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A Systematic Review of Wearable Devices for Orientation and Mobility of Adults With Visual Impairment and Blindness

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ABSTRACT Wearable devices have been developed to improve the navigation of blind and visually impaired people. With technological advancements, the application of wearable devices has been increasing. This systematic review aimed to explore existing literature on technologies used in wearable devices to provide independent and safe mobility for visually impaired people. Searches were conducted in six electronic databases (PubMed, Web of Science, Scopus, Cochrane, ACM Digital Library and SciELO). Our systematic review included 61 studies. The results show that the majority of studies used audio information as a feedback interface and a combination of technologies for obstacle detection - especially the integration of sensor-based and computer vision-based technologies. The findings also showed the importance of including visually impaired individuals during prototype evaluation and the need for including safety evaluation which is currently lacking. These results have important implications for developing wearable devices for the safe mobility of visually impaired people.

INDEX TERMS Visually impaired people, navigation, obstacle detection, systematic review, wearable devices.

I. INTRODUCTION

Visually impaired people face several challenges to accomplish everyday tasks, especially when attempting to have safe and independent mobility. The ability to detect hazards is reduced with visual impairment, which can result in accidents, collisions, and falls, having a negative impact on their physical, psychological and social-economic development [1]–[3]. Visual impairment is often associated with mobility restrictions, leading to various health issues, including loss of independence, social isolation, reduced physical activity, and depression [4]. Improving the mobility skills of visually impaired people may improve their ability to participate in society, enhancing their productivity, self-maintenance, leisure, and overall quality of life [4].

According to the World Health Organization, one billion people have some degree of visual impairment worldwide, including blindness, moderate-to-severe visual impairment, and near visual impairment [5], [6]. The prevalence of visual impairment is notably higher in low and middle-income countries (LMICs) [6]. In LMICs, factors like ageing, infrastructure barriers, and difficulty accessing assistive technologies may increase the occurrence of falls among adults with visual impairment [3].

To have efficient and safe mobility, visually impaired individuals rely on assistive technologies such as white canes, guide dogs, or electronic devices [4]. Although white canes and guide dogs are the most commonly used assistive technologies, they can only partially resolve safe and independent mobility [7], [8]. White canes have a short range for obstacles at ground level and cannot identify obstacles above the waist level [9]. Therefore, electronic travel aids (ETAs) have been

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developed to improve the functionality of the white cane and guide dog [10]–[12]. An ultrasound-based electronic cane was shown to improve the ability to detect objects above the waistline, such as hanging obstacles, compared to traditional white canes [9].

Similar to autonomous vehicles, ETAs use a set of sensors - e.g., ultrasonic, infrared, radio frequency identification (RFID), and global positioning systems (GPS) - and visual technologies - e.g., stereo and RGB-D cameras - to perceive the environment, process the information, and detect objects [11], [13]–[15]. This process must be executed in real-time, under diverse and unknown environmental conditions, and be safe to the users [16]. There are, however, a few differences between both systems. Autonomous vehicle systems are often large in size and require high power consumption [14], [15]. Furthermore, in fully autonomous vehicles, no human driver is involved in controlling the vehicle [17], whereas in navigation aids, there should always be communication with the user through an interface, alerting them about near obstacles, impending danger in a timely manner and suggesting a course of action [16]. Therefore, the ultimate decision and appropriate reaction time solely rely on the user [16].

ETAs are available as traditional handheld and novel wearable devices [12]. Wearable devices collect information about the user or the environment, process it (locally or globally) and return it to the user in real-time through acoustic or haptic signals. Tapu *et al.* [11] observed an increasing development of wearable devices to improve the navigation of visually impaired people and provide safer mobility in known and unknown, indoors and outdoors environments. With the decrease in size and costs of sensors and microprocessors, and the advantages of being discrete, hands-free, wide field of view and immersive interfaces, the development of wearable devices for visually impaired people has increased [18].

Although the interest in wearables for visually impaired people has been increasingly growing, there is a lack of a systematic review of solutions proposed in the scientific literature. Some research present state-of-the-art like Dakopoulos and Bourbakis [8], Elmannai and Elleithy [19], Real and Araujo [18], Seneviratne *et al.* [20], and Tapu *et al.* [11]. Nonetheless, to our knowledge, there is no systematic review of wearable devices focused on the orientation and mobility of visually impaired people.

This paper aims to systematically review existing literature on wearable devices developed to help visually impaired people obtain safe and independent navigation. Safety in the use of wearable devices focused on the orientation and mobility of blind people referred to how one can move without experiencing accidents such as hitting obstacles and falling. This research focuses on technologies used to provide safe and independent mobility, feedback interfaces, and methods employed for user evaluation.

The paper is organized as follows: Section II explains the methods used in the study. Section III and Section IV present the results and discussion, respectively. Section V summarizes and concludes the research findings.

II. METHODS

This systematic review was conducted using Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) 2020 guidelines [21].

A. SEARCH STRATEGY

Studies were identified through searches of six databases: PubMed, Web of Science, Scopus, Cochrane Central Register of Controlled Trials (CENTRAL), ACM Digital Library, and SciELO (Scientific Electronic Library Online). Additionally, to ensure the inclusion of recent articles in this review, the alert function was set in the databases that allowed this option - namely PubMed, Web of Science, Scopus and ACM Digital Library. An additional study [79] was identified through a hand search of the reference list. The search was conducted in June 2020 and used MeSH headings and keywords associated with ‘‘visual impairment’’, ‘‘wearable devices’’, and ‘‘mobility’’. The search strategy, using PubMed, can be viewed in Appendix A.

B. ELIGIBILITY CRITERIA

Studies were included if they: (i) were developed for adults (18 years and older) with visual impairment (low vision or blindness); (ii) reported the development of wearable devices for mobility and/or orientation of visually impaired people. The visual impairment is determined by The International Classification of Diseases 11 (2018) [22] that classified into two groups, namely ‘‘low vision’’ with visual acuity worse than 6/18 to 3/60, or visual field loss to less than 20°; and ‘‘blindness’’ as visual acuity worse than 3/60 or a visual field loss to less than 10°. Studies were excluded if: (i) not written in English nor Portuguese; (ii) were conference abstracts, book chapters, dissertations or review articles; (iii) technology described was not classified as wearable nor developed for orientation and/or mobility purposes.

C. STUDY SELECTION

All titles and abstracts were independently screened by two review authors (ADPS, AHGZ), following the inclusion criteria. Full-text studies were evaluated according to the eligibility criteria. The inclusion or exclusion of studies was discussed by two review authors until consensus was reached or consulted a third and a fourth review author (FOM, AV) for a final decision.

A quality assessment of the studies was not attempted due to the wide range of study designs and the number of studies describing algorithms. Besides, the focus of this review was on the technological characteristics of available wearables. Thus, a quality assessment would not provide additional information related to the objectives of this systematic review.

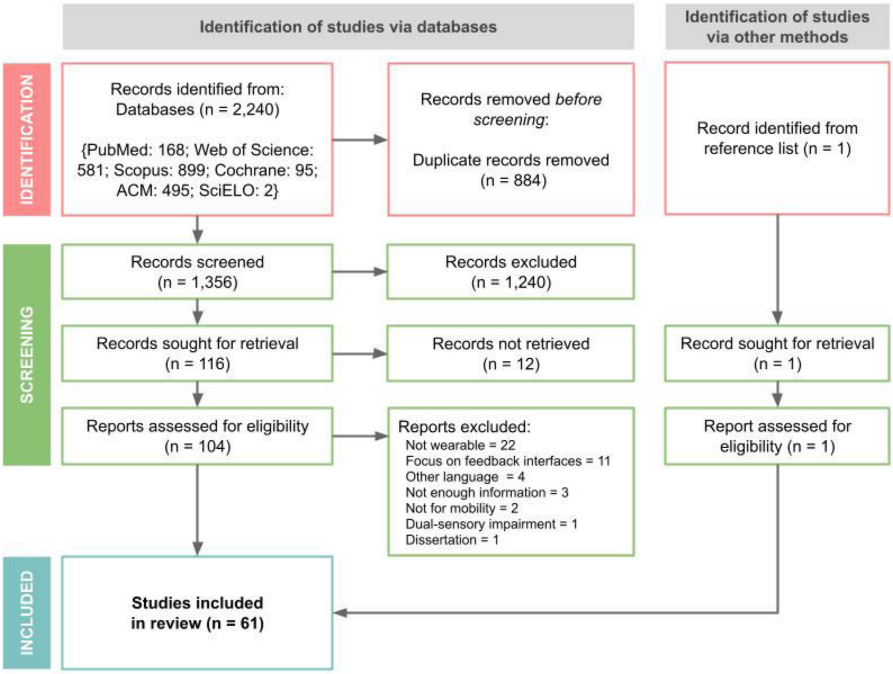

FIGURE 1. PRISMA flow diagram of the search and selection process.

D. DATA EXTRACTION

Data were extracted from each eligible article by two authors (ADPS, AHGZ), independently and cross-checked, and organized in a spreadsheet. Data extraction included authors, year of publication, country of origin, technologies used and their objectives, type of feedback interface, study setting, sample characteristics and methods used for user evaluations, and summary of the findings.

III. RESULTS

A. STUDY SELECTION

A total of 2241 studies were identified through database searches and the reference list. A total of 61 studies (2.72%) were identified as meeting the inclusion criteria. Fig. 1 illustrates the flow diagram of the process of searching and selecting the studies according to the PRISMA flow diagram.

B. STUDY CHARACTERISTICS

A summary of the demographic and methodological characteristics of the included studies is provided in Table 1. The 61 studies were conducted in China (n = 13, 21.31%), United States (n = 10, 16.39%), India (n = 8, 13.12%), Japan (n = 4, 6.56%), United Kingdom (n = 3, 4.92%), Republic of Korea (n = 2, 3.28%), Taiwan (n = 2, 3.28%), and Sri Lanka (n = 2, 3.28%). Other studies included were conducted in Brazil, Canada, France, Germany, Hungary, Iraq, Italy, Jordan, Malaysia, Mexico, Portugal, Romania, Spain, Sweden, Switzerland and Turkey. According to the United Nations [23], countries are classified by their level of development measured by per capita gross national income (GNI). Low-income countries are those with less than $1,035 GNI per capita. Countries between $1,036 and $4,085 are classified as lower-middle-income countries, and those between $4,086 and $12,615 are upper-middle-income countries. Countries with incomes higher than $12,615 are considered high-income countries [23]. In our study, high-income countries were responsible for almost half (n = 30, 49.18%) of the included studies and upper-middle and lower- middle-income countries were responsible for 34.43% (n = 21) and 16.39% (n = 10), respectively. No studies were conducted in low-income countries.

Overall, the included studies were recently published, with the first one published in 2001 and 91.80% published in the last ten years. Although the number of included studies may seem high, the following studies were carried out by the same team, with each study reporting improvements on different stages of the project.

Ross [59] and Ross and Blasch [60] developed and evaluated an orientation and wayfinding aid with 15 participants with visual impairments crossing the streets using different interfaces in random order. Both studies reported the same methodology, sample size, and results. In [59], Ross focused on the design process, whereas in [60], they provided more details about the participants' performance and preferences. Their results indicated a significant decrease in participants' veering performance and that the tapping interface had better results in both performance and participants' preferences.

Bai *et al.* [27], [28] described the development of smart glasses. Initially, the system composed of the RGB-D camera and ultrasonic sensor worked indoors [27]. Later, the authors expanded the navigation capability to outdoors by adding a Convolutional Neural Network (CNN) object recognition module and fusing GPS and IMU data [28]. The system [28] was evaluated and demonstrated to be effective in navigation and recognition in both indoors and outdoors scenarios.

Silva and Wimalaratne [63], [64] developed a belt with ultrasonic sensors to assist indoor navigation. While in [63], Silva and Wimalaratne initially focused on the obstacle's detection and the fuzzy logic model to assess the safety level of the environment, in [64], they added the object recognition model by fusing sonar and vision sensors.

Zhang *et al.* [79], [80] proposed an ARCore-based navigation system. In [79], Zhang *et al.* focused on the device's functionality, whereas in [80], the focus was the user interface. Zhang *et al.* [79] evaluated the performance of an ARCore-supported smartphone to obtain computer vision-based localization as well as a hybrid interaction mechanism (audio and tactile) to provide better guidance. The vibration feedback had good results; however, participants highlighted that the device occupied the hand, which was inconvenient during daily activities. Therefore, they designed and prototyped a sliding wristband using 3D printing [80]. The efficiency and feasibility of the proposed design were evaluated through proof-of-concept experiments in virtual and real-world scenarios with eight participants (four blindfolded and four visually impaired) [80].

Ikeda *et al.* [40], [41] developed a visual aid to assist the mobility of patients with retinitis pigmentosa at night. Although both studies presented similar findings in darkened conditions, the device in [41] increased the performance in view size and image quality compared to [40], which also had high production costs. Ikeda *et al.* used in [41] a high-performance see-through display, implementing a high-sensitivity camera with a complementary metal-oxide-semiconductor (CMOS) sensor, which reduced the production costs, making the new device available commercially. User experiments had a sample size of 8 [40] and 28 [41] patients.

Yang *et al.* [73]–[76] implemented several frameworks throughout the years to improve smart glasses until it was commercially available. In [73], the 3D-printed prototype focused on expanding the detection of traversable areas using the Intel RealSense R200. The approach was tested with visually impaired participants using mixed methods, and it showed a reduction of 78.60% in the number of collisions. Next, the framework proposed in [74] used a polarized RGB-D sensor to improve the traversable area proposed in [73] in addition to detecting water hazards. The approach was tested with blindfolded participants, and it showed a detection rate of 94.40% compared to previous works. The focus in [75] was to decrease the minimum range for detecting the RealSense R200, from 650 mm to 60 mm, to enhance the traversability awareness and avoid close obstacles. Experiments with visually impaired participants showed a reduction of the number of collisions by nearly half. Later, Yang *et al.* [76] enhanced the previous proof-of-concept using deep neural networks to contribute to terrain awareness. Unlike the previous works [73], [74] that use depth segmentation, [76] used a semantic mask to segment the traversable areas. In a closed-loop field test with visually impaired users, the results indicated an improvement in the safety and versatility of the navigation system.

Later, Long *et al.* [52] also used the Intel RealSense R200 and the non-semantic stereophonic interface proposed in [73], which was also employed in [74]–[76]. However, the difference between Long *et al.*'s study [51] and Yang *et al.* [73]–[76] is that, instead of smart glasses, the prototype in [52] is worn on the user's neck. In [52], Long *et al.* proposed a unified framework for target detection, recognition and fusion based on the sensor fusion of a low-power millimeter-wave (MMW) radar and the RGB-D sensor. In addition to technical features, price, dimensions, weight and energy consumption were also considered. The framework proposed by [52] expanded and enhanced the detection range at the same time as it showed high accuracy and stability under diverse illumination conditions. Finally, Long *et al.* [53] proposed a low power MMW radar system using the commercially available smart glasses improved by Yang *et al.* [73]–[76].

Although most studies published different stages of the project, Zhang *et al.* [79], [80] and Ross [59] and Ross and Blasch [60] divided their work into two approaches: one describing the device's functionality [60], [79] and the other focusing on the design process and the importance of including the user throughout the process [59], [80].

C. TECHNOLOGIES

1) SENSORS AND COMPUTER VISION

The 61 included studies reported a variety of technologies that were mainly used for obstacle detection. In addition to detection, some technologies also provided obstacle recognition, that is, the identification of different categories of obstacles (e.g., chair, car, stairs, or a moving person).

Among sensor-based technologies, ultrasonic sensors were the most used in the included studies ($n = 24$). The use of ultrasonic sensors has demonstrated several benefits for mobility performance, including a decrease in navigation time [13], [36], [63], and detection of complex obstacles such as stairs [13], [36] and moving obstacles [7].

Although ultrasonic sensors were the most commonly used sensor, our review showed that the majority of the studies used computer vision-based technologies in their approaches, either by itself or in combination with other sensors. Computer vision-based technologies use the camera as the primary source of information about the environment. In this study, the most popular vision-based technology was the RGB-Depth (RGB-D), a technology that combines stereo cameras, light-coding and time-of-flight (ToF) sensors, computing both RGB color and depth images in real-time to interpret the environment and detect obstacles [25], [51], [73]. The use of RGB-D technologies was observed in 13 studies

TABLE 1. Summary of included studies.

Authors, year, country	Technology objective	Study design	Sample (n)	Age (years)	User evaluation		Summary of findings
					User experience	User safety	
Al-Fahoum *et al*. (2013) [24], Jordan[+]	Obstacle detection and recognition	Observational	Blind (10)	Range: 18-50	Yes (quantitative method)	No	Accuracy of 93% in detecting different shapes, materials, and distances
Aladrén *et al*. (2016) [25], Spain[*] ☆	Obstacle detection	System analysis and case study	User (1)	Not reported	Yes (quantitative method)	No	Detection of main structural elements with 99% precision of floor segmentation and 95% of recall. Successful results were reported in challenging indoor environments
Bahadir *et al*. (2012) [26], Turkey[+]	Obstacle detection	System analysis	NA	NA	No	No	Identification of obstacles' position without failure and operation for 8h without additional battery. No significant difference was observed in the transmission line after 10 washing cycles
Bai *et al*. (2018) [27], China[+]	Navigation directions, obstacle detection and recognition	Observational	Blind and partially sighted (not reported)	Not reported	Yes (mixed methods)	No	Participants arrived at the destination effectively and safely, avoiding obstacles in an indoor environment
Bai *et al*. (2019) [28], China[+]	Navigation directions, obstacle detection and recognition	Observational with survey	Blind (10), partially sighted (10)	Not reported	Yes (mixed methods)	No	Real-time information and object recognition in indoor and outdoor environments were reported
Bhatlawande *et al*. (2014) [12], India[~]	Obstacle detection	Participatory design approach for system development, and observational	Rehabilitation resource persons, volunteer (1), blind (15)	Range: 20-55 (Mean: 38.46)	Yes (mixed methods)	No	Participants safely detected and avoided obstacles of different heights and were able to understand the environment with less effort compared to the white cane alone. Participants also reported satisfaction with the user interface
Brown *et al*. (2019) [29], UK[*]	Obstacle detection	Observational with survey	Control (20), participants with RP (6)	Not reported	Yes (mixed methods)	No	The device showed feasibility, high user acceptability, and potential to improve accuracy, confidence, and independence of users during navigation, especially in dim light
Bryant *et al*. (2004) [30], USA[*]	Obstacle detection and text recognition	Observational with pre and post evaluation	Low vision (2)	Not reported	Yes (qualitative method)	No	Participant 1 was more successful at detecting and avoiding obstacles, showing difficulty with small obstacles. Participant 2 had difficulty in mobility, which influenced the system's performance
Caraiman *et al*. (2019) [31], Romania[+]	Obstacle detection	Observational	VI (4)	Not reported	Yes (mixed methods)	No	Intuitive and efficient, with 85% of task completion rate and good perception of walls
Cardin *et al*. (2007) [32], Switzerland[*] ☆	Obstacle detection	Observational	Blindfolded (5)	Not reported	Yes (quantitative method)	No	Intuitive, easy to use, and it reduced the time to pass through obstacles by 50%
Chen *et al*. (2019) [33],	Obstacle detection with	Observational with	Group 1: VI (4)	Range: 20-35 Range: 20-60	Yes (mixed methods)	No	Participants suggested a reduction of the weight of the head-mounted device and

TABLE 1. ***(Continued.)*** **Summary of included studies.**

China +	object, text and face recognition	interview	Group 2: VI (19)				reported that the device was easy to learn because of the feedback
Cheng (2016) [34], Taiwan *	Obstacle detection	Observational with survey	VI (7)	Range: 20-45	Yes (mixed methods)	No	None of the participants hit the hanging obstacles while wearing the system, indicating the feasibility of the alert mechanism. Satisfactory scores for efficacy, comfort and usage were reported. 42.9% of the participants considered the warning mechanism too loud and suggested substituting songs with voice commands
Elmannai and Elleithy (2018) [35], USA *	Obstacle detection	System analysis and case study	Blindfolded (1)	Not reported	Yes (quantitative method)	No	Detection of 98% of the obstacles and avoidance of 100% with accuracy
Gao *et al.* (2014) [36], USA *	Obstacle detection	Observational	Blindfolded (5)	Not reported	Yes (quantitative method)	No	Navigating with the prototype was faster than with the white cane. Using a combination of both aids resulted in a significant improvement in navigation, especially in an environment with stairs
Gundewar *et al.*(2020) [37], India ~	Obstacle detection	System analysis	NA	NA	No	No	Method effective for obstacle distance measurement, with 90% repeatability achieved
Hicks *et al.* (2013) [38], UK * ☆	Obstacle detection	Observational	Study 1: control (7) Study 2: blind (14), partially sighted (4)	Study 1: range: 22-36 Study 2: range: 20-90	Yes (quantitative method)	No	All participants completed the experiments wearing the visual aid in study 1. In study 2, most participants reacted to obstacles at a similar rate to the control group
Hossain *et al.* (2011) [39], USA *	Obstacle detection	System analysis	NA	NA	No	No	Stairs and holes were detected, but dynamic and static obstacles were not differentiated
Ikeda *et al.* (2015) [40], Japan *	Obstacle detection in a dark environment	Observational	Patients with RP (8)	Not reported	Yes (quantitative method)	No	All patients showed a significant decrease in the number of failures. 7 out of 8 patients walked without failures
Ikeda *et al.* (2019) [41], Japan *	Obstacle detection in a dark environment	Observational	Patients with RP (28)	Mean: 45.61 +/- 10.13	Yes (quantitative method)	No	All participants had the visual acuity significantly improved in the dark, and the time to travel was significantly reduced. The new device reported wider and higher image quality and lower cost than the previous one
Isaksson *et al.* (2020) [42], Sweden *	Obstacle detection	Pilot study – observational with pre- and post-interview	VI (2)	User 1 age range: 60-70 User 2 age range: 18-30	Yes (mixed methods)	No	Users were able to perform the subtasks and showed a low learning curve
José *et al.* (2011) [43] , Portugal * ☆	Obstacle detection	System analysis	NA	NA	No	No	Detection and tracking of moving obstacles, and user warning about the obstacles' position
Katzschmann *et al.* (2018) [44], USA * ☆	Obstacle detection	Observational with survey	Blind (12)	Range: 25-65	Yes (quantitative method)	No	Similar functionalities and safety to a white cane. Additional advantages include discretion, hands-free, detection of high obstacles, and a significant decrease of required contacts. It can be used alone or with a white cane

TABLE 1. ***(Continued.)*** **Summary of included studies.**

Kaur and Bhattacharya (2019) [45], India ~	Obstacle detection and recognition	System analysis and case study	Blindfolded (1) and user group (not reported)	Not reported	Yes (mixed methods)	No	Portable, easy to use, lightweight and less expensive than other systems available. The multimodal CNN-based feature extraction techniques had better performance in the detection of distant objects than raw intensity image. Changes in the feedback interface, detection and classification of objects were done based on the users' feedback
Kiuru *et al.* (2018) [46], Finland *	Obstacle detection	Clinical investigation	VI (25)	Young (< 30), middle age (30-60), and seniors (> 60)	Yes (mixed methods)	Yes	Improvement of the environmental perception for 92% of the users, and increased confidence in independent mobility for 80%. Users reported satisfaction with the wearability and the possibility to use it beneath the clothing
Lee *et al.* (2018) [47], Taiwan *	Obstacle detection	System analysis	NA	NA	No	No	70% of obstacle detection rate, with low power consumption and complexity
Lee *et al.* (2016) [48], Republic of Korea *	Obstacle detection, and navigation directions	Observational with survey	VI (10), and blindfolded students (5)	VI: not reported Blindfolded: range 20-30	Yes (quantitative method)	No	Participants reached the locations safely, without collisions in most trials. High scores for portability, wearability, real-time operation, and user friendly were reported
Lee and Medioni (2016) [49], USA * ☆	Navigation directions and obstacle detection	Observational	Study 1: blind (4) and blindfolded (1) Study 2: sighted (2) Study 3: blindfolded (4)	Not reported	Yes (quantitative method)	No	The system combined with the white cane improved the mobility performance of the blindfolded participants by 57.8% compared to the white cane alone
Li *et al.* (2017) [50], China +	Obstacle detection	System analysis	NA	NA	No	No	The shoelace antenna was validated as a tool to avoid collisions
Lin and Han (2014) [51], Republic of Korea *	Obstacle detection and recognition	System analysis	NA	NA	No	No	The interpretation of the environment was enhanced, allowing the identification of multi-category objects
Ling *et al.* (2019) [1], Malaysia +	Obstacle detection	Observational with interview	Blindfolded (10)	Not reported	Yes (mixed methods)	No	The first experiment reported the detection of real-life obstacles of different sizes and shapes. The second experiment showed lower detection rates. The third experiment showed better detection rates in the outdoor experiment and that the prototype worked better for people with low vision
Long *et al.* (2019) [52], China +	Object detection and recognition	System analysis	NA	NA	No	No	The obstacle detection was improved with more accurate state estimation and stability in different lighting conditions
Long *et al.* (2019) [53], China +	Obstacle detection and recognition	System analysis	NA	NA	No	No	Low power, high range accuracy, small size, and ability to detect a person and a car from up to 10 m and up to 30 m of distance, respectively
Mocanu *et al.* (2016) [54], France *	Obstacle detection and recognition	Observational with interview	VI (21)	Range: 27-67	Yes (mixed methods)	Yes	Dynamic and static obstacles of different size and shapes were identified. Participants evaluated the system as lightweight, friendly, and non-intrusive

TABLE 1. ***(Continued.)*** **Summary of included studies.**

Mohamed Kassim *et al.* (2016) [55], Japan *	Obstacle detection	System analysis	VI (20)	Not reported	Yes (quantitative method)	No	Time to respond to the vibration and to recognize the obstacles' direction was, on average, 1.8 s.
Patil *et al.* (2018) [13], India ~	Obstacle detection	Observational	Totally blind (48), low vision (22)	Not reported	Yes (quantitative method)	No	Detection of staircases, floor, and knee-level obstacles, and better performance than the white cane. However, hole or downhill and downstairs were not identified, and the wet-floor was only identified after stepping on it
Petsiuk and Pearce (2019) [7], USA *	Obstacle detection	Observational	Blindfolded lab researchers (5)	Not reported	Yes (quantitative method)	No	Intuitive feedback and detection range up to 4 m for static objects. Moving objects were tracked up to 0.5 m/s for within 1 m. The failure rate was 6.7% mostly with the model with two vibration motors instead of one. Cost savings from commercial products ranged from 73.5% to 97%
Prattico *et al.* (2013) [56], Italy *	Obstacle detection	System analysis	NA	NA	No	No	Detection of positive and negative obstacles, user warning on time, and over 10h operation
Pundlik *et al.* (2018) [57], USA *	Obstacle detection	Observational	Blind (8) and blindfolded (29)	Blindfolded age range: 21-40 Blind age range: 28-75	Yes (quantitative method)	No	Detection and warning of obstacles beyond the white cane range. A significant decrease in the number of collisions was reported
Ramadhan (2018) [58], Iraq +	Obstacle detection	Not reported	VI (55)	Range: 15-61	Yes (method not reported)	No	Participants reported high satisfaction with the remote user monitoring and improvement of confidence and lifestyle. Results showed the preference for wearing the system on the hands rather than on the white cane
Ross (2001) [a] [59], USA * Ross and Blasch (2002) [a] [60], USA * ☆	Orientation	Observational with survey	Blind and partially sighted (15)	Range: 62-80 (Mean: 68)	Yes (mixed methods)	No	Participants' veering performance significantly decreased. The tapping interface feedback had better performance and evaluation, and changes in the speech interface were also suggested
Schwarze *et al.* (2016) [61], Germany *	Obstacle detection	Observational with interview	VI (8)	Range: 20-50	Yes (qualitative method)	No	Detection of obstacles with a range of 10-20 m
Siddhartha *et al.* (2018) [62], India ~	Obstacle detection	System analysis	NA	NA	No	No	Accuracy of 98% for the detection of obstacles within 200 cm
Silva and Wimalaratne (2019) [63], Sri Lanka ~	Obstacle detection	Observational	Blindfolded (5), VI (3), blind (2)	Range: 22-70	Yes (quantitative method)	No	Reduction of the navigation time and increased safety. The tactile and voice feedbacks presented suitable performance
Silva and Wimalaratne (2020) [64], Sri Lanka ~	Obstacle detection and recognition	Observational with interview	Blindfolded (7), users with age-related vision loss (3)	Range: 22-70	Yes (mixed methods)	No	Obstacle's detection rate of 93% (left), 88% (right), 100% (frontal) and 81% (stairs and walls), proving the safety of the hybrid system. The wearable system was reported more accurate and user-friendly than a white cane
Simões and de Lucena (2016) [65], Brazil +	Obstacle detection	Observational with survey	Users (5)	Not reported	Yes (quantitative method)	Yes	Identification of more than 90% of the visual and RF markers with an average time of 0.4 s, and 98.33% of the obstacles with ultrasonic sensor. Users

TABLE 1. ***(Continued.)*** **Summary of included studies.**

							rated as excellent or very good the quality of guidance (85%) and the reliability (75%) of the system
Sövény *et al.* (2015) [66], Hungary +	Obstacle detection and recognition	System analysis and case study	Blindfolded (1)	Not reported	Yes (method not reported)	No	Real-time operation with processing, on average, of 25 pairs of images in 1 s (using the object detection algorithm), and 1 to 3 images (using the stair detection and crosswalk method)
Sundaresan *et al.* (2014) [67], India ~	Obstacle detection	System analysis	Not reported	Not reported	No (data not reported)	No	The head-mounted unit helped to avoid collisions and obstacles were detected before having contact with them
Takefuji *et al.* (2020) [68], Japan *	Obstacle detection and recognition	Observational with interview	VI (69)	Not reported	Yes (mixed methods)	No	70% of users reported increased confidence in going out with the device
Velazquez *et al.* (2018) [69], Mexico +	Navigation directions	Observational	Undergraduate students (20) and blind (2)	Students: age range: 18-24 (M: 20.5) Blind: 31 and 35	Yes (quantitative method)	No	Tactile feedback intuitive, easy to understand, and recognized with high accuracy. Blind users successfully reached the target destinations
Vignesh *et al.* (2018) [70], India ~	Obstacle and water detection	System description	NA	NA	No	No	Not reported
Vijeesh *et al.* (2019) [71], India ~	Obstacle and water detection	Participatory design approach for system development	VI (10)	Range: 17-22	Yes (method not reported)	No	Development of a model based on the participant's suggestions, using Li-Fi technology to identify the location and the bus number, which were the main difficulties listed by the participants
Wang *et al.* (2020) [72], China +	Obstacle detection	System analysis	Not reported	Not reported	No (data not reported)	No	Good reliability and stability, fast response, and low detection limit were reported. The high performance, good flexibility, and ease of fabrication shows the potential to be used in several applications, including smart textiles and wearable electronics
Yang *et al.* (2016) [73], China + ☆	Obstacle detection	Observational with survey	VI (8)	Not reported	Yes (mixed methods)	No	Reduction in the number of collisions, steps, and performance time by 78.6%, 29.5%, and 43.4%, respectively, compared to the original ground detection. All participants evaluated the system as useful and helpful in complex or unknown environments
Yang *et al.* (2017) [74], China +	Obstacle and water detection	Observational with survey - 2 random groups in different conditions	Blindfolded (10)	Not reported	Yes (quantitative method)	No	Usefulness and reliability were reported. High traversable area detection rate of 94% compared to [68], and avoidance of water hazards and obstacles
Yang *et al.* (2018) [75], China +	Obstacle detection	Observational	Study 1: VI (21) Study 2: VI (10)	Not reported	Yes (quantitative method)	No	Reduction by nearly half in the number of collisions and avoidance of close obstacles
Yang *et al.* (2018) [76], China + ☆	Obstacle detection and recognition, and water detection	Observational with survey	VI (6)	Not reported	Yes (mixed methods)	Yes	Improvement in the safety and versatility of the system. All participants evaluated the system as useful and helpful to avoid obstacles and sense the environment
Younis *et al.*	Obstacle	Participatory	VI (not	Not reported	Yes (method	No	Identification and classification of

TABLE 1. ***(Continued.)*** **Summary of included studies.**

(2019) [77], UK *	detection and recognition	design approach for system development and system analysis	reported)		not reported)		hazards. The majority of the participants preferred the hybrid feedback (visual and vibration)
Zelek *et al.* (2003) [78], Canada * ☆	Obstacle detection	Observational	VI (9)	Range: 25-72	Yes (mixed methods)	No	Navigation around an obstacle course was possible with tactile feedback. Participants were comfortable with wearing the glove and were pleased that some of the parameters could be programmable and customized
Zhang *et al.* (2019) [79], China +	Obstacle detection	Observational with survey	Study 1: participants (2) Study 2: blindfolded (1) Study 3: low vision (3) and blind (1)	Not reported	Yes (mixed methods)	Yes	Tactile information was better evaluated than audio information; however, audio was considered necessary for macro-instructions. Participants reported that instructions were easy to understand, and some of them felt safer than expected. Some participants also expressed concern if the glove would affect holding objects and suggested changing the tactile interface to another part of the body
Zhang *et al.* (2019) [80], China +	Orientation	Observational (part of the testing was conducted in [79])	Blindfolded (4) and VI (4)	Not reported	Yes (quantitative method)	No	Experiments showed the efficiency of the prototype and that extensive virtual training could help users in real test-fields. The virtual test could also be useful for rehabilitation of the spatial perception of visually impaired people

Notes: NA: not applicable; RP: Retinitis Pigmentosa; VI: Visually Impaired people

* High-income countries; + upper-middle-income countries; and ~ lower-middle-income countries according to the UN's Country Classification by per capita [23]

☆ The ten most cited papers until 26 May 2021

[a] Ross (2001) [59] and Ross and Blasch (2002) [60] both reported the same findings

(21.31%) that reported using RGB-D cameras, RGB-D sensors or the RealSense (developed by Intel - Santa Clara, CA, USA), which consists of a range of depth and tracking technologies. Other cameras used in the reviewed studies included stereo cameras (n = 8), USB cameras (n = 4), infrared cameras (n = 3), high-sensitivity cameras (n = 2), micro cameras (n = 2), and smartphone cameras (n = 2). Studies that used computer vision-based technologies reported 99% precision in detecting main structural elements [25] an accuracy of 98% in detecting obstacles and 100% in avoiding them [35]. A decrease in navigation time was also reported in studies using high-sensitivity cameras [41], RGB-D cameras [49], and RealSense [73]. In addition, a reduction in the number of collisions was also reported [35], [49], [57], [73], [75].

In the 36 studies (59.02%) that used a combination of technologies, 29 (47.54%) reported using an integration of computer vision and sensor-based technologies for obstacle detection. Combining computer vision and sensor-based technologies can improve obstacle detection, increase accuracy, and provide efficient and safer mobility in both indoors and outdoors environments [35]. Examples include Bai *et al.* [27] and Mocanu *et al.* [54] that added an ultrasonic sensor to compensate for the limitations of the camera (transparent objects, larger obstructions like walls or doors). The combination of ultrasonic sensors and computer-based technologies reported positive evaluations, including high accuracy in obstacles detection [64], decrease in navigation time [32], [65], reduction of collisions [34], [48], and detection of complex obstacles such as stairs [64], and moving obstacles [54].

Besides the combination of cameras and sensors for obstacle detection, there were also studies that employed a combination of different types of sensors. Prattico *et al.* [56] used ultrasonic and infrared sensors, whereas Chen *et al.* [33] and Hossain *et al.* [39] combined both sensors with a camera. In another direction, ultrasonic sensors were also combined with temperature [67], water [70], [71] and wet floor detector sensors [13].

We also observed a difference between the type of technology chosen according to the income of the country where the study was conducted. Studies published in lower-middle-income countries (n = 10), represented by India and Sri Lanka, used mostly ultrasonic sensors for obstacle detection (n = 8), whereas studies conducted in upper-middle (n = 21) and high-income countries (n = 30) used computer vision-based technologies (n = 33).

Besides obstacle detection, localization systems were also adopted in the included studies featuring technologies such as Inertial Measurement Unit (IMU) sensors (n = 13) - that includes accelerometers, magnetometers, compasses and gyroscopes -, Global Positioning System (GPS) (n = 5), radar (n = 4), and Radio Frequency Identification (RFID) (n = 2).

Location technologies were used to assist local and global navigation. Local navigation refers to orientation instructions to help the user avoid obstacles (e.g., "turn left"), whereas global navigation refers to navigation instructions to help the user reach the desired destination.

2) COMPUTER AND SMARTPHONE CONNECTION

Sixteen studies reported using portable computers in their prototype, either for system analysis [38], [39], [51], [74], [76], [78] or as processing units [25], [30], [31], [43], [49], [52], [53], [59]–[61]. We also observed that 16 studies (26.23%) reported smartphone connection. The use of smartphones varied from processing units [28], [34], [47], [54], capturing devices - camera [54], [64] and GPS [69] -, external communication [58], [67], [70] and user interface [1], [28], [47], [49], [62]–[64], [68], [70]. Gao *et al.* [36] reported Bluetooth connection from prototype to smartphone.

The user interface was provided as output either by warning the user through voice commands, as observed in [1], [28], [62], [68], or as a smartphone application featured in [49], [63], [64], [70]. In Lee and Medioni [49], the user could choose where to go from a list of registered places or translate the names of the places by speech recognition. In Bai *et al.* [28], a smartphone was used in several functions, including entering the navigation mode, obtaining the user's current position, running object recognition algorithms, and playing audio feedback to the user.

Regarding external communication, Ramadhan [58] and Sundaresan *et al.* [67] offered remote user monitoring and the option of contacting the family or caregivers in emergencies. Zhang *et al.* [79] used the smartphone as the major carrier running an augmented reality framework that can track the user position and build a map of the environment in real-time. In addition, the smartphone's integrated sensors (e.g., ambient light, gravity, proximity and gyroscope compass) were also used in [79].

3) SMART CLOTHING

Three studies developed prototypes to be worn as a garment. Bahadir *et al.* [26] developed smart clothing that detected obstacles. Li *et al.* [50] used an antenna, which consisted of a smart radar running along with a shoelace based on on-chip sensing modules, for obstacle detection. Wang *et al.* [72] developed an all-textile flexible airflow sensor that could be integrated into clothing to alert blind people walking outdoors about nearby fast-moving objects.

D. FEEDBACK INTERFACES

Audio feedback was the most used format of the interface, adopted in 27 studies (44.26%). Alerts were emitted in the form of voice commands (n = 16) or sounds, including beep, music or sound instruments as observed in [34], [35], [73]–[76]. Hybrid feedback (i.e., auditory and vibrotactile) was adopted in 17 studies (27.87%), and users could choose the type of feedback according to their preferences in [48] and [55]. Tactile feedback was reported in 11 studies (18.03%).

Studies conducted in lower-middle-income countries employed both audio (n = 5) and hybrid feedback (n = 5). Upper-middle-income countries mostly used audio feedback (n = 12) and high-income countries adopted mostly auditory feedback (n = 10), followed by tactile feedback (n = 8) and hybrid feedback (n = 7). We also observed that high-income countries developed prototypes focused on visual enhancement for low vision users, with visual feedback, as observed in [30], [38], [40], [41], [77]. Table 2 provides a summary of the types of technology and feedback used in the reviewed studies.

E. USER EVALUATION

The reviewed studies reported the use of different study designs in terms of development and evaluation of wearable devices for mobility of visually impaired people. Thirty-seven observational studies (60.66%) collected data by empirical means to evaluate the effectiveness of the wearable device in experimental settings. Eighteen studies (29.51%) focused on system's analysis, using quantitative approach to evaluate conceptual frameworks, models and algorithms developed for the wearable device. Of these, four studies used mixed methods, that is, system's analysis with a single case evaluation of the wearable device (i.e., case studies) [25], [35], [45], [66]. Three studies (4.92%) used participatory design approach for the development of the wearable device [12], [71], [77] and only one study reported a clinical investigation with 2-week evaluation period [46]. One study only reported a system conceptual overview with no type of evaluation described [70] and one study did not reported the method used [58].

A total of 47 studies (77.05%) included user evaluation, whereas, in the remaining studies, it was either missing or only reported on the technical feasibility of their solutions.

1) USER EXPERIENCE

Evaluations were mostly quantitatively (n = 21) or using mixed methods (n = 20). Only two studies employed qualitative methods [30], [61], whereas four studies did not report their methods [58], [66], [71], [77].

Evaluation including visually impaired participants was featured in 37 studies (60.66%), either as the only sample (n = 26), or in combination with sighted blindfolded participants (n = 7), with a control group for the same experiments (n = 2), or with sighted participants for different experiments (n = 2). Seven publications did not provide details about the sample [25], [27], [35], [45], [65], [66], [77].

Training sessions prior to experiment tests were provided in 28 out of 61 studies, whereas two only mentioned giving a brief explanation about the device usage [34], [65]. The training time varied from a minimum of 2 to 3 minutes

TABLE 2. **Types of technology and feedback.**

Technology	Feedback			
	Audio	Tactile	Audio and tactile	Visual [a]
Stereo camera [31], [43], [52], [61], [66], [68], [74], [78]	[43], [52], [61], [66], [68], [74]	[78]	[31]	No
RealSense [28], [29], [52], [73], [75], [76]	[28], [52], [73], [75], [76]	[29]	No	No
USB camera/webcam [12], [37], [45], [51]	[12], [37], [45], [51]	No	No	No
High-sensitivity camera [40], [41]	No	No	No	[40], [41]
CMOS sensor [41]	No	No	No	[41]
Micro camera [32], [47]	No	[32]	[47]	No
Smartphone camera [54], [64]	[54]	No	[64]	No
Camera with infrared LEDs [30]	No	No	No	[30]
Marker camera [48]	No	No	[48]	No
Camera (not specified) [34], [35], [39], [57]	[34], [35], [39]	[57]	No	No
Smart glasses [53], [76], [77]	[53], [76]	No	No	[77]
RGB-D camera [25], [27], [28], [37], [49], [65], [75] RGB-D sensor [52], [53], [74]–[76]	[25], [27], [28], [37], [52], [53], [65], [74]-[76]	[49]	No	No
Infrared sensor [24], [31], [33], [39], [56], [57] Infrared camera [38], [52], [75]	[39], [52], [75]	[56], [57]	[24], [31], [33]	[38]
Time-of-flight camera [42] Time-of-flight sensor [44]	[42]	[44]	No	No
Ultrasonic sensor [1], [7], [12], [13], [26], [27], [32]–[34], [36], [39], [47], [48], [54], [55], [56], [58], [62]–[65], [67], [70], [71]	[1], [12], [27], [34], [39], [54], [62], [65], [71]	[7], [26], [32], [56]	[13], [33], [36], [47], [48], [55], [58], [63], [64], [67], [70]	No
IMU [28], [31], [42], [49], [61], [65] Compass [35], [48], [59], [60], [65] Gyroscope [35], [38], [79] Accelerometer [58]	[28], [35], [42], [61], [65]	[49]	[31], [48], [58]–[60], [79]	[38]
GPS [35], [48], [58], [62], [69]	[35], [62]	[69]	[48], [58]	No
Radar [46], [50][b], [52], [53]	[52], [53]	No	[46]	No
Radio Frequency Identification (RFID) [65], [69]	[65]	[69]	No	No
Laser scanner [45], [51]	[45], [51]	No	No	No
LEDs [30], [34], [38], [71], [72]	[34], [71], [72]	No	No	[30], [38]
Temperature sensor [67] Water sensor [70], [71] Wet floor sensor [13]	[71]	No	[13], [67], [70]	No
Ambient light sensor [79] Attitude sensor [73] Gravity sensor [79] Proximity sensor [79]	No	[73]	[79]	No
Airflow sensor [72] Antenna [50][b]	[72]	No	No	No

[a] Technologies for low vision users
[b] Feedback interface not reported

in [38] up to 30 hours divided into four sessions in [12]. The training instructions also varied from learning how the device works, learning about the experiment, and practising trials.

Twenty-three studies included qualitative user evaluations in the form of interviews (n = 8) or questionnaires (n = 15) addressing the experience using the device (satisfaction, comfort, feedback, usefulness, confidence, feasibility).

Vijeesh *et al.* [71], Yang *et al.* [73], [76], and Zhang *et al.* [79] also provided opportunities for participants to provide suggestions for future improvements.

2) USER SAFETY

User safety evaluation was reported in five studies using interview [54], survey [65], [76], [79], and the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST 2.0) [46]. However, only two studies provided information about safety from the users perspective [46], [54].

Mocanu *et al.* [54] interviewed 21 visually impaired people, with ages from 27 to 67 years. Their results indicated that people of different ages reacted differently to the innovation proposed. While older visually impaired people showed more mistrust to innovations, preferring to rely on their senses instead of the acoustic signals, younger visually impaired expressed more willingness to use the system in their daily routine. In addition, they also highlight that an ETA should be designed to complement the widely used white cane, with additional functionalities, instead of replacing it.

Kiuru *et al.* [46] presented a complete user safety evaluation in their 2-week clinical investigation with 25 visually impaired people, combining qualitative (interviews) and quantitative (QUEST 2.0) measures to verify the prototype's safety and daily usability. On average, the prototype's safety and security scores were 4.0 (SD 0.7) on a 5-point scale. In addition to the QUEST 2.0, 92% of the users evaluated that the device increased their perception of the environment, and 80% responded that it improved their confidence in independent mobility.

Simões and de Lucena [65] conducted a survey with five users that tested ranked the system's reliability as excellent (55%), very good (20%), good (10%), and satisfactory (15%). In Yang *et al.* [76], six visually impaired people scored the prototype's reliability 7.33 (on a 10-point scale) in a maturity analysis based on Dakopoulos and Bourbakis study [8]. Zhang *et al.* [79] conducted a survey with four visually impaired participants that scored the prototype's safety as 3.75 (on a 5-point scale).

Although the number of studies that included user safety evaluation was low, some studies adopted measures to guarantee the participants' safety during the experiments. Safety measures included training sessions by Orientation and Mobility instructors [12], measures to minimize the risks of falls during the experiment [64], researcher walking close to the participants to avoid falls or collisions [33], [57], [69], and careful selection of the environment [42], [69]. Katzschmann *et al.* [44] did not test an unassisted baseline condition due to safety concerns. In addition, some studies expressed concerns about the user's safety in the development of the prototype. Bai *et al.* [28] set the obstacle alert as their highest priority to ensure the user's safety. Kassim *et al.* [55] set a safety zone limit (distance between user and obstacle), based on the human walking speed, which alerts the user when this distance is less than the limit established. Silva and Wimalaratne [63] built a hybrid fuzzy model to evaluate a walking condition's safety level. The model was tested with five blindfolded participants and five visually impaired participants, and the results showed the effectiveness of the model in increasing safety. Although Silva and Wimalaratne [63] included user evaluation with safety considerations, they did not evaluate the safety from the user's perspective.

IV. DISCUSSION

There is a growing interest in developing wearable devices to assist visually impaired people's mobility. Although recent studies are reporting the development and testing of wearable devices for the mobility of visually impaired people, there is a need for more robust evidence supporting the effectiveness and safety of such devices on the user's mobility. This review provides information about technologies and feedback interfaces implemented on wearable devices to improve the mobility of visually impaired adults.

A. TECHNOLOGIES

A variety of technologies have been used to identify a safe path for the user. Our findings show a wide range of studies using computer vision-based technologies. This may be explained by the higher level of scene interpretation that these technologies provide compared to sensor-based technologies [11], [81]. This review shows that studies that used computer vision-based technologies reported high accuracy in detecting obstacles [25], [35], a decrease in the navigation time [41], [49], [73], and in the number of collisions [35], [49], [57], [73], [75]. Another possible explanation for the wide use of these technologies may be due to advances in this field, that according to Plikynas *et al.* [81], enables the development of solutions that can increase the mobility and quality of life of visually impaired people.

In accordance with [81], RGB-D cameras and sensors were the most popular choice among video-based systems. This review shows the use of these technologies for both indoor and outdoor environments, which is contrary to previous studies which suggested these technologies were only applied in indoor environments [81]. Furthermore, our results show that stereo cameras were a popular choice, as Lin and Han reported [51]. These results may be explained by the fact that these types of cameras can sense image depth information, which is an essential feature in object detection and scene interpretation [51], [73]. While stereo cameras compute image depth data captured from two or more lenses, RGB-D cameras compute depth information with RGB values using infrared sensors and color sensors [11], [51], [81].

Consistent with the literature, we also observed that ultrasonic sensors were the most common technology in sensor-based navigation systems [35], [81]–[83]. This result may be explained by the low cost of these sensors [15] or because they do not require light to work, while cameras do [39]. However, ultrasonic sensors can be affected by environmental conditions and/or other sensors [11], [82]. In addition, even though sensor-based systems have high accuracy in detecting obstacles, they are unable to identify and recognize objects [11], whereas computer vision-based systems provide this additional functionality [81]. These reasons may be possible explanations of why the majority of the included studies use a combination of technologies. This result agrees with data obtained in [81] and [84], who observed that combining different technologies, either as reinforcement or complement, may increase functionality and offer a more reliable location system that is available all the time.

Another interesting finding was the use of smartphones in navigation systems. They were used to capture information from the environment, process it, or communicate it to the user. Several reasons may explain these findings, including the fact that smartphones have been widely used by people of different functional capabilities, which may help devices be more user-friendly [82], and the portability and convenience that smartphones offer to the users [83]. Since they are discrete, Fernandes *et al.* [84] argue that using smartphones may help to mitigate the stigma associated with traditional assistive devices.

Although this review included a high number of researches focused on the development of wearable devices for mobility of visually impaired people, our results indicate a lack of smart clothing development, suggesting a potential gap for further research.

B. FEEDBACKS

User interface and feedback modalities are essential features to take into consideration during system development because they have the ability to enhance the accessibility and usability of a system application [85]. This review demonstrated that audio was a common choice for feedback information to the user, which corroborates the results found in [82] and [83]. A possible explanation for this might be due to the simple, timely and prompt cues that this interface provides about the position of an obstacle in the environment [84]. In addition, it may also be explained for several disadvantages presented by the vibration feedback, including insufficient information perception or the direct contact with the user's skin that this type of interface requires, which can be invasive. In accordance with this result, Mocanu *et al.* [54] have demonstrated that acoustic alerts were adopted instead of vibrotactile because the vibration requires direct contact with the user's skin, and visually impaired participants reported that vibration did not provide sufficient information about the environment.

In contrast, some studies reported that the exclusive use of audio information to alert the user is not recommended because it may interfere with the auditory sense, which is required in navigation in an environment [10], [12]. This result is also consistent with Dakopoulos and Bourbakis study [8]. On the other hand, the use of exclusive vibrotactile feedback is also not recommended since many visually impaired persons have diabetes, which may damage their peripheral and autonomic nervous system and compromise their vibrotactile sensitivity and response [5], [86]. This might be a possible explanation for the low adoption of the vibrotactile feedback found in the included studies.

Although there is no consensus regarding which interface channel is the best, we observed that, in general, studies that provide hybrid interface reported more positive evaluations regarding user-friendly and intuitive interface [31], [33], [48], [64], [79]. This result reflects those of Jafri and Khan [87], that found that 70% of the visually impaired participants (n = 10) preferred hybrid feedback as opposed to audio-only or vibration-only. Therefore, in future studies, it may be preferable if the system could provide both interfaces and allow users to choose the type of feedback that meets their demands and/or preferences, as observed in [48] and [55]. This finding is supported by Kuriakose *et al.* [83] that argues that one single channel may not be the best approach since different users may prefer different feedback methods.

C. USER EVALUATION

The findings pointed out the importance of including visually impaired users in the development of assistive devices. In accordance with our findings, several studies have reported that to develop successful and acceptable assistive technologies, the development must follow a human-centered design approach [88]. Therefore, it is essential to understand how visually impaired people move in unknown environments and what are their needs and requirements [84], [85], [89]. In agreement, Kuriakose *et al.* [83] argue that most solutions that may work in theory are not adopted in practice because they do not meet the user's requirements. These findings are also reflected on Katzschmann *et al.* [44], who highlighted that consulting visually impaired users improved the design and functionality of their prototype. Bhatlawande *et al.* [12] also reported positive outcomes in a survey with visually impaired people, their caregivers, and rehabilitation professionals to understand the user's needs and preferences (e.g., appearance, carry method, user interface and feedback, cost and safety).

Our findings show that the majority (77.05%) of the studies reported user evaluation; however, the number of studies that evaluated the prototype's safety was relatively low [46], [54], [65], [76], [79], indicating the need for more robust evidence supporting the safety of these devices on the user's mobility. The remaining studies, although they showed concerns about user safety, lack comprehensive safety evaluations.

Evaluating the prototype safety is as important as evaluating its effectiveness. If the user does not feel safe and confident with the device, it may influence the usage and lead to devices' abandonment or even health problems associated with low mobility. The feeling of safety can be understood as a subjective matter. Tapu *et al.* [11] suggest that interviews are the most appropriate resource to gather such information and better understand the user requirements. Nonetheless, among the 23 studies identified in our review that included qualitative user evaluations, only 8 used interviews. Among the studies that include safety evaluation, in general, surveys were the most common methodological approach, which could lack in-depth information from the user experience. This is an important consideration for future research. Implementing interviews or more qualitative approaches could provide more information about the preferred features to enhance user safety when using a device.

Finally, we also observed a lack of standardized evaluation methods, which was also reported by Plikynas *et al.* [81], who stated that this limits the representativeness of the experiments.

D. LIMITATIONS

The findings of this systematic review should be carefully interpreted. The search did not include grey literature and results from reports, dissertations, books, papers or studies that have not been completed or have not gone through a scientific peer-reviewed process. Some studies did not report the method used for user evaluation or did not provide sufficient information [58], [67], [68], [71], [72], [77]. However, this review followed a systematic procedure and searched peer-reviewed references in six different databases, including the alert function, to ensure the inclusion of relevant papers.

E. FUTURE RESEARCH DIRECTIONS

The findings of this review highlight directions for future development and research. A major concern observed in our review was the size of the device, more specifically, the miniaturization of the device [7], [32], [44], [46], [48], [52], [61]. A similar concern was reported by Kuriakose *et al.* [83], who reported a relationship between the device's size and its adoption. In accordance, Kiuru *et al.* [46] pointed out that with the optimization of components, the size and weight of the device will decrease, influencing the comfort and wearability, which can increase the usage.

Another interesting finding of this review was regarding the cost of developing a wearable device. This finding is also reflected in Kuriakose *et al.* [83], who highlighted that the cost is one of the reasons that influence the use of assistive devices. In addition, since most visually impaired people live in low- and middle-income countries, low-cost is a concern that needs to be taken into consideration. Several studies have reported suggestions for reducing the costs of the devices, including the use of additive manufacturing technologies [7], [73], [80], the implementation of open-source programming [7], [28], [33], [37], [77], [79], and the use of cloud servers, which eliminates the need for using an expensive high-performance processor [33]. An example is observed in Petsiuk and Pearce [7], whose prototype with 3D printed components and open-source programming resulted in cost savings from 73.5% to 97% compared to available commercial products. Another suggestion may be using computer vision-based technologies such as RGB-Depth (RGB-D). The increased use of this technology in devices for visually impaired people support this recommendation, and it might be explained due to its versatility, portability, and low cost [25], [73]. Lowering the cost of a wearable device could particularly benefit LMICs since it could provide access to more people.

This review also highlights the importance of including users in the development of assistive devices. However, our findings revealed a lack of participatory design approaches among studies. In this context, future research could benefit from this interaction.

A wide range of studies focused on the development and evaluation of algorithms for improving obstacle detection was also observed; however, there was not a standardized evaluation method. Thus, further research may examine the current challenges and complexity of the algorithms for offering different functionalities.

Recommendations for future development and evaluation of wearable devices for visually impaired people can be viewed in Appendix B.

V. CONCLUSION

This systematic review on wearable devices for the mobility of visually impaired people considered the technologies, feedback interfaces, and user evaluation methods used in the included studies. This study contributes to the improvement of existing recommendations and guidelines for assistive technology developers. This review also provides recommendations on reducing the costs of wearable devices to provide access to more people, especially in lower- and upper-middle-income countries, where more people live with visual impairment.

The findings show that the majority of studies featured a combination of technologies, especially integrating sensors (e.g., ultrasonic sensors) and computer vision (e.g., RGB-D and stereo cameras) for increasing accuracy in obstacle detection. While the majority of the reviewed studies (44.26%) have used audio feedback, there is no consensus on the best feedback channel. In fact, some studies recommend using hybrid feedback instead of audio-only or vibration-only interfaces.

Although studies including user evaluation reported several benefits to the user's mobility, there is a great diversity of study designs and a lack of user safety evaluation and standardized evaluation methods, limiting the conclusions about the effectiveness and safety in using the investigated technologies. Future research should focus on stronger evidence supporting the effectiveness and safety of wearable devices on the user's daily mobility.

Finally, the results suggest that including visually impaired users in the design and evaluation processes have shown improvements in the design and functionality of the wearable device. This study also highlights the need for more research and data in low-income countries to ensure fair access to technology in these countries.

APPENDIX A

Example of search strategy using PubMed - Date: 04 June 2020

	Search terms	Records
#1	wearable*[Title/Abstract] OR “wearable assistive device*”[Title/Abstract] OR “wearable sensor*”[Title/Abstract] OR “wearable device*”[Title/Abstract] OR “wearable technolog*”[Title/Abstract] OR “body-worn”[Title/Abstract] OR “waist-worn”[Title/Abstract] OR “wrist-worn”[Title/Abstract] OR “hip-worn”[Title/Abstract] OR “ankle-worn”[Title/Abstract] OR “wearable electronic device*”[Title/Abstract]	13512
#2	wearable electronic devices[MeSH Terms]	11514
#3	[1] OR [2]	22942
#4	(mobility[Title/Abstract] OR navigat*[Title/Abstract] OR travel*[Title/Abstract] OR walk*[Title/Abstract] OR ambulation[Title/Abstract] OR orientation[Title/Abstract] OR gait[Title/Abstract] OR locomotion[Title/Abstract] OR wayfinding[Title/Abstract] OR "route following"[Title/Abstract] OR ((obstacle[Title/Abstract] OR object)[Title/Abstract] AND (avoid*[Title/Abstract] OR detect*[Title/Abstract] OR recognition))[Title/Abstract])	573,366
#5	(mobility limitation OR spatial navigation OR walking OR orientation OR orientation, spatial OR gait OR locomotion[MeSH Terms])	591,238
#6	[4] OR [5]	890,720
#7	(((low*[Title/Abstract] OR handicap*[Title/Abstract] OR subnormal*[Title/Abstract] OR impair*[Title/Abstract] OR partial*[Title/Abstract] OR disab*)[Title/Abstract] AND (vision[Title/Abstract] OR visual*[Title/Abstract] OR sight*))[Title/Abstract] OR ((blind[Title/Abstract] OR “visual* impair*”)[Title/Abstract] AND (people[Title/Abstract] OR person*))[Title/Abstract] OR ((visual[Title/Abstract] OR vision)[Title/Abstract] AND disorder*)[Title/Abstract] OR blind*[Title/Abstract])	473,552
#8	(visually impaired persons OR blindness OR vision, low OR vision disorders[MeSH Terms])	103,917
#9	[7] OR [8]	501,546
#10	[3] AND [6] AND [9]	168

APPENDIX B

Recommendations for the design and development of wearable devices for Orientation and Mobility of Adults with Visual Impairment and Blindness extracted from included literatures.

TECHNOLOGIES

- Reduce weight and size of the device (miniaturization) [7], [32], [44], [46], [48], [52], [61]
- Add image/face recognition [33], [54]

FEEDBACK

- Introduce or replace the speaker’s tune/song alert mechanism (computer-generated) real human voice 24], [34], [67]

USER EVALUATION

- Test in indoor and outdoor scenarios [28], [29]
- Test with a larger sample of users [31], [36], [42], [76]
- Provide more intensive training protocol [57], [67]

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