Review of Recent Trends in Home-based Rehabilitation Assistive Devices Design for Shoulder Movement

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Assistive technology offers patients going through shoulder rehabilitation new possibilities for home-based rehabilitation. In our review, home-based rehabilitation refers to rehabilitation practices that can be completed in a home context. This review conducts a categorised comparison of home-based rehabilitation assistive device designs for shoulder movement by analysing literature to understand the developmental trends and challenges. This review focuses on applied interaction technologies, medical conditions, modes of intervention, control strategy, outcome measures, weight and portability, device operation, and interdisciplinary developers. The review also shows that assistive devices can be classified into three application areas: (1) robotic devices, (2) wearable devices, and (3) mechanical devices. In addition, current challenges, and possible directions for the future development of assistive shoulder rehabilitation are outlined at the end of the paper. Despite many existing digital technologies already used in shoulder home-based rehabilitation, there is a research gap in how existing design approaches can be informed by interdisciplinary knowledge inputs such as: engineering, interaction design, and rehabilitation study with end-user representatives.

CCS CONCEPTS • Human-centred computing • Human computer interaction (HCI) • Interaction devices

Additional Keywords and Phrases: Assistive devices, Wearable devices, Robotic devices, Mechanical devices, Interdisciplinary design, Interaction design, Home-based rehabilitation, Shoulder rehabilitation

1 INTRODUCTION

1.1 Assistive Technologies and Digital Health

The proliferation of Information Technology and mobile internet has opened a new era of digital health for patient care in the healthcare industry. Assistive technologies involve the systems or services related to delivering assistive products. Assistive products can enhance patients' well-being by maintaining or improving their functions and independence [1]. For example, new and emerging assistive technologies include remote patient monitoring and wearables and have improved health outcomes for people with chronic conditions [2]. Currently, digital health and assistive technologies sit at the intersection of science and technology with health, healthcare, living, and society [3]. For a broader economic context, the global market for smart wearable health (SWH) devices was predicted to reach 87 and 93.19 billion dollars in 2025 and 2027 [4].

As the assistive technology market continues to grow rapidly, healthcare professionals are more recently utilising digital healthcare technologies to monitor people's data during home rehabilitation activities and during the process of telerehabilitation [5]. Stakeholders, such as healthcare practitioners and researchers, have also adopted digital health interventions aiming to increase accessibility for patients, reduce costs, personalise medications, and improve patient care outcomes. For example, Isernia, Pagliari, Jonsdottir, Castiglioni, Gindri, Gramigna, Palumbo, Salza, Molteni and Baglio [6] created a human empowerment ageing and disability programme for digital health rehabilitation. Their findings suggest that a telehealth-based method is a feasible and efficient way of providing rehabilitation care from the clinic to individuals who suffer from chronic neurological diseases and may not have access to always engage in rehabilitation care at the clinic.

While rehabilitation can improve a patient's mobility, rehabilitation has a high expense inherent to providing care due to factors such as patient transportation or the therapy itself (e.g., therapists' salaries, rehabilitation places, etc.). These considerations restrict how often and how long patients can interact with the rehabilitation therapies [7, 8]. Furthermore, current shoulder rehabilitation approaches are not only labour- and time-intensive, but they also require people to return to the clinic for treatment [9]. These factors result in low patient compliance and impact a patient's motivation to comply with the rehabilitation therapy process. The following section will go into more detail about the current literature on assistive devices of shoulder joint rehabilitation in the home setting [10].

1.2 Assistive Devices of Shoulder Joint Rehabilitation at Home

As traditional shoulder rehabilitation efforts face challenges in accessibility for patients, recent literature has focused on improving the long-term benefits in home-based rehabilitation. Despite the extensive benefits technology can offer to healthcare and home rehabilitation, there is a limited understanding of the impacts of digital technologies, in relation to shoulder rehabilitation at home [11]. Brackenridge, V Bradnam, Lennon, J Costi and A Hobbs [3] identified 141 robotic devices designed to facilitate rehabilitation for stroke patients in a hospital setting. However, few devices considered the opportunity for at-home rehabilitation therapy.

In regards to home-based rehabilitation, rehabilitation varies according to each patient's preferences, needs, and disease progression [12]. Vaartio-Rajalin, Rauhala and Fagerström [12] suggested that home-based rehabilitation therapies could benefit from improved portability, responsiveness, comfort, and safety of the devices used so better human-centred rehabilitation strategies can be developed in the future. Rehabilitation in more familiar environments, such as at home, also enhances the effectiveness of training [13]. However, if taken home, the device should be adapted to ensure patient safety [14].

Patients in rehabilitation have shown improved upper limbs' recovery associated with more comprehensive training. However, monitoring of shoulder motion is challenging due to the complexity of joint kinematics, which requires the development of protocols exploiting sensing technology and should be both reliable and unobtrusive. As discussed, the emergence of assistive devices suggests a promising future in which shoulder rehabilitation exercises can be carried out at home.

1.3 Aims of this Research

This review aims to provide a broad state-of-the-art analysis to help researchers investigate assistive devices in a home-based context. It also creates a categorisation of assistive device types, provides suggestions for future research, and identifies current trends.

2 ANATOMY OF SHOULDER COMPLEX AND SHOULDER KINEMATICS

The shoulder is an important human joint as it connects the human arm with the rest of the body. The human shoulder is comprised of three bones (clavicle, scapula, and humerus) and four independent joints (glenohumeral, acromioclavicular, scapulothoracic and sternoclavicular) [15]. Figure. 1 presents an illustration of the anatomy of the shoulder complex and kinematics. The shoulder also has three rotational movements consisting of (1) flexion/extension, (2) abduction/adduction, and (3) internal/external rotation [16]. Joint movements are a key factor for a person's mobility during daily activities [17]. However, patients who suffer from shoulder degenerative changes and damage may experience shoulder kinematics alteration, which can affect their full range of shoulder mobility [18]. Wearable sensors that measure upper limb and/or shoulder kinematics have been suggested for use in people suffering from musculoskeletal or neurological conditions such as stroke, multiple sclerosis, osteoarthritis, rotator cuff tear and frozen shoulder [19]. A systematic review by Carnevale, Longo, Schena, Massaroni, Lo Presti, Berton, Candela and Denaro [19] identified seventy-three studies focused on evaluating upper limb motion for musculoskeletal diseases (i.e., osteoarthritis, rotator cuff tear, frozen shoulder), twenty-six studies on neurological diseases and in neurorehabilitation applications (i.e., stroke, multiple sclerosis), fifteen studies on general rehabilitation aspects (e.g., home-based rehabilitation, physiotherapy monitoring) and seventeen studies focusing on validation and development of systems as well as algorithms for monitoring shoulder kinematics. Whereas most studies focus on the musculoskeletal and neurological diseases and elements surrounding rehabilitation practices, there is an emerging research focus on home-based rehabilitation shoulder assistive technology practices that have not been adequately explored. As such, the following section will discuss the literature review search strategy that was used.

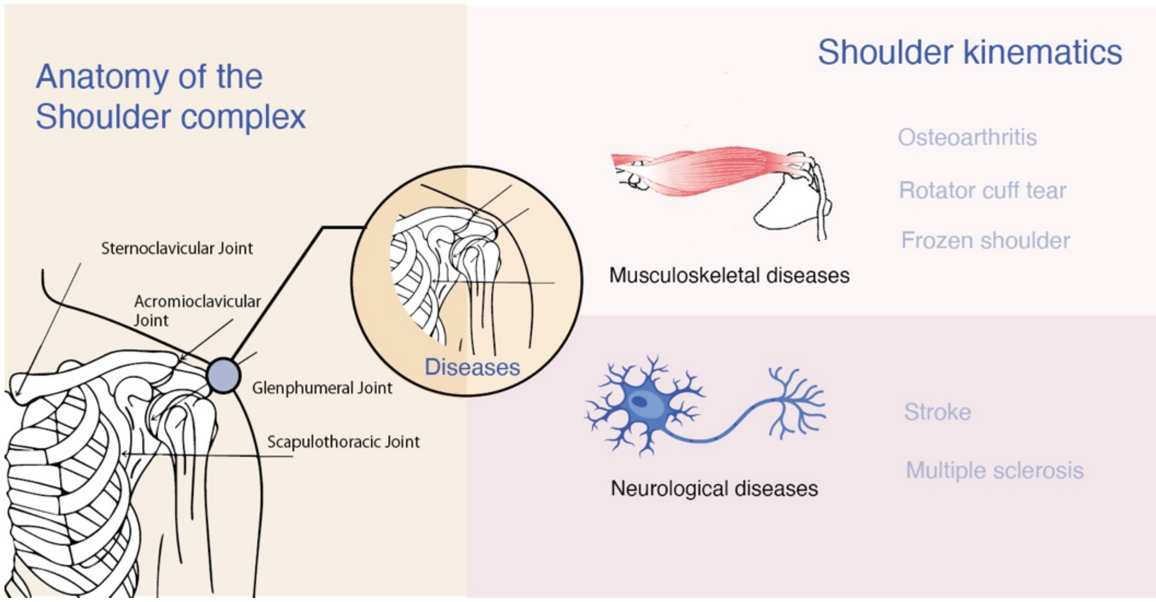

Figure 1: Anatomy of the Shoulder Complex and Shoulder Kinematics

3 SEARCH METHOD

A literature review was carried out to explore how home-based rehabilitation assistive shoulder devices are designed.

Inclusion and Exclusion Criteria: The inclusion criteria consisted of full papers written in English and conference papers regarding shoulder home-based rehabilitation. The exclusion criteria included review papers, books, white papers, and the papers outside of the primary scope of this review: not relevant to shoulder home-based rehabilitation.

Databases Searched: During the database search stage, the following bibliographic electronic databases were searched: IEEE Xplore, Biomed Central, and PubMed. High-quality peer-reviewed and scholarly articles were reviewed. In addition, Akbari, Haghverd and Behbahani [20] were included in the screening process as a separate source as their paper was a comprehensive review of home-based rehabilitation technologies for the upper and lower limbs from 2010-2020.

Search Terms: The search included the following keywords: “home rehabilitation devices” AND “home-based rehabilitation devices”, AND “shoulder rehabilitation device”. The search was conducted in October 2022. Therefore, we restricted the search of home-based assistive devices for shoulder rehabilitation from January 2015 to October 2022.

Review Process: In total, we reviewed 823 papers. Figure 2 shows the screening and reviewing process. First, the investigators independently reviewed the titles and abstracts using the eligibility criteria mentioned above. Then, the full-text articles were independently evaluated to select those that would be included within the review analysis. In all review stages, at least two reviewers would screen and vote. If a tiebreaker was needed, a third blind reviewer would review and then vote to break the tie. The screening process resulted in 24 original research papers for review. Thus, this review seeks to answer the following three research questions:

- What types of home-based rehabilitation assistive devices are produced for the shoulder?
- What are the main design considerations when developing home-based rehabilitation assistive devices for the shoulder?
- What are the challenges of designing home rehabilitation assistive devices for the shoulder?

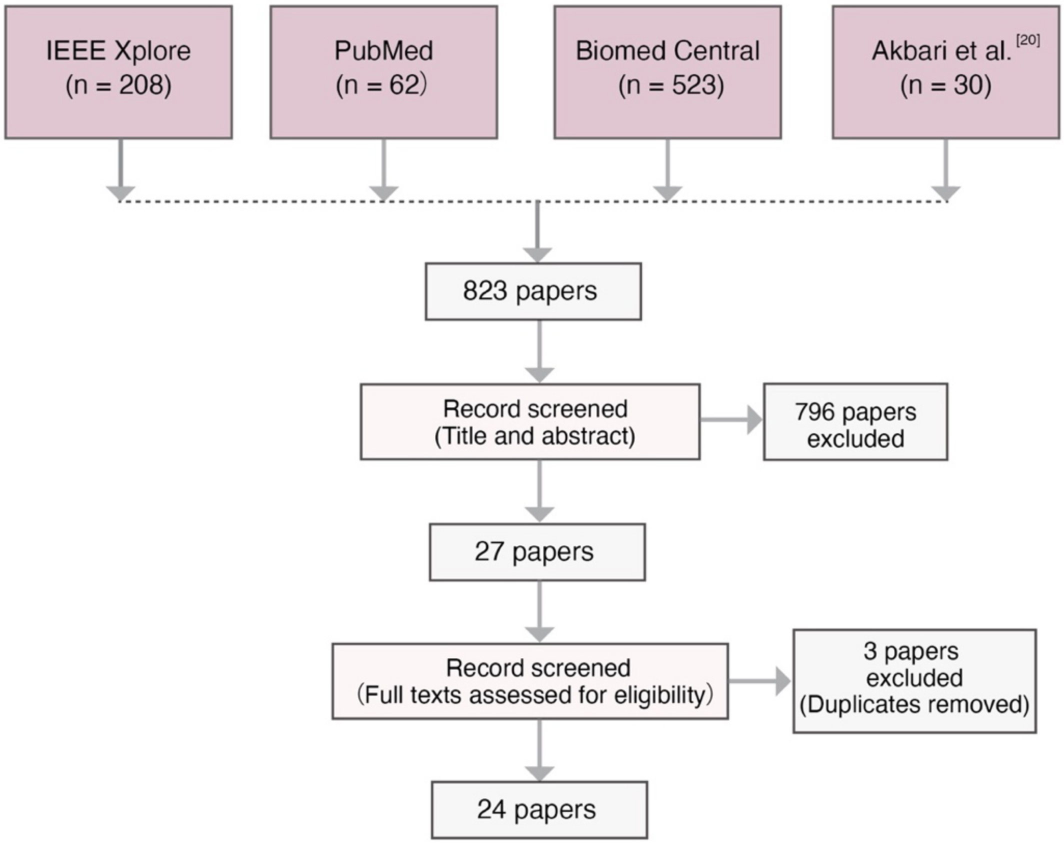

Figure 2: Search process flow of review of home-based shoulder rehabilitation assistive devices.

4 RESULT

This paper reviews 24 mobility home-based rehabilitation assistive devices for shoulders, from January 2015 to October 2022. Assistive devices were classified into three categories based on the analysis of a comprehensive review of the existing literature on assistive devices: (1) robotic devices, (2) wearable devices, and (3) mechanical devices (see Figure 3). The main characteristics of these three categories will be discussed in the future sections. The publications were coded, inductively generated during the review and screening process, and applied to relevant data points.

Using the three categories of assistive devices, section 4.1 discusses the literature on home-based shoulder rehabilitation robotic devices (Table 1). Then, sections 4.2 and 4.3 discuss the wearable and mechanical devices for home-based shoulder rehabilitation (Table 2 and Table 3).

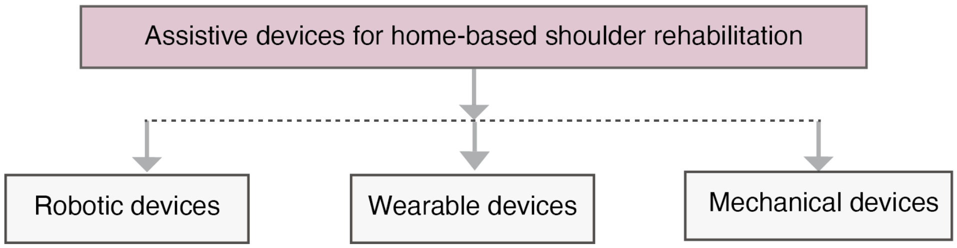

Figure 3: The three assistive device categories are classified for home-based shoulder rehabilitation.

4.1 Home-based Rehabilitation Robotic Devices for Shoulder

Robotic devices are usually combined with sensors technology or cross-platform systems such as the Internet of Things (IoT), Augmented reality (AR) technology, Virtual reality (VR) technology, and mobile application that have been applied in shoulder rehabilitation. Our review identified 10 robotic devices, of which can be discussed in three categories: (1) robots with VR or virtual game environments, (2) lightweight robots, and (3) robots for caregivers and therapists.

Robots with VR or Virtual Game Environments. RUPERT is an upper extremity exoskeleton robot that is wearable, portable, inexpensive, and simple for stroke patients [21]. The robot system has five parts: shoulder, elbow, wrist flexion/extension, humeral internal/external rotation, and forearm pronation/supination, and is driven by compliant and safe pneumatic muscles. The main purpose is to help the arm move in three-dimensional space and carry out a daily training schedule in a virtual environment. Moreover, the robotic exoskeleton and the video game are collectively categorised as new neuroanimation therapy because they were utilised in tandem. For example, the MindPod Dolphin® system provides motivating and intensive virtual reality-based training with a robotic arm for the upper limb with novel neuroanimation therapy [22]. Armeo®Power, an upper limb exoskeleton device from Hocoma AG in Volketswil, Switzerland, was used to unweight the patient's paretic arm for this system. The patients need to control the devices to perform many game tasks. The patients need to control the devices to perform many game tasks. The patients need to use the device to perform many game tasks. The participants in this research reported that patients are more likely to participate in therapy when it is engaging and enjoyable, which can lead to increased motivation and adherence to therapy. The main advantage of neuroanimation therapy is that it provides a fun and engaging way for patients to work on their cognitive and physical abilities. In addition, multisystem involvement carries over to functional tasks and high levels of patient engagement. In summary, neuroanimation therapy is a potentially valuable addition to rehabilitation therapy as it is motivating, stimulating, and cost-effective. It can be used to improve cognitive and physical function and help patients with socialisation. It thus provided an innovative and valuable treatment for people who suffered a stroke. HoMEcare aRm rehabiLItatioN (MERLIN) was designed with an unactuated training device employing serious games and a telerehabilitation platform in the patient's home situation. Following training with MERLIN, results indicated improved upper limb function [23]. Rozevink, van der Sluis and Hijmans [24] applied MERLIN in another study that shows the highly motivated, moderately afflicted chronic stroke patients could benefit from telerehabilitation based on serious games performed at home using non-robotic equipment.

Moreover, the combination of robotic systems and game-based telerehabilitation can offer an engaging environment for patients [25]. Catalan, Garcia, Lopez, Diez, Blanco, Lledo, Badesa, Ugartemendia, Díaz and Neco [26] conducted a user study to compare two rehabilitation systems with motivating game tasks. The result shows that with the use of a PupArm robot, home therapy with HomeRehab can be just as effective as therapy in clinical settings.

Lightweight robots. Three robotic designs for assistive technologies were lightweight. The ArmAssist, a telerehabilitation platform designed by Tomić, Savić, Vidaković, Rodić, Isaković, Rodríguez-de-Pablo, Keller and Konstantinović [27] is a portable device designed to help promote at-home rehabilitation following strokes. The programme heavily emphasises arm-reaching exercises. In this preliminary study, they measured the natural orientation of the forearm, particularly the yaw angle during exercise, which corresponds to the device orientation. The results showed that the angle is highly dependent on the position of the forearm and other relevant anthropometric information, including arm length and shoulder position. This implies that when selecting the optimal device orientation, the subject's limb information and forearm position should be taken into account. Li, Tyson, Preston and Weightman [28] proposed a new lightweight robot equipped with 4 degrees of freedom for domestic upper limbs to offer an appropriate rehabilitation solution for individuals. Their research provides insights into how to make rehabilitation robots wearable by combining topology optimisation and additive manufacturing techniques, addressing the essential design requirements for rehabilitation robots. Liu, Guo, Yang, Hirata and Tamiya [29] developed a novel bilateral robot that uses surface electromyography (sEMG)-based stiffness control and adapts stiffness to the user's dynamic motion in real-time. The experimental results demonstrated that the proposed sEMG-based joint stiffness control method enabled subjects to adapt the stiffness of the variable stiffness actuator to meet different task demands while tracking accuracy and comfortability.

Robots for Caregivers and Therapists. Three of the robots were designed with a care- giver or therapist in mind to help the patient in their rehabilitation therapy. For instance, Modi, Sunny, Khan, Ahmed and Rahman [30] developed a cross-platform telerehabilitation system that combines the Industrial Internet of Things (IIoT) platform with a robotic system called xARm-5 by utilising an augmented reality (AR) user interface created with Vuforia Studio and sharing bidirectional data through the IIoT platform. The suggested system enables a therapist to deliver upper limb rehab exercises remotely and provides rehabilitation therapies to people suffering from upper limb dysfunctions. According to experimental findings, the xArm-5 could be teleoperated from the created AR platform and/or used with a joystick to deliver conventional upper limb rehab exercises. A therapist can confirm that the robot is delivering passive therapy for shoulder and elbow movements by monitoring rehabilitation robot trajectories along with the AR digital twin of the robot, with the designed AR-based user interface.

Liu, Guo, Yang, Hirata and Tamiya [31] developed a tele-rehabilitation system with a supervised training method based on sEMG that enables the therapist to kinaesthetically sense the patient's muscle exercises. It consists of two parts: a master controller for therapists and a responder for patients. On the master side, a 6-degrees of freedom (DOF) haptic device is used for therapist manipulation. On the responder side, they created a powered variable-stiffness exoskeleton device (PVSED) for upper limb rehabilitation at home. A Transmission Control Protocol/Internet Protocol (TCP/IP) technology is utilised to transfer data between these two sides. Results demonstrated that the suggested tele-rehabilitation system increased therapist-patient interaction interactivity and allowed therapist-in-the-loop to dynamically regulate the intensity of rehabilitation.

From the study of O'Neill, Proietti, Nuckols, Clarke, Hohimer, Cloutier, Lin and Walsh [32], the researcher can identify that an inflatable soft-bodied wearable robot can be used to reduce the therapist's stretching fatigue when they assist with severe stroke rehabilitation. The finding shows the potential of adopting a fabric-based inflatable actuator as a device that is secured to the torso and arms by functional garments, to reduce the influence of gravity and help raise the arm.

Table 1. Summary of the home-based rehabilitation robotic devices for shoulder movement: January 2015 to October 2022.

Device / Author Name	Supported movements	Medical conditions	Features	Mode of intervention	Weight and portability	Device operation	Control strategies	Outcome measures	Developers
RUPERT [21]	Shoulder, elbow, wrist, arm	Stroke	Virtual environment training, mechanism	Wearable exoskeleton robotic, Mechanism	N/A	Unilateral	Partial assistance	Fugl-Meyer Assessment (FMA), Wolf Motor Function Test (WMFT)	1 mechanical engineer, 1 bioengineer, 1 engineer (not specified)
MindPod Dolphin® [22]	Shoulder, elbow, hand, arm	Stroke	VR	Wearable exoskeleton robotic	N/A	Unilateral	N/A	Shoulder ROM	2 rehabilitation researchers
HoMEcare aRm rehabiLItatioN (MERLIN) [23][24]	Shoulder, elbow, wrist, arm	Stroke	Computer, robotic devices, serious games, and a telerehabilitat-ion platform	Robotic device	N/A	Unilateral	N/A	Functional Ability Scale (FAS), time score per item /Usability, adapted intrinsic motivation inventory, Quebec user evaluation of satisfaction with assistive technology	6 rehabilitation researchers, 1 human-computer interaction designer / 6 rehabilitation researchers, 2 engineers (not specified)
HomeRehab [26]	Shoulder, elbow	Stroke	Desktop-type 2 DoF robotic system, motors, power source, controller, WiFi	Robotic device	7 kg, Not portable	Unilateral	Partial assistance	Usability, movement parameters	6 biomedical neuro-engineers, 1 computer scientist, 1 telecommunication engineer, 2 interdisciplinary researchers (biomedical engineering and computer science / design, biomedical neuro-engineering)
ArmAssist Robotic System [27]	Shoulder, elbow, wrist, arm	Stroke	Computer, robotic devices	Robotic device	N/A	Unilateral	N/A	FMA of upper extremity motor score, WMFT, Barthel Index (BI)	3 rehabilitation researchers
Li et al. [28]	Shoulder, elbow, wrist, arm	Stroke	Computer, closed mechanical chain structure, games, grip force sensor	Robotic device	12.5 kg, Not portable	Unilateral	N/A	Joint angle, speed of joint	2 biomedical engineers, 1 rehabilitation researcher, 1 occupational therapist

A home-based bilateral rehabilitation system [29]	Shoulder, elbow	Stroke	Surface electromyog-raphy (sEMG)-based real-time stiffness control	Wearable exoskeleton robotic	3.1kg, Portable	Bilateral	Triggered passive assistance	sEMG signals,tracking accuracy, force measurement, safety loop, stiffness range	4 biomedical engineers, 1 neurosurgeon
IIoT-Based 5DOF Robotic Arm [30]	Shoulder, elbow	Stroke	Five-degrees of freedom (DoF) robot arm, Internet of Things (IoT) platform, AR, camera, Kinect sensor	Cross-platform robotic device	N/A	Unilateral	Passive assistance	Joint angles, torques, and speed of joint	4 engineers, 1 computer scientist
Liu et al. [31]	Shoulder, elbow, arm	Stroke	Computer, TV, sEMG, wearable exoskeleton robotic	Wearable exoskeleton robotic	N/A, High portable	Unilateral	Passive assistance	Subject's physical and biological data (joint angle, contact force, sEMG signals)	4 engineers (not specified), 1 neurosurgeon
Inflatable soft wearable robot [32]	Shoulder, elbow, wrist, finger	Stroke	sEMG, inf-latable actuator	Soft wearable robotic	Portable	Unilateral	N/A	FMA, Active range of motion (AROM), shoulder ROM, contact force, heart rate, sEMG signals, wrist and finger extensors	6 biomechanics engineers, 1 robotics engineer, 1 interdisciplinary researcher (mathematics, computational science, medicine)

4.2 Home-based Rehabilitation Wearable Devices for Shoulder

The automated, unsupervised, and objective evaluation of home exercise programmes, as well as the patient's compliance with the recommended treatment plan can be made possible by wearable technology and straightforward metrics. Sensor technologies are regularly used in emerging wearable technologies such as movement monitoring and tele-rehabilitation. In our review, we identified 12 wearable devices. The 12 wearable devices will be discussed in the following four categories: (1) Motion capture: based on Microsoft Kinect^{TM}, (2) Motion monitoring, (3) Inertial Measurement Unit (IMU) sensors and (4) Wearable sensor.

Motion Capture: based on Microsoft Kinect^{TM}. Triandafilou, Tsoupikova, Barry, Thielbar, Stoykov and Kamper [33] created a networked multi-user Virtual Environment for Rehabilitative Gaming Exercises (VERGE) system for home therapy. Stroke therapists and/or other survivors can play together in different physical locations, within the same virtual environment. Each user's movement controls an avatar through kinematic measurements made with the in-expensive Kinect^{TM} gadget. During the VERGE Trajectory Trace activity, a participant tries to remove the shown trajectory. The user uses the Kinect to control the avatar while wearing an Xsens 3D motion tracker system vest that continuously measures hand and shoulder displacement for experimental analysis. The participants' comments show how important it is for technology to be sufficiently adaptive to cater to individual users' varying goals and preferences. As a method for functional rehabilitation of upper and lower limb at home, Tannous, Istrate, Perrochon, Daviet, Benlarbi-Delai, Sarrazin, Tho and Dao [34] developed GAMEREHAB@HOME as a method for functional rehabilitation of the upper and lower limb at home. It is a new engineering system that includes two serious game scenarios, and the virtual game scenarios lead to a high level of patient immersion. To animate a 3D avatar throughout rehabilitation and estimate various joints' kinematic data for clinical monitoring, a multisensory fusion of the Kinect camera and inertial sensors was created.

Motion Monitoring. Myo armband is a wearable device that applies sEMG in combination with comprehensive rehabilitation and physical fitness training to treat frozen shoulder syndrome. The system enables the physician to provide remote medical treatment counselling in real-time. The results indicate that the device can be used to support interactive analysis [35]. Wazir, Bethi, Kumar, Caruso and Kapila [36] used a medical device consisting of a wearable pendant sensor to monitor optimal lymph flow therapy compliance. Wearable pendant sensors collect people's movement data whilst people's breathing data is captured by a smartphone's microphone worn on the user's upper arm. The data is then transferred to remote nurses through cloud platforms for monitoring. The results show that the device could monitor compliance parameters like maximum shoulder range of motion.

IMU Sensors. Chae, Kim, Lee and Park [37] developed a novel home-based rehabilitation system based on the smartwatch and the smartphone application featuring a machine learning algorithm to record the frequency with which an individual undertakes rehabilitation exercises. Meanwhile, IRTATS, a reach-to-target assessment and training system was developed by Fan, Zhang, Wang, Bai and Wu [38]. This technique is used to find tracking signals on a camera and three marker straps. The IRTATS can be used in small clinics, at home, without internet connectivity, and with audio-visual feedback and personal goal setting. The purpose of the study was to assess the validity of ROM assessment using IRTATS. The results show IRTATS was a cost-effective method that was easy to train individuals to use to achieve specific individual goals and monitor their progress during therapy sessions.

Alternatively, some systems apply IMU sensors. These wearable devices with IMU sensors will connect with new technologies, such as games, mobile applications, and VR-based technology. For example, Lin, Lin, Lin, Chuang, Hsu and Lin [39] created an IMU-based motion capture system composed of two wearable devices. They conducted a comparative study with chronic stroke survivors to assess their shoulder joint rehabilitation. Results show that the system is a cost-effective tool for providing home care treatment for stroke survivors. Yin and Xu [40] proposed a wearable device with IMU sensors connected to a game console, offering various game difficulty levels in different rehabilitation stages.

Moreover, Chen, Lin, Tsai, Chuang and Lee [41] designed a wearable motion sensor device connected to a mobile application to assist people with adhesive capsulitis for shoulder rehabilitation by conducting home-based exercises and improving the accuracy of rehabilitation. The mobile application measures the shoulder range of motion using a wearable motion sensor device and reports people’s rehabilitation data to physiotherapists. With the use of wireless inertial sensors and virtual reality technology, a new shoulder joint mobility self-measurement system was developed that enables people to test themselves at home on four shoulder joint movements. The system architecture is composed of two units: a WIMU and a VR-based interactive self-guided program. Correlation and differential analysis results were compared with traditional measurement methods and found to be highly correlated, indicating that the proposed system is accurate. Additionally, when interviewed, people indicated they were confident that they could measure their own shoulder joint mobility [42].

ArmTracker is a portable system consisting of wearable IMU sensors to capture arm and torso kinematics data for shoulder rehabilitation for both the public and athletes. ArmTracker was tested by tracking the daily arm activity of one patient with BMD and one unimpaired patient. The results demonstrated that the ArmTracker system could provide accurate data on upper body kinematics over an extended period [41, 43].

Wearable Sensor. Bellomo, Paolucci, Saggino, Pezzi, Bramanti, Cimino, Tommasi and Saggini [44] performed a methodical clinical study to test the efficacy of a new rehabilitative device, WeReha. In their study, they tracked the daily functional recovery of 22 patients with chronic stroke in a 12-week physiotherapy program as well as their satisfaction and acceptance of techniques. Their findings suggest that the WeReha project can serve as a comprehensive telerehabilitation resource in home-based recovery activities for these patients, although it is not a traditional therapy for patients with stroke.

Table 2. Summary of the home-based rehabilitation wearable devices for shoulder movement: January 2015 to October 2022.

Device / Author Name	Supported movements	Medical conditions	Features	Mode of intervention	Weight and portability	Device operation	Control strategies	Outcome measures	Developers
Mobini et al. [33]	Shoulder, hand, wrist, elbow, head, waist position	Stroke	Microsoft Kinect for Xbox 360, Microsoft Kinect's skeleton tracking driver, TV	Wearable sensor	N/A	Bilateral	Motion sensing in-put devices intervention	Mean velocity (MV), normalized mean speed (NMS), normalized speed peaks (NSP), logarithm of dimensionless jerk (LJ), curvature (C), spectral arc length (SAL), shoulder angle (SA), elbow	2 mechanical engineers,1 bioengineer
MYO [34]	Shoulder, arm, hand	Frozen shoulder	sEMG, Gyroscope, accelerometer , and orientation sensor, USB Bluetooth ,sur face electromy-ography technology	Wearable device	N/A, Portable	Unilateral	Physical medicine and rehabilitati-on (PMR)	FMA	1 computer scientist, 1 interdisciplinary researcher (biomedical engineering and computer science)
Wearable pendant sensor (WPS) device [35]	Shoulder, arm	Lymphed ema	WPS, IoT, Bluetooth, Smartphone, Low energy endowed microcontrolle rs (μC)	Wearable device	N/A, Portable	Bilateral	N/A	Shoulder ROM, breathing	2 engineers, 3 mechanical engineers
Home-based rehabilitation (HBR) system [36]	Shoulder, elbow, hand	Stroke	IMU sensor, Bluetooth, Mobile application	Wearable device	N/A	Bilateral	N/A	Shoulder ROM, WMFT, evaluated psychologic depression using Beck Depression Inventory (BDI), FMA of Upper Extremity, grip power	1 engineer, 1 rehabilitation researcher, 1 mechanical engineer, 1 interdisciplinary researcher (mechanical engineering and rehabilitation)

IRTATS [37]	Shoulder, hand, elbow	Stroke	A camera & a processor bases system box, TV, USB sticker, IMU sensor, Microsoft Kinect	Wearable device	N/A	Bilateral	N/A	Value of shoulder displacement, the number of times set velocity value was exceeded, shoulder ROM, AROM, the movement time (MT), maximum velocity (MV), the number of velocity peaks (NVP), and the hand path ratio (HPR), the number of times the set velocity value was exceeded)	5 rehabilitation researchers
Wearable devices for upper limb rehabilitation [38]	Shoulder, elbow, forearm joint	Stroke	IMU sensor	Wearable device	N/A	Unilateral	Wearable device intervention	FMA, AROM, deviation angle	4 biomedical engineers,1 electrical engineer, 1 medical researcher
Wearable Controller system [39]	Shoulder, elbow, arm	General rehabilitat-ion	IMU sensor	Wearable device	N/A	Unilateral	Partial assistance (AAN); resistance	Body and arms angle	1 computer scientist, 1 interdisciplinary researcher (industrial design and computer science)
Motion Sensor Device [40]	Shoulder, shoulder joints	Frozen shoulder	IMU sensor, mobile application	Wearable device	N/A	Unilateral	Wearable device intervention	Shoulder ROM, pain and functional scores, exercise completion rates	3 medical researchers, 2 interdisciplinary researchers (education and medical research)
Wireless inertial sensors combined with the virtual reality interactive technology system [41]	Shoulder	Frozen shoulder	IMU sensor, VR	Wearable device	N/A	Unilateral	Wearable device intervention	Shoulder joint movement degree	2 computer scientists, 1 rehabilitation researcher

ArmTracker [42]	Shoulder, elbow, arm	Becker muscular dystrophy	IMU sensors, microcontroll-er, A high-speed SD card	Wearable device	0.20kg, Portable	Bilateral	N/A	ROM, Functional Workspace Distribution, Accelerometry	2 mechanical engineers, 1 rehabilitation researcher, 3 interdisciplinary researchers (industrial design engineering and biomedical engineering / mathematics and computer science / industrial engineering and biomedical engineering)
Virtual Environment for Rehabilitative Gaming Exercises (VERGE) system [43]	Shoulder, Arm, hand	Stroke	Microsoft Kinect, VR, IMU sensor, Xsens 3D motion tracking	Wearable device	N/A	Bilateral	N/A	Arm displacement, time with reach distance, time with hand elevation	3 biomedical engineers, 1 rehabilitation researcher, 1 occupational therapist, 1 interdisciplinary researcher (interaction design / computer art / rehabilitation)
GAMEREHAB @HOME [44]	Shoulder, elbow, knee joints, hip	Frozen shoulder	Microsoft Kinect, inertial sensors, visual sensors	Wearable device	N/A	Bilateral	N/A	Joint angle	3 biomedical engineers, 1 engineer (not specified), 2 rehabilitation researchers, 2 interdisciplinary researchers (electrical engineering and physical science / rehabilitation and biomedical engineering)
WeReha [45]	Shoulder, elbow, hand	Stroke	Inertial Bluetooth sensor, Indoor sensors	Wearable device	N/A	Bilateral	N/A	Berg Balance scale (BBS), BI, FMA, modified Rankin scale (mRS), technology acceptance model (TAM) questionnaire	6 rehabilitation researchers, 1 bioengineer, 1 psychologist

4.3 Home-based Rehabilitation Mechanical Devices for Shoulder

In our review, only two mechanical devices were discussed in the literature: (1) Spring-cam-wheel system and (2) SpringWear. Both mechanical devices utilised elastic springs. To offset half of the gravitational moment felt during shoulder elevation motions, Asgari, Hall, Moore and Crouch [45] proposed the Spring-cam-wheel system which incorporated a benchtop model as well as a new wearable passive cable-driven exoskeleton. Specifically, preloaded elastic springs were used in the mechanically passive exoskeleton. The researchers concluded that their exoskeleton prototype needed to be refined through further iterations before proceeding to conduct testing on more human participants. It is crucial to understand how passive exoskeletons interact with their users. In the SpringWear device, Chen and Lum [46] present cross-sectional research to evaluate the performance of thirteen participants who are chronically stoked in range of motion and functional tasks and test how the changes in the movement pattern occurred by using the device, SpringWear. They concluded that while SpringWear improves the available workspace during upper limb movements, there are no improvements in consistency in accomplishing the functional aim. In summary, these mechanical devices can potentially reduce the effort required to improve mobility performance during task practice.

Table 3. Summary of the home-based rehabilitation mechanical devices for shoulder movement: January 2015 to October 2022.

Device / Author Name	Supported movements	Medical conditions	Features	Mode of intervention	Weight and Portability	Device operation	Control strategies	Outcome measures	Developers
Spring-cam-wheel system [45]	Shoulder, arm	Rotator cuff tear	Spring operated, 3D printed ABS plastic	Wearable mechanical-ly passive exoskeleton	1.75kg, Portable	Unilateral	Triggered passive assistance	Verbal subjective feedback of the effectiveness, ease of use, discomfort, compatibility	4 biomechanical engineers
SpringWear [46]	Shoulder, flexion, elbow extension and forearm supination / pronation	Stroke	Assistive devices for spring / motor operated	Wearable, spring operated, upper extremity exoskeleton	1.2kg, Portable	Unilateral	Triggered passive assistance	Shoulder and elbow flexion / extension (FE), forearm prona-tion / supination, hand ROM	2 biomedical engineers

4.4 Result: Analysis

The following section is the second stage of the analysis. Particular themes that emerged include: (1) interaction technologies applied in assistive devices, (2) device operation, (3) devices for medical conditions, (4) control strategies, (5) outcome measures, (6) weight and portability, and (7) interdisciplinary developers.

Interaction Technologies Applied in Assistive Devices. Rehabilitation outcomes depend significantly on patients consistently following a prescribed set of targeted exercises [47]. Applying interaction technologies in assistive devices can achieve patients' full rehabilitation potential when they work synergistically. The finding of this review suggests assistive devices are now being created with the following features: training programmes, game training programmes [22-24, 26, 34, 38-40], VR or Virtual training environments [21-24, 26, 33, 35, 39, 42, 48], Microsoft Kinect^{TM}-based programmes [30, 33, 34, 38], TV training programmes [31, 38], connected mobile applications [37, 41], IoT platforms [30, 36], and AR training environments [30].

VR technology and sensing techniques are often applied in rehabilitation. We found that a majority of typical solutions of wearable devices use inertial measurement units (IMUs) sensors [33, 37-43] and report the angular rate and gravity in serving to monitor home-based exercises and improve the accuracy of rehabilitation [49]. Common types of wearable devices include armbands, pendant sensors, smartwatches, and tracker system vests. Furthermore, rehabilitation data collection technologies include surface electromyography (sEMG)-based stiffness control [29, 31, 32, 35], grip force sensors [28], Xsens 3D motion tracking[33], visual sensors [34], inertial sensors [34], gyroscope [35], accelerometer [35], orientation sensor [35], low energy endowed microcontrollers (μC) [36], wearable pendant sensors (WPS) [36], microcontroller [43], inertial Bluetooth sensors [44] , and indoor sensors [44]. Related hardware includes computers [23, 24, 27, 28, 31], Microsoft Kinect^{TM} [30, 33, 34, 38], Bluetooth [35-37], TV [31, 38], camera [30, 38], USB sticker [35, 38], and SD card [43].

Device Operation. The devices used unilateral or bilateral modes of intervention, meaning they assisted with one limb (unilateral) or both limbs (bilateral). While most devices only supported the bilateral operation, there were nine assistive devices consisting of one robotic device and eight wearable devices that offered bilateral training. The training model for shoulder exercises can be tailored to analyse different movements, including moving an arm to the side, moving an arm to the front, shoulder shrugs, and twists.

Devices for Medical Conditions. Only two of the assistant devices [41, 42] were specifically designed for only shoulder rehabilitation. Most devices focus on the entire region of the upper limb, including the shoulder. Sixteen of the assistive devices (66.67%) in this review are designed for stroke rehabilitation [21-24, 26-33, 37-39, 44, 46]. Three of the assistive devices (16.67%) are designed for frozen shoulder rehabilitation [34, 35, 41, 42]. Only one assistive device (4.17%) was designed for rotator cuff tears [45]. There are many musculoskeletal diseases related to shoulder rehabilitation that have not been explored in the literature. Future researchers or designers of assistive devices should consider designing more devices for these target users (e.g., multiple sclerosis, osteoarthritis).

Control Strategies. The control strategies of robotics devices include passive assistance [30, 31], partial assistance [21, 26], and triggered passive assistance [29]. The two reviewed mechanical devices were both triggered by passive assistance [45, 46].

Outcome Measure. There was a total of 40 different outcome measurements found across the 24 devices. In order of frequency, here is a list of the measurements that were used: 1. Shoulder range of motion (ROM) [22, 32, 36-38, 41]; 2. Fugl-Meyer Assessment (FMA) of upper extremity [21, 27, 32, 35, 37, 39, 44]; 3. Joint angle [28, 30, 31, 34, 40]; 4. Usability [24, 26, 45]; 5. surface electromyography (sEMG) signals [29, 31, 32, 35]; 6. Active range of motion (AROM) [32, 38, 39]; 7. Wolf Motor Function Test (WMFT) [21, [21, 27, 37]; 8. Contact force [31, 32]; 9. Speed of joint [28, 30]; 10. Barthel Index (BI) [27, 44].

Weight and Portability. Weight and portability are important characteristics to consider for home-based rehabilitation, yet these factors were only considered in 6 papers [26, 28, 29, 43, 45, 46]. Most papers did not include measurements for both factors.

Interdisciplinary Developers. A majority of these devices (18 papers, 75%) are created by interdisciplinary researchers, such as designers (e.g., human-computer interaction designers and industrial designers), computer scientists, engineers (e.g., biomedical engineers, industrial engineers, robotic engineers, telecommunication engineers, mechanical engineers, biomechanical engineers, industrial design engineers), rehabilitation researchers (e.g. neurosurgeons, occupational therapists and physiotherapists), and psychology researchers. The wide diversity of researchers and disciplines in assistive technologies can make the design process complicated. Difficulties may stem from many factors including the user's unique needs, the need for the designer to possess a diverse expertise background, and the involvement of numerous stakeholders with different objectives in the process. Nevertheless, multidisciplinary processes between interdisciplinary experts and validated learning approaches are a crucial factor to successfully designing assistive technologies [50].

5 DISCUSSION AND FUTURE DIRECTION

The results indicated that assistive devices can be classed as robotic, wearable, and mechanical devices. The reviewed assistive devices are the following: 10 robotic devices, 12 wearable devices, and 2 mechanical devices. Much of the current assistive rehabilitation healthcare literature focuses on the development of wearable and robotic 17 devices. This review identified fewer mechanical devices, which might have been more challenging to use in home rehabilitation. With the assistance of home-based telerehabilitation, patients can extend institutional rehabilitation by enhancing and prolonging the therapy [51]. Based on our analysis in this review, the following key directions for future research have been considered in Figure 4: (1) Lightweight and portable, (2) Affordability, (3) Human-centred design solutions and interdisciplinary perspectives, (4) Patient's motivation in the rehabilitation process, (5) Smart remote healthcare with new internet-based technologies.

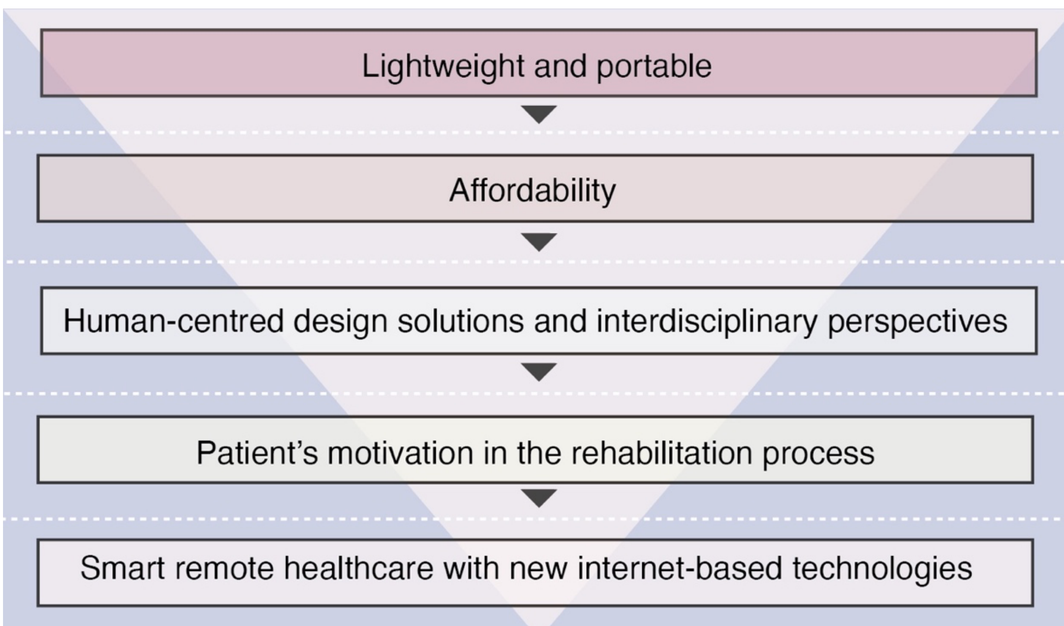

Figure 4. Future consideration for home-based rehabilitation assistive device design for shoulder.

This review concludes that future work should focus on the principles of designing home-based rehabilitation assistive devices for the shoulder, and that researchers may need to consider interdisciplinary contexts while creating new assistive devices. Design principles can facilitate the understanding of health outcomes and methods used while enabling insights to be quickly translated into prototypes and solutions for further testing and refining [52].

However, designing the strategic approach to assist interdisciplinary researchers in developing shoulder rehabilitation device innovations has not yet been defined and explored in a medical context. To address the identified challenges, we believe that adopting a co-design approach is crucial for fostering collaboration among developers, particularly when various stakeholders and experts are actively engaged and contribute throughout the process. Co-design also helps researchers focus on what kind of users they are dealing with, the users' needs they trying to address in the design challenge, and whether their needs are being addressed well enough [53]. During the various phases of the research and design process, the design process offers health rehabilitation practitioners new perspectives on health challenges, especially for key questions that inform the device design.

In summary, existing research has generally tended to focus on wearable devices and robotic devices for shoulder rehabilitation. New and emerging methods that focus on home-based rehabilitation are important for future research as they can facilitate shoulder movement recovery while being more accessible than traditional rehabilitation. In particular, the development of robotic and wearable devices for home-based shoulder rehabilitation is a dynamic and rapidly expanding research area. Traditional healthcare interventions for shoulder rehabilitation are transitioning to smart remote healthcare by incorporating new internet-based technology and rehabilitation features. Furthermore, the development of assistive technology processes should enhance the participants' voices and consider their ideas and needs. Apart from these considerations, this paper highlights the challenges that patients face and that these challenges can be integrated into the device's design processes.

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