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Exoskeletons for Elderly Activity of Daily Living Assistance: A Review of Upper Limb Exoskeletons and Assessments

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Abstract

Population ageing is a major global issue. The elderly population aged 65 and above made up approximately 9% of the world's population in 2019, with projections indicating this will rise to 16%, or 1.5 billion individuals, by 2050. The elderly experience a natural decline in strength, endurance, agility, and flexibility. Exoskeletons have the potential to assist the elderly in daily tasks, improve mobility and balance, and provide additional strength, endurance, and capability to maintain accurate limb movement. Their application leads to a more independent and autonomous life, fostering healthy ageing and ageing in place. However, their development requires thorough considerations of functionality and user experience criteria, such as addressing the alignment with human joints, social acceptance, and motivation for exoskeleton usage. This review presents an overview of upper-limb exoskeletons designed to assist the elderly in activities of daily living, focusing on exoskeleton types and assessments. Eighteen upper limb exoskeletons were identified from the literature and categorised based on supported body segment and structure. Most of the exoskeletons are either in the embodiment design or prototyping stages and their evaluations were predominantly performed in the laboratory or simulated environment. Elderly participation in exoskeleton assessment is currently limited. There is a lack of standardized exoskeleton assessments essential for certifications, commercialization, and universal benchmarks in diverse studies. These standards would ensure consistent, repeatable, reliable, validated, and comparable findings.

1. Introduction

1.1 Population Ageing

Population ageing is a global pressing issue that demands an immediate response by implementing policies and programs to support the elderly and their families. The worldwide proportion of the elderly aged 65 and above was 9% in 2019 and is expected to reach 16%, with a staggering 1.5 billion persons by 2050 [1]. Eastern and Southeast Asia has the largest population aged 65 and above, with around 260 million in 2019, followed by Europe and Northern America with over 200 million and Central and Southern Asia with 119 million [1]. The elderly population aged 65 and above is forecasted to grow substantially, with Eastern and Southeast Asia experiencing significant growth from 261 million to 573 million and Central and Southern Asia from 119 million to 328 million by 2050 [1].

The United Nations classifies a nation as ageing, aged, or super-aged based on the proportion of the elderly population aged 65 and above, with thresholds set at 7%, 14%, and 21% of the total population, respectively [2]. The current Malaysian population stood at 32.7 million in 2022 compared to 32.6 million in 2021, with the percentage of the elderly population aged 65 and above increasing from 7.2% in 2021 to 7.3% in 2022 [3], [4]. Malaysia has an ageing population and will reach the aged population status within the next two decades [3], [4]. Meanwhile, Taiwan transitioned to an ageing society in 1993, has become an aged society in 2018, and is projected to become a super-aged society in 2026 [5]. The Taiwanese elderly aged 65 and above exceeded the youth population aged 0 to 14 in 2017 and is expected to increase by 108.4% by 2065 compared to 2018 [5].

Medical care, hygiene, and food supply advancements have lowered the mortality rate and increased the human lifespan. Shifts in family values and the increasing opportunities for females in education and job employment have contributed to an increased rate of late marriages and delayed childbearing. These factors lead to a shorter reproductive period and fewer children born [5]. The decline in the birth rate has led to a higher percentage of elderly, particularly pronounced in developed nations [2]. In Malaysia, the duty to care for the elderly commonly falls on family members, which can be challenging for young adults to juggle between careers, daily routines, and caring for elderly parents [6]. On the other hand, China is witnessing a shift from the traditional practice of elderly residing with their children toward a Western-style care approach due to societal changes driven by the one-child policy and extensive urbanisation [7], [8].

An elderly care centre is an option for providing specialised care and social comfort. However, there are concerns about the sufficiency of the quantity and quality of elderly care centres to meet the surging demand of the ageing population, not only in developing countries like Malaysia [6] but also in developed countries like Taiwan, the United Kingdom, and the United States [7], [8]. In Malaysia, there are about 365 registered elderly care centres, complemented by various unregistered facilities nationwide. To cater to the ageing population's needs and uphold operational standards, the country may require roughly 2,000 registered elderly care centres by 2030 [6]. Unfortunately, the elderly care centres still fall behind in standardised geriatric operational procedures, technology usage, trained caretakers, updated equipment, appropriate facilities and sufficient indoor and outdoor space [6]–[8]. Furthermore, many elderly care centres are suffering from severe financial constraints, although some manage to operate sustainably through funding from government, private, charity collections and small businesses [6], [9].

1.2 Activities of Daily Living (ADLs)

Activities of daily living (ADLs) reflect an individual's functional ability to perform fundamental and routine tasks and are a significant factor in determining the need for assistance or support. ADLs are classified based on the level of challenge and difficulty involved in the activity, specifically as basic, instrumental, and advanced ADLs, as shown in Table 1. Basic ADLs denote self-care activities and fundamental physiological needs to keep living. Instrumental ADLs represent an activity that requires thinking and organisational skills for independent living, and advanced ADLs are action-driven by personal preferences and motivations beyond the need for independent living.

Healthy ageing is influenced by the continuous interaction between the elderly's functional ability, intrinsic capacity, and surrounding environment [10]–[12]. Given that most daily activities rely on upper limb movements, upper body power and endurance strength [13], personalised assistive devices like exoskeletons hold the potential to support the elderly in their pursuit of healthy ageing. However, the design of upper limb exoskeletons is challenging due to complex upper limb anatomy, movement type, range of motion, a high degree of freedom, and dynamic shoulder girdle movement [14]–[16]. These complexities highlight the need for thorough consideration of upper limb exoskeleton development to accommodate the diverse tasks performed by the shoulder, arm, and hand and address the unique requirements of the elderly.

The elderly generally prefer ageing in place by continuing to reside in their family homes for as long as possible [17]–[20]. Living in a familiar environment improves the well-being of the elderly and leads to a positive experience in later life [20], [21]. However, the desire to live independently may increase the risk of accidents, injuries, and diseases due to physical and mental deterioration [18]. Maintaining the well-being of the elderly by preserving their physical function is critical to reducing geriatric healthcare costs [22]. The global change in ageing demographics is expected to create a strong demand for robotic technologies like exoskeletons to assist the elderly [19], [23]–[25]. With their potential to help in activities of daily living (ADLs), increase mobility, and reduce physical fatigue, exoskeletons hold promise to enable independent and autonomous lives [26], [27].

Table 1 *Levels of activities of daily living adapted from [28], [29]*

ADLs Level	Category	Activities
Basic	Personal hygiene	Bathing, personal grooming, dressing, toileting, continence
	Feeding	Eating and drinking
	Mobility	Transferring (sit to stand), walking
Instrumental	Preparing food	Preparing foods and drinks
	Medicament	Responsibility for own medication
	External hygiene	Housekeeping, doing laundry, caring for household objects
	Mobility	Lifting and reaching, using transportation, shopping
	Communication	Telephone use
	Management	Handling finance
Advance	Personal motivation	Sophisticated kitchen activities, household appliances and daily technology usage, cognitively stimulating/intellectual activities, craftwork and arts, self-development/self-realisation/self-educational activities, caring for household objects
	Mobility	High-level gardening, transportation by motorised vehicles, sports, going on holiday
	Communication	The use of sophisticated communication devices or cell phones and email
	Societal interaction/ relationship	Intimate relationships, caring for or assisting others, semi-professional work, engagement in organised social life or leisure activities, complex economic activities, and transactions

1.3 Exoskeleton

An exoskeleton is comprised of either rigid, soft or a combination of rigid-soft links equipped with rotating joints that transfer torque to the joint axes. Rigid exoskeletons offer precise force transmission, structural strength, and rigidity, but they may be bulky and have issues with adjustability and alignment between human joints and exoskeleton axes [30]–[32]. Hence, they are unsuitable for body segments with limited space, like the distal hand. Soft exoskeletons are typically lighter and less bulky since some of the components, such as the actuator, batteries, and control unit, can be placed separately [24], [30], [31]. They exhibit low inertia, indirectly reducing the energy consumption and metabolic cost of wearing the exoskeleton [32]. Furthermore, their flexibility to fit on the skeletal structure enhances user comfort and safety [31]. However, soft exoskeletons generally transmit lower maximum force than rigid exoskeletons, mainly supporting tensile loads [31], [32].

Exoskeletons can be classified based on mode of operation, either active, passive, or hybrid types. Active exoskeletons comprise actuators, motors, and external power sources to enhance the user's physical capabilities. They are typically bulky, lack portability, demand high power, and are more expensive than passive exoskeletons [33], [34]. On the other hand, hybrid active-passive exoskeletons integrate electrically controlled actuators with functional electrical active assistance or resistance. They balance portability and precise self-control, delivering assistive or resistive forces without compromising mobility [33]. In contrast, passive exoskeletons operate without actuators, motors, and external energy sources. They utilise materials, springs, and counterweight mechanisms to assist body movements [35]–[37]. These exoskeletons feature a simple structure, sensing, control, and operational maintenance and are typically lightweight and less bulky than active exoskeletons [38]–[40]. Furthermore, they do not require any battery management, thus being safe to use in various environmental conditions. Active and hybrid exoskeletons risk battery-related problems, including explosion and thermal destruction by insufficient cooling or operating in high-temperature conditions [46].

Exoskeletons are becoming increasingly important as devices that can be worn to help with physical rehabilitation and ADLs. Significant advancements have been reported for upper limb rehabilitation using exoskeletons, with some being integrated into clinical practice and commercialised [42], [43]. However, these rehabilitation systems often require continuous monitoring and assistance from therapists and are typically bulky, heavy, and impractical for daily tasks at home [44], [45]. To the best of the authors' knowledge, only two review articles have explicitly addressed exoskeletons for elderly activities of daily living assistance, focusing on upper limb [24] and lower limb exoskeletons [25]. However, these reviews focused primarily on the technical aspects of active exoskeletons, such as the type of actuator, power source, sensor and sensing systems, prototype material, degree of freedom, and control schemes for the assistive mechanisms. These reviews did not extensively examine exoskeleton assessment, which is necessary to understand the exoskeleton's effectiveness, safety, and acceptability for assisting the elderly in ADLs. Another review article [46] highlights the technological progress of robotics applications to support independent living among the elderly. There has not been commercially widespread adoption of any robotic application designed to assist upper limb function for ADLs [47]. However, commercially available robots only support a single activity due to the ease of production and ensure robust and reliable performance [46].

This review presents an overview of upper limb exoskeletons designed for the elderly in performing ADLs, covering the exoskeleton types, development stages and assessment process. It specifically focuses on the involvement of the elderly in the development process, the ADLs-related tasks performed, assessment criteria, and the assessment environment. Furthermore, the design challenges in developing exoskeletons for the elderly are discussed, emphasising functional performance and user experience tailored to the specific needs of the elderly population.

2. Methodology

2.1 Literature Review Strategy

The exoskeletons in this reviewed article aim to assist upper limb motion for elderly or physically weak individuals. The selection of articles for this literature review was cascaded into seven steps (Figure 1). An electronic article search was performed in ScienceDirect, Scopus and PubMed databases using combinations of these keywords, “exoskeleton or wearable” and “elder or older or geriatric”. The article search based on keywords was done within the article title, abstract, and keywords in step 2.

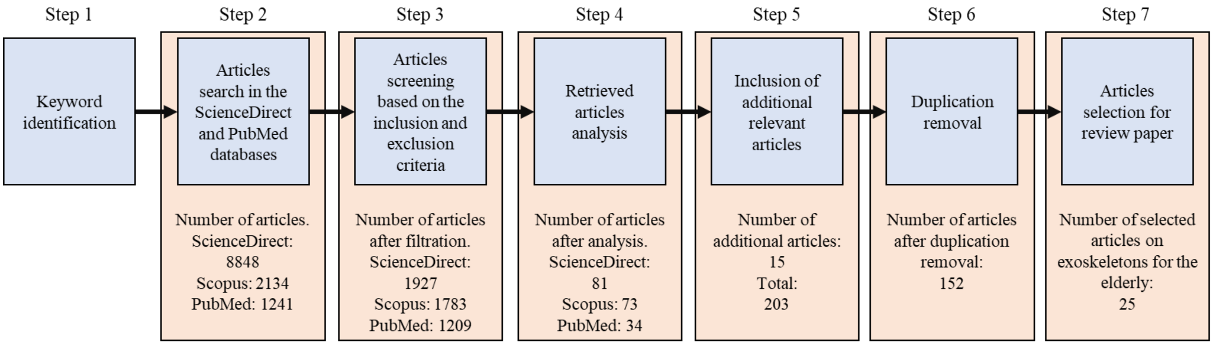

Fig. 1 *The article selection process for review article*

Next, the titles and abstracts of the searched articles were screened according to the inclusion and exclusion criteria in step 3. The selection was limited to only peer-reviewed research and review articles published in English between January 2010 and December 2022. Articles from unrelated subjects, such as biochemistry, genetics, molecular biology, environmental sciences, arts, and humanities, were also excluded. Articles were analysed for information regarding exoskeleton types and their respective assessment. Articles that address the exoskeletons to assist the elderly and physically weak in ADLs were selected in step 4. However, articles on wearable sensor technology and information and communication technology for the elderly population were excluded from this review. On the other hand, some articles related to geriatric exoskeletons were not listed in the article search since this keyword was not used in the title and abstract. Thus, step 5 was introduced to include additional relevant articles by screening through references and citations of the retrieved articles in step 4. The duplicated articles were filtered out in step 6, leading to the selection of an article focusing on upper limb exoskeletons in step 7.

Articles search (step 2) in ScienceDirect and PubMed databases based on the defined keywords (step 1) yielded 8848 and 1241 articles, respectively. Following a thorough screening (step 3) and analysis (step 4), the retrieved articles were reduced from 1927 to 81 in ScienceDirect, 1783 to 73 in Scopus, and 1209 to 34 in PubMed. Furthermore, 15 additional articles on upper limb exoskeletons for the elderly cited in the retrieved articles were included (step 5). Duplicate articles were removed, resulting in 152 articles in total (step 6). Upon consolidation, 25 articles on 18 upper-limb exoskeletons assisting the elderly or physically weak in ADLs were included in this review (step 7).

2.2 Analysis of Articles

A thorough analysis of exoskeleton types, development stage and their respective assessment was conducted upon selecting articles. Exoskeleton types were categorised based on targeted human joints, their structural design and power source. The targeted human joints were defined as single or multi-joint exoskeletons, including full-body, shoulder-elbow-hand, shoulder-elbow-wrist, shoulder-elbow, shoulder, and hand exoskeletons. Furthermore, exoskeleton types based on the mode of operation are active, passive, or hybrid, and structural designs are rigid, soft, or hybrid. For exoskeleton assessment, the selected articles were analysed based on assessment methods (objective or subjective evaluation), assessment setup (conducted on-site, in the laboratory, or simulated environment), subjects included in the study, and the task performed. The objective assessment analyses the effect on muscle activity, metabolic rate, biomechanics, and ergonomics. Meanwhile, the subjective assessment includes the study of specific task completion, comfort, usability, wearability, convenience, stability, and overall wearing satisfaction.

3. Result

3.1 Exoskeleton Types

The review included a total of 18 different upper limb exoskeletons; one full-body exoskeleton [48]–[50], two shoulder-elbow-hand exoskeletons [51], [52], two shoulder-elbow-wrist exoskeletons [53], [54], three shoulder-elbow exoskeletons [55]–[60], four shoulder exoskeletons [61]–[64] and six hand exoskeletons [44], [65]–[70].

3.1.1 Full Body Exoskeleton

A full-body exoskeleton designed for the elderly is the AXO-SUIT. AXO-SUIT is a modular and active system comprising upper-body (UB-AXO) and lower-body (LB-AXO). The combination of both modules creates a full-body exoskeleton (FB-AXO). FB-AXO provides support and assistance for the back, shoulder, elbow, hip, knee, and ankle joints, enabling the elderly to perform activities such as walking, standing, carrying, and handling tasks [48]–[50].

3.1.2 Shoulder-Elbow-Hand Exoskeleton

There are two shoulder-elbow-hand exoskeletons: Modular Mobile Robotic Platform [51] and Multimodal Neuroprosthesis (MUNDUS) [52]. Both exoskeletons support shoulder flexion-extension and abduction-adduction, elbow flexion-extension, forearm pronation-supination, and finger flexion-extension. The Modular Mobile Robotic Platform also assists with internal-external shoulder rotation [51].

The Modular Mobile Robotic Platform is an active exoskeleton mounted to a wheelchair. It is equipped with autonomous navigation and a multimodal interface to assist individuals with mobility impairments in performing various ADLs, such as cleaning the face, brushing teeth, and preparing and consuming meals [51]. MUNDUS is designed for attachment to a wheelchair and supports the shoulder and elbow. MUNDUS enables users to reach objects, position their arms, grasp them, and move them to the mouth or relocate them in the workspace [52]. MUNDUS is a hybrid exoskeleton with different power modes based on the user’s needs. In active mode, the user's intentions are predicted through neuromuscular activation, head/eye-tracking systems, and a brain-computer interface [52].

3.1.3 Shoulder-Elbow-Wrist Exoskeleton

There are two shoulder-elbow-wrist exoskeletons: Cable-driven Upper Limb Exoskeleton (CABexo) [53] and Upper Limb Exoskeleton System for Assistance in ADLs (SPexo) [54]. Both are active exoskeletons and assist shoulder flexion-extension and abduction-adduction, elbow flexion-extension, forearm pronation-supination, and wrist abduction-adduction and flexion-extension. SPexo also assists in internal-external shoulder rotation [54]. CABexo is a cable-driven exoskeleton using epicyclic gear for helping the elderly with physical disabilities [53]. SPexo is mounted on a wheelchair and assists with self-feeding and hair-combing tasks. SPexo supports the upper limb motion trajectory tracking to reach objects using Kinect's vision sensor [54].

3.1.4 Shoulder-Elbow Exoskeleton

There are three shoulder-elbow exoskeletons: Power-Assist Exoskeleton [55], [56], Low-cost Upper Limb Exoskeleton [57], [58] and Motorised Wilmington Robotic Exoskeleton (WREX) [59], [60]. These exoskeletons provide active assistance for shoulder flexion extension and elbow flexion extension. The Power Assist Exoskeleton, mounted on a wheelchair, also supports shoulder abduction-adduction and forearm pronation-supination [55], [56]. It is designed to assist physically weak individuals with eating, grasping tools, and brushing teeth and uses electromyograms to predict motion intention [55], [56]. The Low-Cost Upper Limb Exoskeleton is designed to assist elderly and disabled individuals with upper limb weakness during ADLs. It can be mounted directly on the user or a cart [57], [58]. The Motorized WREX is developed based on commercially available passive WREX and can be mounted on the user or wheelchair [59], [60].

3.1.5 Shoulder Exoskeleton

There are four shoulder exoskeletons. Passive Shoulder Exoskeleton with Variable Stiffness Mechanism [64] and Assistive Shoulder Exoskeleton with Hyper-Redundant Kinematics [63] are rigid and hybrid, respectively. Soft Robotic Exoskeleton (EXOSLEEVE) [61] and Soft Wearable Robot for Shoulder [62] are soft exoskeletons.

The Passive Shoulder Exoskeleton with Variable Stiffness Mechanism [64] and Soft Robotic Exoskeleton (EXOSLEEVE) [61] are designed to assist with shoulder flexion/extension and abduction/adduction, respectively. Soft Wearable Robot for Shoulder is designed to help with shoulder flexion/extension and abduction/adduction [62]. Finally, the Assistive Shoulder Exoskeleton is mounted to a wheelchair and intended to assist with shoulder flexion/extension and internal/external rotation [64]. The Assistive Shoulder Exoskeleton with Hyper-Redundant Kinematics is a cable-driven exoskeleton that assists shoulder flexion/extension and internal/external rotation [63].

While most shoulder exoskeletons are active, the Passive Shoulder Exoskeleton with Variable Stiffness Mechanism [64] is passive. Additionally, most shoulder exoskeletons are soft. However, the Passive Shoulder Exoskeleton with Variable Stiffness Mechanism [64] and Assistive Shoulder Exoskeleton with Hyper-Redundant Kinematics [63] are rigid and hybrid exoskeletons, respectively. EXOSLEEVE and Soft Wearable Robot for Shoulder are soft exoskeletons and pneumatically actuated. EXOSLEEVE assists shoulder abduction/adduction [61], while Soft Wearable Robot for Shoulder provides shoulder assistance in flexion/extension and abduction/adduction [62].

3.1.6 Hand Exoskeleton

There are six hand exoskeletons: Force Augmenting Exoskeleton [69], Cable-driven Hand Exoskeleton (known as mano) [65], Hand Extension Robot Orthosis Grip Glove (HERO) [66], Kist Upper-Limb Exoskeleton (KULEX) [44], [67], EXOMUSCLE [68], and Soft Power-Assist Glove [70].

All hand exoskeletons are soft type, except for the Force Augmenting Exoskeleton. All hand exoskeletons are active type except for EXOSMUSCLE. Mano [65] was designed to assist flexion extension to all fingers and enhance grasping, gripping, and pinching capabilities. In addition to helping in hand movements, the mano [65] was also used in neurorehabilitation for individuals with hand sensorimotor impairments. The Hand Extension Robot Orthosis (HERO) Grip Glove significantly improves finger extension and range of motion, allowing the user to grasp and manipulate objects such as small boxes, water bottles, pens, and forks by providing grip and pinch strength for those without active grip strength [66]. KULEX includes forearm support, wrist support, and a grasping module to assist the elderly and disabled with pinching, grasping, and holding during ADLs, such as pinching a pen and holding a water bottle. The preliminary conceptual design of KULEX was previously reported in [44], [71]. EXOMUSCLE is a passive exoskeleton that assists the elderly in gripping and grasping the wok while cooking [68]. The Soft Power-Assist Glove utilises curved and spiral rubber muscles to assist in index finger flexion-extension movements and facilitate thumb base flexion for enhancing object grasping [70].

3.2 Development Stage and System Types of Exoskeletons

Among the 18 upper limb exoskeletons, 16 are in the prototyping stage [44], [48], [49], [51], [55]–[70], while two are in the embodiment design stage [53], [54]. Based on structural design, there are six soft exoskeletons [61], [62], [65], [66], [68], [70], eleven rigid exoskeletons [44], [48], [49], [51]–[56], [58]–[60], [64], [67], [69] and one hybrid exoskeleton [63]. Three of the soft exoskeletons are cable-driven [65], [66], [68] and two are pneumatic-driven exoskeletons [61], [62]. Categorised by mode of operation, i.e. active or passive, there are fifteen active [44], [48], [49], [51], [53]–[56], [58]–[63], [65]–[67], [69], [70], two passive [64], [68] and one hybrid exoskeleton which operates based on user's capability [52]. Table 2 lists the reviewed exoskeletons regarding the exoskeleton category, name, development stage, structural design (rigid, soft or hybrid), mode of operation (active, passive or hybrid) and supported upper limb joint movement.

Table 2 *List of the upper limb exoskeletons designed to assist the elderly or physically weak individuals in ADLs*

Exoskeleton category	Exoskeleton name	Development stage	Structural design	Mode of operation	Supported upper limb joint movement
Full body	AXO-SUIT [48]–[50]	Prototype	Rigid	Active	Shoulder (FE, AA, IE), Elbow (FE), Hip (FE), Knee (FE), Ankle (DP)

Shoulder-elbow-hand exoskeleton	Modular Mobile Robotic Platform [51]	Prototype	Rigid	Active	Shoulder (FE, AA, IE), Elbow (FE), Forearm (PS), All Finger (FE)
	Multimodal Neuroprosthesis with Modular Robotic Hand Orthosis [52]	Prototype	Rigid	Hybrid active and passive	Shoulder (FE, AA), Elbow (FE), Forearm (PS), Finger (FE)
Shoulder-elbow-wrist exoskeleton	Cable-driven Upper Limb Exoskeleton (CABexo) [53]	Embodiment design	Rigid	Active	Shoulder (FE, AA), Elbow (FE), Forearm (PS), Wrist (AA, FE)
	Upper Limb Exoskeleton for Assistance in ADLs (SPexo) [54]	Embodiment design	Rigid	Active	Shoulder (FE, AA, IE), Elbow (FE), Forearm (PS), Wrist (AA, FE)
Shoulder-elbow exoskeleton	Power Assist Exoskeleton [55], [56]	Prototype	Rigid	Active	Shoulder (FE, AA), Elbow (FE), Forearm (PS)
	Low-Cost Upper Limb Exoskeleton [57], [58]	Prototype	Rigid	Active	Shoulder (FE), Elbow (FE)
	Motorised WREX [59], [60]	Prototype	Rigid	Active	Shoulder (FE, IE), Elbow (FE), Forearm (PS)
Shoulder exoskeleton	Soft Robotic Exoskeleton (EXOSLEEVE) [61]	Prototype	Soft	Active	Shoulder (AA)
	Soft Wearable Robot for Shoulder [62]	Prototype	Soft	Active	Shoulder (FE, AA)
	Assistive Shoulder Exoskeleton with Hyper-Redundant Kinematics [63]	Prototype	Hybrid soft and rigid	Active	Shoulder (FE, IE)
	Passive Shoulder Exoskeleton with Variable Stiffness Mechanism [64]	Prototype	Rigid	Passive	Shoulder (FE)
Hand exoskeleton	Cable-driven Hand Exoskeleton (*mano*) [65]	Prototype	Soft	Active	All fingers (FE)
	Hand Extension Robot Orthosis Grip Glove (HERO) [66]	Prototype	Soft	Active	All fingers (E), Thumb (Abduction)
	Kist Upper-Limb Exoskeleton (KULEX) [44], [67]	Prototype	Rigid	Active	Index finger (FE)
	EXOMUSCLE [68]	Prototype	Soft	Passive	All fingers (FE)
	Force Augmenting Exoskeleton [69]	Prototype	Rigid	Active	All fingers (FE)
	Soft Power-Assist Glove [70]	Prototype	Soft	Active	Index finger (FE) Thumb (Flexion)

Notes: FE = flexion-extension, AA = abduction-adduction, IE = internal-external rotation, PS = pronation-supination

3.3 ADLs-Related Exoskeleton Assessments

The exoskeleton assessments were performed in laboratory settings and simulated environments representing real-life scenarios, namely in living rooms [51] and kitchens [51], [68]. Only functional tests for mano [65] on two spinal cord-injured patients were performed at the users' homes.

SPexo [54] and CABexo [53] are still in the embodiment design stage. Motorised WREX [59], [60], and Soft Power-Assist Glove [70] were assessed on the control strategies. Force Augmenting Exoskeleton underwent structural design optimisation and performance evaluation to counterbalance gravitational torque during shoulder flexion extension [69]. As a result, these five exoskeletons, namely SPEXO, CABexo, Motorised WREX, Soft Power-Assist Glove and Force Augmenting Exoskeleton, are excluded from Table 3.

Table 3 summarises the exoskeleton assessment, including the number of participants, health condition, the ADLs-related task performed and the evaluated parameter. The evaluation of the interaction between the user and the exoskeleton can be categorised into objective and subjective assessments. Objective assessments provide insights into muscle activity, metabolic rate, brain pattern, biomechanics, ergonomics, joint kinematics and kinetic, offering a comprehensive understanding of the exoskeleton's impact on the user. Subjective assessments focus on factors like task completion, comfort, usability, wearability, convenience, stability, and overall satisfaction to gauge user acceptance and exoskeleton effectiveness. As a result, the combination of objective and subjective assessments provides valuable insights into the overall exoskeleton performance and the user's experience.

In this review, eight exoskeletons underwent objective assessments, two were subjected to subjective evaluations, and three were evaluated using objective and subjective measures. The subjective assessments were performed on the Modular Mobile Robotic Platform [51] and MUNDUS [52], while the combination of both assessments was done on AXO-SUIT [49], [50], mano [65], and HERO [66]. Muscle activation via sEMG was evaluated in four exoskeletons [49], [61], [62], [69] and brain pattern monitored using EEG was analysed for mano [65]. Joint kinetics and kinematics were assessed for three exoskeletons [65]–[67]. Additionally, functional performance validation studies were conducted to evaluate tool trajectory for the Power Assist Exoskeleton [55], [56] and Low-cost upper-limb exoskeleton [57], [58].

Subjective assessments comprising task completion in reaching, grasping, pinching, or object manipulation were conducted on four exoskeletons [51], [52], [65], [66]. The task completion assessment was determined using a 3-level score assessment on MUNDUS (from 0, unsuccessful, to 2, completely functional) [52]. The usability and user satisfaction were evaluated on four exoskeletons [49], [51], [65], [66]. Various methods were utilised for these assessments, including the System Usability Scale (SUS) [51], Quebec user evaluation of satisfaction with assistive technology version 2.0 (QUEST) [66] and modified User Satisfaction Questionnaire (USQ) [49].

The participants involved in the exoskeleton assessment presented in Table 3 were in healthy condition. However, there were specific cases where participants with health conditions were included, such as individuals with multiple sclerosis for Modular Mobile Robotic Platform [51] and MUNDUS [52], participants with spinal cord injury for MUNDUS [52] and mano [65], and stroke survivor for HERO [66].

A significant observation is the limited involvement of the elderly in the assessment process. Only two exoskeletons, AXO-SUIT [48]–[50] and MUNDUS [52], included elderly participants aged 50 and above. The AXO-SUIT assessment was customised in two levels by age group to address age-related safety and feasibility concerns [49]. Level 1 involved healthy young adults between 18 and 49, with a complete physical assessment protocol and a 1-hour testing assessment duration. In contrast, level 2 included healthy elderly aged 50 and over, with simplified physical assessment protocols and a 30-minute assessment duration.

Table 3 *Assessment of upper limb exoskeletons designed to assist the elderly or physically weak individuals in ADLs*

Exoskeleton name	Participants detail (M-male, F-female)	Participants (physical) health condition	ADLs-related tasks performed	Evaluated parameter
AXO-SUIT [48]–[50]	Two age groups: 7M and 24F with a mean age of 71 ± 12. 1M and 2F aged 27-29.	healthy	Lifting and lowering a 6 kg load; picking up and pouring 1-litre water; carrying a 6 kg load while walking [49]	Objective Assessment: Muscle activity for biceps brachii and middle deltoid. Subjective Assessment: usability and user satisfaction

Exoskeleton name	Participants detail (M-male, F-female)	Participants (physical) health condition	ADLs-related tasks performed	Evaluated parameter

AXO-SUIT [48]–[50]	Two age groups: With ages≥ 18 and ≥ 50, the number of participants and genders were unknown.	healthy	Carrying a 6 kg load on flat ground and up/downstairs; standing firmly in free space; walking up/downstairs [48]	Objective Assessment: Muscle activation on biceps brachii and middle deltoid
	24 participants aged 20 - 62.		Lifting and lowering a 6 kg load, carrying a 6 kg payload while walking, walking on a treadmill, standing stably in free space, and walking up/downstairs [50]	Objective Assessment: Muscle activity for biceps brachii and middle deltoid. Subjective Assessment: usability and user satisfaction
Modular Mobile Robotic Platform [51]	1M with age unknown	with multiple sclerosis	Worktop adjustment, switching on a table lamp and television and eating.	Subjective Assessment: Usability and user satisfaction
MUNDUS [52]	3M aged 33, 44 and 79	with incomplete spinal cord injury	Arm reaching different points in the working space and drinking	Subjective Assessment: Task completion
	1M aged 49 and 1F aged 37	with multiple sclerosis		
Power assist exoskeleton [55], [56]	1M, age unknown.	healthy	Eating tasks (reaching spoon and dish)	Objective Assessment: Tool trajectory and position
Low-cost upper-limb exoskeleton [57], [58]	The number of participants, gender, and age are unknown.	-	Movement with straight-line trajectory [58]	Objective Assessment: Joint angle at shoulder and elbow
	6 participants. Gender and age are unknown.	-	Movement with sine wave trajectory mimicking moving objects [57]	
EXOSLEEVE [61]	3 participants. Gender and age are unknown.	healthy	Shoulder abduction at 90° over 6 seconds, followed by adduction at the same speed	Objective Assessment: Muscle activation on medial deltoid
Soft wearable robot for the shoulder [62]	3M with a mean age of 26 ± 3.6	healthy	Arm abduction at 90°; arm flexion extension while maintaining arm abduction at 90°; isometric maximum voluntary contractions during abduction; with 1.3kg and without load.	Objective Assessment: Muscle activation on the medial deltoid, posterior deltoid, pectoralis major and infraspinatus
Assistive shoulder exoskeleton [63]	5M with a mean age of 25.4 ± 1.7	healthy	Maintaining arm flexion at 90° flexion; dynamic arm flexion, arm range of motion.	Objective Assessment: Muscle activation on the anterior deltoid, medial deltoid, and biceps brachii
Exoskeleton name	Participants detail (M-male, F-female)	Participants (physical) health condition	ADLs-related tasks performed	Evaluated parameter

mano [65]	The number of participants, gender, and age are unknown.	healthy	Hand closing-opening; object grasping; load lifting (0 to 0.7kg) suspended from the index finger's distal phalanx by a nylon rope.	Objective Assessment: Naturalness in the grasping motion and force at the fingertips
	Two participants, gender unknown, aged 38 and 48.	with spinal cord injury	Grasping, displacing, releasing objects; performing ADLs like eating, cleaning teeth, and drinking.	Subjective Assessment: Task completion, usability, and user satisfaction
	7M and 2F with a mean age of 23 ± 5.	healthy	Resting, exoskeleton-induced hand motions, right-hand motor imagery.	Objective Assessment: Brain patterns
HERO [66]	Eleven participants. Gender and age are unknown.	stroke survivors with minimal or no active finger extension	Index finger range of motion, gripping, pinching; grasp-lift-release small box; reach-grasp-lift-hold water bottle and twisting off the lid with the opposite hand; grasp; manipulating pen and fork	Objective Assessment: Index finger range of motion, grip, and pinch strength Subjective Assessment: Grasp task completion, usability, and user satisfaction
KULEX [67]	5 participants. Gender and age are unknown.	healthy	Tip pinching (pen), power grasping motion (water bottle)	Objective Assessment: Naturalness in the grasping action, pinch motion, and power grasping
EXOMUSCLE [68]	5F with a mean age of 23.8 ± unknown.	healthy	Transferring wok from one location to another	Objective Assessment: Muscle activation on biceps, flexor digitorum superficialis and flexor carpi radialis
Force-augmenting exoskeleton for the human hand [69]	5M and 5F aged 18 - 23	healthy	Full hand grasping, pinching, palmer pinching, lifting a 2.4kg tote bag and 0.5kg water bottle.	Objective Assessment: Muscle activation on flexor carpi ulnaris and radialis, pronator teres and palmaris longus

4. Discussion

This review presents 18 upper limb exoskeletons designed to assist elderly or physically weak individuals in performing ADLs. Table 2 provides an overview of all 18 exoskeletons, and Table 3 summarises the assessment of 13 exoskeletons. Five upper limb exoskeletons, namely SPexo [54], CABexo [53], Motorised WREX [59], [60], Soft Power-Assist Glove [70], and Force Augmenting Exoskeleton [69] were excluded from Table 3 due to various reasons, such as still in embodiment design stage [53], [54], being evaluated on control strategies performance [59], [60] and undergoing design optimisation and performance evaluation [69]. Table 3 summarises the assessment of 13 upper limb exoskeletons, including participant number, health conditions, ADLs-related tasks performed, and evaluated parameters. Sixteen of the 18 upper limb exoskeletons are in the prototyping stage, with two in the embodiment design stage, indicating that all 18 exoskeletons are still under development and assessment and not yet ready for commercialisation. Despite the promising results of the evaluations, most of the presented exoskeletons still need to be prepared for practical usage in assisting daily life activities at home. Further development and testing are required to improve exoskeletons' efficacy and safety before exoskeletons can be widely adopted to help individuals with upper limb impairments.

Exoskeletons focusing on shoulder and elbow joints are designed to assist in the upper-limb movement trajectory for object-reaching and hand orientation via forearm pronation-supination. Wrist exoskeletons improve hand stability and positioning by assisting wrist movements. For instance, wrist flexion-extension and abduction-adduction are necessary for ADLs involving grasping, gripping, and manipulating objects. Hand exoskeletons, on the other hand, are intended to assist in object manipulation involving gripping, holding, grasping, and pinching. Furthermore, effective movement coordination between the shoulder, elbow, forearm, and wrist is required to reach a specific destination and transport objects within the workspace. Given these age-related changes, exoskeletons are seen as having great promise in assisting and enhancing the performance of daily tasks for the elderly. The review discusses the design challenges and recommendations associated with developing exoskeletons for the elderly, focusing on two key aspects - functional performance and user experience.

4.1 Challenges from the Functional Performance Perspective

The overall exoskeleton functional performance comprises the technological, biomechanical, and physiological indicators [72]. The technological indicator includes kinematic and kinetic compatibility between the exoskeleton and human joints. Kinematic compatibility ensures that the functionality and usability of an exoskeleton do not jeopardise the user’s comfort and safety [72]. The failure in kinetic compatibility to transmit the required power/torque may adversely affect the user’s speed, strength, and endurance in performing a task [73]. The kinematic and kinetic compatibility significantly affects the selection of exoskeleton structure, actuator, sensor, transmission, and controller systems [72], [74].

However, the review highlights a significant research gap, as there is currently a lack of involvement of the elderly in exoskeleton assessment and comparative studies investigating user-exoskeleton interactions between young adults and the elderly. The elderly experience significant physical and physiological changes with reduced muscle strength, flexibility, agility, and endurance [75], [76]. Muscle mass and strength deteriorate up to 30% to 50% between the ages of 30 and 80 years, with a decline rate of nearly 12% to 14% per decade after the age of 50 years [75]. Moreover, there are substantial differences in reaching for objects between adults and the elderly, including distal hand manipulation, kinematic trajectory, time to initiate movement [77], time to execute the tasks [80], movement consistency and accuracy [77], [79], [80]. Nearly double the relative effort is required by healthy elderly to perform ADLs compared to adults [76]. The feedback from the elderly on functional requirements for AXO-SUIT highlighted their primary necessity for upper limb support, specifically in power-based activities (e.g., pushing and pulling) and strength endurance-based activities (e.g., carrying objects) [81].

Altered motor recruitment patterns of shoulder muscles are observed in the elderly, with a general trend towards delayed muscle onset times in the elderly population, except for the upper trapezius muscle [82], [83]. Consequently, motion intention recognition and controllers developed based on the characteristics of the young adult and adult population may not effectively cater to the unique conditions experienced by the elderly. These findings emphasise the significance of considering the requirements and physiological distinctions of the elderly population in the design of exoskeletons.

Certain modifications in the experimental setup may be necessary to assess the interaction between exoskeletons and the elderly. These could involve a shorter duration of each experiment, simplified experimental procedures, longer ample time between experiments, slower movement speed, and lower load magnitude compared to the adult and elderly groups. The final physical testing on the AXO-SUIT for elderly participants also involved shorter durations and simplified procedures, emphasising the importance of feasibility, safety, and ethical considerations in these investigations [48], [49]. Conducting these comparative studies can significantly advance our understanding of exoskeleton design for the elderly and contribute to the development of more effective and user-friendly geriatric exoskeletons.

The geriatric exoskeleton design must account for the unique anthropometry of the elderly. Anthropometric standards derived from adult populations may not be suitable for this demographic due to age-related changes in body composition [84], including variations in bone, muscle, and fat tissues with age [85]. Factors like spinal disk thinning, vertebrae height reduction, and conditions like scoliosis can significantly alter an individual's body stature [86]. The increasing prevalence of overweight among the elderly, with a threefold increase globally since 1975, highlights the importance of considering these unique design requirements for this demographic [87]. Consequently, exoskeleton design for the elderly should consider these unique anatomical features to ensure optimal fit, comfort, and functionality. Inadequate adjustability of the exoskeleton to accommodate these differences restricts the user's range of motion [49]. Any misalignment between the human anatomy and the exoskeleton kinematics may lead to discomfort, skin irritation/sores, joint dislocation, or/and fracture [88], [89].

4.2 Challenges from the User Experience Perspective

The elderly consider adopting new technologies to stay socially connected and avoid potential feelings of isolation [90]. However, their perceptions and acceptance of exoskeleton technology are influenced by numerous factors, such as perceived usefulness, perceptions and stigma associated with dependency and ageing [23]. The stigma of being seen as dependent or experiencing a decline in abilities is perceived as unacceptable and potentially results in the rejection of technology adoption [91]. Their motivation to embrace technology is also influenced by personal factors related to the degree of shame or embarrassment associated with using specialised devices [86] and concern about being seen as physically disabled by others [19], [92].

To address these challenges, it is essential to tailor exoskeleton design according to the specific needs and concerns of the elderly population, including their social and psychological aspects. The exoskeleton, with consideration for functional, aesthetically pleasing, and unobtrusive, reduces the stigma associated with technology adoption [92]. For instance, the elderly prefer minimalistic designs rather than bionic or organic aesthetics, which might not align with the mainstream aesthetics perspective [92]. The concept of a lightweight, less bulky, soft exoskeleton that can be worn beneath clothing makes it nearly invisible to others, potentially avoiding judgment associated with using assistive devices in public [32], [62].

The main design challenge in addressing user experience is the absence of standardised technological acceptance models and tools to evaluate how the elderly perceive exoskeletons before, during, and after use [93]. Standardised assessments are pivotal in advancing exoskeleton development by allowing researchers and manufacturers to focus on essential system features, compare exoskeletons to specific tasks, detect design issues or improvements, and clarify performance standards [94]. Standardised test procedures are a universal benchmark for various exoskeleton assessments and studies, ensuring consistent, repeatability, reliable, and comparable evaluations across diverse research endeavours [94], [95]. Standardised tests enable certification for commercialisation with validated product safety [96] and performance claims to enhance user confidence in adopting exoskeletons [97].

Existing exoskeleton assessments, such as the System Usability Scale (SUS), Quebec user evaluation of satisfaction with assistive technology version 2.0 (QUEST) and modified User Satisfaction Questionnaire (USQ) have been employed in appraising usability and user experience in previous studies [49], [51], [66]. SUS is a subjective assessment based on ten statements on product usability [98]. In contrast, QUEST assesses the user satisfaction perspective regarding assistive devices (such as weight, durability, etc.) and services (such as service delivery, follow-up services, etc.). However, SUS and QUEST do not include specific concerns regarding the elderly’s perception and acceptance of using exoskeletons. Alternatively, Exoscore can be used to evaluate geriatric exoskeleton types due to its generality in addressing elderly-specific concerns, for instance, self-efficacy to wear the exoskeleton without the need from another person. The issue of difficulties putting on the exoskeleton is highlighted in the AXO Suit assessment [49]. Exoskeleton assessment based Exoscore is divided into three phases: perception before using the exoskeleton, experience while using and perceived impact after using the exoskeleton [93]. The perception and perceived impact evaluations were built upon merging several technological acceptance models, whereas the experience impact is solely based on the System Usability Scale [99].

4.3 Future Prospective

Encouraging greater participation of the elderly in exoskeleton technology's development and assessment phases is essential for ensuring its relevance and adoption within this demographic. It includes establishing easily accessible sites, prioritising convenience, and facilitating smooth visitation and support during the development and assessment stages. On the other hand, current approaches for objective and subjective exoskeleton assessments face significant challenges due to the limitations of non-configurable exoskeleton designs. This rigidity limits assessment repeatability and comparability across diverse studies and lacks clarity on the critical design features that maximise the benefits of assistance to the user. These constraints present significant obstacles to the development of exoskeletons tailored to meet the specific requirements of elderly users.

Emulators or testbeds emerge as a more adaptable and cost-effective approach to exoskeleton development and evaluation. These configurable instrumented wearables enable the exploration of a wide range of assistance strategies and design considerations without the need for time-consuming iterative design cycles and expensive specialised prototypes [101]. The real-time configurability of exoskeleton parameters offered by emulators provides flexibility and versatility unmatched by non-configurable exoskeletons, making them ideal for user-device interaction and human-in-the-loop optimisation [102]. Emulators present an efficient method for evaluating various designs and assistive strategies customised to meet the specific needs of elderly users, exemplified in optimising ankle exoskeleton assistance in walking for both adults and the elderly population [103]–[105].

The user-centred approach using musculoskeletal modelling (MM) provides a deeper understanding of human biomechanics and can be used for assessing the interaction between the user and exoskeleton. MM employs inverse dynamics and Hill-type musculotendon models, enabling joint moments estimation from measured kinematics, kinetics, and electromyographic signals without invasive or direct in vivo measurement [106]. MM enables joint loading and metabolic cost estimation, providing valuable insight into defining ideal assistive strategies, simulation-based exoskeleton development, design parameters evaluation and the human body's reaction to the exoskeleton [107]–[111].

Integrating machine learning (ML) with biomechanics enables effective user-centric exoskeleton design, testing, and evaluation. ML models learn from the extensive data gathered using various sensors, such as electromyography (EMG), inertial measurement unit (IMU), motion capture, and force plates. The ML models potentially identify patterns and correlations between various biomechanical variables that would be challenging to perceive using traditional analytical methods. The ML approach has been used for joint moments estimation at the wrist and metacarpophalangeal joints [109] and hip [110]. ML is also instrumental in modelling human locomotion control [112], [113], recognising human motion intention [114]–[117], and movement control, such as in EMG-based controller for shoulder exoskeleton [117] and neuro-muscular electrical stimulation based controller for upper limb exoskeleton [118], [119]. Considering the variations in joint kinematics and muscle activity between the elderly and adults [77], [79], [80], [82], [83], ML application potentially provides population-specific considerations for exoskeleton design and control systems. Recent ML applications include optimising exoskeleton designs in personalising the mechanical parameters of chainmail for hand exoskeletons [120].

5. Conclusion

Population ageing is a global issue. Exoskeleton technology is essential in accommodating healthy ageing by augmenting elderly performance to meet the physical demands of daily living activities and compensate for age-related deterioration in muscle strength, flexibility, agility, and endurance. A shift in focus towards developing solutions explicitly tailored to the needs of elderly populations is deemed essential, aligned with the recent progress and intensification in the research, development, and commercialisation of exoskeletons for industrial and rehabilitation. The review highlights a critical gap in the development and assessment of upper limb exoskeletons for the elderly. Most exoskeletons were still in the prototype stage, primarily evaluated in laboratories or simulated environments with limited involvement from the elderly in the development and assessments. Establishing standardised assessment protocols comprising objective and subjective criteria is necessary as a universal benchmark for researchers, developers, and policymakers. These protocols ensure consistent, repeatability, reliable, and comparable evaluations across studies and settings. The assessments should be tailored for the elderly to evaluate the human-exoskeleton interaction, considering physical, physiological, and psychological deterioration due to ageing. These considerations facilitate the customisation of functional and user experience specifications to enhance overall exoskeleton performance, addressing the potential stigma and fostering acceptance of exoskeleton usage. An urgent call is extended to researchers, developers, and policymakers to prioritise the development and deployment of exoskeletons addressing the distinct requirements of the elderly. This dedication is honoured as a strategic effort to harness the potential of exoskeleton technology in promoting healthy ageing and ageing in place.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm the contribution to the paper as follows: ***study conception and design:*** *HHH;* ***data collection:*** *MFAJ, HHH;* ***analysis and interpretation of results:*** *MFAJ, HHH;* ***draft manuscript preparation:*** *MFAJ, HHH;* ***critical feedback****: MFSFS, WZWH, TTL. All authors reviewed the results and approved the final version of the manuscript.*

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