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Review

Door-Opening Technologies: Search for Affordable Assistive Technology

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Abstract: To the authors' knowledge, currently, there is no review covering the different technologies applied to opening manual doors. Therefore, this review presents a summary of the various technologies available on the market as well as those under research and development for opening manual doors. Four subtopics—doorknob accessories, wheelchair-mounted door-opening accessories, door-opening robots, and door-opening drones—were used to group the various technologies for manually opening doors. It is evident that opening doors is a difficult process, and there are different ways to solve this problem in terms of the technology used and the cost of the end product. The search for an affordable assistive technology for opening manual doors is ongoing. This work is an attempt to provide wheelchair users and their healthcare providers with a one-stop source for door-opening technologies. At least one of these door-opening solutions could prove beneficial to the elderly and some wheelchair users for increased independence. The ideal option would depend on an individual's needs and capabilities, and occupational therapists could assess and recommend the right solutions.

Keywords: wheelchair; door-opening; assistive technologies; robotic arms; robots; drones; manual doors; wheelchair-mounted accessories; legged robots; wheeled robots

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1. Introduction

According to the latest data from the World Health Organization (WHO), around 1.3 billion people, or about 16% of the world's population, are estimated to live with some form of disability [1]. According to the United Nations (UN), around 80% of people with disabilities live in developing countries, and around 20% of the world's poorest people have some kind of disability [2]. According to the International Labour Organization (ILO), employment rates are lower for people with disabilities compared to non-disabled people, with employment rates for people with disabilities in some countries below 30% [3].

Wheelchairs are one of the most widely used assistive devices by people with disabilities. However, according to the WHO, it is estimated that only 5–15% of people worldwide who require a wheelchair have access to one [4]; in other words, around 20 million people worldwide need wheelchairs but do not have them [5]. Even those people who have access to a wheelchair face several accessibility challenges in their daily lives. Some of the challenges faced by wheelchair users are maneuvering through narrow doorways or passages, building entrances that lack ramps, high door thresholds, and accessing manual doors.

Narrow doorways require complex maneuvering skills for wheelchair users to enter without bumping into the door frame. Opening inward swinging doors (or pulling doors backward) requires backing up and proper positioning of the wheelchair with respect to the door, which could be a difficult task for some wheelchair users, especially in tight spaces with higher chances of collisions with walls. Also, high door thresholds (over 20 mm) increase the risk of tipping. Wheelchair users also need to apply greater force than other individuals to open several types of doors. Heavy fire doors, for instance, may be difficult to open and may close too quickly. Some wheelchair users may experience difficulty operating certain types of door handles, particularly if they have limited hand use.

To the authors' knowledge, currently, there is no review covering the different technologies applied to opening manual doors. Therefore, this review presents a summary of the various technologies available on the market as well as those under research and development for opening manual doors. It should be noted that this review does not discuss technologies that convert manual doors into automatic doors, for example, automatic door operators [6,7]. This work is an attempt to provide wheelchair users and their healthcare providers with a one-stop source for door-opening technologies. Some of these technologies were specifically developed for the elderly and wheelchair users to be used as assistive technologies, while others were developed for the opening of manual doors in emergencies and hazardous areas. At least one of these door-opening solutions could prove beneficial to the elderly and some wheelchair users for increased independence. The ideal option would depend on an individual's needs and capabilities, and occupational therapists could assess and recommend the right solutions.

2. Door-Opening Technologies

This section discusses the different technologies available on the market as well as those under research and development for opening manual doors. The door-opening technologies can be broadly classified into four different categories and are discussed under the following sub-topics: doorknob accessories, wheelchair-mounted door-opening accessories, door-opening robots, and door-opening drones.

2.1. Doorknob Accessories

This section discusses the accessories that could be attached to the doorknobs or used to manipulate the doorknobs to assist in opening doors. Some wheelchair users face difficulties turning or rotating doorknobs, especially round knobs. To assist wheelchair users with this problem, there are different accessories available on the market. Non-slip doorknob grips, typically made of silicone or rubber, slip over doorknobs [8,9]. The contoured surfaces of the non-slip doorknob grips allow better grasping and easier turning of the doorknobs. Doorknob extenders attach to doorknobs and modify the length of the doorknobs. The illustration in Figure 1 shows a doorknob extender attached to a doorknob with a circular cross-section.

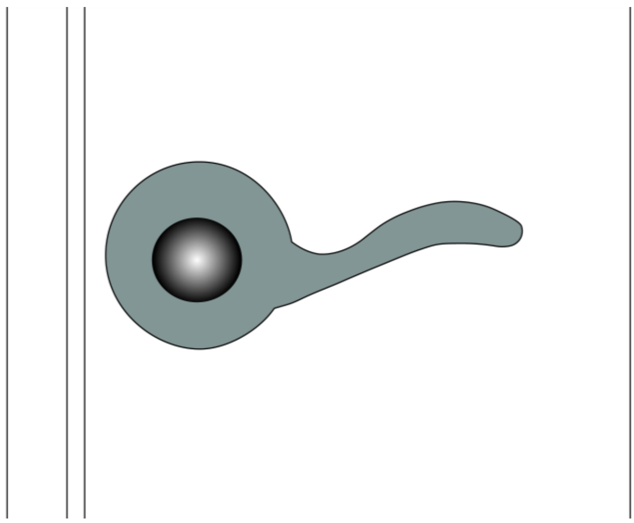

Figure 1. Illustration of doorknob extenders that assist in turning doorknobs with spherical cross-sections.

The extended doorknob structures allow wheelchair users to easily grab and turn the doorknob. This is compliant with the Americans with Disabilities Act (ADA) requirement for levers to be angled and have a large grip surface [10]. A variety of doorknob extender lengths and styles are available for the user to choose from. For example, the illustration in Figure 2 shows a doorknob extender attached to a doorknob with a non-circular cross-section [11].

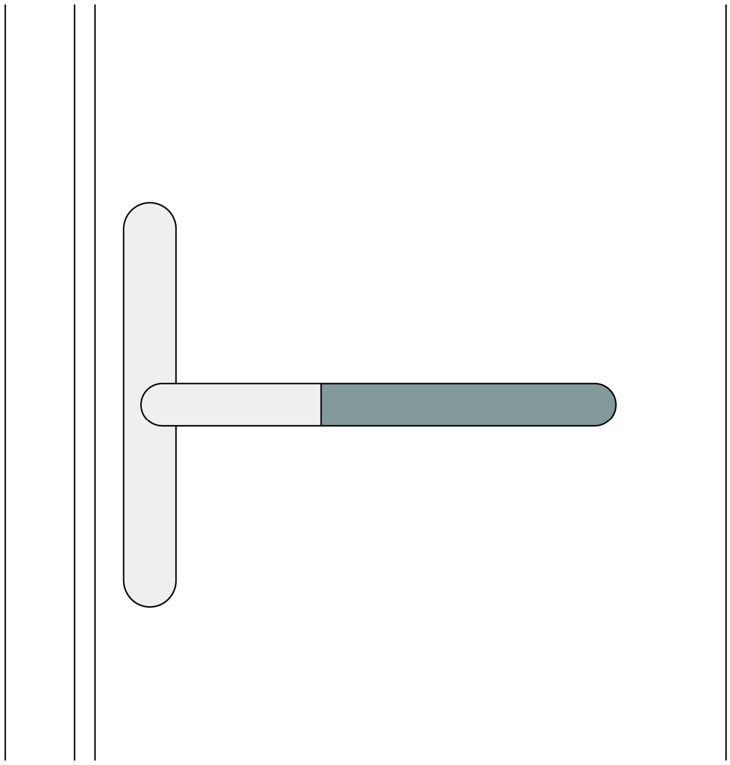

Figure 2. Illustration of doorknob extenders that assist in turning doorknobs with non-spherical cross-sections.

Long-reach doorknob turners do not attach to doorknobs like the doorknob extenders but are assistive tools with long handles that provide easier reach to doorknobs [12]. These long assistive tools, with a hook-like structure at their far end, allow wheelchair users to easily reach doorknobs from a distance and turn the doorknobs. Some doorknob turners also have a built-in tool at the handle end for unlocking deadbolts. The long-reach assistive tools could prove beneficial to those wheelchair users who have difficulty reaching or turning doorknobs. In summary, these accessories can assist with opening doors and make manual doors more accessible for wheelchair users, but they might not be suitable for all wheelchair users.

Table 1 summarizes the doorknob accessories that assist wheelchair users in opening manual doors. Both non-slip doorknob grips and doorknob extenders stay attached to the doorknobs, whereas the long-reach doorknob turners are used when needed and remain with the wheelchair user when not in use. All the doorknob accessories are available commercially. Depending on the kind of door and the attachment, doorknob accessories that help wheelchair users open manual doors might cost different amounts. Nonetheless, these doorknob add-ons are reasonably priced; they usually cost less than USD 50 [8,9,12,13].

Table 1. Doorknob accessories that assist in opening manual doors.

Door Opening AT	Features/Specifications	Commercial Availability	Cost
Non-slip doorknob grips	Attach to doorknob; Improve doorknob gripping and turning; Materials: Silicone or rubber; Dimensions: 2–3″ L × 1.6–2″ D	Yes	<USD 50
Doorknob extenders	Attach to doorknob; Reduce doorknob turning effort; Materials: Rubber or plastic; Dimensions: 4.25–7″ L × 2″ W	Yes	<USD 50
Long-reach doorknob turners	Aid reach to doorknobs; Materials: Aluminum and rubber; Dimensions 23.5″ L × 2.25″ W	Yes	<USD 50

L—Length, W—Width, D—Depth.

2.2. Wheelchair-Mounted Door-Opening Accessories

This section discusses the different accessories that could be mounted onto wheelchairs for opening doors. Wheelchair-mounted robotic arms (WMRAs) are mounted on one side of a powered wheelchair to provide manipulation assistance to users, especially those with limited upper-limb mobility [14–17]. The robotic manipulator arm can move over a working volume to reach and grip objects thanks to several jointed arms equipped with electric motors, giving users assistance with manipulation [18]. The two major companies that sell robotic arms that could be mounted onto wheelchairs are Exact Dynamics [19] (Manus and iARM arms) and Kinova [20] (JACO and MICO arms) [21]. The wheelchair-mounted robotic arms can be used to perform a variety of activities of daily living (ADLs), including reaching for objects, feeding oneself, dressing, and writing. Apart from these daily activities, the wheelchair-mounted robotic arms could be used for door-opening applications (see illustration in Figure 3). The typical workflow for using the wheelchair-mounted robotic arm is as follows: grip and turn the doorknob and maneuver through the door.

The wheelchair user detects the door and its doorknob. Multiple joints in the robotic manipulator arms are powered by motors and are used to extend, position, and orient the end-effector gripper. The robotic arms may operate in a semi-autonomous manner by using sensors such as cameras, laser scanners, and ultrasonic sensors to sense their surroundings. The wheelchair user grasps and turns the doorknob with the robotic arm's end-effector gripper. Grippers are made to hold onto things like doorknobs. The knob or handle shape is conformed to by the soft gripping surfaces. Certain grippers are equipped with sensors that adjust the grip force when turning knobs or handles and pulling doors in order to prevent damage. Low speeds, force-limited grippers, and collision avoidance are some examples of safety measures that guard against user injury. Lastly, the wheelchair user uses the mechanical arm to push or pull the door open and navigate the doorway.

Robotic arms mounted onto wheelchairs function by means of a controller, actuators, and sensors. The sensors identify the user's intention, including the desired arm movement. The arm is then moved in accordance with the actuators. The arm moves precisely and with ease, thanks to the controller. The person using the wheelchair can control the robotic arm with a variety of methods, such as a joystick, a head tracker, or even their thoughts [22]. Different levels of human control over the robotic arm are possible thanks to the control interfaces, which range from joysticks to brain–computer interfaces. By planning movements and paths, the integration of a robot operating system (ROS) permits sophisticated controls and autonomy. Programming enables the use of buttons or voice instructions to carry out pre-programmed actions, such as opening doors. Furthermore, the grabbing and manipulating skills of robotic arms are being improved through the use of machine learning techniques. Recently, Intel's Loihi chip has been used to demonstrate neuromorphic adaptive control of a wheelchair-mounted robotic arm [23,24].

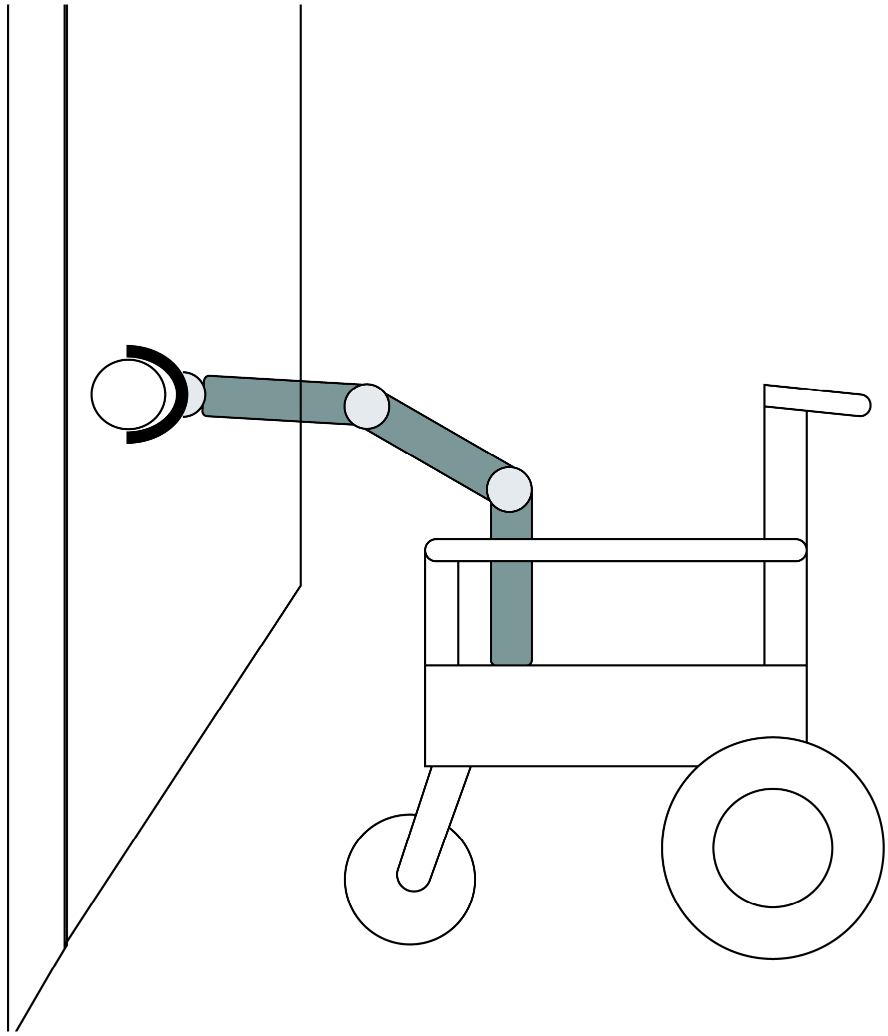

Figure 3. Illustration of a wheelchair-mounted robotic arm (WMRA) with a gripper end-effector, which assists wheelchair users in turning doorknobs and opening manual doors.

Another interesting example of wheelchair-mounted door-opening accessories is the wheelchair-mounted arc-shaped accessory. Unlike the previously discussed wheelchair-mounted robotic arms, this door-opening accessory is a non-powered mechanical device attached to the front and sides of a wheelchair. The first prototype of the arc-shaped wheelchair-mounted accessory was manufactured using conventional manufacturing techniques and off-the-shelf components [25]. The arc-shaped accessory consists of multiple wheels and is attached to the front of a wheelchair. The arc shape, along with the wheels of the accessory, allows the wheelchair user to easily push or glide against positive obstacles such as doors, walls, and furniture [25–27]. Figure 4 shows a photograph of a wheelchair-mounted arc-shaped accessory manufactured entirely using 3D printing [27]. Although the wheelchair-mounted arc-shaped accessory allows easy pushing or gliding against obstacles (including doors), a major limitation of this accessory is that it is neither capable of turning doorknobs nor capable of pulling doors.

Table 2 summarizes the wheelchair-mounted door-opening accessories that assist wheelchair users in opening manual doors. Both wheelchair-mounted accessories are attached to the wheelchair while in use for opening doors and can be detached when not needed. Robotic arms that are mountable onto wheelchairs are available commercially. The cost of a wheelchair-mounted robotic arm can be high and varies depending on the features. The lightweight controller-equipped wheelchair-mountable robotic arms from Exact Dynamics (Manus and iARM arms) and Kinova (JACO and MICO arms) range in price from USD 20,000 to 35,000 when equipped with grippers [21]. The wheelchair-mounted arc accessory is still under research and development and is not available on the market. However, the cost of the prototype manufactured using conventional manufacturing and off-the-shelf components was reported to be less than USD 100 [25].

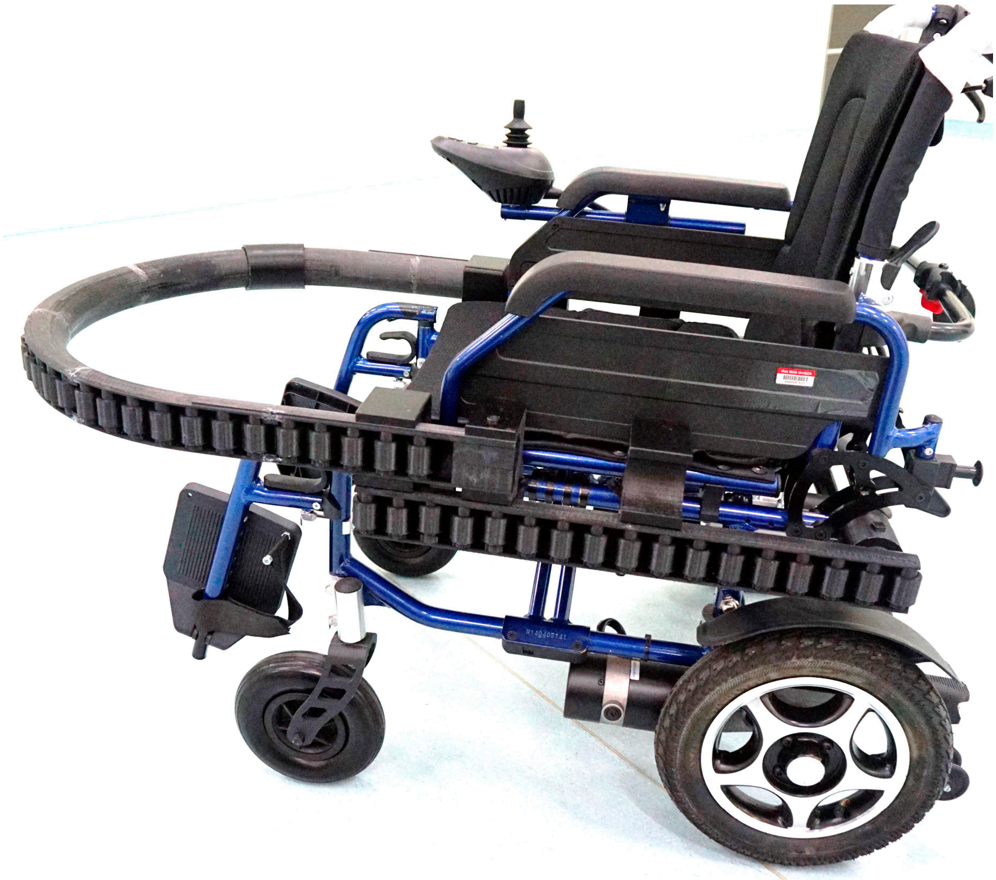

Figure 4. Photograph of an entirely 3D-printed wheelchair-mounted accessory comprised of multiple wheels along the periphery of the accessory that assists the wheelchair users to easily push or glide against positive obstacles.

Table 2. Wheelchair-mounted accessories that aid in opening doors.

Door Opening AT	Features/Specifications	Commercial Availability	Cost
Wheelchair-mounted robotic arm	Attached to wheelchair; Allows turning of doorknobs and pulling or pushing of door; Weight: ~5–9 kg (JACO–iARM); Payload: ~1.5 kg; Power consumption: ~25 Watts; Maximum reach: ~3 ft Degrees of freedom (DOF): 6	Yes	USD 20k–35k
Wheelchair-mounted arc-shaped accessory	Attached to wheelchair; Only allows pushing of door; Weight: ~2.15 kg; Dimensions: 42″ L × 26.3″ W	No	<USD 100

L—Length, W—Width.

2.3. Door-Opening Robots

This section discusses standalone mobile robots that could also be used for opening doors. Service robots, personal robots, or assistive robots are standalone mobile, typically wheeled, autonomous robotic devices that assist the elderly with mobility limitations and wheelchair users in various activities of daily living [28–32]. These standalone autonomous robotic devices are equipped with on-board sensors, cameras, and processors, along with one or more robotic arms. Apart from other tasks, these standalone autonomous devices equipped with robotic arm(s) could be used for door-opening applications (see illustration in Figure 5) [33,34].

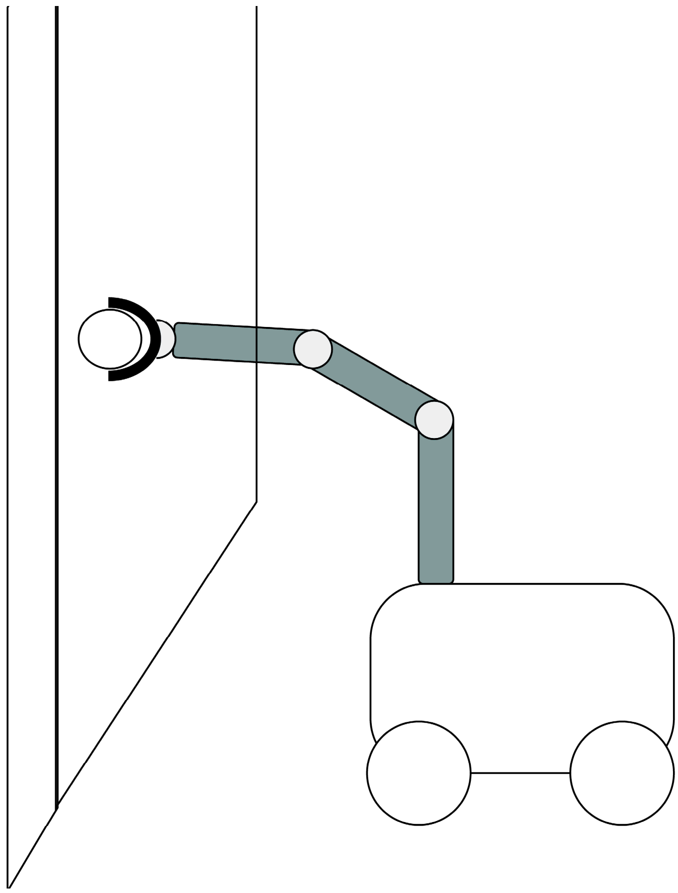

Figure 5. Illustration of an autonomous door-opening robot equipped with a robotic arm.

One example of an autonomous service robot is the Care-O-Bot wheeled robot, which, apart from performing household tasks, is able to manipulate doorknobs and open doors [28,35]. Another example of an autonomous wheeled personal robot is the PR2, which is capable of turning doorknobs and pulling doors [29]. An interesting autonomous wheeled service robot is based on a Segway platform and is called the HERB (Home Exploring Robotic Butler). The HERB, developed by Intel Research and Carnegie Mellon University, is able to manipulate doorknobs and open doors [30,36,37].

Robots have always had difficulty opening doors because of several issues, such as door forms, sizes, handles, and pressures needed to open them [38]. Robots that open doors usually follow this workflow: they detect the door, locate the doorknob, grasp and turn it, and then move through the door [39]. The robots use a variety of sensors, including proximity sensors, laser scanners, and cameras, to identify the presence of doors. After taking a picture of the door with the camera, software is used to evaluate the image. By utilizing proximity sensors, robots can prevent accidents with furniture and walls by detecting the presence of items in their route. By utilizing the camera to determine the form and position of the handle, the robot recognizes the doorknob. The robot then grabs the doorknob and turns it with its mechanical arm. The end-effector gripper on the robotic arms may be extended, positioned, and oriented thanks to a number of joints that are motor-driven. Grippers are made to hold onto push plates, lever handles, or circular knobs.

The knob or handle shape is conformed to by the soft gripping surfaces. In order to prevent damage, sensors measure forces and adjust grip strength while pulling doors and twisting knobs or handles. At last, the robot opens the door by pushing or pulling it open, and it moves through the doorway.

The standalone wheeled robotic devices operate automatically when triggered by sensors or remote controls. The standalone wheeled robotic devices incorporate safety features, including low speeds, soft force application, and collision avoidance, to keep people safe. While the control systems of standalone wheeled robotic devices adhere to pre-established motion sequences, certain robots additionally employ artificial intelligence methods such as deep learning and machine vision. For example, the door-opening robot created by Waseda University and Hitachi employs a modular method of opening doors [40,41]. Through the division of the task into three simple phases, this robot has learned how to open doors. It was equipped with distinct modules for traveling through doors, opening doors, and detecting doors. The robot was equipped with one pull-opening module and one push-opening module for each task. This method makes it simple to adjust the robot to different types of doors. In another interesting example, researchers from the University of Cincinnati are teaching autonomous wheeled robots using deep reinforcement learning to pull open self-closing doors [42,43] without using a robotic arm and without a pre-planned trajectory.

Another class of door-opening robots is the legged door-opening robots. A well-known example is Boston Dynamics' four-legged SpotMini fitted with the Spot Arm, a robotic arm with a gripper on the end to grasp and turn door handles [44]. SpotMini is equipped with an array of sensors comprising proprioception sensors in the limbs, a solid-state gyro (IMU), and depth cameras. These sensors support mobile manipulation and navigation. Without human assistance, SpotMini is capable of functioning independently. Opening doors play a key and crucial role in indoor rescue. Door-opening robots, particularly legged robots, may have a wider range of applications. They might be employed, for instance, in rescue operations where it is anticipated that legged robots will replace people in the event of a natural disaster, such as an earthquake, or in situations deemed too dangerous for humans to handle, including radioactive and toxic explosions [45].

Table 3 lists the technical specifications of the door-opening robots. Table 4 summarizes the door-opening robots. Both wheeled and legged robots capable of opening doors are available commercially. The cost of door-opening robots varies depending on the type of features available in the robot. The cost of the Care-O-Bot ranges from USD 66,000 to 232,000, depending on the configuration [46]. The cost of the single-armed PR2 was around USD 285,000, while the two-armed version was around USD 400,000 [47]. The cost of the UBR-1, a spin-off successor to the PR2, is around USD 35,000 [47]. The cost of HERB 2.0 is around USD 500,000 [30]. Many other door-opening robots are still in the research and development phase and not available on the market. The four-legged Boston Dynamics' SpotMini costs approximately USD 75,000 [48], and along with Spot Arm and ancillary equipment, the cost goes up to around USD 200,000 [49].

2.4. Door-Opening Drones

This section discusses drones that are used for opening doors. Drones are unmanned aerial vehicles (UAVs) with a wide range of applications, including product delivery, asset inspection, search and rescue, law enforcement and military services, disaster management, and emergency medical services [50–55]. Drones are emerging as safe alternatives to humans in applications involving inaccessible environments or dangerous scenarios [56]. In cases of medical emergencies, when a person is stuck in remote locations and an ambulance is unable to reach a patient in time, medical drones are being used for emergency medical services [53,57]. Door-opening drones are unmanned aerial vehicles (UAVs) equipped with the capability to open doors.

The Lemur-2 drone by BRINC has a blade attachment to break glass and is able to push doors that are ajar [58]. The drone could be user-operated or in autonomous mode.

The onboard 3D LIDAR sensor makes real-time floor plans. Lemur-2 was developed for use by law enforcement personnel and is National Defense Authorization Act (NDAA) compliant. Although Lemur-2 is able to break glass panes to access buildings, it lacks the ability to turn doorknobs.

Table 3. Technical specifications of robots that open doors autonomously.

Specification	Care-O-Bot	PR2	UBR-1	HERB 2.0	SpotMini
Weight (kg)	140	226.8	73	127	31.7–32.7
Dimensions (L/W/H) (″)	28.3/28.3/62.2	26.3/26.3/65	19.5/19.5/38–52	24.4/25.8/55	43.3/19.7/24
Payload (kg)	5	1.8	1.5	-	5
Maximum reach (″)	35.4	-	29.75	-	70.9
Degrees of freedom (DOF)	7 (arm) 29 (overall)	7 (arm) 20 (overall)	7 (arm) 13 (overall)	7 (arm) 27 (overall)	7 (arm) 12 (overall)
Sensors	Camera; laser scanners; time-of-flight sensor	Camera; tilting laser range finder; fingertip pressure sensors	Laser scanner; tilting 3D depth sensor; telescopic spine	Cameras; spinning 3D laser; laser range finders; fingers (position, strain, tactile sensors); Segway base	Cameras; 3D depth sensors; time-of-flight sensor

L—Length, W—Width, H—Height.

Table 4. Robots that open doors autonomously.

Door Opening AT	Features	Commercial Availability	Cost
Door opening robots	Wheeled; Allows turning of doorknobs and pulling or pushing of door	Yes	USD 35k–500k
Four-legged robots	Legged; Allows turning of doorknobs and pulling or pushing of door	Yes	USD 75k–200k+

A team of researchers at Purdue University has developed a drone called the BoomCopter that is able to open and close doors, flip switches, and attach sensors to walls. The BoomCopter was designed to perform tasks in environments that would be considered dangerous or inaccessible to humans. The BoomCopter (see the illustration in Figure 6) utilizes a tri-rotor design, allowing it to hover in the same way as the more common quad-rotor design [59,60].

The BoomCopter drone features a horizontal robotic arm with a propeller mounted at 90 degrees to move the drone back and forth as it hovers. The robotic arm is equipped with different end-effectors to accomplish specific tasks. The BoomCopter can be operated either remotely by a user or autonomously using on-board sensors, cameras, and processors. For autonomous mode operation [61], the BoomCopter drone could be trained to recognize items such as door handles using computer vision techniques and be able to open doors. Another group demonstrated the capability of a drone to push a rolling cart and a door [62]. In a related study, a team from ETH Zurich demonstrated a planning and control method that enables drones to manipulate articulated objects with the least amount of operator-provided priors [63]. Recently, the group presented a reinforcement learning method for drones to learn motion behaviors for a manipulation task such as a door-opening task [64].

The tiny drones known as FlyCroTugs provide an intriguing example of drone technology in action. Researchers from Stanford University and Ecole Polytechnique Federale de Lausanne (EPFL) created the FlyCroTugs, which are tiny drones that collaborate to carry out activities in hazardous or unreachable places for humans. By coordinating their movements, the quadrotor FlyCroTugs drones can lift or transport heavy objects up to 40 times their own weight. These tiny drones can attach to different surfaces and apply force via the winches and replaceable adhesives on their bases. The ability of two FlyCroTugs to coordinate their activities in order to open doors was demonstrated [55,65–67]. While the second tiny drone fixed itself to the ground and pulled open the door, the other tiny drone turned the doorknob. FlyCroTugs' ability to anchor is made possible by the drone's base using replaceable adhesives. The adhesives could contain ridged silicone (inspired by Gecko feet) to cling onto glass and microspines for slicing through tough surfaces such as stucco, carpet, or rubble [66].

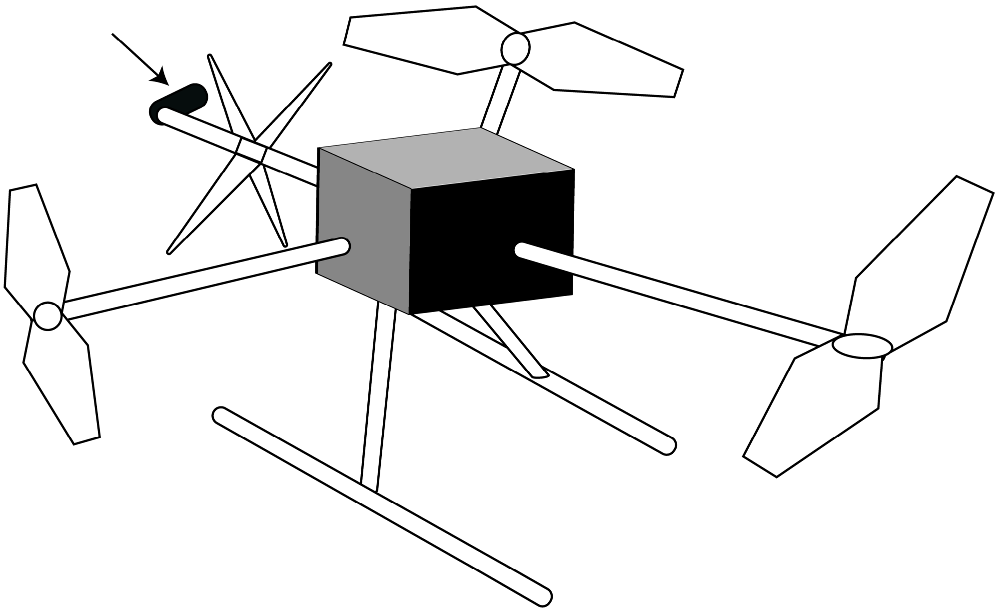

Figure 6. Illustration of a remote-controlled drone equipped with an end-effector (indicated with an arrow), which assists the drone operator in turning doorknobs and opening manual doors.

Table 5 lists the technical specifications of the door-opening drones. Table 6 summarizes the door-opening drones. The Lemur-2 drone is commercially available and costs around USD 10,000 to 20,000 [68]. The BoomCopter, FlyCroTug, or other drones discussed here are still in the research and development phase and are not available on the market.

Table 5. Technical specifications of drones that open doors autonomously.

Specification	Lemur-2	BoomCopter	FlyCroTug
Weight (kg)	1.5	2.3–2.9	0.1
Dimensions (L/W/H) (″)	13/16/4	23.6/27.6/11.4	4/4/-
Propeller design	Quadcopter	Tricopter with a horizontally mounted reversible propeller	Quadcopter
Payload (kg)	0.45	1.86–1.2	0.02 (flight) ~4 (tugging)
Flight time (min)	20	13–21.4	5
Flight range (km)	-	8.8–14.4	-
Sensors	Forward and downward LiDAR (Light Detection and Ranging) sensor; dual tracking cameras (daytime, night vision, thermal)	GPS module; force sensor; sonar sensor; camera; flight management unit (FMU)	Autopilot module (inertial measurement unit, barometer)

L—Length, W—Width, H—Height.

Table 6. Drones that open doors autonomously.

Door opening AT	Features	Commercial Availability	Cost
Single drone	Attachment breaks glass; Drone can push doors already ajar	Yes	USD 10k–20k
Single drone	Attachment turns doorknobs and pulls or pushes door	No	–
Swarm of tiny drones	One drone turns doorknob; Another drone pulls the door	No	–

3. Discussion

This work presents an overview of the different manual door-opening technologies currently under development and on the market. Four subtopics—doorknob accessories, wheelchair-mounted door-opening accessories, door-opening robots, and door-opening drones—were used to group the various technologies for manually opening doors. It is evident that opening doors is a difficult process, and there are different ways to solve this problem in terms of the technology used and the cost of the end product.

It should be noted that some of these technologies were specifically developed as assistive technologies targeting the elderly and wheelchair users, while others were developed for use in emergencies and hazardous areas. The doorknob accessories, although highly affordable, might not always be useful for all wheelchair users. The wheelchair-mounted robotic arms are available at a price of USD 20,000+. The door-opening robots are available at a price of USD 35,000+. The door-opening drones are available at a price of USD 10,000+. It would be interesting to see the costs of the various technologies presented here that are still in the research and development phase.

Though costly, wheelchair-mounted robotic arms can significantly enhance the quality of life (QoL) for those with mobility impairments or upper body infirmities. Using a robotic arm mounted onto a wheelchair has several advantages, including better quality of life, less caregiving stress, more independence and self-assurance, and higher engagement in everyday activities. All things considered, WMRAs are warmly embraced due to their capacity to significantly increase the user's workspace by fusing the wheelchair's mobility with the robotic arm's flexible manipulation capabilities [69]. Comparably high-priced, independent door-opening robots can significantly enhance the quality of life for anyone with mobility issues or upper body infirmities, particularly the elderly.

Although pricey, the door-opening drones are effective. Even though these drones can unlock doors, there are ethical and legal issues that need to be resolved before they are widely used in public areas. Regulations pertaining to drones differ by nation and location [70]. There's a good chance that these rules may be updated soon, given the popularity of personal flying cars.

Table 7 compares the four categories of door-opening technologies discussed in this review in terms of average cost, acceptability, and accessibility. Based on the cost ranges listed in Tables 1, 2, 4 and 6, the average cost of the doorknob accessories is the lowest, and that of the door-opening robots is the highest. Studies involving end-users can provide a better understanding of the accessibility and acceptability of door-opening technologies. Table 7 attempts to rate the accessibility and acceptability of the door-opening technologies from a technological perspective.

The doorknob accessories are highly affordable compared to other technologies, but they need to be installed on all the doors that an end-user needs to access. Also, wheelchair users would have to reach forward to grasp and turn the doorknobs. Hence, the lowest accessibility rating. The door-opening robots are highly functional but can only improve accessibility for the building in which they are located. On the other hand, the door-opening drones can be carried along by the end-user and used for any door in any building, hence having a better accessibility rating than the door-opening robots. In narrow doorways, door-opening robots or drones could cause hindrance while holding open a self-closing door for the wheelchair to pass through the doorway. The wheelchair-mounted door-opening accessories, especially robotic arms, overcome this issue and can be used for any door in any building. Hence, it has the highest accessibility rating. The rationale for the acceptability ratings is the same as discussed for accessibility ratings.

Table 7. Comparison of door-opening technologies.

Door Opening AT	Average Cost	Accessibility	Acceptability
Doorknob accessories	+ *	+	+
Wheelchair-mounted door-opening accessories	+++	++++	++++
Door-opening robots	++++ **	++	++
Door-opening drones	++	+++	+++

* Lowest, ** Highest.

4. Conclusions

In conclusion, there is still a need for affordable assistive technology for opening manual doors. This review aims to serve as a one-stop source for door-opening technology for wheelchair users and their healthcare providers. It is hoped that some wheelchair users may find some use for at least one of these door-opening devices. The best choice would be determined by each person's unique needs, skills, and occupational therapists' recommendations.

5. Future Directions

Overall, the search for an affordable assistive technology for opening manual doors is ongoing. It is noteworthy that although around 20 million people worldwide need wheelchairs, they do not have access to one [4,5]. Therefore, there is a critical need for the development of affordable technologies for opening manual doors for use by a larger population of wheelchair users. The affordable assistive technology could be a combination of the different technologies presented in this work or might make use of an entirely novel technology.

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