A Review of Intelligent Walking Support Robots: Aiding Sit-to-Stand Transition and Walking

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***Abstract*— Nowadays, numerous countries are facing the challenge of aging population. Additionally, the number of people with reduced mobility due to physical illness is increasing. In response to this issue, robots used for walking assistance and sit-to-stand (STS) transition have been introduced in nursing to assist these individuals with walking. Given the shared characteristics of these robots, this paper collectively refers to them as Walking Support Robots (WSR). Additionally, service robots with assisting functions have been included in the scope of this review. WSR are a crucial element of modern nursing assistants and have received significant research attention. Unlike passive walkers that require much user's strength to move, WSR can autonomously perceive the state of the user and environment, and select appropriate control strategies to assist the user in maintaining balance and movement. This paper offers a comprehensive review of recent literature on WSR, encompassing an analysis of structure design, perception methods, control strategies and safety & comfort features. In conclusion, it summarizes the key findings, current challenges and discusses potential future research directions in this field.**

***Index Terms*— Walking support robot, human-robot interaction, walking aid, rehabilitation, servant robot.**

I. Introduction

IN MODERN times, many countries are grappling with challenges posed by aging population, as the increasing proportion of older adults has led to a rise in new social issues [1]. According to a report [2], a significant proportion of individuals experience difficulties with lower limb movement, indicating an anticipated increase in the number of people with disabilities. Limited mobility poses challenges in daily life, requiring assistance from others to complete even basic tasks such as walking. The growing demand for the nursing industry, especially due to the aging population, has put immense pressure on the nursing staff, leading to a decline in their sense of happiness [3]. Moreover, individuals who are unable to move normally, such as the older adults or those with disabilities, are likely to be confined to a fixed position, resulting in the atrophy of their lower limb muscles, which in turn further decreases their mobility [4]. Therefore, assisting people with limited mobility to walk has become a crucial aspect of modern nursing work.

In order to assist individuals with reduced mobility, medical professionals often recommend mobile devices to patients to assist moving, which can significantly reduce the amount of muscle power required for patients to walk [5]. Because the prolonged use of passive devices [6] can sometimes lead to muscle damage, which may negatively affect their rehabilitation [7], mobility smart devices are often a better choice. Considering the varied mobility levels of different users, researchers have developed numerous types of devices. For example, intelligent wheelchairs have been designed for people who are completely unable to move independently [8], wearable exoskeletons have been designed for people with insufficient lower limb muscle strength [9], intelligent prostheses have been designed for the disabled [10], and WSR have been designed for people who still have a certain degree of walking and interaction ability [11].

The complete human mobility encompasses both STS and walking activities, with both being equally vital. In fact, STS transitions are considered one of the most muscle-demanding tasks in daily activities [12]. We have identified interesting similarities between robots designed for walking and those designed for STS. These commonalities encompass aspects like hardware design, perception methods, user adherence and safety concerns. This motivates us to collectively consider robots that support STS transition and support walking. Additionally, we have uncovered an interesting fact: robotic platforms in the form of manipulators have emerged as a novel development for providing walking support. This differentiates us from previous related research [13], [14], [15]. To the best of our knowledge, this is the first comprehensive review that takes into account both STS transition and walking assistance and considering all types of robots.

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Although WSR have shown promising potential in the healthcare industry, further development and widespread adoption of this technology require addressing critical challenges. This study aims to bridge this gap by analyzing existing research. This paper's primary objectives can be specified through three research questions from different perspectives (user perspective, robot perspective and researcher perspective):

(1) *What hardware structure, sensors and control methods are usually employed in the design of WSR?*
(2) *How can the user's comfort and safety be ensured during the use of WSR?*
(3) *What are the challenges and future directions for WSR as it apply to real-world?*

The remainder of this paper focuses on these issues. Section II introduces the review methodology of this paper. Section III provides an overview of WSR, including their design and types. Section IV introduces perception strategies for WSR, including environment perception and user intention perception. Section V discusses control strategies for WSR, including walking control and assisting strategies for STS. Section VI covers safety and comfort considerations for WSR. Section VII outlines the challenges WSR faces when transitioning from the lab to real-world applications. Finally, Section VIII concludes the paper and proposes potential future research directions.

II. Review Methodology

A. Search Strategy

We have conducted a literature search on Google Scholar and Web of Science, covering the period from 2019 to 2023. The search utilized combinations of two sets of keywords. The first set includes: "walk aid, walker, rollator, walk assistance, sit to stand", and the second set includes: "fall prevention, robot, comfort, safety". The BOOL form can be expressed as "((((((TS=(walk aid)) OR TS=(walker)) OR TS=(walk assistance)) OR TS = (rollator)) OR TS = (sit to stand)) AND ((((TS = (robot)) OR TS = (fall prevention)) OR TS = (comfort)) OR TS = (safety)))". In total, 4711 researches were retrieved. Additionally, an extra 29 researches were cited in this paper, as they were considered useful for providing a brief overview of the background and future development prospects of WSR applications.

B. Selection Criteria

Each research evaluation was divided into two stages. In the first stage, we initially reviewed the titles and abstracts of the articles, eliminating those that did not meet the criteria. In the second stage, we examined the conclusions and content of the selected researches. The assessment criteria for the researches are as follows:

Inclusion:

(1) The hardware design and control methods of WSR.
(2) An important part of walking support, such as fall prevention and user state perception.
(3) Researches that are provided as full-text version.

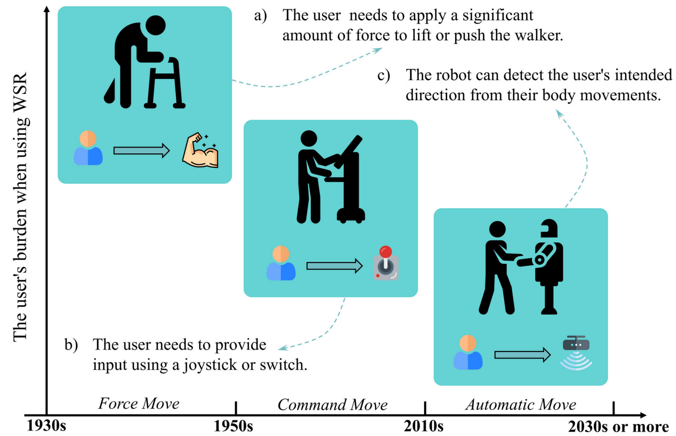

Fig. 1. Illustration of the continuous evolution of the movement mode of WSR from physical strength to joystick and towards automatic movement by burdens brought to users.

Exclusion:

(1) Non-English researches.
(2) Researches that focus on other devices like passive walkers, stationary gait trainer or exoskeletons.
(3) Researches that in the form of short paper ($\leq$ 3 pages), manuals, which do not provide enough information.
(4) Researches subjected to secondary analysis (eg. reviews, surveys).
(5) Researches lacking actual user operation experiments.

C. Data Extraction and Quality Assessment

We have conducted a data analysis of the obtained researches. Information about the structure, sensors and assistance features employed by WSR was recorded when the literature clearly indicated these aspects. If a document only covered specific functions of walking support or duplicated information about WSR platforms already included in the statistics, it was excluded from the statistical analysis. Instead, focus was placed on the distinctive methods highlighted in the research. The quality assessment of the literature was independently performed by two reviewers (YS, CX), and in cases of conflicting opinions, a third reviewer was invited to participate in the quality assessment to make the final decision. Finally, 113 researches were included in the review.

III. The Overall Design of WSR

Rapid advancement in perception technology has resulted in several iterations of the movement mode of WSR, including the transition from force move to command move, and eventually towards automatic move [23], as illustrated in Figure 1. During assisted walking, the user's arm may provide additional support to help bear some of the body weight and maintain balance. This can help to alleviate the strain on the legs and make walking less exhausting for the individual.

Except for a few WSR that use quadrupedal platform [24] or inverted pendulum base [25] for movement, most WSR are composed of similar parts: handles that provide support, sensors that detect the environment and user status and wheeled mobile base that allows the WSR to move freely. According to

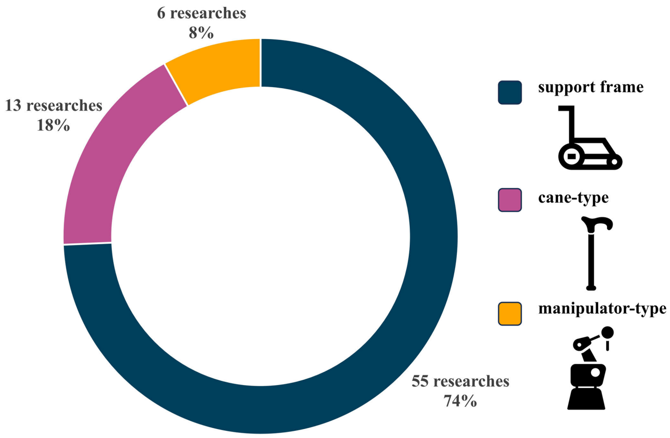

Fig. 2. The distribution chart of WSR's structures over the last five years.

different structures, WSR can be divided into support frame-based robots [16], [17], [19], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], cane-type robots [18], [20], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88] and manipulator-type robots [21], [22], [89], [90], [91], [92]. Support frame-based robots, like rollators, provide robust support. But they tend to be bulky and have limited accessibility in certain spaces, making them more suitable for medical environments such as hospitals. In contrast, cane-type robots are smaller, more portable, and can easily navigate through narrow entrances, although their supporting stability may be relatively weaker. The selection of the two robot types above is contingent on the user's operating environment. Besides, as manipulators break fences and begin to coexist with humans in shared spaces, some researchers have explored the potential application of robotic arms in the field of walking assistance. The primary advantage of manipulators lies in its ability to freely adjust the contact positions when interacting with users, adapting to different individuals and various situations. We have conducted a statistical analysis of the structure of WSR over the past five years, and as shown in Figure 2, the majority of WSR in the studies adopted a support frame-based structure.

WSR can be classified based on their primary function as robots for assisted STS or robots for walking assistance. Certain robots are capable of performing both functions [43], [59], offering users comprehensive support. The various types of WSR need distinct design requirements and sensor deployments.

Robots for walking assistance, also known as Walking-aids, rollators or walkers, assist users during their walking process by compensating for their lack of coordination and lower limb strength through the robot's supporting force. Some robots also offer auxiliary path planning functions during walking. The handle position of these robots typically remains stable to provide consistent support for the user.

STS is a key skill to assess the self-care ability of the older adults [93]. Due to the shift in the user's center of gravity during the STS process, a robot designed for sitting and standing assistance typically needs the capability to adjust the position of the contact point vertically.

In addition to the previously mentioned WSR types, some service robots also integrate walking support into their functionality. These robots can assist users in walking while also performing tasks like grasping and delivering objects. Usually, these service robots are manipulator-type robots. Similar to the way the end-effector is used for executing handling tasks, service robots usually employ its end-effector to establish contact with the user for providing support. These robots can have either single [21] or dual arm [91], with designers typically installing handles at the end of the manipulator arms to facilitate user gripping. By switching between different end-effectors [89], WSR can transition between various tasks. Figure 3 lists some classic robot designs belonging to the categories mentioned above.

Some representative robots mentioned above have been listed in Table I, and are classified according to the authors, years of publication, types of sensors and usage scenarios. We only considered sensors that perceive the environment and user state in walking support, excluding sensors used for self-state estimation and those not utilized during the process.

IV. Perception

A. Environmental Perception

Perceiving the external environment is a natural human instinct. However, the lack of perception of the environment exists among older adults with limited mobility. WSR can utilize its own sensors to make up for this defect. The ability of WSR to perceive the environment can be divided into two aspects: perception of obstacles and perception of terrain.

1) Obstacle Perception: As a prerequisite for navigation functionality, WSR needs corresponding sensors to perceive the positions of obstacles. ultrasonic [40], laser [61], [65], [94] and camera [37], [77] are the most common sensors used for obstacle detection. Additionally, sometimes multiple sensors are used together to enhance the accuracy of obstacle perception. For example, the simultaneous use of ultrasonic sensors and infrared sensors for obstacle perception not only reduces the cost but also ensures the accuracy of obstacle detection [40].

2) Terrain Perception: In addition to detecting obstacles, it is also important for WSR to detect uneven terrain, such as potholes on the ground. In a recent study conducted by Rufei et al. [95], 2D and 3D LiDAR information were combined to detect ground potholes. The point cloud data was first preprocessed to remove noise, and then the local datum plane of the road surface was constructed by fitting. A continuous depth image of the road surface was then generated. The accuracy of detecting ground potholes reached 86.1%. Another approach involves using an ultrasonic sensor angled downward at 45 degrees to detect pits on the ground [96]. When a pit is detected, the user is alerted through a combination of red LED lights, buzzers, and motor vibrations.

Correctly identifying special terrain and responding appropriately are also crucial during the operation of WSR. Wet surfaces on the ground can damage the robot's hardware and

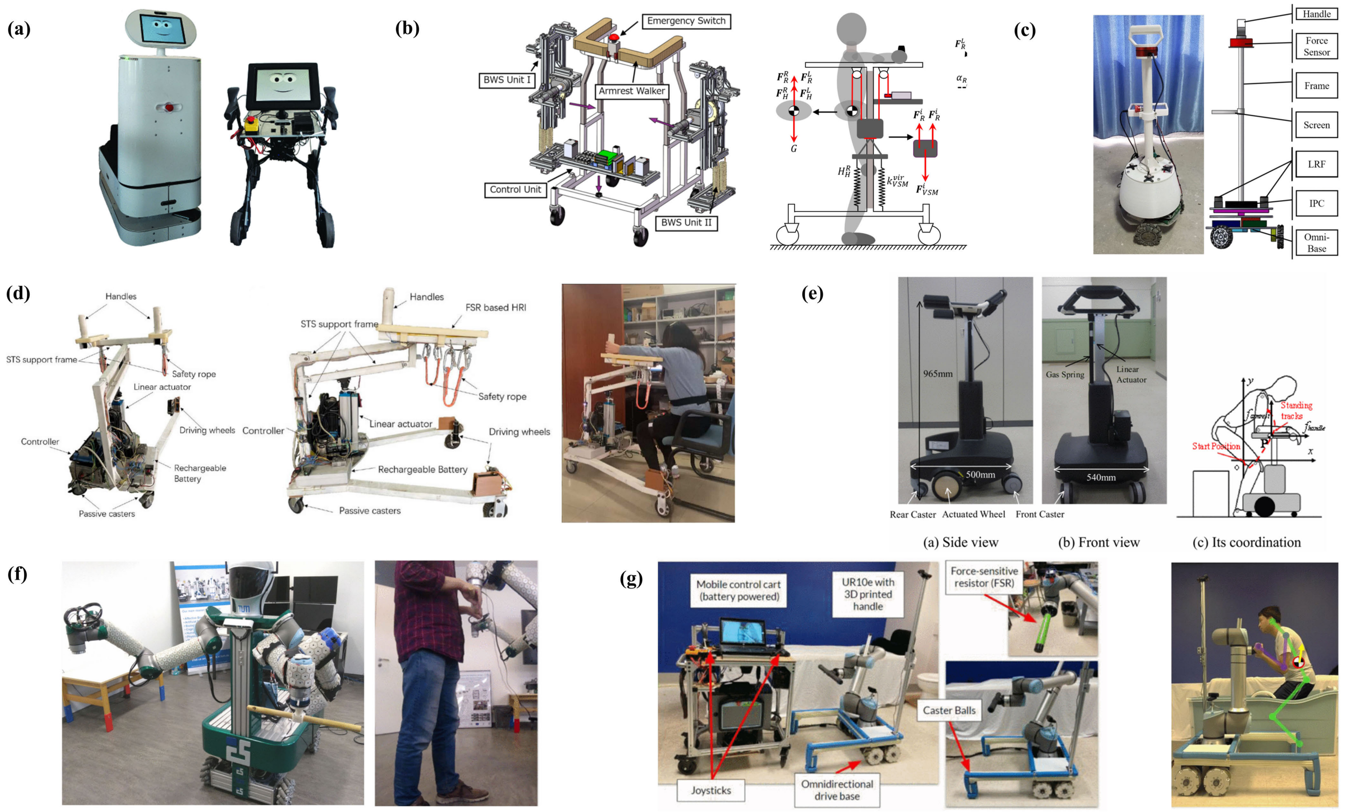

Fig. 3. Robot for walking assistance: (a)smart rollator [16]. Copyright 2022, IEEE. (b) rehabilitation robot [17]. Copyright 2021, IEEE. (c) cane-type walking aid robot [18]. Copyright 2021, IEEE. Robot for STS: (d) support frame-based robot for STS assistance [19]. Copyright authors. (e) cane-type robot for STS assistance [20]. Copyright 2019, IEEE. Service robots with supporting function: (f) TOMM [21]. Copyright 2019, IEEE. (g) mobile manipulator for STS [22]. Copyright 2023, IEEE.

TABLE I
COMPARISON OF ROBOTS FOR WALKING ASSISTANCE AND STS ASSISTANCE

Author	Year	Sensor Type	Function	Structure Type
Itadera et al. [91]	2019	F/T sensor, Camera, Radar	ALL	Mobile Manipulator
Oigawa et al. [42]	2019	F/T sensor, Laser range finder	WAR	Support Frame
Sierra et al. [35]	2019	Radar, Camera	WAR	Support Frame
Zhao et al. [51]	2022	F/T sensor,Proximity sensor	WAR	Support Frame
Horn et al. [16]	2022	Acoustic sensor,Camera	WAR	Support Frame
Dong et al. [17]	2021	F/T sensor, Smart shoe	WAR	Support Frame
Lee et al. [66]	2022	Laser range finder,Ultrasonic sensor	WAR	Support Frame
Ogata and Matsumoto [71]	2020	Accelerometer, IMU, Tactile sensor	WAR	Support Frame
Itadera et al. [78]	2019	F/T sensor, Laser Range Finder, Camera	WAR	Cane-type
Yan et al. [18]	2021	F/T sensor, Laser range finder	WAR	Cane-type
Ding et al. [89]	2022	F/T sensor	WAR	Mobile Manipulator
Itadera et al. [21]	2019	F/T sensor	WAR	Mobile Manipulator
Wenxia et al. [19]	2021	F/T sensor, Wearble sensor	STS	Support frame
Huang et al. [69]	2021	Wearble sensor, Camera	STS	Support frame
Li et al. [92]	2021	Wearble sensor	STS	Manipulator
Bolli et al. [22]	2023	F/T sensor, Camera	STS	Mobile Manipulator

pose a potential danger to users. Some WSR use water level gauges or humidity sensors to sense the water level on the ground and provide users with feedback to help avoid puddles that may be dangerous [97].

When people use a passive walking aid to climb a slope, they often have to exert a significant amount of force to overcome gravity, which can be challenging. However, WSR can sense the slope of the ground and adjust its motor output to assist people with disabilities in climbing uphill. This can greatly enhance convenience and ease for users. WSR can utilize IMU [71] or tilt sensors [49], [52] to determine the slope of the ground and provide appropriate gravity compensation to assist with uphill climbing. Furthermore, pressure sensors attached to the soles of users can be used to measure plantar pressure and identify corresponding slope changes based on pressure variations [98]. This enables the robot to provide more effective assistance for users during uphill climbs.

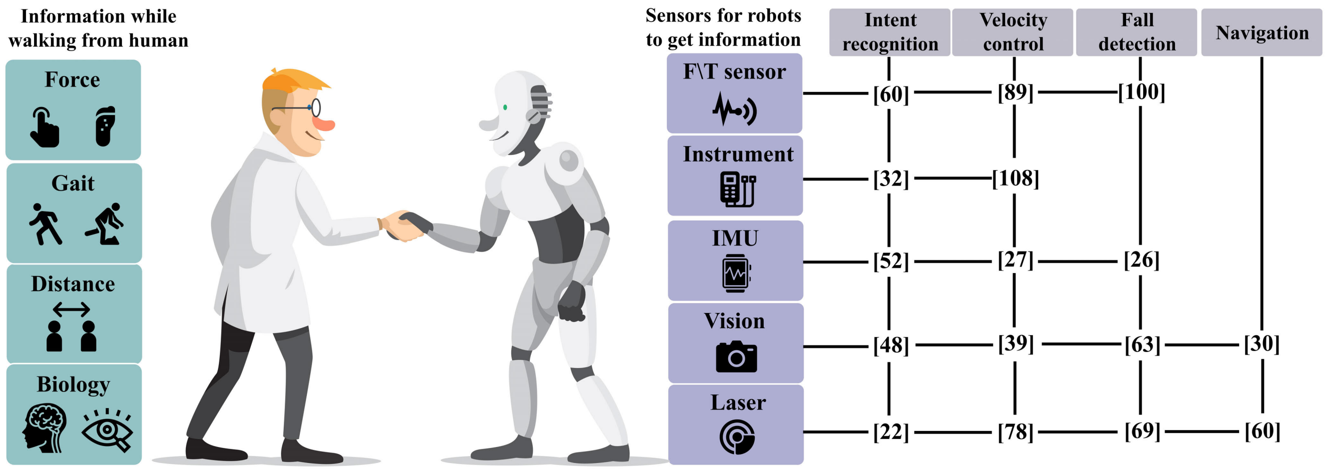

Fig. 4. When people walk with WSR, their status information can be divided into multiple aspects, such as gait pattern, balance and posture. The robot can utilize various sensors to detect and analyze this information, and apply it to provide intelligent support. By doing so, WSR can provide tailored assistance to meet the specific needs of the user, improving their overall walking experience.

B. Human Body State Perception

To be an effective collaborative robot, WSR should be capable of perceiving both its surrounding environment and the state and intentions of its users. Figure 4 illustrates various methods by which robots can gather information from users, which can be classified into two categories: contact (wearable sensor, tactile sensor, bioelectric sensor, joystick, touch screen, etc.) and non-contact types (laser radar, camera, voice recognition, etc.).

Some WSR offer human-machine interfaces like joysticks or touch screens [27], but they may not always provide a simple and user-friendly interactive interface, especially for older adults who are not familiar with these devices. Compared to fixed motion commands, most recent WSR rely on perceiving naturally emitted information from users, such as interaction force, gait patterns, and biological signals. This subsection will focus primarily on these type of perception methods.

1) Force Perception: Force can naturally reflect the user's movement intention. By measuring the interaction force between the user and the WSR, a sensitive and intuitive control interface can be provided. Most WSR choose to install force sensors at the handle, and such force sensors can be either a six-dimensional F/T sensor [21] or an array of force sensors [40]. The application of low-cost force sensors in WSR is also a challenge [99].

In addition to the magnitude of force, the location where the force is applied is also valuable information that reflects the contact situation. This is typically conveyed through robot skin. Itadera and Cheng [60] installed tactile sensors on the handles of a WSR to detect the location of applied force. To enhance the precision of force measurement, a six-dimensional F/T sensor was placed in the middle of the handle. While tactile sensors may not offer the same level of sensing accuracy as F/T sensors, they do provide users with more grip points and can furnish the robot with the position of these grip points.

Plantar pressure is also a crucial factor in studying movement stability during a person's movement. Adding force sensors to shoes can serve as tools for evaluating support effectiveness [17], gait analysis [47] or fall detection [100].

2) Gait Perception: Wearable sensors are commonly regarded as reliable source for capturing human gait. The specific installation location depends on the researcher's objectives [34]. For instance, Hassani et al. attached three IMU to the user's sternum and the lateral mid-thigh to analyze patient gait [101]. Martinez-Hernandez et al. placed a nine-axis IMU on the user's thigh to collect intent data during STS transitions [102]. Wenxia et al. installed five wearable sensor units on the user's waist, thighs, and shins to build a real-time human body model [19]. However, a study [103] indicates that wearable sensors, due to the need for wearing, may have lower comfort compared to methods based on non-wearble ones (radar, camera, etc.).

Due to the distance constraints between WSR and users during operation, using cameras to perceive user's gait is a challenging task. Some studies [22], [72] choose to place cameras in the external environment, maintaining a distance from users to capture their entire body maximally. However, this approach may impose limitation on the range of WSR usage. A more general approach is to mount cameras on the WSR and only detect specific parts of the user's gait, such as using a camera dedicated to capturing lower limb gait [45], [68], [80], [103] or upper limb gait [54]. Additionally, obtaining the full-body posture by installing multiple sensors complementarily is also a possible solution, such as using laser for lower limbs and cameras for upper limbs [41], or directly using two cameras for capturing upper and lower limbs [104].

Radar or laser range finders typically estimate human gait by acquiring 2D data of the user's lower limbs [105]. For example, Zhao et al. defined a series of walking patterns and estimate the current user's movement intent through the position of the user's feet [51]. The k-means method is utilized to classify leg positions obtained from a lidar, determining the left and right legs based on prior knowledge. This information is then employed to learn the relationship between user intent and gait through a neural network model [29]. High-dimensional radar also holds potential application value in gait analysis [106].

3) Distance Perception: In contrast to the user's gait, some researches focus more on the user's current position, typically represented in a 2D world coordinate system with a set of state variables:

$$\boldsymbol{x_u} = \left(x \ \ y \ \ \theta\right)^T \tag{1}$$

The state can be acquired through cameras [46], [81] or laser sensors [18]. Another challenging aspect in this task is the estimation of the user's state to enhance the accuracy of position detection. After determining precise information about the user's position, WSR can accompany the user in walking with a relatively fixed posture [18], [46].

4) Biology Perception: Biological signals are often used to assess the effectiveness of WSR [36], [39], [72], [92] or express the intensity of a user's specific intent. Chang et al. classified standing, sitting and quiet intentions based on user's electroencephalogram (EEG) combined with Support Vector Machine [107]. Chen et al. estimated muscle stiffness using electromyography (EMG) signals, and WSR rapidly avoided obstacles when EMG stiffness increased [70]. Wang et al. provided support by installing EMG sensors on four muscles of the user's healthy leg to estimate the current walking intent intensity [108].

User and WSR's voice interaction is also a crucial part of the support process. WSR can use the user's voice to discern requests for assistance [54], modifications to the destination [16], or the user's current location [29] during the support process.

Considering the application of biological signals in WSR, they are either used in conjunction with other interfaces [29], [70] or responsible for a specific part of WSR [54], [107], [108]. The complete implementation of WSR motion solely based on biological signals has not been achieved. Research in the field of smart wheelchairs [109] and brain-controlled robot [110], [111], [112] may contribute to advancing this process.

5) Sensor Fusion: Various sensors on WSR have distinct responsibilities; force sensors are responsible for detecting user interaction force, radar monitors lower limb movements and cameras, along with wearable sensors, capture the user's gait. Extracting user intent from this array of information holds significant value. Ding et al. obtained upper limb force information from force sensors, and through an admittance control model, acquired user position and velocity. They fused this information with lower limb motion data obtained through radar using a Kalman filter to enhance the accuracy of the user position and velocity information [73]. Molano et al. designed three distinct LSTM blocks for force sensors, LIDAR and cameras to fuse data and drive WSR movement [48]. Wang et al. utilized wearable sensors for posture acquisition, 2D laser sensors for lower limb movement, and defined fuzzy rules for fall detection [33].

6) Discussion: We have conducted a frequency analysis of sensor usage on WSR over the past five years, and the results, as depicted in Figure 5, indicate that F/T sensors, laser sensors, and vision sensors are predominant. To assess the effectiveness of the sensors described above for sensing body state, this study evaluates the sensors based on a set of important features for assisted locomotion. The classification features are listed below:

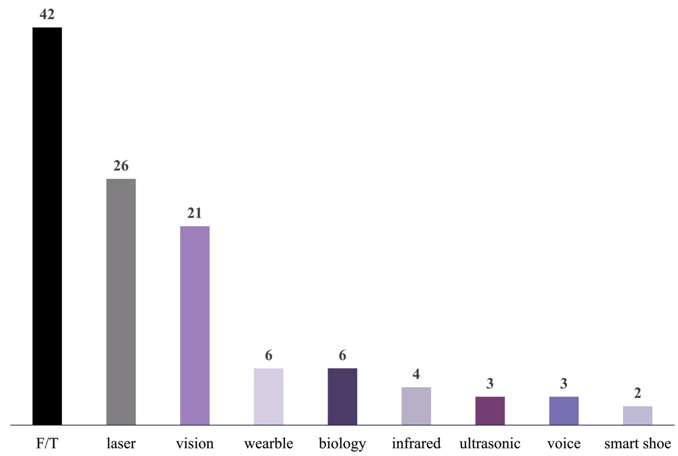

Fig. 5. The usage of sensors on WSR in the past five years.

(1) Input signal

The input signal represents the information received by the robot from the user. This information can be passively obtained by the robot through sensors or actively provided by the user to control the robot.

(2) Burden of use

The burden of use refers to the physical and mental effort required by the user to control the robot through the sensor. This effort includes the consumption of muscle strength and attention, and a heavy burden of use can cause the user to feel tired after using the robot for a period of time. If the user only needs to complete normal walking motions without any additional or unnecessary actions, then the burden of use is defined as low. If the user needs to perform actions beyond walking to indicate their intent to WSR, such as applying pressure or engaging in voice interaction, the burden is considered high.

(3) Degree of invasiveness

The degree of invasiveness refers to the inconvenience caused by the sensors that the user needs to wear or interact with when using the robot, which is closely related to the user's comfort level. If the user needs to wear sensors in advance before using the WSR, the degree of invasiveness is high; whereas, if the user doesn't need to make any preparations before using the WSR, the degree of invasiveness is low.

(4) Completeness

Completeness refers to whether the information obtained by the sensor can accurately express the user's intention without the assistance of other sensors. We evaluate completeness based on current available literature. If more than half of the literature using the sensor considers it as a separate function rather than an integral part of the walking support process, we define its completeness as low; otherwise, we define it as high.

TABLE II
SENSOR CLASSIFICATION FOR HUMAN BODY STATE PERCEPTION

Sensor	Input signal	Burden of use	Degree of invasiveness	Completeness
F/T sensor	Interaction force	high	low	high
Smart shoe	Plantar pressure	low	high	high
IMU	Human motion model	low	high	high
EEG,EMG	Bioelectric information	low	high	low
Vision sensor	Human motion model	low	low	high
Distance sensor	Human motion model	low	low	high
Voice sensor	Human voice	high	low	low

Table II presents the evaluation of sensors based on the aforementioned characteristics, with each characteristic graded as low, medium, or high. This table aims to offer guidance for future developers in the process of selecting sensors.

V. CONTROL STRATEGIES

A. STS Control Strategies

The stand-up-sit-to-stand movement process can be divided into three phases: trunk flexion, hip lift-off and the knee-hip extension. Joint torque is an important parameter for evaluating human motion, and it can feedback the user's comfort level [92]. In order to obtain user joint moments to evaluate the effectiveness of STS movements, as well as to generate optimal trajectories, it is usually necessary to build a model for the user's human body.

WSR utilizes sensors on the robot to perceive the user's human body model and adjust the robot's motion planning accordingly. Cao et al. [113] have utilized the sensor system on WSR to measure various parameters during STS training, including ground reaction force, pressure center, rope tension, trunk motion trajectory and rotation angle of each body segment. They utilized Tracked Control Based on Training (TCBT) to facilitate safe and natural subject training in the transition from sitting to standing, and employed Impedance Control Based on Training (ICBT) to capture the subjects' motion intentions and enhance the training intensity. Bolli et al. [22] proposed an optimal support strategy for STS assistance based on the user's human body model captured by visual sensors. They calculated the optimal trajectory of the handle to maximize the product of the user interaction force and the moving speed of the center of mass. Sharma et al. [114] utilized IMUs to collect human reference trajectories and encode them into dynamic motion primitives. This information is then sent to the robot's actuators to facilitate admittance control. Based on the analysis of human-to-human supporting activities, Li et al. [92] proposed a five-segment human body model that minimizes body joint torque. They generated the corresponding trajectory of the robotic arm's end to reduce the joint torque of the user during the support process.

During the STS transfer process, it is essential for WSR to understand and mimic human behavior. However, obtaining accurate active joint torque values is challenging, making it difficult to establish an accurate model of the man-machine coupling system. The use of learning methods can overcome the problem of model inaccuracy and obtain appropriate stand-up-sit-down motion trajectories. Wenxia et al. [19] proposed a sit-stand motion control method for a WSR using fuzzy learning methods. By reducing the dimensionality of the state-action pair using a sit-stand-stand motion controller to control the linear actuator and the moving base of the robot, the method effectively controlled the robot's movement. Sharma et al. [115] consolidated collocation-based optimal control method with the stochastic trajectory optimization method based on Policy Improvement with Path Integral method to generate optimal STS trajectory. The modeling methods and main application techniques presented above are listed in Table III.

TABLE III
STS MODELING AND STRATEGIES

Publication	Human Model	Method
[19]	triple link model	Fuzzy-Sarsa learning
[113]	triple link model	TCBT, ICBT
[92]	seven linked model	OC
[22]	five-linked model	LSTM
[115]	four-linked model Hill-type muscle model	OC, PI^2
[116]	6-link musculoskeletal model	OC, MPC
[91]	N/A	LSTM
[102]	N/A	Bayesian formulation

When using learning-based methods for robot STS control, the dataset is a critical factor in determining the control effect. Bennett et al. [117] collected pressure data from seats, floors and other sources for healthy and unhealthy people, providing an open-source dataset for complete stand-sit-stand movements. Other useful datasets include [118] and [119].

B. Walking Control Strategies

1) Position Based Control: For older adults or those with cognitive defects, WSR assume the responsibility of guiding users. Common navigation solutions in WSR closely resemble the navigation methods used in mobile robots. In such scenarios, users follow the feedback from WSR to navigate around obstacles and reach their destination. Slade et al. used a 2D lidar to determine the positions of users and obstacles, applied the A* algorithm to calculate a path to the target location, and provided feedback to guide users forward [85]. Borgese et al. manually operated WSR in unfamiliar environments to build a map. After constructing the map, they employed the Dijkstra algorithm for global path planning and used DWA for local path obstacle avoidance [94].

In addition, considering the cost of sensor usage, some rules specified by the designers can also be employed to guide users.

TABLE IV
SUMMARY OF POSITION BASED CONTROL METHODS

Publication	Navigation method	Sensors	Environment
[85]	A*	2D Lidar	Grid Map
[86]	A*	RGB-D camera	POI Graph
[94]	Dijkstra, DWA	2D Lidar	Grid Map
[37]	UTRL-RRT	RGB-D camera	Grid Map
[77]	Avoidance command	RGB-D camera	Obstacle, Wall
[120]	A*	Lidar	Grid Map
[121]	A*	RGB-D camera	Point Cloud Map
[40]	Fuzzy Logic	Ultrasoinc sensor	Obstacle
[26]	Comfort-based Planner	F/T sensor, Laser Range Finder	Grid Map

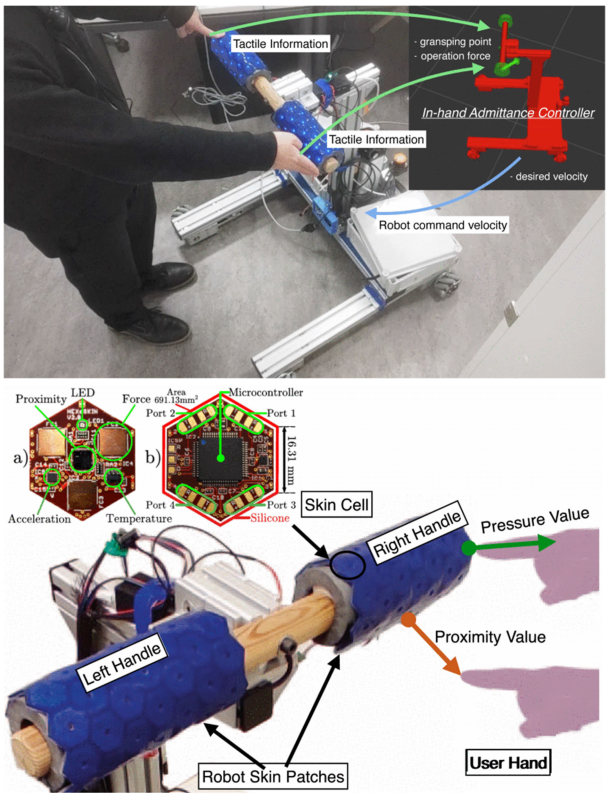

Fig. 6. Installing robot skin on the handle of the robot allows for the perception of the magnitude and location of applied force [60]. Copyright 2022, IEEE.

In [40], eight ultrasonic sensors were installed on the WSR, with five used for obstacle detection and three for detecting holes on the ground. The researcher defined information such as obstacles, destinations and ground depressions as fuzzy variables, and established corresponding fuzzy rules to control the forward movement of WSR. User factors need to be considered in position-based control. The control strategy, while effective in ensuring safety, removes the user's involvement in the path planning process, which can lead to the discomfort of the user [26]. The position-based control methods used on the WSR are summarized in Table IV.

2) Human Intension Based Control: From the user's perspective, WSR should be compliant, meaning that the robot should move forward in accordance with the user's intended motion. Upon sensing the user's model information or interaction force through the sensor, the robot can estimate the user's intention.

In addition to a few WSR utilizing learning-based [30] or command-based [57] methods to infer user's walking intentions using F/T information, in most cases, WSR connects the force information collected by the handle force sensor with an impedance control (admittance control) model. The admittance control model typically exists in the following form:

$$\boldsymbol{M}_v \ddot{\boldsymbol{p}} + \boldsymbol{D}_v \dot{\boldsymbol{p}} = \boldsymbol{f} \tag{2}$$

where $\boldsymbol{p} = \begin{pmatrix} x & y & \theta \end{pmatrix}^T$ is the vector of WSR's current position, $\boldsymbol{f} = \begin{pmatrix} f_x & f_y & \tau \end{pmatrix}^T$ is the vector of the user's operation force applied to WSR. In impedance control mode, users can manipulate the WSR in a natural way without the need for extensive training. The selection of appropriate impedance control parameters $\boldsymbol{M}_v, \boldsymbol{D}_v$ is a challenging problem as it directly affects the user's gait when operating the WSR [72], [122]. In this case, variable impedance control is a potential solution. Ding et al. [89] utilized a variable impedance controller to adjust to variations in the force exerted by the user on the walker, reducing the damping parameter $\boldsymbol{D}_v$ when the force applied by the user increases. This method allows users to operate the WSR with only a small amount of force.

Another concern in the impedance control mode is the handling of abnormal force. For example, when a user exerts force on the handle due to a fall, the WSR needs to distinguish such abnormal force and should not maintain compliance to such force; otherwise, the WSR might move forward rapidly, posing greater danger to the user. Itadera et al. [21] simplified the human model to a inverted pendulum and used model predictive control to calculate the optimal assistive force based on the estimated user's current state. Experiments confirmed that when a user was about to fall, the assistive force could balance the force applied by the user to the WSR, helping the user maintain posture and preventing further fall. Their subsequent research distinguished cases where only one hand was gripping the handle of the WSR by installing tactile sensors [60].

The user's gait can be used to perceive the current walking situation and provide appropriate control strategies for WSR. By analyzing gait patterns and specifying fuzzy logic, it is possible to capture the user's walking intent and detect abnormal gait [51]. Learning-based methods also contribute to analyzing the user's gait and controlling WSR movement [41].

Once the user's position is determined, maintaining a relatively fixed position for the user based on their walking stability is crucial [46]. Estimating the current user state and tracking expectations are key issues. Yan et al. [18] estimated the user's position using an observation model based on the LRF's foot position information and proposed a finite-time control method for WSR to track the expected position and avoid collisions with the user. Panahi et al. [34] modeled the human using an inverted pendulum model, coupling the human's model with WSR's model through parallel linear spring-damper systems, and used a fuzzy controller to assist user walking.

3) Shared Control: In a support scenario, obstacles such as tables, chairs and other items may impede progress. To detect obstacles in the surrounding environment, WSR can use ultrasound, laser radar, vision and other methods. Safely guiding users to their destination without colliding with external obstacles is a challenge in the walking control of WSR. Similar to the field of autonomous driving, WSR should be capable of determining whether a human intention is reasonable [123]. The autonomous mobility of the robot user should not be compromised, and the WSR should provide the user with the impression that they are controlling the robot, and that it is moving as desired. At the same time, the robot's intelligence should not be ignored. It should utilize its intelligence to assist users in reaching their destination safely.

In many situations, we are confronted with conflicts between the user's intent and the WSR's inclinations. Shared control typically revolves around the question of when the robot should take the lead and when the user should be in control. One possible approach is to determine this based on the strength of the user's intent. Yeoh et al. [55] addressed conflicts between robot-dominated and user-dominated control modes by using compliant handles to switch between modes. Chen et al. [70] utilized muscle stiffness feedback from EMG to represent the intensity of the user intent. Another potential option is for WSR to take control authority in hazardous situations, forcing it to follow a safe path when a collision is imminent [37].

VI. Safety and Comfortability

A. Evaluation

It is important to note that the comfort of the user when using a robot is highly personal and dependent on factors such as age, living habits and personal preference. Therefore, it is necessary to conduct targeted assessments of the comfort of the user in supporting activities. Compared to passive four-legged walkers and rollators, WSR can provide greater stability while reducing aerobic demand, which can lead to increased the comfort of the user [11].

A common method for evaluating the comfort of the user is through the use of questionnaires [35], [48], [54]. Researchers can choose to inquire about the comfort of specific functions of a WSR or inquire holistically to obtain feedback [54]. In addition, EMG [92] or wearable sensors [81] can analyze the user's physiological conditions to assess their current comfort level.

B. Vibration Feedback

During the operation of WSR, particularly while traversing bumpy sections of the road, users may feel considerable force feedback that could lead to discomfort resulting from vibration effects [124]. To solve this problem, the robot's structure can be modified to dampen the vibration. The extended use of assisted mobility devices may result in spinal injuries and raise the likelihood of musculoskeletal disorders like low back pain and physical distortion [125]. As a result, it is advisable to enhance the vibration damping capability of WSR during the design phase. The force feedback perceived by the user while utilizing the armrest is influenced by factors such as the armrest's structure, size and height [126]. Zhang et al. [127] developed a dual-degree-of-freedom dual-axis vibration model and a human-machine coupling vibration model to simplify the comprehensive analysis of the robot's vibrations. They further assessed the sensitivity of the vibration response to the damping ratio, mass ratio and natural frequency.They examined the influence of each parameter on the vibration response and the comfort of the user during assisted activities. Furthermore, research has also discussed the perspective that control algorithms can reduce vibrations. Mahdi et al. [43] incorporated safety functions into the software, including the S-curve velocity profile, to decrease the vibration and shock of the mechanism, resulting in smoother robot operation.

The conventional round wheels used in most WSR can be difficult to handle on rough or uneven terrain, which can make outdoor walking paths difficult. When encountering an obstacle, the counterforce on the WSR is transmitted to the user, and a collision could lead to a fall. To reduce vibration feedback, one solution is to replace the wheeled mobile base with a crawler base, which performs better at crossing obstacles. An experiment has demonstrated that the muscle strength required by users is significantly decreased when employing a crawler based robot instead of a wheeled robot [67].

C. Fall Detection and Prevention

According to the World Health Organization, falls are one of the main causes of death for the older adults, as about 10% to 15% of falls can cause serious injuries. Consideration must be given to the potential occurrence of falls when using WSR [128]. There are various methods to implement fall detection in WSR, and the accuracy depends on the method and the user state information obtained. For instance, Cao et al. [75] determined the likelihood of a fall by measuring the force magnitude and its rate of change at the waist position of the WSR, achieving a recognition accuracy of 95.8% through training a deep neural network. Chalvatzaki et al. [74] proposed an LSTM-based human gait stability predictor using upper limb posture from an RGB-D camera and lower limb posture from LRF as input, achieving an accuracy of 84.36%. Chang et al. [88] used IMUs on a smart cane and smart glasses worn by the user to assess the user's state and detect falls, reaching an accuracy of 98.3%. We have compiled a table of fall prevention methods for robots based on robot type, sensor type, detection method, and detection accuracy, as shown in Table V. It's important to note that the listed sensors only consider those used in the fall detection process, excluding sensors responsible for other functionalities.

TABLE V
SUMMARY OF FALL DETECTION FOR WSR

Publication	Structure Type	Sensors for Fall Detection	Method	Accuracy
[74]	Support frame	Laser Range Finder, RGB-D Camera	LSTM	84.36%
[75]	Support frame	F/T sensor	DNN	95.8%
[73]	Support frame	F/T sensor, Radar	PLT-SPRT	94.9%
[33]	Support frame	Wearble sensor, 2D Laser sensor	Fuzzy Logic	94.7%
[88]	Cane	IMU	Rule based	98.3%
[51]	Support frame	F/T sensor, Proximity sensor	Fuzzy Logic	96.2%
[68]	Support frame	RGB-D Camera	Rule based	96.7%

Once the falling trend of the user is detected, many WSR will choose to brake immediately to ensure safety in the assisting process [63]. Zhang et al. [56] used the inverted pendulum model to analyze whether the human body is in the stable area. When the user is not in the stable area, that is, there is a risk of falling, the robot stops moving and an airbag pops out to protect the user's safety. The walking aid designed by Pereira et al. [76] stops when it detects that the user is close to falling and uses the large wooden table on the robot to prevent the user from falling. A more intelligent way to prevent falls is to adjust the robot configuration according to the user's falling state. Naeem et al. [82] devised a set of impedance controllers tuned with a genetic algorithm based on force/torque constraints, and applied model reference adaptive control to the cane robot to overcome system uncertainties. Through this approach, WSR can achieve real-time fall prevention. The previously mentioned method [21] of using MPC to compute optimal assisting forces has also been experimentally validated to address fall situations. Considering the risk of potential collisions between the elderly and the WSR when the robot stops abruptly, such intelligent fall prevention methods may be a preferable choice.

D. Safety Guarantee System

The hardware and software design of WSR are directly related to the user's personal safety and must be free of defects. In addition to the emergency switch that must be equipped on the robot, according to the recommendations of the International Standards Organization in ISO/TS 15066, the stress of contact between collaborative robots and human should be limited within a certain range. One possible solution is to maintain hardware compliance to reduce the risk of possible collisions. For example, Zhao et al. [29] designed a soft haptic interface for WSR to minimize potential damage from collisions. Thompson and Walker [129] equipped WSR with airbags to offer cushioning for users in the event of a collision.

Another notable aspect is dealing with potential failures during WSR operation. A sudden failure of an actuator during operation could lead to horrible consequences, necessitating an increase in redundancy during robot operation. For example, Liao et al. [130] developed an unsupervised learning approach to address fault detection and recovery issues using historical sensor data. In addition, Sun et al. [131] proposed a nonlinear robust redundant input reliable control method using Lyapunov function. The designed safety controller can guide WSR along the path specified by the therapist, even if one wheel fails. This controller can avoid danger caused by sudden failure.

VII. CHALLENGES BEYOND THE LAB

A. User Acceptance

Researches indicate that some users may have trouble accepting WSR as new robot companions. Part of the reason stems from the psychological state of older adults, despite a decline in mobility, for fear that using WSR makes them appear sick and weak. This perception could potentially harm their social image, and some older adults may prefer using umbrellas to walk instead of WSR [132]. If these psychological issues of users are not solved and social cognition of WSR is not changed, no matter how advanced the WSR are, they cannot assist users in mobility.

User's lack of trust in WSR is also a crucial factor preventing their acceptance. In comparison to passive walkers, users are concerned that WSR's actions may cause harm, as they feel a lack of control over WSR and perceive a lack of predictability in their response [133]. Building trust between WSR and users is a lengthy process, but destroying this trust can occur with just one failure. Therefore, WSR must avoid any actions that could damage user trust. This implies that responses to any situation must undergo careful consideration, including handling user abnormal states [134] and collisions. Simultaneously, WSR must ensure system security, respect user privacy, safeguard the security of health-related data, and ensure compliance with healthcare standards and local laws and regulations in data processing [135]. Adopting a user-centered approach in WSR design, such as an appealing appearance, appropriate size and weight, ease of use [136], or designing control schemes with stronger customization, contributes to enhancing user trust. When designing, it is essential to reflect on mature solutions from other fields. For example, users navigating with WSR desire to maintain a good visibility [26], a consideration often overlooked in the navigation of mobile robots.

Additionally, WSR can sometimes cause confusion for users who are using it for the first time. There should be training guidance to help older adults to know about WSR, reducing cognitive burden and mitigating potential dangers from inappropriate use. Training is lacking in the research on passive walkers, with a previous publication [137] indicating that only 25% users received training before using passive walk aids. Proper guidance methods must be established to instruct users in the correct usage of WSR. One potential solution is to provide guidance through appropriate voice interactions between WSR and users. This can significantly reduce user's anxiety when using WSR, leading to improved usability [138].

Cost is also a significant barrier for the practical application of WSR. Many existing WSR use expensive sensors, users and healthcare institutions may be unwilling to bear such high costs. Future WSR research needs to strike a balance between usability and cost to find the most suitable solutions [11].

B. Environmental Barriers

The environment imposes limitation on the scope of WSR usage. In outdoor activities, WSR face challenges posed by surfaces such as rough terrain [67] and icy conditions [139]. In some cases, WSR even struggle to function smoothly indoors, and users resort to alternatives like canes, furniture and walls [140]. For the majority of WSR, their wheeled base prevent them from climbing stairs. Therefore, despite only one case [24] using legged base in this review, we still believe it holds significant application potential. Additionally, users encounter challenges in scenarios such as opening doors and entering bathrooms [141]. The structural design of WSR constrain their mobility, especially for support frame-type WSR. These types of WSR are large in size compared to cane-type robots, making them difficult to navigate through narrow spaces. The wheeled design may also pose difficulties when crossing carpets [142]. Overcoming these challenges requires improvement in home and public space designs and deliberate WSR structure to ensure maximum versatility.

VIII. Conclusion and Future Direction

As science and technology advance and social issues arise, the market for nursing service for people with mobility disabilities is growing, and assistive robots will gradually become commonplace in thousands of households. Until now, WSR are still mainly in the laboratory stage and have not yet achieved large-scale commercialization. This paper provides a comprehensive overview of recent advancements in WSR, including perception strategies, STS control strategies, walking control strategies, as well as discussions on users comfort, safety and other relevant aspects of WSR.

The structure of WSR can be divided into support frame-based, cane-type and manipulator-type. Among them, the support frame-based WSR is preferred by most researchers due to their strong support capability. The cane-type WSR are more convenient for navigation in narrow spaces. Additionally, the manipulator-type WSR, as a novel structural form, exhibit versatility and find application across diverse scenarios. To gain a comprehensive perception of the surrounding environment and capture the user's transmitted information with high redundancy, the WSR will be equipped with as many sensors as possible. These sensors can detect the environment, helping the robot to assist users in avoiding obstacles and obtaining user information. Among them, F/T sensors are commonly used in WSR as they offer users a natural human-machine interface. Balancing the user's comfort, the cost of sensors and the accuracy of the user intention perception is a crucial issue, future WSR need to consider these factors comprehensively when selecting sensors.

When designing the control strategy for the WSR, both traditional model-based control methods and learning-based control methods have shown promising results in STS control. The control of WSR is a sub-problem of man-machine cooperation control. In situations where a user's intention conflicts with the robot's logical judgment, the WSR must determine the correct option to ensure both the user's comfort and safety. A common approach to this issue is to allocate relative weight between robot control and user control using optimization or learning methods based on the current situation.

Both the hardware and software of the WSR are crucial to prioritize safety and comfort during the supporting process. This includes reducing the vibration feedback experienced by the user during the robot's operation and addressing the risk of the user falling or experiencing an unexpected collision with the robot.

Additionally, WSR need to consider the challenges in practical applications, analyze issues from the user's perspective, and prepare for widespread adoption–a dimension currently lacking in most WSR. To transition WSR from the lab to the real world requires the development of more versatile robotic platforms, along with the enhancement of relevant laws and regulations and support from the social environment.

Although WSR have achieved much success in lab, their widespread use is still limited due to several challenges. Based on the review of advanced WSR, we propose the future directions in the field of WSR:

A. Cost-effective robot platform

WSR need to maintain reasonable cost to ensure greater user acceptance, with sensors being the primary cost component. Therefore, it is necessary to explore ways to minimize the number and cost of sensors used while ensuring accurate detection of the user states and environmental conditions. Using multiple low-cost sensors and fusing their information is one solution. Besides reducing costs, it can also enhance the functionality of WSR to increase its utility. For users, WSR that provide both STS assistance and walking assistance are more attractive choices, avoiding the need for users to purchase multiple devices. Additionally, another potential method to enhance cost-effectiveness is to add functionalities such as manipulation to WSR, rather than considering WSR solely as a dedicated mobility-aid device. In other words, developing support function for manipulator-type service robots may increase people's willingness to use them, as there is a higher budget for service robots.

B. Applicability in real-world

It is essential to ensure that WSR can perform as expected in real-world scenarios. Potential issues in real environments, such as potholes in urban terrain and cluttered indoor spaces, must be considered. Currently, most WSR have only been validated in controlled laboratory settings, lacking experiments in more general and realistic situations. The experimental environment for robots is mostly flat ground, which cannot always meet the requirements of practical application scenarios. WSR need to be tested and improved in scenarios with bumpy roads. Complex indoor situations, such as cluttered obstacles and challenging areas like carpets, must be taken into account, and convincing solutions should be provided. Different disabilities among the older adults need to be considered, with corresponding solutions proposed. For example, ensuring that older adults with impaired cognitive function can still timely recharge WSR, or ensuring that visually impaired older adults can correctly locate handles.

C. Handling of abnormal cases

WSR need to accurately perceive the user's intentions, so that they can move in the user's desired directions. However, whether it is an intention perception strategy based on user interaction force or an intention perception strategy based on user mannequin, there is a risk of misunderstanding on the part of the user's intentions. A more accurate method for perceiving intentions requires the robot to utilize both user force feedback information and the user's human body model information, and fuse the data obtained by the two methods to determine the user's motion intentions. Additionally, the robot should be able to distinguish whether the user's intention is reasonable. When the user provides unreasonable instructions due to falls or sudden illness, the robot should filter out these inappropriate intentions. The data fusion method can improve the accuracy of intention recognition and should be actively applied in the field of WSR. As human-machine collaboration activities are the most unpredictable, users may sometimes make incorrect decisions, such as advancing towards obstacles that were not detected in time. Therefore, WSR should adopt a more reasonable human-machine fusion control strategy. It should allow the user to feel that they are in control of WSR, but also enable the robot to take over control in emergencies to ensure the user's safety and comfort while reaching their desired destination.

Falls are one of the main causes of death among the older adults, and they often occur when the user's center of mass changes, such as during walking with assistance, STS interaction, etc. As a robot designed for these types of scenarios, WSR should fully consider the occurrence of abnormal gait and make adequate plans for all types of abnormal gait, as well as timely adjust the robot's configuration in case of emergencies to help the user regain mobility stability. WSR should also have a plan for hardware or software failures to prevent possible danger.

D. Strategies for different disabilities

Most existing WSR assume that all users are the same, but in reality, users differ in height, weight, hemiplegia and muscle atrophy. Adopting a fixed configuration for the support mechanism is not always the most reasonable choice. The design of the assisting robot should be able to meet the needs of different users and various usage scenarios. Additionally, WSR typically provide the same assisting mode for all users, overlooking the individual differences among them. In reality, the reasons for different users' discomfort are diverse. Although an intention recognition method may function well for healthy individuals, it may not be satisfactory for those with physical disabilities. To solve this problem, corresponding support modes need to be designed for different patient types, which requires the collaboration of researchers in the clinical medicine field.

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