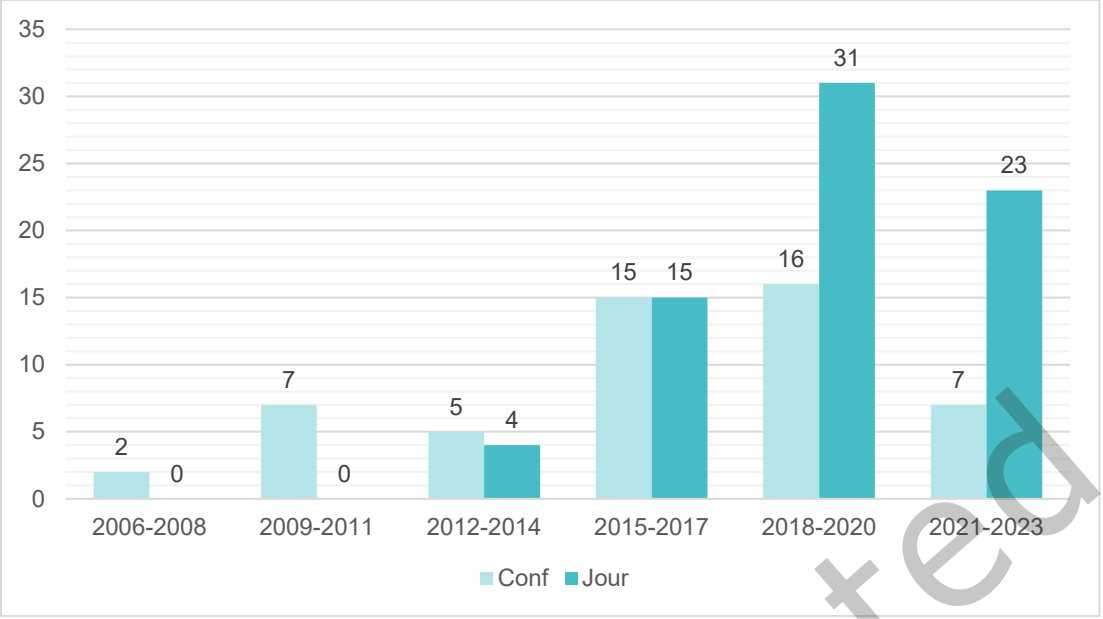

Figure 3: Yearly distribution of conference proceedings and journal articles

The frequencies of the purpose of design and assessment types are given in Table 2. Since we included the assistive and rehabilitative hand exoskeleton studies, the purpose of the exoskeleton design was coded as "assistive" and/or "rehabilitative". The studies aimed at both functions were coded for both. Assistive systems are those which aim to actively or passively assist the AoDL. Rehabilitative systems focus on restoring the function of the impaired hand by supporting repetitive movement. Similarly, two types of assessments were identified to have been reported in the articles, namely system validation and user study, while some studies applied both or neither. The goal of system validation is to confirm the mechanical/electrical functioning and control performance of the system. This type of assessment does not involve or aim at user input. User study was coded when the articles reported involving healthy subjects or patients in any type of explorative or experimental setup to identify or validate system requirements.

Table 2: Frequency of the purpose and assessment type

Purpose of design	
Assistive	33
Rehabilitative	66
Both (assist + rehab)	25
Assessment type	
System validation	82
User study	9
Both (system + user)	29
None	3

The results show that the majority of hand exoskeleton studies focus exclusively on rehabilitation (n=66). The number of studies targeting assistive hand exoskeletons is half the number of studies with rehabilitation

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purposes (n=33). However, a considerable number of studies (n=25) aim at providing both assistance in AoDL and rehabilitation through repetitive tasks for the recovery of functions of the impaired hand. Very few articles report solely on user studies (n=9) (see the following sections for details). More articles report both user studies and validation of the system (n=29). The vast majority of the papers (n=83) report exclusively on the assessment of the system performance. Only 3 papers did not report any type of assessment.

Figure 4 and Figure 5 present the yearly distributions of the frequencies of the device purpose and assessment type. The first three intervals are largely dominated by studies of devices for rehabilitation purposes, while the last three intervals witness an increasing prevalence of studies focusing on assistive (n=8, n=12, n=11) and multi-purpose hand exoskeletons (n=7, n=9, n=7). The rise in the number of reported hand rehabilitation systems continues in each interval until the last one. Similarly, there were almost no user studies reported in the first three intervals, but their late emergence leads to a consistent increase in recent years. Studies reporting exclusively on system performance assessment show a slower but steady increase, whereas the proportion of hybrid assessment types including both system and user validation multiplied in the last two intervals, catching up with the system validation studies.

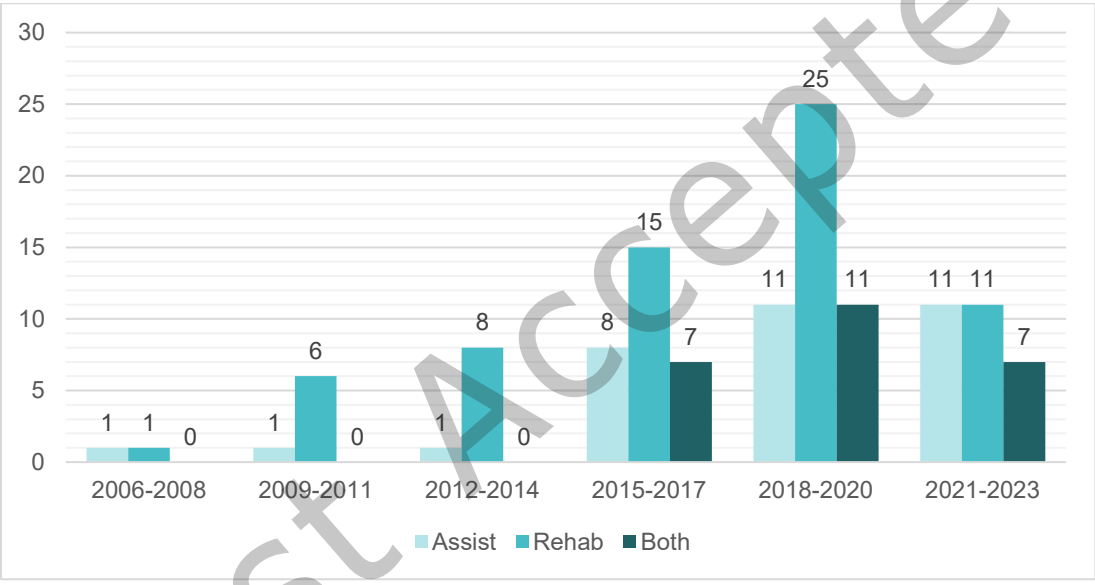

Figure 4: Yearly distribution of assistive and rehabilitative device studies

3.2 User-centered Design Criteria

We identified eight constructs in our analysis of the reported design criteria in the articles which can be associated with positive user experience. The descriptions of user-centered criteria identified in the articles are given below:

- *Adaptability* refers to the fitness of the exoskeleton to various hand sizes (physical) and differing rehabilitation needs (neurological). This construct is often worded in the articles as adjustability, flexibility, and customizability.
- *Affordability* is related to the overall cost of the exoskeleton system. Design tactics to decrease the cost include 3D-printing the finger modules, material alterations and overall simplification of the system.
- *Acceptability* is a concern related to user acceptance, willingness to use, and overall experience with the device. This is linked to the comfort, usability, and appearance of the skeleton.
- *Comfort* in use refers to the physical compatibility of the skeleton design with the human hand to diminish the physical burden and pain induced by wearing and repetitive movement. Therefore, comfort is closely related to the mechanical features and fastening methods of the exoskeleton.

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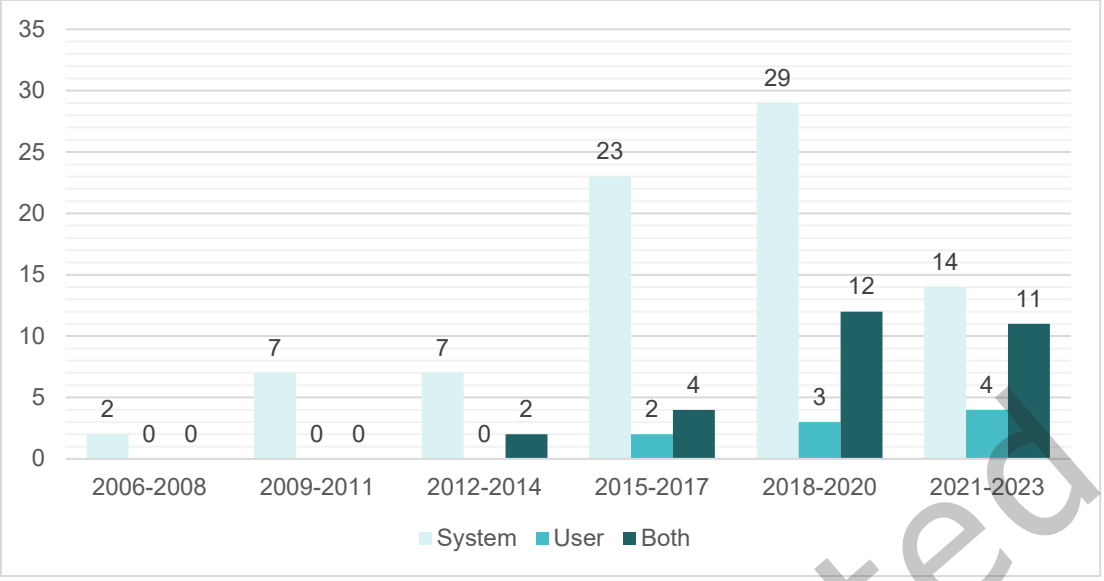

Figure 5: Yearly distribution of system and user assessment studies

- *Portability* is achieved by fulfilling a set of physical requirements ranging from diminishing overall weight to allowing mobile/autonomous use. Size, weight, compactness, and battery life are critical aspects to achieve portable systems.
- *Safety* in hand exoskeletons is identified by the kinematic compatibility between the skeleton and the user's hand by avoiding rotational misalignment of the joints. Incompatibility of movements is considered to be potentially hazardous as it might lead to both discomfort and injuries, therefore the range of motion and smoothness of the trajectory of movement should be paid special attention.
- *Simplicity* of the exoskeleton refers to keeping the actuation, mechanism, and overall structure as minimalist and straightforward as possible. Structural and visual simplicity and compactness can foster ease of use and user acceptance.
- *Wearability* can be achieved by the ease of donning and doffing the device and supporting prolonged usage. The former is related to the actual taking on and off the skeleton easily and independently, whereas the latter is affected by comfort and portability, hence device size and weight.

Figure 6 shows the frequency of each user criterion. The most frequently targeted requirements mentioned in the articles are comfort (n=46), wearability (n=43), portability (n=39) and adaptability (n=34). Less frequently mentioned requirements are affordability (n=23), safety (n=21), simplicity (n=9) and acceptability (n=4). No user-centered criteria were reported as design requirements in almost a quarter of the articles (n=30).

3.3 User Research Trends

We made a closer inspection of all 38 papers which reported participation of human subjects in the process. At this point, we did not discriminate studies based on user type (e.g., healthy or patient), yet coded them separately to be able to identify existing trends. Full-text analysis of the articles allowed identification of sample size and characteristics (healthy, patient, expert, caretaker), types of impairment, the purpose of the conducted user study (functional test, requirements gathering, formative evaluation, usability test), and data collection methods in each article. The summary of the findings is presented in Table 3.

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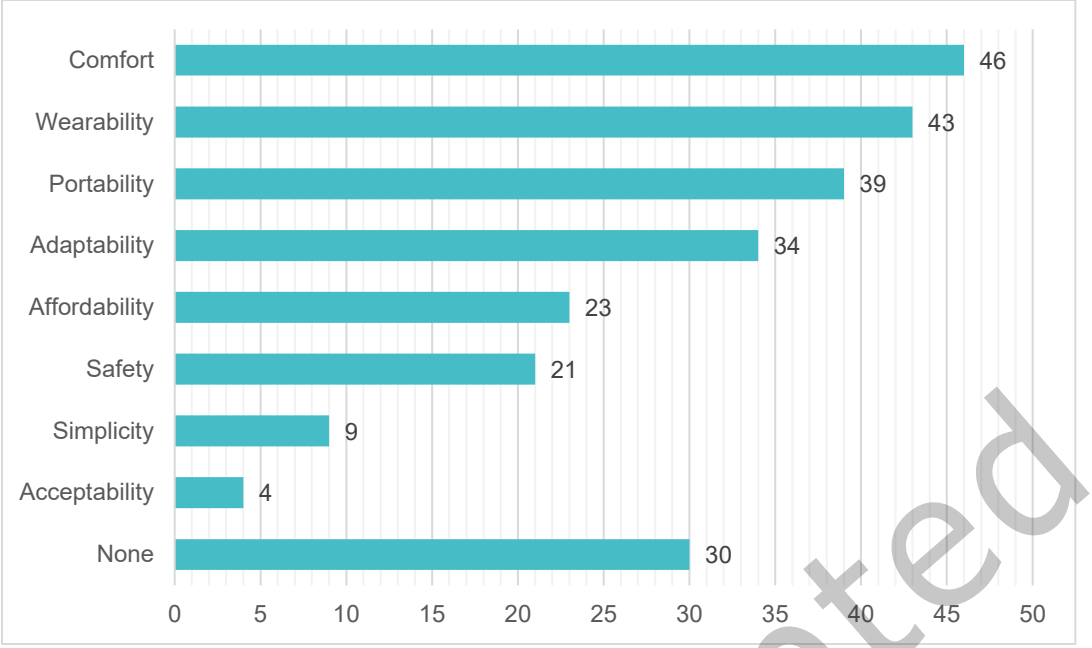

Figure 6: Frequency of user criteria

Twenty-five studies involved end-users (patients), 11 studies included only healthy subjects, and one included only experts. Secondary users (experts and/or caretakers) in addition to patients were involved in three studies. One article did not specify any user characteristics. The majority (n=21) had sample sizes between one and five, one was not specified, and some of the larger sample sizes consisted of only healthy subjects e.g., [72,73,87,99,103,105,106].

Functional tests are the most common method of user involvement as it is the sole purpose for almost half of the studies (n=17). Vast majority of the studies involving healthy participants utilized functional tests. Functional tests aim to validate that the system provides the intended function for the users, i.e., the physical support for the planned tasks targeting the impaired hand. This can be quantified by task-oriented performance evaluation, a method where the users are instructed to perform a series of predefined tasks. The tasks are usually based on existing clinical performance tests and a selection from task libraries, such as The Anthropomorphic Hand Assessment Protocol (AHAP) [99], Action Research Arm Test (ARAT) [71,86,106], Wolf Motor Function Test (WMFT) [71], Fugl-Meyer Assessment (FMA) [71,86], Assisting Hand Assessment (AHA) [84], Box and Block Test (BBT) [86,88,93,99], Jebsen-Taylor Hand Function Test (JTHFT) [92,94,99,104,107], Toronto Rehabilitation Institute–Hand Function Test (TRI-HFT) [104,107]. Two studies used EEG monitoring [73,74].

Ten studies exclusively reported usability tests. Eleven others reported a usability study in addition to others. A custom-designed questionnaire is the most common usability measure along with observations, interviews and alike verbal questioning, though the techniques and protocols for these methods are not specified. More structured subjective assessments include System Usability Scale (SUS) [80,82], User Satisfaction Evaluation Questionnaire (USEQ) [83], Usefulness Satisfaction and Ease of Use Questionnaire (USE) [85], Capabilities of Upper Extremities Questionnaire (CUE-Q), Orthotics Prosthetics Users Survey (OPUS) [107], Borg RPE scale, Borg CR-10 scale [102], and Quebec User Evaluation of Satisfaction with Assistive Technology 2.0 (QUEST) [88,99,104,107]. One study used system logs as a structured, indirect observation method [82]. Two articles did not disclose the methodology of the usability assessment.

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Table 3: Summary of the user research methodology reported in the articles

Source	Participants and Sample size	Impairment	Purpose	Data collection method
[71]	Patient (n=3)	Stroke	Functional test	Task-oriented performance evaluation
[72]	Healthy (n=13)	NA	Functional test	Task-oriented performance evaluation, EEG monitoring
[73]	Healthy (n=14)	NA	Functional test	Task-oriented performance evaluation, EEG monitoring
[74]	Healthy (n=5)	NA	Functional test	Task-oriented performance evaluation
[75]	Healthy (n=1), Patient (n=1)	Stroke	Functional test	Task-oriented performance evaluation
[76]	Patient (n=1)	Spinal cord injury	Usability test	Not specified
[77]	Patient (n=3)	Stroke	Functional test	Task-oriented performance evaluation
[78]	Patient (n=3)	Stroke	Functional test	Task-oriented performance evaluation
[18]	Expert (Clinician) (n=28), Patient (n=9)	Spinal cord injury, Stroke	Usability test	Questionnaire (custom-designed), Observation (not specified), Post-session open questions (not specified)
[79]	Patient (n=5)	Hemiparesis (reason not specified)	Usability test	Questionnaire (custom-designed Likert scale with two questions on perception of using the device and ease of donning and doffing)
[80]	Patient (n=2)	Spinal cord injury, Stroke	Functional test, Usability test	Task-oriented performance evaluation; System Usability Scale (SUS), Questionnaire (custom-designed)
[81]	Patient (n=3)	Stroke	Functional test	Task-oriented performance evaluation
[82]	Expert (n=not specified), Caretaker (n=not specified), Patient (n=10)	Stroke	Requirements gathering, Formative evaluation, Usability test	Focus group, In-depth interview, Cultural probes; Cognitive Walkthrough, Cooperative Evaluation, Think-aloud; System Usability Test (SUS), System Logs
[83]	Expert (Physical Therapist) (n=5)	NA	Usability test	User Satisfaction Evaluation Questionnaire (USEQ), composed of questions from the Suitability Evaluation Questionnaire (SEQ), Post-session interview
[84]	Patient (n=1)	Stroke	Functional test	Task-oriented performance evaluation
[85]	Patient (n=2)	Stroke	Functional test, Usability test	Task-oriented performance evaluation; Usefulness Satisfaction and Ease of Use Questionnaire (USE)
[86]	Patient (n=11)	Stroke	Functional test	Task-oriented performance evaluation
[87]	Healthy (n=16)	NA	Functional test	Task-oriented performance evaluation
[88]	Patient (n=11)	Stroke	Functional test, Usability test	Task-oriented performance evaluation; Quebec User Evaluation of Satisfaction with Assistive Technology 2.0 (QUEST)

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[89]	Patient (n=13)	Spinal cord injury, Hand sensorimotor impairments (not specified)	Usability test	Questionnaire (custom-designed), Observation (not specified), Post-session questions (not specified)
[90]	Healthy (n=1)	NA	Functional test	Task-oriented performance evaluation
[91]	Not specified (n=1)	NA	Usability test	User feedback (not specified)
[92]	Patient (n=4)	Spinal cord injury	Functional test	Task-oriented performance evaluation, Post-session interview
[93]	Patient (n=1)	Spinal cord injury	Functional test	Task-oriented performance evaluation
[94]	Healthy (n=1), Patient (n=1)	Muscular dystrophy	Functional test	Task-oriented performance evaluation
[95]	Healthy (n=2), Patient (n=5)	Spinal cord injury	Functional test, Usability test	Task-oriented performance evaluation, Questionnaire (reused from Almanera et al. [18])
[96]	Healthy (n=not specified)	NA	Usability test	Observation (not specified), Post-session questions (not specified)
[97]	Patient (n=2)	Amyotrophic lateral sclerosis	Functional test, Usability test	Task-oriented performance evaluation, Post-session questions (not specified)
[98]	Patient (n=1)	Spinal muscular atrophy	Functional test	Task-oriented performance evaluation
[99]	Healthy (n=10)	NA	Functional test, Usability test	Task-oriented performance evaluation, Quebec User Evaluation of Satisfaction with Assistive Technology 2.0 (QUEST)
[100]	Healthy (n=6), Patient (n=2)	Spinal cord injury	Functional test	Task-oriented performance evaluation
[101]	Patient (n=30)	Elderly with rheumatoid arthritis	Usability test	Questionnaire (custom-designed)
[102]	Healthy (n=5)	NA	Usability test	Borg RPE scale, Borg CR-10 scale
[103]	Healthy (n=30)	NA	Usability test	Single-item comfort rating (Likert)
[104]	Patient (n=2)	Cervical spinal cord injury	Functional test, Usability test	Task-oriented performance evaluation, Capabilities of Upper Extremities Questionnaire, Orthotics Prosthetics Users Survey, Quebec User Evaluation of Satisfaction with Assistive Technology 2.0 (QUEST)
[105]	Healthy (n=52)	NA	Functional test, Usability test	Task-oriented performance evaluation, Single-item comfort rating (Likert), Average number of cycles to get used to the device, Observation (average time spent for donning)
[106]	Healthy (n=10)	NA	Functional test, Usability test	Task-oriented performance evaluation, Single-item performance rating (Likert)

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[107]	Healthy (n=4), Patient (n=2)	Traumatic brain injury, Brachial plexus palsy	Functional test, Usability test	Task-oriented performance evaluation, Capabilities of Upper Extremities Questionnaire (CUE-Q), Orthotics Prosthetics Users Survey (OPUS)-Satisfaction module, Quebec User Evaluation of Satisfaction with Assistive Technology 2.0 (QUEST)

Only one article [82] reported a full iterative design cycle involving multiple research techniques and purposes. Starting with requirements gathering, the authors reported the use of ethnographic methods, namely focus groups, in-depth interviews and cultural probes. After the identification of user needs, the produced design solutions are reported to have been subjected to formative evaluation in an iterative design process by utilizing cognitive walkthrough, cooperative evaluation, and think-aloud protocols. Summative evaluation (usability test) included the use of SUS and analysis of system logs.

4 DISCUSSION

We conducted a scoping review of the conference proceedings and journal articles reporting the development processes of hand exoskeletons for assistive and rehabilitative purposes. Our findings help in understanding the contemporary trends in user requirements and user-centered practices in the field, as well as identifying gaps and areas for improvement. Both the rising number of publications and the increased ratio of journal articles are indicators of growing interest in the field. In this section, we will discuss the state-of-the-art and offer directions for design and user involvement methodologies to improve the usability and usefulness of hand exoskeleton systems.

4.1 User Requirements for Decent User Experience with Hand Exoskeletons

The vast majority of the studies we reviewed proposed hand exoskeleton systems for only rehabilitation or hybrid purposes (both rehabilitation and assisting). The abundance of efforts on rehabilitative devices could be the result of the significant challenges brought by the complex functions of the hand. The human hand mediates many diverse tasks and activities (e.g., holding, carrying, opening, turning and operating tools and things). Consecutively, the kinematic structure of the hand is quite complex. It is difficult to engineer solutions that function well for most activities.

There is also an increasing trend in projects aiming at developing exoskeletons for assisting AoDL. These devices are overwhelmingly soft exoskeletons, e.g. [80,85,94,95,108–118]. Limitations of rigid exoskeletons are often mentioned in the literature as being heavy, bulky, complex structures [8]. This is no exception for hand exoskeletons. Such systems would be challenging in terms of usability and user acceptance in daily use contexts. Therefore, it is predictable that assistive hand exoskeletons mainly make use of lighter, compact and safer technologies such as pneumatic muscle wires, tendon/cable-driven systems for actuation etc. which is achievable by soft exoskeletons. However, it is known to come with the cost of decreased accuracy [2,8]. Technological advancements for compact actuation systems with better performance will undoubtedly afford better user experience with both assistive and rehabilitative exoskeletons and perhaps accelerate the commercialization of multi-purpose devices which can be used in both clinical and daily settings.

Our findings demonstrate that certain pragmatic concerns dominate the user criteria in the design process. Among them, the most frequent criteria are wearability, comfort and portability. These aspects are closely related to the size, weight and compactness of the hand exoskeleton. Although there are currently technological limitations, the research community is seemingly well aware of the implications of such physical requirements on user experience with the device. It can be expected that technological advancements towards lighter and more compact components and systems will have a positive impact on wearable, comfortable and portable devices, hence better usability.

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Wearability is also associated with ease of donning and doffing the device. This is a critical concern, especially considering the mechanical complexity of the exoskeleton and the limitations of using the impaired hand, see for example [18,76,78–81,83–86,88,119–128]. This is particularly important for autonomous use in daily contexts where the users may not always be supported by experts or caretakers. Assistive devices need to be compatible with the functional requirements of daily use. This brings forth the emphasis on prolonged, contextual use. Although home deployment is considered effective for rehabilitation due to increased access to the device [6], exoskeletons for rehabilitation purposes are often used for a limited period in clinical, or at least controlled and stationary settings. Assistive devices, on the other hand, should afford usage for longer periods within the natural context of daily living. For this reason, comfort and portability become even more prominent aspects of positive user experience and facilitators of higher user acceptance. Soft robotics might offer better potential wearability improvement compared to rigid systems, due to their lightweight structures with better alignment with the finger joints [63].

Another frequent concern appears to be the *adaptability* of the exoskeleton to the different needs of a variety of users. Adaptability is commonly associated with the physical suitability and adjustability of the device to various hand sizes. Rehabilitation devices in clinical settings are intended to be used by multiple users with different characteristics [2]. Even though anthropometric data is used to support ergonomic and mechanical decisions, e.g., [110,121,129–132], age, gender, ethnicity and severity of the impairment play an important role in the physical fit. This urged the research teams to experiment with alternative ways to adjust and fasten the exoskeleton in a way that it fits with different hands. For this purpose, different materials are used including Velcro [71,133], elastic bands [71], silicon [75] and adjustable straps [134]. Different design approaches are applied such as adopting movable inner mechanisms [121], providing slots for a range of attachments [135] and using mechanically individual modular parts [18]. A more precise approach is to use photogrammetry to create a 3D model of the patient's hand and manufacturing tailored 3D printed skeletons [136]. Since adaptability is associated with properly fitting and fastening the device to the user's body, it potentially affects safety, comfort, and system performance. Further commercialization might bring opportunities for customization according to different user characteristics.

The *affordability* of the hand exoskeleton was aimed at many projects. However, these efforts were limited to the material and design alterations of the exoskeleton to decrease manufacturing costs, e.g., [77,81,83,91,120,122,123,125,137–141]. Some studies recommend 3D printing as a low-cost manufacturing method to promote affordability of the device e.g., [120,137,142]. Affordability or the cost of a design or service is more complex than the mere material price. For commercial products and services, affordability is a dynamic concept which can include many aspects such as purchasing, maintenance and upgrade costs. Furthermore, expenses linked to regulatory requirements for medical devices, such as approvals, testing, and documentation, will add to the overall cost, particularly for devices at higher TRLs. A wider perspective on affordability might call for alternative design approaches such as modular systems for ease of repair and upgrade, and devices evolving together with the needs of the patient, therefore contributing to adaptability.

The importance of providing a safe interaction between the device and the user is also frequently mentioned. *Safety* is often assessed by researchers as the kinematic compatibility between the device and the hand to avoid pain and injury, e.g., [75,80,83,131,143–145]. This is indeed an essential user requirement. Devices for autonomous use without professional supervision call for additional safety concerns. Especially for portable, assistive hand exoskeletons, all safety standards for wearable technologies must be followed. Since assistive devices are intended to be used in uncontrolled environments, many issues such as waterproof design, safe cleaning and user safety in case of malfunctioning should come to mind. Rigid exoskeletons pose heightened safety risks compared to soft exoskeletons due to exposed mechanical and electrical components, which makes them less compatible with autonomous use.

A few articles mentioned the *simplicity* of the device as a goal [18,77,78,81,91,92,124,146]. Since many existing structures are big and cumbersome, an important question raised is how to simplify the mechanisms and functions to make the hand exoskeleton more usable and acceptable, without sacrificing too much from the function. The advantage of soft exoskeletons over rigid systems in terms of simplicity is evident, despite lesser performance especially for rehabilitation. For some occasions, prioritizing tasks instead of targeting the

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full spectrum of hand functions could be an opportunity for optimization. However, simplification of the device remains largely dependent on technological advancements towards compact and effective components.

Acceptability is the least frequently mentioned user-centered criterion. According to the Technology Acceptance Model (TAM), perceived usefulness and ease of use form the user's attitude towards using or abandoning the technology [147,148]. User acceptance of assistive technology, or willingness to use it, is also associated with perceived usefulness, comfort, and usability [8,46,149]. In our review of hand exoskeleton studies, acceptability was associated with the actual amount of use, usability and patient motivation [82], visual appeal [84], wearing comfort [89], and general liking [79]. All studies that aimed at user acceptance were planned to be used either mainly at home, or in both home and clinical settings, and one [84] report a device designed for child users. The reason why there are not many studies targeting user acceptance is probably due to the level of maturity of the product design of the existing exoskeleton systems. Acceptance is related to many factors from long-term usability to perceived usefulness, as well as contextual factors [150,151]. Because of the lack of devices that are for long-term, daily usage of end-users, it is difficult to assess their acceptability. Among the projects that targeted user acceptance, only one study assessed long-term usability [82]. Others are limited to first impressions and limited experience with the devices. Since the grounds for device adaption are not yet established, it is hard to talk about the reasons and conditions for technology acceptance or abandonment.

4.2 End-User Involvement in the Design Process of Hand Exoskeletons

According to International Standards Organisation (ISO), to ensure user-centred solutions, it is vital to involve users throughout the design and development process, which consists of 'understanding and specifying the context of use', 'specifying requirements', 'producing design solutions', and 'evaluating the designs' [152]. More than two-thirds of the reviewed articles did not report any user involvement in the exoskeleton development process. We made an in-depth analysis of the 38 articles which reported some type of user involvement. We did not eliminate the studies involving only healthy subjects (n=11), because we wanted to identify which assessment goals called for the participation of target or faux users, rather than evaluating the clinical efficacy of the developed systems. As can be anticipated, the sole purpose of most studies recruiting only healthy subjects is to validate the system performance via functional tests.

Our findings show that functional tests are by far the most common way of engaging users as almost half of the studies reported only task-oriented assessments. The methods of functional tests are more or less standardized: The user is asked to perform a set of predefined tasks while the functional performance of the system is measured. These studies typically employ existing tests to choose and assess certain hand functions, such as Action Research Arm Test [153], Wolf Motor Function Test [154], Fugl-Meyer Assessment [155], Assisting Hand Assessment [156], Box and Block Test [157], or Jebsen-Taylor Hand Function Test [158]. However, many studies performing task-oriented performance evaluations involved healthy subjects instead of patients [72–74,87,90,99,105,106]. Functional tests are vital to assess the performance in the use of the designed system. They are system or device-oriented rather than user-oriented assessments because they aim to validate that the system is functioning the way it is intended to. In functional tests, the user is passive, and their input is indirect because their opinions or suggestions are not asked directly.

Twenty-one papers reported usability tests of sorts, some of which were conducted with a small sample size of less than five, which is an acceptable number for qualitative, formative evaluation [159,160]. Although there is not a universally viable minimum sample size for usability studies, the optimum number of testers depends on the goal (formative vs. summative) and the context of the research (academy vs. industry) [161]. Since the reviewed articles do not report design iteration plans based on usability test results, it is not definitive that the goal of the usability tests was formative evaluation. Summative evaluation, in other words, usability validation, user validation or user acceptance test, usually requires a larger sample size, typically around 12-20 participants [159].

Few studies reported the use of standardized tools for usability assessment, namely System Usability Scale [162], User Satisfaction Evaluation Questionnaire [163], Usefulness Satisfaction and Ease of Use Questionnaire [164], and Quebec User Evaluation of Satisfaction with Assistive Technology 2.0 [165]. The most common method for usability inspection appears to be custom-designed questionnaires. Though useful for a quick

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assessment, these ad hoc methods are less reliable than standardized usability questionnaires [166]. A similar concern about validity and reliability can be raised for some of the qualitative, open-ended methods reported in the studies. Qualitative methods such as interviews and observations are popular ethnographic methods in social sciences [167]. They can provide rich information about user experience and expectations, as long as they are planned, conducted, analyzed and reported rigorously. Unfortunately, neither can be said for the reviewed articles. Many studies simply mentioned 'asking questions' and 'observing user interactions', without disclosing important information about tools and procedures for data collection and analysis, such as the list and order of questions, the observation procedure, and how the responses and interactions were recorded and analyzed.

Only one article reported user research for requirements gathering [82]. It is also the only study that reported longitudinal, contextual research. In this article, the authors reported the design and development of an exoskeleton for post-stroke patients for home-based rehabilitation. The system allows independent use at home and remote supervision by the clinician. The requirements-gathering phase involved several qualitative methods including focus groups, as well as in-depth interviews and cultural probes in the home context (methodological details are not reported). This helped them understand the general attitude of the potential users towards the technology and investigate the contextual needs. Based on the identified user requirements, the team created the prototypes in an iterative process where they received formative feedback and improved the design. The final prototypes were evaluated via a 6-weeks longitudinal study in participants' homes. Device logs and post-use SUS tests were employed for usability evaluation.

The fact that not many user involvement studies were reported for requirements gathering is problematic because early involvement is key for better user experience by providing an effective understanding of the user needs [168]. It is also important that the process and results of early user involvement are meticulously reported so that the findings are reliable and usable by others. Systemic involvement of secondary and tertiary users is also vital to gain a holistic perspective of the experience to develop product service systems that meet the needs of multiple stakeholders [14].

Current efforts in the development of hand exoskeletons focus on excellence in functional performance based on technological and clinical requirements. This is a challenging task due to technological limitations, which have a significant impact on comfort, portability, wearability, and simplicity, consequently the usability and user acceptance of the device. Prioritization and customization of the supported functions elicited by early user involvement can be a distinctive design approach. For instance, Radder et al. [40] conducted focus groups with elderly and stroke patients with reduced hand functions to identify the priorities of the end-users. They found that users want assistance in daily activities involving household chores, personal hygiene and care, eating and drinking, and hobbies or outdoor activities. Likewise, Boser et al. [169] conducted interviews to identify prioritized activities and grouped them according to the need for assistance in precision (e.g. do zippers, tie shoes, scratch face), power (e.g. carry bags, open jars, shovel snow), and other assistive support (e.g. use a cell phone, wash hair, put on clothes). Another study by Kobbelgaard et al. [10] conducted contextual interviews with people living with severe paralysis to identify user-centered requirements for arm exoskeletons. Their insights indicate six prioritized actions: eating, drinking, itching, reading, brushing teeth and shaving. They also emphasize the importance of independence and dignity. For example, eating is not only a physical function of holding knives and forks but also a dignified experience one enjoys in the company of others. This is inspiring as it calls for alternative design approaches, such as possibility-driven design, a concept suggested by Desmet and Hassenzahl [170]. They suggest that the conventional, problem-driven approach in design aims to "cure" the problem by enabling the transition from a negative to a neutral state as much as possible (in this case, the neutral state is the fully-functioning, healthy hand). Possibility-driven approach, on the other hand, grounds design decisions directly on the well-being of users, not necessarily through the mediation of clinically measurable standards of health. Such user-centered design approaches, rather than technology-push, can lead to more simplistic, acceptable, and innovative solutions.

4.3 Engineering Design Strategies to Support Robot-Assisted Stroke Rehabilitation

Robot-assisted rehabilitation is a contemporary method of neurorehabilitation that has demonstrated effectiveness in individuals who are recovering from a stroke. Clinicians frequently employ robots in stroke

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therapy due to their ability to enable users to do highly repetitive movements with precision. However, studies on extended stroke recovery suggest significant enhancements are necessary for robotic rehabilitation to effectively supplement conventional therapy [171].

Based on the review data and particular outcomes for hand exoskeletons, it is evident that the design strategy and methodology need to be restructured in order to ensure the acceptability of these systems for rehabilitation and enhance their performance. Raising acceptance will lead to enhanced long-term usage and enable the achievement of iterative cycles for system improvement.

In the optimization process of exoskeleton mechanism synthesis, size, weight, and compactness should be prioritized so as to improve portability, comfort, and wearability. In order to concentrate on wearability, designers must be particular about the topology of the optimized mechanism, which will result in an easy-to-use device free of extraneous complexities [172].

Mechanism synthesis and control system design can both help to improve adaptability. In mechanism design, the exoskeleton mechanism can be synthesized in a robust manner that decreases the vulnerability of kinematic and kinetic performance to phalanx size of the patient. This will streamline the utilization of the same mechanism by diverse patients with varying finger dimensions [134,173–175]. An alternate approach is to design an adaptive system that adjusts the required link lengths based on the sizes of the phalanxes for each patient. In this method, the topology may be optimized to minimize the requirement for redesigning and remanufacturing links for each patient. The mechanism must consistently retain the necessary performance through either a robust structure or an adaptable design. Furthermore, the actuation type must be adjustable according to the patient's condition. Initially, when there is no motor function in the fingers, a fully actuated mechanism will offer full assistance to start the therapy. Transitioning from fully actuated to underactuated mechanisms would enhance motor variability and exploratory behavior, both of which are crucial for recovering motor skills. This switching should be decided based on the kinematic and kinetic metrics that describe motor learning together with the EEG and EMG measurements [176].

Adaptability should be taken into account while designing the control system for hand exoskeletons. The spasticity and motor function of the individual patient exhibit variability even within a single treatment session. Throughout the whole rehabilitation process, it is crucial to carefully choose, modify, and apply the control system topology based on the patient's condition. Kinematic and kinetic performance metrics that describe the motor relearning are essential to determine the selection and adaptation. Together with the control system topology, selection of assistive or resistive strategies will shape the motor performance and motor relearning during robotic rehabilitation [177–179].

Engaging users in the design or development of a rehabilitation robot is a complex endeavor. This necessitates the use of formative assessments and an augmented number of iterations in the design cycle. Usability testing and evaluations must be considered in addition to functional tests and associated assessments. During the optimization phase of exoskeleton design, it is necessary to construct and employ cost functions that include multiple domains and objectives. Motor function improvement is necessary during robotic treatment. Nevertheless, this improvement does not necessarily indicate a simultaneous enhancement in motor relearning. It signifies that the ability to apply the motor skill to everyday activities or generalize it is unattainable. The complete robotic rehabilitation process must be guided by motor learning principles, from system design to execution. Furthermore, including user needs and involving them in the design process would augment the usability and effectiveness of the hand exoskeletons, alongside the fundamental principles and foundations of motor control and learning. The patient's well-being and motivation should be taken into account along with their functional performance throughout therapy and everyday activities [170].

Hence, it is necessary to develop a novel design strategy and methodology that encompasses both motor control and learning principles, as well as user expectations and engagement, in order to elevate the robotic hand rehabilitation to a more advanced level.

4.4 Future Directions and Suggestions for User Research

We presented our review of the studies which reported the development of hand exoskeletons for assistive and rehabilitative purposes. The reviewed articles were published between 2006 and 2023. Because we included the studies that reported the design and development processes of the systems for an intended user, the results

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mainly come from engineering fields. This was a deliberate decision to be able to present an overview of the user-centered requirements considered in the development of hand exoskeletons, and the ways users are invited to participate in the identification and assessment of design requirements. Studies without any report on the design and development process were excluded from the review, though they were quite rare, they are included in literature and discussions [40,51,52,169].

Developing user-friendly interfaces for products as complex as exoskeletons necessitates optimization of technical and user requirements following a human-centered design process by identifying, delivering and validating the needs and characteristics of the targeted users. In addition to demographics, anthropometrics and human motion data, information about opinions, desired features and data regarding the context of use are also needed [14]. Manufacturing for such an emerging market requires time to understand the requirements, as the path to commercialization involves the creation of new standards and regulations [180]. It is vital to assure that the systems will remain reliable and functional in real-life contexts by addressing user needs, as it is mandatory for moving from lab settings to acceptance in the real world [8].

The field of wearable assistive robotics is maturing. Wearable exoskeletons are a new generation of robots. The service delivery model is as important as the design of the device because it interests not only primary and secondary users but also establishments such as health institutions, governmental agencies and NGOs [17]. As the hand exoskeleton designs advance in terms of device performance and usability, issues such as developing product service systems, stakeholder management and overall service delivery issues will come to the forefront. Naturally, the current efforts are concentrated on engineering a technically viable device, though the perceived service de-livery process of assistive technologies is a significant aspect which impacts user experience and device abandonment [181].

4.5 Limitations of the Review

In this review study, we identified the user criteria intended by the research teams of hand exoskeletons. The user criteria are neither always explicitly articulated in the papers, nor always assessed to confirm whether or not they are achieved. Hence, the user criteria we identified is not a definitive list, but rather a reflection of current efforts and concerns among the community of researchers. Additionally, most of the included papers report early-stage works with low technology readiness levels (e.g., proof of concept or prototype validation). Naturally, there are very few studies that tested the systems with actual target user groups (e.g., stroke patients). Therefore, we refer to the broader literature to offer methodological recommendations as current practices do not provide comprehensive guidance in user involvement. With more systems achieving higher TRL in the near future, we will have the opportunity to assess the usefulness, usability and user acceptance of these devices as well.

5 CONCLUSION

The design and development of hand exoskeletons is a recent but growing field of research. Since there are not many user studies to identify the priority needs, a mandatory set of tasks are selected to be performed based on clinical requirements to restore or support clinically prioritized hand functions. Naturally, current efforts are mostly limited to lab/clinical settings. Unlike impairments affecting other body functions, there are not many mainstream assistive devices for flawed hand functions. For instance, there are widespread assistive solutions for mobility impairments such as wheelchairs, crutches and prostheses. There are not many widely accessible options for the operation of impaired hands, which makes even partial recovery of functional deficiencies a priority for most.

Our review demonstrated the current trends and gaps in common contemporary research practices. The novelty of our work stems from being the first comprehensive review study which aims to contribute to the understanding of user requirements and planning user-centered design methodologies in the design and development of hand exoskeletons. We contribute to the relevant literature by presenting a comprehensive overview of user requirements and user-centered practices in the development of hand exoskeletons, therefore expanding the knowledge for mechanical design; and proposing engineering design strategies for improved adaptability and overall usability of rehabilitative hand exoskeletons.

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Articles addressing user studies are very limited as the overwhelming majority report validation of the designed system. This demonstrates that present efforts are still concentrating on fulfilling engineering requirements, such as the mechanical functioning of the system. Validated systems are likely to be tested with end-users, although the current methodology is mostly limited to functional tests with limited sample size. Nevertheless, the increase in the prevalence of user studies in the last few years can be seen as an indicator of growing confidence in fulfilling technical requirements. All these findings demonstrate the existence of a gradually maturing field of research.

Our review underscores the necessity to restructure design strategies for better acceptance and performance, prioritizing factors like portability and wearability. Mechanism synthesis and control system design are crucial for enhancing adaptability, requiring robust or adaptive structures and adjustable actuation types. Involving users in the design process through formative assessments and usability testing is vital, alongside considering motor learning principles for effective rehabilitation. Overall, a novel design strategy integrating user expectations, motor control, and learning principles is essential to advance robotic hand rehabilitation.

Maturing of the field and commercialization of the outputs require standards in user requirements and user research practices to assure useful, usable and acceptable products and services. In this study, we systematically reviewed the existing work to identify both common and overlooked issues in terms of user requirements for hand exoskeletons, as well as the extent and characteristics of current user-centered practices in the field. Based on our findings, we proposed suggestions for a better representation of user needs and expectations in the design process. Our study is expected to guide research and design teams in their work on developing, evaluating, and refining exoskeleton systems through a user-centered perspective. The findings and suggestions can have wider implications for research and practice in the fields of wearable robotics and assistive technologies.

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