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TOPICAL REVIEW

Wearable Obstacle Avoidance Electronic Travel Aids for Blind and Visually Impaired Individuals: A Systematic Review

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ABSTRACT **Background** Wearable obstacle avoidance electronic travel aids (ETAs) have been developed to assist the safe displacement of blind and visually impaired individuals (BVIs) in indoor/outdoor spaces. This systematic review aimed to understand the strengths and weaknesses of existing ETAs in terms of hardware functionality, cost, and user experience. These elements may influence the usability of the ETAs and are valuable in guiding the development of superior ETAs in the future. **Methods** Formally published studies designing and developing the wearable obstacle avoidance ETAs were searched for from six databases from their inception to April 2023. The PRISMA 2020 and APISSER guidelines were followed. **Results** Eighty-nine studies were included for analysis, 41 of which were judged to be of moderate to high quality. Most wearable obstacle avoidance ETAs mainly depend on camera- and ultrasonic-based techniques to achieve perception of the environment. Acoustic feedback was the most common human-computer feedback form used by the ETAs. According to user experience, the efficacy and safety of the device was usually their primary concern. **Conclusions** Although many conceptualised ETAs have been designed to facilitate BVIs' independent navigation, most of these devices suffer from shortcomings. This is due to the nature and limitations of the various processors, environment detection techniques and human-computer feedback those ETAs are equipped with. Integrating multiple techniques and hardware into one ETA is a way to improve performance, but there is still a need to address the discomfort of wearing the device and the high-cost. Developing an applicable systematic review guideline along with a credible quality assessment tool for these types of studies is also required.

INDEX TERMS Blind, visually impaired, wearable, obstacle avoidance, electronic travel aids, systematic review.

I. INTRODUCTION

As estimated by Global Vision Database 2019 Blindness and Vision Impairment Collaborators, in 2020, around 43.3 million individuals were blind and 295 million individuals had moderate to severe vision impairments, and by 2050, these two groups are predicted to reach to 61.0 million and 474 million, respectively [1]. Vision plays a crucial role in navigation since it facilitates movement from one location to another, which is an essential part of daily life [2]. Navigating independently is thus a major challenge for blind and visually impaired individuals (BVIs) [3]. In addition to the decline in mobility, vision loss is also associated with reduced participation in daily living and social activities, and reduced ability in detecting hazards which can subsequently result in accidents, collisions, falls, and even mortality [4], [5]. Improving mobility skills may also improve BVIs' self-maintenance and overall quality of life, leading to more active participation in social life and leisure, and enhanced productivity [5], [6]. To have safe, efficient, and independent mobility, BVIs

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rely on assistive technologies [5], [6]. Traditional assistance such as guide dogs and white canes are still widely utilized. However, these aids do not adequately solve independent navigation difficulties [7], [8]. Guide dogs are not employable on a large scale due to high cost and short useful life (five years only) [8]. The white cane cannot detect obstacles beyond its reach (within three to six feet usually), and thus the users only perceive restricted environmental information about the surroundings [8]. The white cane is not useful in detecting potentially dangerous obstacles at the head level, such as tree branches and suspended trash cans [3], [8]. Thus, white cane users can be injured from time to time [3]. In the survey by Manduchi et al., nearly 40% of BVIs who use a cane reported head-level accidents at least once per year; and 23% of these incidents required medical intervention [9].

Electronic travel aids (ETAs) have been developed to improve the functionality of the conventional aids [5]. They facilitate safer and simpler displacement [10] by providing additional perception of the environment [11], improving the detection range of obstacles and landmarks, and also giving a better orientation [10], [12]. ETAs are available as traditional handheld devices, smart canes, and novel wearable devices [13]. The wearable device has the particular strength of leaving both hands free [14]. For BVIs, wearable devices gather information about the user and/or the environment, process it (locally and/or globally) and return it to the BVIs in real-time through acoustical and tactile feedback/signals to substitute for visual information [5], [15]. A variety of wearable-based devices such as ultrasonic obstacle detection glasses [16], laser-scanners [17], and many others have been developed to address the obstacle avoidance for BVIs [18]. Most of these assistive technologies have limitations, e.g., ultrasonic-based device has short range capacities for object detection [18] and cannot recognize the type of obstacles [10], laser-based device may harm people around the users if it directly hits their eyes. [18].

Which environmental detection techniques are adopted by available wearable ETAs to ensure safe and accurate mobility? Do these wearable ETAs adequately meet the needs of BVIs for obstacle avoidance in independent travel? How can deficiencies in available devices be eliminated? An evidence-based review can provide unbiased and comprehensive answers. We therefore conducted this systematic review, aiming to understand the categories, control module, techniques (sensors) employed, feedback interfaces, users' experience and assessments, and potential limitations of existing wearable ETAs.

II. MATERIALS AND METHODS

A. ELIGIBILITY CRITERIA

This review was performed and reported in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement guideline [19], and A priori, Plan, Identify, Screen, Select, Extract and Report (APISSER) guideline [20], respectively. Only formally published original studies designing and developing wearable obstacle avoidance ETAs were included in this review. In addition to a description of the development process of the device and the technologies employed, the eligible study should include at least one test in a real environment with the volunteer(s) or researcher(s) wearing the device. The volunteer could be BVIs or healthy-sighted people who successfully simulated the visual characteristics of BVIs by being blindfolded. Also, the device included in the study should have obstacle avoidance as its primary function or had both obstacle avoidance and other functions. The publication date of the studies was not limited, while the language was restricted to English and/or Chinese.

Studies were excluded if the wearable navigation device presented was not specifically designed for BVIs. Although ETA, electronic orientation aid (EOA) and position locator device (PLD) are all devices that can be used to assist BVIs to navigate independently, there are differences between the three. ETA is defined as a device that converts environmental or user information, while EOA focuses on providing direction to the user and PLD emphasizes positioning information [5], [21]. Hence, we also excluded studies in which the device presented was primarily developed as an EOA or PLD rather than an ETA.

B. SEARCH STRATEGY AND DATA EXTRACTION

Following consultation with a professional librarian with an engineering and computer science background who assisted in the development of the overall search strategy, we used filters to reliably identify relevant studies and undertook a comprehensive search of four English and three Chinese electronic databases –MEDLINE (via PubMed), Association for Computing Machinery (ACM) digital library, Institute of Electrical and Electronic Engineers (IEEE) Explore, Web of Science, China National Knowledge Infrastructure (CNKI), Chongqing VIP database (CQVIP), and Wanfang database –from their inception date until April 2023. The search was conducted by combining search terms from three categories: (1) BVIs; (2) obstacle avoidance; and (3) wearable device or wearable technology. Searches were supplemented by retrieval from other sources, including the conference proceedings relevant to engineering or computer science in the State Library Victoria (Melbourne, Australia) and any additional articles meeting eligibility criteria that were cited in reference lists of the included papers, grey literature, and existing systematic reviews, to avoid potential omission (See **Appendix 1** for detailed search terms and search strategies).

EndNote software (Version 20.1) was used to store the results of search and to remove duplicate articles. If multiple papers were judged to be reporting on different stages of the same device, the paper with the most comprehensive information and the most recent date was retained. After screening the titles and abstracts by using the Rayyan software, full texts were acquired and cross-checked for eligibility by two researchers (PJ-X and FY-Z). Two predetermined data forms were utilized to extract the following information from each study; identification information, publication year, country, wearing area, control module, human-computer feedback mode, type and characteristic of environmental detection techniques employed (technology, model, number, features), cost, limitation, socio-demographic characteristics of users (sample size, gender, age, type of visual impairment), user assessment (experience, safety, comfortability), and other key findings. We also endeavoured to contact the corresponding author of the original study to access missing data or to clarify other unclear or uncertain information.

C. STUDY QUALITY AND RISK OF BIAS ASSESSMENT

There is no recognised tool for appraising the methodological quality and risk of bias (RoB) of studies pertaining to design/development of an engineering product, including wearable devices. The tools used widely in the medical research, such as the Cochrane RoB tool, the JBI Critical Appraisal Checklist, the Jadad/Modified Jadad Scale, etc., are applicable to randomized controlled trials, cross-sectional studies or case-control studies rather than the types of studiesin the current review. Hence, we developed an instrument in-house via reviewing the relevant published literature and consulting industry experts. A four-item quality assessment checklist was identified in a previous systematic review of a similar topic [18]. That checklist was adapted for our current research topic, resulting in a more rigorous and eligible tool for assessing the quality of evidence in this review (**Appendix 2**). The tool comprises five domains, judging the methodological quality of eligible studies on different dimensions. To quantify the assessment for further analysis, weights are assigned to all five domains based on a 3-point Likert (Note each domain was rated on a scale from 0 to 1 yielding a possible total score ranging from 0 to 5 points). A total score between 2.5 and 3.5 points was considered as moderate-quality; a total score more than 3.5 points was considered as high-quality; while, a total score less than 2.5 points was considered as low-quality (Please refer to **Appendix 2** for the specific scoring criteria). Using this tool, two evaluators (PJ-X and FY-Z) carried out standalone appraisal (including determining risk of bias and assessing the internal validity) of all the included studies. If consensus could not be reached, a third assessor (R-VS) was consulted in resolving any discrepancies.

III. RESULT ANALYSIS

A. STUDY SELECTION

Of the 3941 potentially relevant records retrieved through the target databases and state library in Victoria in the preliminary identification 2194 articles met the inclusion criteria. On examining the title and abstract of these articles, 236 studies were retained for further full-text screening. We limited the review to obstacle avoidance, wearable device, device for the BVIs, and some other conditions, and decided on the final resulting 89 eligible studies to be included (**Figure 1**).

B. STUDY DESCRIPTION

In 89 included studies, 55 (61.8%) were journal articles. The remaining studies sourced from the conference proceedings (n = 25, 28.1%) and dissertations (n = 9, 10.1%) (**Table 1**). All except six studies [21]–[26] were published within the last decade. The rate of the annual publication basically showed gradual increase in research papers in this area.

The research teams were from many different countries. The top output country was mainland China [27]–[55], involving 29 studies. The United States [23], [56]–[61] (n = 7), India [62]–[67] (n = 6), Germany [68]–[72] (n = 5), Japan [24], [73]– [75] (n = 4), Thailand [76]–[79] (n = 4), Italy [80]–[82] (n = 3), Portugal [83], [84] (n = 2), Brazil [85], [86] (n = 2), United Kingdom [87], [88] (n = 2), South Korea [89], [90] (n = 2), Malaysia [26], [91] (n = 2) and Spain [92], [93] (n = 2) contributed two to seven studies each. Other 18 countries or region, namely Saudi Arabia [94], Iraq [95], Romania [96], France [11], Canada [97], Indonesia [98], Israel [21], Colombia [99], Bangladesh [18], Taiwan (China) [100], Greece [101], Philippines [102], Sweden [103], Slovenia [104], Pakistan [105], Switzerland [22], Australia [25], Egypt [106] and Sri Lanka [86] had one study published, respectively (**Table 1**).

C. DESCRIPTION OF THE DEVICES INVOLVED IN THE STUDIES

1) PART OF THE BODY WHERE DEVICE IS WORN

The body parts where these devices could be worn were diverse and flexible. In 60 studies, devices were developed to be worn on a single part of the body. Of these, 58 devices were required to be worn at a fixed location; while the other two provided alternative options. Specifically, Liu's device was suitable to be worn on head, shoulder, wrist or waist [37], and Lee's device could be used as a jacket or shoulder bag [90]. In 25 studies, the device consisted of a combination of multiple components, and users had to wear multiple components of a device on two or more body parts. The other four studies [32], [44], [52], [69] only reported that the device was wearable, but did not clarify where the device should be worn (**Table 1**).

Illustrations of some devices worn by users, clearly indicating their wearing positions on the body, are presented in **Figure 2**. The devices or device components were worn on the eyes in approximately one-third (n = 27, 30.3%) studies. Twenty-three studies mentioned their devices or device components were worn in positions involving extremities and limbs, including arms, wrists, hands including one [91] on fingers, legs, ankles, and feet. There were also devices or device components that, in descending order, needed to be worn on the waist and abdomen (n = 25), entire torso and chest (n = 20), head (n = 12) including one [72] on forehead, shoulder (n = 5), back (n = 1), ear (n = 1), and neck (n = 1). **Figure 3** further visualises the percentage of each body parts involved in the wearable devices.

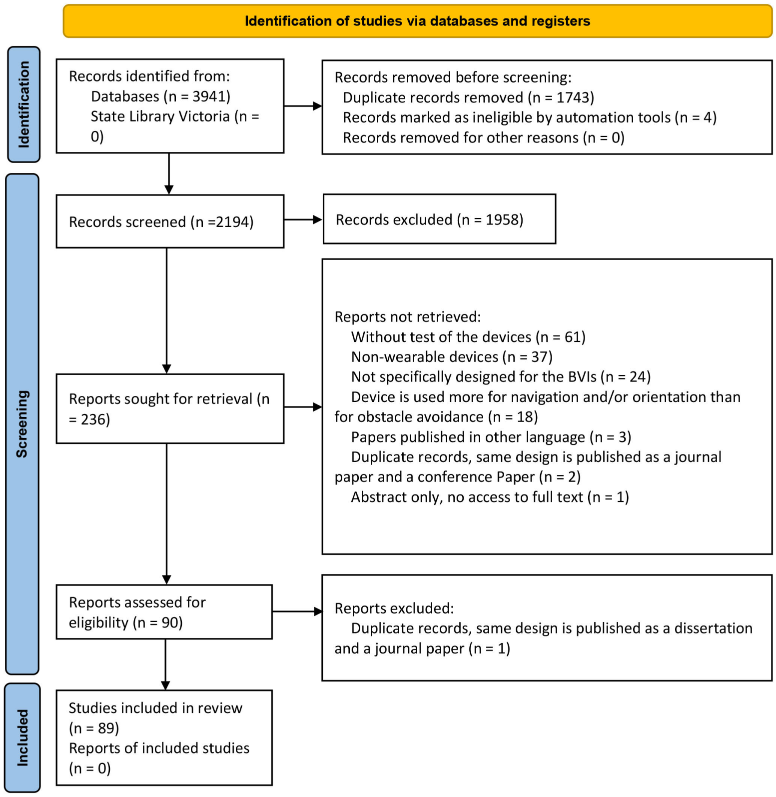

FIGURE 1. **Flow diagram of the study selection process.**

2) DATA COMPUTING AND SYSTEM CONTROL

The processor, as the brain of the device, was responsible for the management of all the operations of the sensor node to manage the sensor node activity while meeting the energy consumption, size, and cost constraints [107]. In 59 studies, the designed device adopted a single processor for data calculation and system control. In 23 studies, such tasks were completed by the device with two control modules. The remaining seven studies did not provide information on processor [41], [53], [60], [63], [69], [79], [82] (**Table 1**).

Different types of processors were identified in the studies. They included laptop, microcontroller, portable computing unit, and others. The scale of each processor and model employed is shown in **Figure 4**. Of all the devices developed, portable computing units and embedded systems were the most widely used. Twenty-one studies illustrated devices were equipped with laptops as the computing and control cores. Devices in 18 studies used microcontrollers, and the models of these microcontrollers varied. The Arduino series boards were popular. By comparison with other development tools, it was adopted by more devices. Raspberry Pi series was another popular development option. Nvidia Jetson which delivered advanced artificial intelligence (AI) platform was used in three devices. The other processors also implicated smartphone due to its powerful integration and computing unit and data calculation via cloud service. The latter usually relies on a local module with internet access for data uploading.

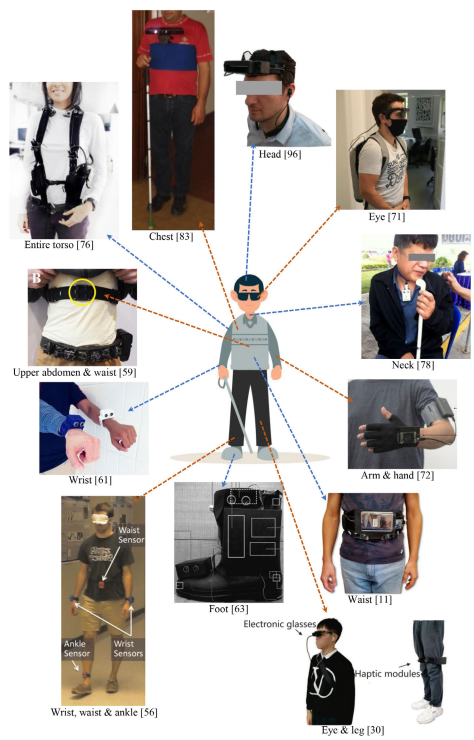

FIGURE 2. **Examples of different wearing positions on the body.**

3) ENVIRONMENT DETECTION TECHNIQUES

The environment detection techniques involved in the studies included ultrasonic sensors, different types of cameras, LiDAR sensor, infrared sensor, laser sensor, 3D CMOS image sensor, and Time of Flight sensor for the obstacle detection. Seventeen studies also investigated the effectiveness of perceiving the environment through a combination of two or more techniques (**Table 1**).

In light of the review results, computer vision-based technology (camera) was the most popular. The RGB-D camera stood out from many cameras and gained favour in 20 studies. Ultrasonic sensors were also often selected because of their low cost and high accuracy in obstacle detection (**Table 1**).

In two studies [39], [44], in addition to the active obstacle avoidance function, the developers further added LED visual module to warn pedestrians to stay away, thus achieving passive obstacle avoidance at the same time (**Table 1**).

4) HUMAN-COMPUTER FEEDBACK

All but two studies [30], [41] described the form of human-computer feedback used by the devices (**Table 1**). Of the devices reviewed, 22 employed an individual acoustic notification (e.g., voice command, orientation guide, etc.) and 20 utilised a single acoustic alarm/signal (e.g., buzz, music, natural sound, etc.). Zuo and Wang used a combination of acoustic alarm and notification in their device [44].

In 21 studies, the device was equipped with independent haptic vibration.

Hybrid feedback with both acoustics and tactility was used in 22 devices.

Meers and Ward [25] provided feedback to the user via transcutaneous electro-neural stimulation on the hands.

In two studies [57], [83], the researchers applied braille display as the device's feedback interface, and one study [57] also combined braille display with haptic vibrations to amplify the feedback effect.

5) COST OF DEVICE

Three studies reported that the cost of their devices were below 70 USD, with the cheapest only costing 17.82 USD [61]. The devices in four studies [30], [58], [62], [72] cost over 200 USD. The device developed by Katzschmann et al. consisted of a belt and a haptic strap, which were approximately 1300 USD and 150 USD, separately [59]. Ali A. et al. acknowledged that their device might be relatively expensive for some users from developing countries [65].

Eighteen studies claimed that the devices were low-cost but did not detail the specific amount (**Table 1**).

6) POWER CONSUMPTION

One study mentioned that the power consumption by the device is about 75 mW when used with a Li-PO battery 1,150 mAh at 3.7 volts [78]. Another study described that the average power consumption per second of the device was estimated to be 226.92 mA [31]. The remaining 87 studies (97.8%) did not supply information on power utilised of the device.

D. CHARACTERISTICS OF TRIALS USED TO TEST THE RELIABILITY OF DEVICES

The obstacle avoidance effects of wearable devices were generally validated in the trials that simulated the real-life scenarios of BVIs.

1) USER SOCIO-DEMOGRAPHICS

Seventy-five studies (84.3%) reported the sample size included in the trials, ranging from one to 70 participants; and 76 studies (85.4%) reported socio-demographics data of the involved participants. The age of these participants was between 12 to 75 years old (**Table 2**).

Seventy-two studies reported the vision type of the participants, that is, 23 studies only included BVIs in the trials; 34 studies only included blindfolded volunteers in the trials; and the remaining studies included both (**Table 2**).

2) USER EXPERIENCE

The user experience and evaluation to the device were generally investigated by interview or questionnaire survey. The efficacy and safety of the devices were usually the primary concern of both researchers and users. Comfortability and cognitive load while wearing the device were reported by participants in 23 studies. Thirteen studies indicated that the device was easy for users to learn and utilize. Thirteen studies documented the user's further demands and suggestion for device improvements after completing the trials (**Table 2**).

E. STUDY QUALITY APPRAISAL

Of the 89 included studies, seven (7.9%) [11], [28], [30], [45], [53], [54], [90] were evaluated as high-quality studies, 34 (38.2%) [26], [27], [29], [34], [36], [49], [57]–[59], [61]–[65], [67], [68], [71], [72], [75], [78], [81], [85], [87]–[89], [92]–[94], [96], [98], [100], [102], [103], [108] were rated as moderate-quality studies, and the remaining 48 (53.9%) were judged as low-quality studies (**Table 3**).

IV. DISCUSSION

A. SUMMARY OF FINDINGS

Wearable obstacle avoidance ETAs have evidently attracted growing research interest, reflected by the significantly increased publication rate in the last decade. In the reviewed studies, most devices were designed to be equipped at eye level to simulate human vision. The portable computing units by Arduino and Raspberry Pi series were widely selected as the processers to control the sampling of the available sensors, control the various parts of the node, and manage the exchange of the data between the different components. Limited to the computing resource, they however had to be replaced by laptops in those devices where the system required higher performance. Cameras and ultrasonic devices are the most frequently used techniques in executing environmental detection tasks. RGB-D camera, instead of the earlier ordinary cameras, has been configured into the ETAs to optimise its performance. Although ultrasonic

TABLE 1. Technology characteristics of the obstacle avoidance ETAs included in the 89 reviewed studies.

Authors, year	Country	Wearing part of body	Processor	Characteristics of environment detection techniques				Human-computer feedback	Cost	Limitation	Other key finding
				Technology	Model	Number	Features				
Sun, 2014 [39]	China	eye	microcontroller STC89C52	ultrasonic sensor	HC-SR04	1	- detection range (≤ 3 m)	acoustic alarm	NR	NR	- included GPS module for localisation
				LED visual module	NR	8	- warn pedestrians to stay away				
Yang et al., 2021 [48]	China	eye	Raspberry Pi 4B	ultrasonic sensor	NR	NR	NR	acoustic notification	NR	NR	None
				camera (not specified)	NR	NR	- invoke OpenCV library for traffic light detection and pedestrian crossing detection				
Huang et al., 2022 [51]	China	waist	microcontroller STC89C52	ultrasonic sensor	HC-SR04	3	- detection range (≤ 4 m) - average error (±0.66%)	acoustic notification	low	- detect limited types of obstacles (fail in measuring puddles)	- included GPS module for localisation
Ge et al., 2022 [50]	China	head, chest & waist	smartphone & cloud computing unit	smartphone camera	NR	1	NR	acoustic notification & haptic vibration (on head and waist)	low	NR	- haptic vibration spatial resolution in the scalp area is 2-3 cm, slightly better than the back
Jin, 2021 [46]	China	entire torso (clothing)	Arduino Lite	ultrasonic sensor	URM07	3	- detection range (≤ 7.5 m) - detection angle (60°) - average error (±1.66%)	acoustic alarm	low	- not comfort (too heavy)	- included GPS module for localisation, and a 3-axis accelerometer for fall detection - obstacle avoidance accuracy (≥95%)
Zhao, 2021 [49]	China	hand, waist & back (bag)	Arduino UNO & laptop	stereo camera	ZED	1	- detection range (0.3 – 25 m) - FOV (90° (H) x 60° (V) x 100° (D)) - YOLOv3 and SLAM algorithm for obstacle detection at 30 fps	acoustic notification & haptic vibration (on hand)	NR	NR	None
Zuo and Wang, 2020 [44]	China	not specified	Freescale I.MX6 Dual Lite	ultrasonic sensor	HC-SR04	1	- detection range (0.02 - 4 m) - average error (±0.2m)	acoustic alarm & notification	NR	NR	None
				USB camera / webcam	NR	1	- invoke OpenCV library for haptic paving detection and pedestrian crossing detection				
				LED visual module	NR	1	- warn pedestrians to stay away				
Hu, 2016 [40]	China	eye	Raspberry Pi 2B	ultrasonic sensor	HC-SR04	1	- detection range (0.02 - 4 m)	acoustic notification	NR	- not able to provide localisation information and path planning	None
				camera	Raspberry Pi camera	1	- 5 megapixel - invoke OpenCV library for traffic light detection and pedestrian crossing detection				
Hu, 2021 [45]	China	eye	laptop	RGB-D camera	Realsense R200	1	- FOV (59° (H) x 42° (V)) - error (≤ ±12.96%)	acoustic alarm (3 kind of signals)	NR	- overexposure in certain specific outside environment effecting depth calculation	- include attitude sensors measure inertial and geomagnetic data
Shi et al., 2022 [52]	China	not specified	Sipeed Maixduino & cloud computing unit	camera (not specified)	NR	1	- YOLOv5 algorithm for obstacle detection and haptic paving detection	acoustic notification	NR	NR	- included GPS module for localisation
Wang et al., 2020 [42]	China	entire torso (clothing)	Arduino UNO	ultrasonic sensor	JSN-SR04T	3	- detection range (≤ 7.5 m) - waterproof	acoustic notification	NR	- not able to detect dynamic and tiny obstacles	None
Zhu et al., 2020 [43]	China	entire torso (clothing)	Arduino LilyPad	ultrasonic sensor	NR	3	NR	acoustic alarm	NR	NR	- experimentally shown to improve reaction speed to obstacles
(Shen and Yuan, 2021 [47]	China	entire torso (vest)	laptop	RGB-D camera	NR	1	- detection range (0.5 - 5 m) - error (≤ ±3%)	acoustic notification & haptic vibration	NR	NR	None
Ren et al., 2020 [41]	China	head	not specified	monocular camera	NR	1	- detection range (≤ 7 m) - error (≤ ±5% within 8 m)	NR	NR	NR	None
Pundlik et al., 2018 [60]	US	shoulder (bag) & wrist	not specified	miniature camera	NR	1	NR	haptic vibration (on both wrists)	NR	- fail to provide warning due to limited sensitivity and specificity - improper positioning of the camera on the user's body and its relatively small field of view lead to missed warnings	- the device augmented white cane for better performance - reduce ~68% collisions - walking speed slow down ~8%
Bouteraa, 2021 [94]	Saudi Arabia	eye & hand	Arduino Due	ultrasonic sensor	HC-SR04	3	- detection range (0.02 - 4 m)	acoustic notification & haptic vibration (on hand)	low	NR	- the navigation system exhibited less walking time and collision than those using the conventional white cane for both outdoor and indoor environments
				LiDAR sensor	Mini LiDAR	1	- detection range (0.3- 12 m)				
Ghaderi et al., 2015 [69]	Germa ny	not specified	not specified (a standard processor)	dynamic vision sensor	NR	2	NR	acoustic alarm (3 kind of signals)	NR	- the scenarios do not fully capture the complexity of a real-world scenario involving different types of obstacles	- the system achieved satisfying performance (>75%) in object detection, size discrimination, and horizontal object localization
Chen et al., 2021 [29]	China	head	an embedded graphics processing module made by NVIDIA	RGB-D camera	ORBBEC	1	- about 25 fps for SLAM - about 10 fps for semantic segment	acoustic notification	NR	- limited indoor location information restricted by the computing power and accuracy of the device	None

TABLE 1. ***(Continued.)*** **Technology characteristics of the obstacle avoidance ETAs included in the 89 reviewed studies.**

Shen et al., 2022 [75]	Japan	chest, waist & hand	Raspberry Pi 3B+ & Raspberry Pi Zero	camera	Raspberry Pi camera	1	- 8 megapixel - accelerate with Intel Neural Compute Stick 2 - compress YOLOv3 model by 5% for obstacle detection	haptic vibration	NR	- when the situation became more complex, the number of collisions became higher	- collision rate (8.15%)
Cheng, 2016 [100]	Taiwan (China)	head	Arduino Mega v3	ultrasonic sensor	HC-SR04	3	NR	acoustic alarm	low	NR	- none of the participants hit the suspended objects while wearing the proposed guiding system
				camera	FlyCamOne eco v2	1	NR				
Barontini et al., 2021 [81]	Italy	chest & arm	laptop (ASUS UX310U)	RGB-D camera	Asus Xtion Pro	1	- detection range (0.8 - 3.5 m) - invoke Shi-Tomasi corner detector in OpenCV library for obstacle detection	haptic vibration (on arm)	NR	- not capable to distinguish between moving or fixed obstacles - the camera is completely blind in a dark environment - cannot guarantee a safe navigation in a crowded place	- different guidance instructions could be needed for people using the white cane and for those who do not.
Ramadhan, 2018 [95]	Iraq	wrist	microcontroller ATmega328 & Arduino UNO	ultrasonic sensor	HC-SR04	1	- detection range (0.02 - 4 m)	acoustic alarm & haptic vibration	NR	NR	- included GPS module for localisation
Katzschmann et al., 2018 [59]	US	upper abdomen & waist	microcontroller MBED NXP LPC1768	infrared sensor	Terabee TeraRanger One	7	- Time of Flight based - detection range (0 - 14 m) - FOV (70° (H) x 45° (V)) - 2 downward-facing & 5 horizontals - average error (±4 cm)	haptic vibration (around upper abdomen)	- belt components (~1.3k USD) - haptic strap components (~150 USD)	NR	None
Martinez et al., 2020 [71]	Germany	eye	laptop (Lenovo Thinkpad Yoga 14)	RGB-D camera	Realsense R200	1	- about 10 fps for semantic segment by SwaftNet model	acoustic alarm	NR	NR	None
Caraiman et al., 2019 [96]	Romania	head	laptop	stereo camera	Leopard LIOV580	1	- error (±0.26 cm) at 5 m - achieve 3 fps - ground surface segmentation	acoustic notification	NR	NR	- the effectiveness of the overall performance (88.5%)
				infrared sensor	Occipital PS1080	2	NR				
Gao et al., 2015 [56]	US	wrist, waist & ankle	Arduino (ATmega168)	ultrasonic sensor	MaxSonar-EZ2	3	- detection resolution (1.0 cm^2 at distance of 70 cm)	acoustic alarm & haptic vibration (on waist and ankles)	NR	- not tested by visually impaired people	- reported error less than 10% when the device augments white cane
Brown et al., 2019 [80]	Italy	chest, waist & ankle	Intel Compute Stick CS125	RGB-D camera	Realsense R200	1	NR	haptic vibration (on undershirt and ankles)	NR	NR	- significantly slower navigation but collision reduce
Petsiuk and Pearce, 2019 [61]	US	wrist	Arduino Nano	ultrasonic sensor	HC-SR04	1	- detection range (0.02 - 4 m) - detection angle (15°) - detection resolution (0.5 cm^2 within 4 m)	haptic vibration	17.82 USD (23.81 USD with optional module)	NR	- failure rate (6.7%)
Mocanu et al., 2016 [11]	France	waist	Arduino Micro & smartphone (Android Samsung S7)	ultrasonic sensor	MaxSonar LV EZ-0	4	- detection range (≤ 6 m) - detection angle (±40°) - average error (±2 cm)	acoustic alarm	low	NR	- average processing speed (10 fps)
				smartphone camera	Samsung S7	1	- extract interest by FAST algorithms for obstacle detection at 10 fps				
Kilian et al., 2022 [72]	Germany	arm & hand	Raspberry Pi 4	stereo camera	Pmdtechnologies Pico Flexx	1	- Time of Flight based - detection range (0.1 - 2 m) - FOV (62° (H) x 45° (V))	haptic vibration (on hand)	~600 USD	- objects close to the ground (thresholds, tripping hazards and steps) or the recognition of approaching staircases were deliberately excluded - the risk of a technical failure or error - the limit of a single battery charge - other smaller everyday drawbacks (waterproofness, robustness, etc.)	- the system achieved a frame rate of 25 fps and a measured latency of about 50 ms
Yang et al., 2016 [54]	China	eye	laptop (Microsoft Surface Pro 3)	RGB-D camera	RealSense R200	1	- obtain preliminary ground segmentation by the RANSAC algorithm and increase the horizontal field angle of the traversable area from	acoustic notification	NR	NR	- the average processing time of a single frame was 610 ms - average collisions to with traversable area expansion was 78.6% less
Yang et al., 2018 [53]	China	eye	not specified (a portable processor)	RGB-D camera	RealSense R200	1	59° to 70° via seeded region growing - proposed an ERF-PSPNet to achieve real time semantic segmentation	acoustic notification	NR	- some failures due to the semantic classification framework	than that with original ground detection - participants were aware of obstacles and semantics with the system and could make use of the stereo sound to keep away from hazards

TABLE 1. ***(Continued.)*** **Technology characteristics of the obstacle avoidance ETAs included in the 89 reviewed studies.**

da Silva et al., 2021 [137]	Brazil	eye	Arduino Pro Micro	infrared sensor	E18-D80NK	1	- detection range (0.03 - 0.8 m) - smooth noise by a Kalman filter	acoustic notification	NR	NR	- sensibility (93%) and specificity (95%)
Leporini et al., 2022 [82]	Italy	eye	not specified	ultrasonic sensor	NR	3	- detection range (≤ 8 m)	haptic vibration	NR	- some inaccuracies with the detection of open doors and bottom-placed objects	None
Zeng et al., 2012 [68]	Portugal	shoulder (bag)	laptop	RGB-D camera	Microsoft Kinect	1	- detection range (0.8 - 4 m)	acoustic alarm	NR	- not conveniently and comfortably carried by the user	None
Filipe et al., 2016 [83]	Germany	chest	laptop	stereo camera	NR	1	- detection range (0.1 -7 m) - Time of Flight based	tactile obstacle (abstract) symbols on a portable multi-line braille display	NR	- multiple and heavy equipment - sometimes failed to detect spinning obstacles from too few reflection points	- the proposed system required much more time than users' with the white canes
Vorapatratorn and Nambunmee, 2014 [78]	Thailand	neck	microcontroller PIC16F684	ultrasonic sensor	40T/R-12B	1	- detection range (within 1.3 m)	haptic vibration	low	- long-term testing needs to be conducted to examine possible side effects	- power consumption (75mW) - collision rate reduced from 33.33% to 6.67%
Vorapatratorn et al., 2015 [76]	Thailand	entire torso (vest)	microcontroller AT91SAM3X8E	ultrasonic sensor	US-015	4	- detection range (0.02 -4 m) - detection angle (45°)	haptic vibration	low	NR	- average collision rate (17.78%) - the device augmented white cane for better performance
Vorapatratorn and Teachavorasinskun, 2017 [79]	Thailand	ear & waist	NR	ultrasonic sensor	US-015	4	- detection range (0.02 -4 m) - detection angle (45°)	haptic vibration	NR	NR	NR
Yánez et al., 2016 [84]	Portugal	forehead, chest & leg	Raspberry Pi 3 & cloud computing unit	ultrasonic sensor	NR	4	- detection range (0.02 -4 m)	acoustic alarm	NR	- not tested by visually impaired people - cannot geographically locate the user	None
				camera	Raspberry Pi camera	1	- 8 megapixel - cloud image recognition vis Wi-Fi module				
Boudreault et al., 2016 [97]	Canada	head	laptop	RGB-D camera	Microsoft Kinect	1	NR	haptic vibration	NR	- the camera was situated in front of the helmet prevented to detect all the obstacles	None
Min Htike et al., 2021 [88]	UK	head	Microsoft HoloLens v1	camera & RGB-D camera	Microsoft HoloLens v1	1	- FOV (30° (H) x 17.5° (V)) - AR based prototype develops in Unity - YOLOv3-Lite algorithm for obstacle recognition	acoustic notification	NR	- slow and sparse depth mapping, limited camera, small screen sizes, weight, and cost	- designed for people with low vision
Lu et al., 2021 [55]	China	wrist	microcontroller nRF51822	ultrasonic sensor	NR	1	NR	acoustic notification & haptic vibration	NR	NR	- the device augmented white cane for better
Tao et al., 2018 [35]	China	waist, leg & foot	microcontroller STM32F103VET6	ultrasonic sensor	HC-SR04	7	- waist (5) & foot (2) - average error (±4.13%)	haptic vibration (on waist and legs)	NR	NR	- correct accumulated error to improve the accuracy of positioning via fusing 5 attitude detection module data
Lu and Jiang, 2013 [32]	China	not specified	embedded devices S3C6410	ultrasonic sensor	US-100	1	- detection range (0.02 – 4.5 m)	acoustic alarm	NR	NR	- include GPS module for tracking corner-points extraction and navigation
Liu, 2014 [33]	China	waist, leg & foot	microcontroller STM32F103VET6 & E8_BOARD-I_V1	ultrasonic sensor	HC-SR04	7	- waist (5) & foot (2) - detection range (0.02 - 4 m) - detection angle (15°) - average error (±1.83 cm)	acoustic notification & haptic vibration (on waist and legs)	low	NR	None
Liu, 2020 [37]	China	head, shoulder, wrist or waist	Raspberry Pi 4B & Arduino Nano	ultrasonic sensor	US-100	3	- detection range (0.02 - 4 m) - detection angle (58.5°)	acoustic notification & haptic vibration	low	- limited detection accuracy, and human-computer feedback latency	- included GPS module for localisation
Lu, 2015 [34]	China	waist, leg & foot	microcontroller STM32F103VET6 & E8_BOARD-I_V1	ultrasonic sensor	HC-SR04	7	- waist (5) & foot (2) - detection range (0.04 - 4 m) - detection angle (15°) - average error (±2.89 cm)	acoustic notification & haptic vibration (on waist and legs)	low	- wired connected device - not able to detect dynamic obstacles and detect in complex terrain	- gravitational acceleration of the sensor obtained by filtering out the motion acceleration data from 5 attitude detection module with Kalmar filter
Huang, 2020 [36]	China	eye	laptop	ultrasonic sensor	HC-SR04	2	- detection range (0.01 - 4.5 m) - detection angle (15°)	acoustic notification	NR	- poor angular resolution of the ultrasonic sensor - algorithm detection speed is not fast enough - inability to detect small obstacles	- average speed of pathway detection after fusion (10 fps) - focused on transparent obstacle detection
				RGB-D camera	Realsense R200	1	- detection range (indoor 0.5 – 4 m) (outdoor ≤ 10 m)				
Yao, 2021 [38]	China	waist	Arduino & laptop	camera (not specified)	NR	NR	- average error (12.92%)	haptic vibration	low	- susceptible to changes in ambient light	None
Kang et al., 2017 [89]	Korea	eye	laptop	camera	NR	1	- 320 × 240 video at 25 fps streamed by Wi-Fi - measure the deformations and estimate the collision risk by deformable grid	acoustic alarm	NR	NR	None

TABLE 1. *(Continued.)* **Technology characteristics of the obstacle avoidance ETAs included in the 89 reviewed studies.**

Saputra et al., 2014 [98]	Indonesia	waist	laptop	RGB-D camera	Microsoft Kinect	1	- detection range (0.8 - 4 m) - FOV (57.5° (H) x 43.5° (V)) - auto-adaptive thresholding depth histogram algorithm for obstacle detection - average error (±30 cm at 3 m)	acoustic notification	NR	- not differentiate perfectly between the object and the floor at distance further than 2500 mm	- average error of the system to calculate the closest object (130.796 mm)
Shoval et al., 2003 [21]	Israel	waist	laptop	ultrasonic sensor	NR	8	- detection range (≤ 3 m) - detection angle (15°) (total 120°)	acoustic alarm	NR	- image mode on the device is usually quite slow at less than half of a typical adult's full walking speed - the ultrasonic sensor-based, obstacle-avoidance system is not sufficiently reliable at detecting all obstacles under all conditions	None
Xia et al., 2022 [31]	China	eye	microcontroller GD32F103VET6 & floating-point unit Sipeed Maix Nano	laser sensor	VL53L0 V2	1	- Time of Flight based	acoustic notification	40.30 USD	NR	- obstacle avoidance accuracy (96.67%) (night < daytime) - average power consumption (226.92 mA/s) - included GPS module for localisation
				camera	OV7740	1	- 2 megapixel - YOLOv3tiny algorithm for traffic light detection				
Toro et al., 2020 [99]	Colombia	chest & waist	Nvidia Jetson TX2 & Arduino Nano	stereo camera	Zed Mini	1	- detection range (0.15 - 12 m) - FOV (90° (H) x 60° (V) x 110° (D)) - YOLO algorithm for object detection - integrate visual-inertial algorithm for SLAM	haptic vibration (on waist)	NR	NR	- the system processed at 11 fps
Khampachua et al., 2016 [77]	Thailand	wrist	smartphone	ultrasonic sensor	HC-SR04	1	- detection range (0.2 - 5 m)	acoustic alarm & haptic vibration	NR	NR	- the device augmented white cane for the best performance
Bhattacharya and Asari, 2021 [66]	India	hand	Raspberry Pi 4B & smartphone	smartphone camera	NR	1	- average time taken for a frame (474ms)	haptic vibration	low	NR	- average accuracy (84.45%)
Everding et al., 2016 [70]	Germany	head	microcontroller (not specified)	dynamic vision sensor	NR	1	- detection range (0.5 - 8 m) - average accuracy for object detection (99%±1%)	acoustic alarm	NR	- subjects were static during the test	None
Khan et al., 2020 [108]	Bangladesh	eye	Raspberry Pi 3B+	ultrasonic sensor	HC-SR04	1	- detection range (0.02 - 1.2 m)	acoustic notification	68 USD	- cannot detect wet-floor and staircases	- the blind assistant provided slightly faster navigation than the white cane
				camera	Raspberry Pi camera	1	- 8 megapixel - MobileNetv2 algorithm for object detection at 1 fps - average error (<20% in range of 15-20 m)				
Rey et al., 2015 [85]	Brazil	head	Arduino UNO	ultrasonic sensor	HC-SR04	1	- detection range (0.02 - 4 m) - detection angle (30°)	haptic vibration	NR	NR	- collision rate (31.1%)
Salonikidou et al., 2012 [101]	Greece	hand	Arduino UNO	ultrasonic sensor	Maxsonar EZ4	1	- detection range (≤ 5 m)	acoustic notification & haptic vibration	low	NR	None
Alayon et al., 2020 [102]	Philippines	lower abdomen & wrist	Arduino & Laptop	RGB-D camera	Microsoft Kinect	1	- detection angle (58°)	haptic vibration (on wrist)	NR	NR	- failure rate (0.6026%)
Isaksson et al., 2020 [103]	Sweden	eye	Nvidia Jetson TX2 & Laptop	stereo camera	Melexis EVK75123	1	- Time of Flight based - detection range (≤ 4 m) - FOV (99.3° (H) x 70.6° (V))	acoustic alarm	NR	NR	None
Dunai et al., 2012 [93]	Spain	eye	FPGA	3D CMOS image sensor	NR	NR	- Time of Flight based - detection range (0.5 - 5 m) - detection angle (60°)	acoustic alarm	NR	NR	None
Stopar, 2020 [104]	Slovenia	eye & waist	microcontroller Adafruit HUZZAH32	ToF sensor	NR	10	- detection range (≤ 4 m) - detection angle (22°) - FOV (64° (H) x 55° (V))	haptic vibration (on waist)	NR	NR	None
Wang et al., 2017 [57]	US	chest & waist	embedded computer	RGB-D camera	NR	1	- structured light based - detection range (≤ 3 m) - point cloud array at 10 fps	haptic vibration (on waist) & braille display	NR	NR	None
Ahmad et al., 2016 [105]	Pakistan	waist	Intel NUC	RGB-D camera	Microsoft Kinect	1	- detection range (0.4 - 2 m)	haptic vibration	low	- cannot detect uneven surface and stairs	None
Li et al., 2022 [30]	China	eye & leg	NVIDIA Jeston Nano & cloud computing unit	ultrasonic sensor	URM09-Analog	1	NR	acoustic notification & haptic vibration (on legs)	~400 USD	- the performance would be influenced by the network status	- the transmission and processing of the system depended on network state
				RGB-D camera	RealSense D435i	1	- ORB-SLAM2 and fuzzy-based algorithm for navigation - Yolov4-Lite algorithm for obstacle detection at 39 fps				

TABLE 1. *(Continued.)* Technology characteristics of the obstacle avoidance ETAs included in the 89 reviewed studies.

Ali A. et al., 2021 [65]	India	eye	Google Glass & smartphone	camera	Google Glass	1	- 5 megapixel - invoke custom vision API from Azure Cognitive Services for object detection	acoustic notification	expensive	- proposed system is highly dependent on a strong internet connection - expensive in developing countries and is not easily affordable - run only for 4 hours per charge while using the application continuously	None
Aladrén et al., 2016 [92]	Spain	chest	laptop	RGB-D camera	Asus Xtion Pro	1	- range segmentation algorithm at 2 fps	acoustic notification	NR	NR	- the system run at 0.3 fps - the algorithm was robust to lighting changes, glows, and reflections
Bai et al., 2018 [27]	China	eye	embedded CPU board	ultrasonic sensor	HC-SR04	1	NR	acoustic notification	low	NR	None
				fish camera & RGB-D camera	NR	1	- visual SLAM algorithm for navigation				
Elmannai and Elleithy, 2018 [58]	US	chest	microcontroller FEZ Spider	camera	GHI Electronics	2	- detection range (0 - 9 m) - ORB algorithm for object detection	acoustic notification	242.41 USD	- walls and large doors may not be detected	- included GPS module for localisation - the system run at a maximum of 20 fps - obstacle detection accuracy (98%) - obstacle avoidance accuracy (100%)
Patil et al., 2018 [63]	India	foot	not specified	ultrasonic sensor	NR	6	NR	acoustic notification & haptic vibration	NR	- unable to sense a pit or downhill - unable to sense downstairs - sense a wet-floor only after a user step on it	- detect water by liquid detector sensor
Ifukube et al., 1991 [24]	Japan	eye	a microprocessor	ultrasonic sensor	NR	1	- transmitter (1) & receiver (2) - have a wide frequency range and broad directivity	acoustic alarm	NR	- the size of device is relatively large	None
Meers and Ward, 2005 [25]	Australia	eye, shoulder (bag) & hand	laptop	stereo camera	Videre Design DCAM video camera	2	- calculate depth by stereo disparity algorithm	electro-neural stimulation (on hand)	NR	- cannot calculate the disparity due to a lack of identifiable features (featureless surfaces)	- the system achieved 15 fps
Pawar et al., 2022 [67]	India	eye & waist	smartphone & microcontroller ESP32	smartphone camera	iPhone 12 Pro Max	1	- detection range (object detection ≤ 2.89 m) (optical character recognition ≤ 4.2 m) - EfficientDet Lite1 algorithm for object detection - Midas v2.1 small algorithm for monocular depth mapping - Firebase ML Vision algorithm for optical character recognition	acoustic notification & haptic vibration (on waist)	NR	NR	- included GPS module for localisation - the system run at 8 fps for outdoor mode / 4 fps for indoor mode
Bai et al., 2019 [28]	China	eye	smartphone	RGB-D camera	RealSense D435	1	- OTSU and RANSAC algorithm for ground segmentation - PeleeNet + SSD for obstacle detection	acoustic notification	NR	NR	- the system achieved at approximate 20 fps
Bhatlawande et al., 2014 [62]	India	wrist & waist	BeagleBoardxM & LaunchPad MSP430	ultrasonic sensor	Maxbotix MB 1340	1	NR	acoustic notification & haptic vibration (on wrist)	~300 USD	- cannot recognize obstacles	- avoided possible obstructions from a safe distance using the combined aid (proposed system + white cane)
				USB camera / webcam	Logitech C525	1	- FOV (69°) - mobility algorithm for path and obstacle detection				
Cardin et al., 2007 [22]	Switzerland	entire torso (vest)	microcontroller PIC16F87 & microcontroller PIC18F6720	ultrasonic sensor	NR	4	- detection range (0.03 - 3 m) - detection angle (60°) - error (≤ ±1%)	haptic vibration	NR	- the difference of the ultrasonic reflectance of the different materials reduces the performance of the system - failure due to the occlusion of the sensor by the user's hands	- a reduction of 50% of the time to pass through the obstacles
Hicks et al., 2013 [87]	UK	eye	laptop	depth camera	ASUS Xtion Primesense 1080	1	- infrared based - detection range (0.5 - 8 m) - FOV (58° (H) x 45° (V)) - display frame rate (between 25–30 fps)	LED display	NR	NR	- designed for partially sighted individuals
Kaur and Bhattacharya, 2019 [64]	India	chest	Odroid XU4	laser sensor	Hokuyo URG-04LX-UG01	1	- detection range (0.02 - 5.6 m) - detection angle (240°)	acoustic notification	low	NR	- the system run at 1 fps
				USB camera / webcam	Logitech C270	1	- 3 megapixel - multimodal CNNs with different types of features like edges, Gaussian, and optical flow are used				
Lee et al., 2014 [90]	Korea	entire torso (clothing) or shoulder (bag)	Xhyper-PX270 & UST -MPB-Atmega128v2.0	ultrasonic sensor	SRF02	8	- detection range (0.2 - 6 m) - detection angle (38°-40°) - time spent on scanning and feedback (0.45 + 0.6 s)	acoustic notification & haptic vibration (on jacket)	NR	NR	- included GPS module for localisation
				marker camera	NR	1	- FOV (40° -46°)				
Ling et al., 2019 [91]	Malaysia	finger	Arduino Pro Mini	ultrasonic sensor	Maxbotix HRLV-	1	- detection range (0.3 - 5 m) - resolution (1mm)	acoustic alarm	low	- many factors effect to the success rates of detection	None

TABLE 1. ***(Continued.)*** **Technology characteristics of the obstacle avoidance ETAs included in the 89 reviewed studies.**

					Maxsonar-EZ1						
Kassim et al., 2016 [73]	Japan	eye & wrist	Arduino Pro Mini	ultrasonic sensor	Maxbotix MB1003	4	- detection range (0.15 - 6.45 m)	acoustic notification & haptic vibration (on wrist)	NR	NR	None
Silva and Wimalaratne, 2020 [86]	Sri Lanka	waist	Arduino & cloud computing unit	ultrasonic sensor	NR	5	- detection range (0.02 -4 m)	acoustic notification & haptic vibration	NR	NR	None
				smartphone camera	NR	1	- only triggered when obstacle detected				
Takefuji et al., 2020 [74]	Japan	chest	Nvidia Jetson TX2	stereo camera	ZED Mini	1	- detection range (≤ 3 m) - FOV (60° (H) x 90° (V)) - YOLO algorithm for obstacle detection at 14-17 fps	acoustic notification	NR	- the information in YOLO is greatly affected by frames	None
Aguerrevere et al., 2004 [23]	US	eye	microcontroller MicrochipTM PIC16F77	ultrasonic sensor	OOPIC	6	NR	acoustic alarm	NR	- all of subjects navigated with similarly high levels of efficiency (84.7% - 99.2%) - average navigation speed recorded (34.43 ft/min)	None
Sainarayanan et al., 2007 [26]	Malaysia	head & entire torso (vest)	single board computer PCM-9550F	camera	KODAK DVC325	1	- fuzzy based learning vector quantization network for identifying objects	acoustic alarm	NR	- depth information was not considered	None
Darwish et al., 2023 [106]	Egypt	waist	laptop	ultrasonic sensor	NR	2	- detection range (0.02 - 5 m) - detection angle (60°) - feature extraction using Wavelet Transform - neutrosophic logic classifier	NR	NR	- unknown how truth, falsehood, and indeterminacy influence one another in the decision-making process - inference rules and the membership functions were also developed by hand - characteristics requires an optimization method	- accuracy rate (97.2±1%)

Abbreviations NR, Not reported; BVI, Blind and visually impaired; CNN, Convolutional neural network; FAST, Features from accelerated segment test; FOV, Field of view; FPGA, Field Programmable Gate Array; GPS, Global positioning system; ORB, Oriented FAST and Rotated BRIEF; RANSAC, Random sample consensus; SLAM, Simultaneous localization and mapping; SSD, Single-shot detector; ToF, Time of flight; YOLO, You only look once.

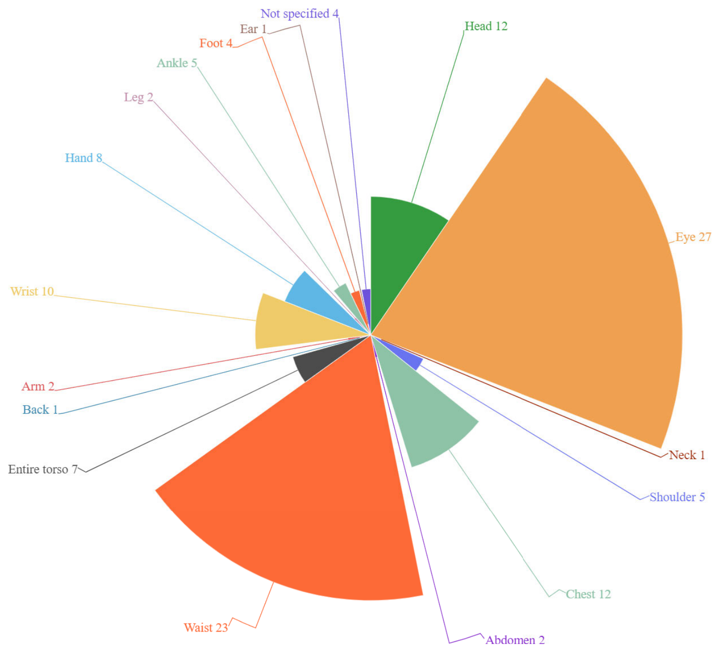

FIGURE 3. **Number of body parts to be worn.**

sensor is not a state-of-the-art technology, its cost-effective nature made it the primary choice for many device developers. The most common human-computer feedback modality was acoustic feedback, including acoustic notifications and acoustic alarms. Haptic or audio-tactile hybrid modes were employed in some other devices. More than two-thirds of the included studies did not provide cost information, making it hard to judge the affordability of their devices to the BVIs. The trial designed to test the efficacy of device in different studies varies considerably in their methodology, such as test scenarios, subjects, and/or evaluation criteria. Of particular note is that only 43.2% of the studies recruited real BVIs to validate the effects of their devices, which might lower the power of tests. Feedback and improvement suggestions from BVIs were sought in even fewer studies. This is a major weakness as the end user would provide the best feedback of the devices useability and efficacy and help developers to move in the best direction. Over-

TABLE 2. Socio-demographic characteristics and use experience of the ETAs users in the 89 reviewed studies.

Author, year	User socio-demographics			Use experience			
	Sample size (M=Male, F=Female)	Age (year)	Type of visual impairment (No.)	Effectiveness (Focus on obstacle avoidance; safety)	User-friendliness (Ease of utilising the device)	Wearing comfort / cognitive load	Demands on improving the designed device
Sun, 2014 [39]	NR	NR	NR				
Yang et al., 2021 [48]	NR	NR	NR				
Huang et al., 2022 [51]	NR	NR	NR				
Ge et al., 2022 [50]	6 (3M, 3F)	18-31	- Blindfolded (5) - Blindness (1)				
Jin, 2021 [46]	10	20-25	- Blindfolded			•	
Zhao, 2021 [49]	1	NR	- Blindfolded				
Zuo and Wang, 2020 [44]	1	NR	- Blindfolded				
Hu, 2016 [40]	NR	NR	NR				
Hu, 2021 [45]	12	17-19	- Visual impairment (3) - Blindness (9)	•	•	•	
Shi et al., 2022 [52]	NR	NR	NR				
Wang et al., 2020 [42]	1	NR	- Blindfolded				
Zhu et al., 2020 [43]	6	18-22	- Blindfolded	•			
Shen and Yuan, 2021 [47]	1	NR	- Blindfolded				
Ren et al., 2020 [41]	1	NR	- Blindfolded				
Pundlik et al., 2018 [60]	37	24-75	- Blindfolded (29) - Visual impairment (diabetic retinopathy) (1) - Blindness (congenitally) (7)				
Bouteraa, 2021 [94]	18	NR	- Blindfolded (2) - Visual impairment (16)	•		•	•
Ghaderi et al., 2015 [69]	10	28.7 ± 6.7	- Blindfolded				
Chen et al., 2021 [29]	NR	NR	NR				
Shen et al., 2022 [75]	3 (3M)	20-25	- Blindfolded		•	•	
Cheng, 2016 [100]	7 (5M, 2F)	20-45	- Blindfolded (5) - Visual impairment (1) - Blindness (1)	•		•	•
Barontini et al., 2021 [81]	23 (13M, 10F)	average 33	- Blindfolded (16) - Blindness (congenitally) (7)	•	•	•	
Ramadhan, 2018 [95]	55 (27M, 28F)	15-61	- Blindfolded - Visual impairment				
Katzschmann et al., 2018 [59]	16	25-65	- Blindness	•	•	•	
Martinez et al., 2020 [71]	5 (4M, 1F)	30-40	- Blindfolded (4) - Blindness (1)	•		•	•
Caraiman et al., 2019 [96]	4	NR	- Visual impairment				
Gao et al., 2015 [56]	22	NR	- Blindfolded				
Brown et al., 2019 [80]	26 (12M, 14F)	22-83	- Blindfolded (20) - Visual impairment (6)				
Petsiuk and Pearce, 2019 [61]	5	NR	- Blindfolded				
Mocanu et al., 2016 [11]	21	27-67	- Visual impairment	•	•	•	
Kilian et al., 2022 [72]	14	25-72	- Blindfolded (6) - Blindness (8)	•	•	•	•
Yang et al., 2016 [54]	8	NR	- Visual impairment (5) - Blindness (3)	•		•	•
Yang et al., 2018 [53]	6 (4M, 2F)	NR	- Visual impairment	•		•	•
da Silva et al., 2021 [137]	5 (2M, 3F)	20-32	- Blindfolded			•	•
Leporini et al., 2022 [82]	2 (1M, 1F)	47-70	- Blindness	•			
Zeng et al., 2012 [68]	6 (3M, 3F)	average 33.7	- Blindness		•	•	•
Filipe et al., 2016 [83]	2 (1M, 1F)	NR	- Blindness				
Vorapatratorn and Nambunmee, 2014 [78]	15 (9M, 6F)	average 35.5	- Blindness	•	•		•

TABLE 2. ***(Continued.)*** **Socio-demographic characteristics and use experience of the ETAs users in the 89 reviewed studies.**

Vorapatratorn et al., 2015 [76]	NR	NR	NR				
Vorapatratorn and Teachavorasinskun, 2017 [79]	6	NR	NR				
Yánez et al., 2016 [84]	1	NR	- Blindfolded				
Boudreault et al., 2016 [97]	13 (6M, 7F)	NR	- Blindfolded	•		•	•
Min Htike et al., 2021 [88]	18 (8M, 10F)	29-75	- Visual impairment (15) - Blindness (3)	•		•	
Lu et al., 2021 [55]	NR	NR	NR				
Tao et al., 2018 [35]	NR	NR	NR				
Lu and Jiang, 2013 [32]	NR	NR	NR				
Liu, 2014 [33]	1	NR	- Blindfolded				
Liu, 2020 [37]	24	15-35	NR	•		•	
Lu, 2015 [34]	10	NR	- Blindfolded				
Huang, 2020 [36]	1	NR	- Blindfolded				
Yao, 2021 [38]	6 (2M, 4F)	NR	- Blindfolded	•	•		
Kang et al., 2017 [89]	9	NR	- Blindfolded				
Saputra et al., 2014 [98]	10	20-40	- Blindfolded				
Shoval et al., 2003 [21]	NR	NR	NR				
Xia et al., 2022 [31]	1	NR	- Blindfolded				
Toro et al., 2020 [99]	2	20-30	- Blindfolded				
Khampachua et al., 2016 [77]	5	NR	- Blindfolded				
Bhattacharya and Asari, 2021 [66]	15	NR	- Blindfolded				
Everding et al., 2016 [70]	11 (9M, 2F)	average 28	NR				
Khan et al., 2020 [108]	60 (30M, 30F)	NR	- Blindness				
Rey et al., 2015 [85]	29 (30M, 30F)	average 23.93	- Blindfolded	•		•	•
Salonikidou et al., 2012 [101]	16 (13M, 3F)	16-54	- Blindfolded (11) - Visual impairment (5)				
Alayon et al., 2020 [102]	2	NR	- Blindfolded (1) - Blindness (1)				
Isaksson et al., 2020 [103]	2 (2M)	18-70	- Visual impairment (1) - Blindness (1)			•	
Dunai et al., 2012 [93]	20	NR	- Blindness				
Stopar, 2020 [104]	13 (12M, 1F)	average 29.5	- Blindfolded	•			
Wang et al., 2017 [57]	15	NR	- Blindness (6) - Blindness (congenitally) (9)				
Ahmad et al., 2016 [105]	2	NR	- Blindfolded (1) - Blindness (1)				
Li et al., 2022 [30]	5	NR	- Blindfolded (3) - Visual impairment (2)				
Ali A. et al., 2021 [65]	55	12-50	- Visual impairment	•	•	•	•
Aladrén et al., 2016 [92]	NR	NR	NR				
Bai et al., 2018 [27]	2	NR	- Visual impairment (1) - Blindness (1)				
Elmannai and Elleithy, 2018 [58]	1	NR	- Blindfolded				
Patil et al., 2018 [63]	70 (41M, 29F)	NR	- Visual impairment (48) - Blindness (22)				
Ifukube et al., 1991 [24]	2	24-29	NR				
Meers and Ward, 2005 [25]	5	NR	- Blindfolded				
Pawar et al., 2022 [67]	5 (3M, 2F)	19-22 (average 21)	- Blindfolded				
Bai et al., 2019 [28]	10	NR	- Visual impairment (10) - Blindness (10)	•	•		•

TABLE 2. ***(Continued.)*** **Socio-demographic characteristics and use experience of the ETAs users in the 89 reviewed studies.**

Bhatlawande et al., 2014 [62]	15 (10M, 5F)	20-55	- Blindness	•	•	•	
Cardin et al., 2007 [22]	5	NR	- Blindfolded				
Hicks et al., 2013 [87]	7	22-36	- Blindfolded			•	
Kaur and Bhattacharya, 2019 [64]	1	NR	- Blindfolded				
Lee et al., 2014 [90]	15	NR	- Blindfolded (5) - Visual impairment (10)	•	•	•	
Ling et al., 2019 [91]	10	NR	- Blindfolded				
Kassim et al., 2016 [73]	20	NR	- Visual impairment				
Silva and Wimalaratne, 2020 [86]	10 (6M, 4F)	22-70	- Blindfolded (7) - Visual impairment (3)				
Takefuji et al., 2020 [74]	69	NR	- Visual impairment				
Aguerrevere et al., 2004 [23]	4	NR	- Blindfolded				
Sainarayanan et al., 2007 [26]	NR	NR	- Blindness				
Darwish et al., 2023 [106]	NR	NR	NR				

Abbreviations NR, Not reported.
Notes The "•" symbol indicates that related user experience is reported in the study reviewed.

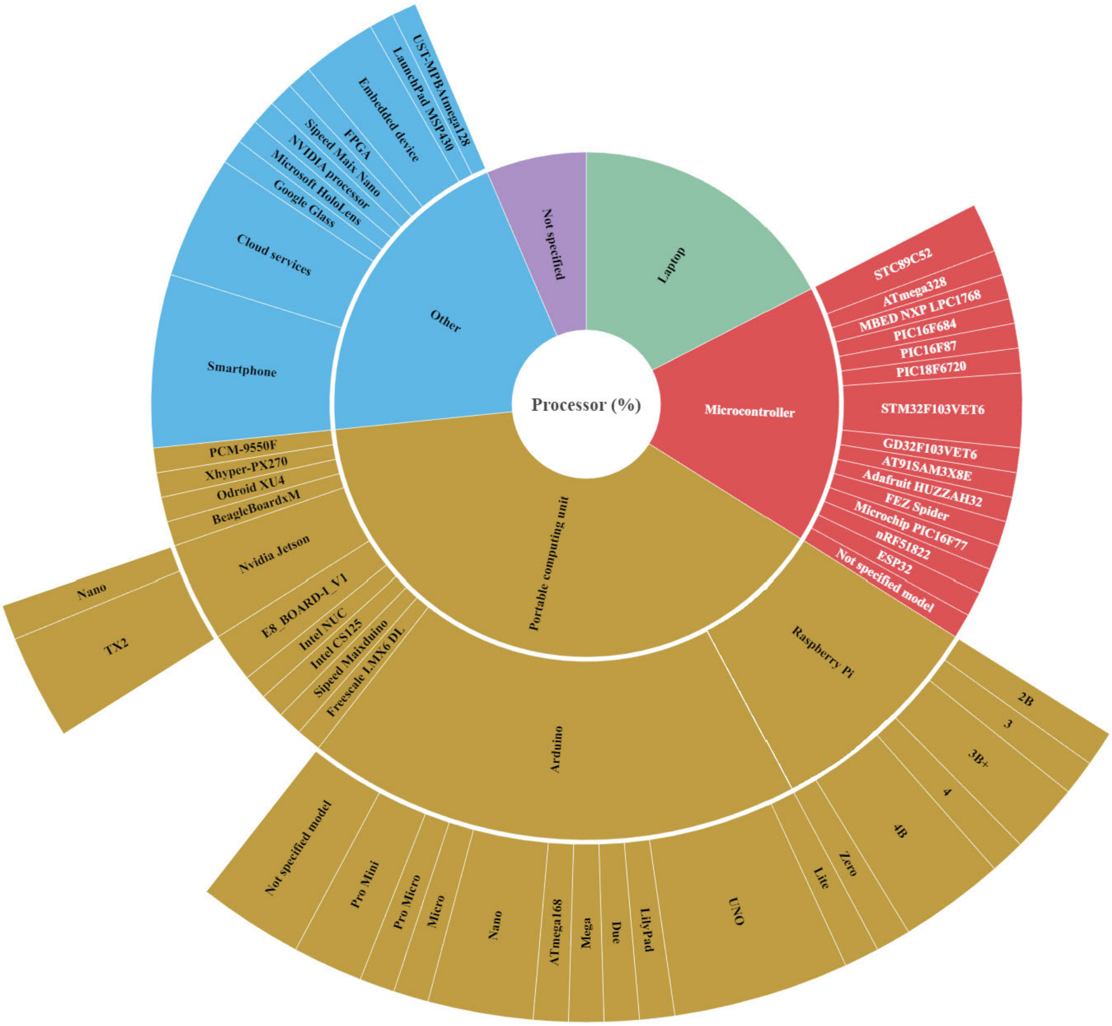

FIGURE 4. **The percentage of each processor and model.**

all, the quality of the studies was low to moderate mainly due to a lack of reporting the device's real-time feature in obstacle detection and the participants' ergonomics-related data.

B. STRENGTHS AND LIMITATIONS

To the best of our current knowledge, this is the first systematic review investigating the wearable obstacle avoidance ETAs. The 89 included studies originated from 32 countries,

TABLE 3. Methodological quality assessment of the 89 reviewed studies.

Author, year	Item 1	Item 2	Item 3	Item 4	Item 5	Total scores	Overall quality
Sun, 2014 [39]	0.5	0	0	0	0	0.5	low
Yang et al., 2021 [48]	0.5	0	0	0	0	0.5	low
Huang et al., 2022 [51]	1	0	0	0	0	1	low
Ge et al., 2022 [50]	0.5	0	0	1	0	1.5	low
Jin, 2021 [46]	1	0	0	0.5	0.5	2	low
Zhao, 2021 [49]	1	1	1	0	0	3	moderate
Zuo and Wang, 2020 [44]	0.5	0	0	0	0	0.5	low
Hu, 2016 [40]	1	0	1	0	0	2	low
Hu, 2021 [45]	1	1	1	1	1	5	high
Shi et al., 2022 [52]	0.5	0	0	0	0	0.5	low
Wang et al., 2020 [42]	0.5	0	0.5	0	0	1	low
Zhu et al., 2020 [43]	0.5	0	0.5	0.5	0.5	2	low
Shen and Yuan, 2021 [47]	1	0	0.5	0	0	1.5	low
Ren et al., 2020 [41]	0.5	0	1	0	0	1.5	low
Pundlik et al., 2018 [60]	0	0	0	1	0	1	low
Bouteraa, 2021 [94]	1	0	0	1	1	3	moderate
Ghaderi et al., 2015 [69]	0.5	0	0	0.5	0	1	low
Chen et al., 2021 [29]	1	1	1	0	0	3	moderate
Shen et al., 2022 [75]	1	0.5	0	0.5	1	3	moderate
Cheng, 2016 [100]	0.5	0	0	1	1	2.5	moderate
Barontini et al., 2021 [81]	0.5	0	0.5	1	1	3	moderate
Ramadhan, 2018 [95]	0.5	0	0	1	0	1.5	low
Katzschmann et al., 2018 [59]	1	0	0.5	1	1	3.5	moderate
Martinez et al., 2020 [71]	0.5	1	0	1	1	3.5	moderate
Caraiman et al., 2019 [96]	0.5	1	0	1	0	2.5	moderate
Gao et al., 2015 [56]	1	0	0	0.5	0	1.5	low
Brown et al., 2019 [80]	0	0	0	1	0	1	low
Petsiuk and Pearce, 2019 [61]	1	0.5	1	0.5	0	3	moderate
Mocanu et al., 2016 [11]	1	1	1	1	1	5	high
Kilian et al., 2022 [72]	0.5	1	0	1	1	3.5	moderate
Yang et al., 2016 [54]	1	0.5	1	1	1	4.5	high
Yang et al., 2018 [53]	1	0.5	1	1	1	4.5	high
da Silva et al., 2021 [137]	0.5	0	0	0.5	1	2	low
Leporini et al., 2022 [82]	0	0	0	1	0.5	1.5	low
Zeng et al., 2012 [68]	0.5	0	0	1	1	2.5	moderate
Filipe et al., 2016 [83]	0.5	0	0.5	1	0	1.5	low
Vorapatratorn and Nambunmee, 2014 [78]	1	0	0.5	1	1	3.5	moderate
Vorapatratorn et al., 2015 [76]	1	0	0.5	0	0	1.5	low
Vorapatratorn and Teachavorasinskun, 2017 [79]	0.5	0	0.5	0.5	0	1.5	low
Yánez et al., 2016 [84]	0.5	0	0	0	0	0.5	low
Boudreault et al., 2016 [97]	0.5	0	0	0.5	1	2	low
Min Htike et al., 2021 [88]	0.5	0	0	1	1	2.5	moderate
Lu et al., 2021 [55]	0	0	0.5	0	0	0.5	low
Tao et al., 2018 [35]	0.5	0	1	0	0	1.5	low
Lu and Jiang, 2013 [32]	0.5	0	1	0	0	1.5	low
Liu, 2014 [33]	1	0	1	0	0	2	low
Liu, 2020 [37]	0.5	0	0	0.5	1	2	low
Lu, 2015 [34]	1	0	1	0.5	0	2.5	moderate
Huang, 2020 [36]	1	1	1	0	0	3	moderate
Yao, 2021 [38]	0	0	0	0.5	1	1.5	low
Kang et al., 2017 [89]	1	1	1	0.5	0	3.5	moderate
Saputra et al., 2014 [98]	1	0	1	0.5	0	2.5	moderate
Shoval et al., 2003 [21]	0.5	0	0	0	0	0.5	low

TABLE 3. *(Continued.)* **Methodological quality assessment of the 89 reviewed studies.**

Xia et al., 2022 [31]	1	0	0	0	0	1	low
Toro et al., 2020 [99]	0.5	1	0	0.5	0	2	low
Khampachua et al., 2016 [77]	0.5	0	0	0.5	0	1	low
Bhattacharya and Asari, 2021 [66]	1	0	0	0.5	0	1.5	low
Everding et al., 2016 [70]	1	0	0	0.5	0	1.5	low
Khan et al., 2020 [108]	1	1	0	1	0	3	moderate
Rey et al., 2015 [85]	1	0	0.5	0.5	1	3	moderate
Salonikidou et al., 2012 [101]	0.5	0	0	1	0	1.5	low
Alayon et al., 2020 [102]	1	0	0.5	1	0	2.5	moderate
Isaksson et al., 2020 [103]	0.5	0	1	1	0.5	3	moderate
Dunai et al., 2012 [93]	0.5	0	1	1	0	2.5	moderate
Stopar, 2020 [104]	0.5	0	0	0.5	0.5	1.5	low
Wang et al., 2017 [57]	0.5	1	0.5	1	0	3	moderate
Ahmad et al., 2016 [105]	0.5	0	0	1	0	1.5	low
Li et al., 2022 [30]	1	1	1	1	0	4	high
Ali A. et al., 2021 [65]	0.5	0	0	1	1	2.5	moderate
Aladrén et al., 2016 [92]	0.5	1	1	0	0	2.5	moderate
Bai et al., 2018 [27]	0.5	0	1	1	0	2.5	moderate
Elmannai and Elleithy, 2018 [58]	1	1	1	0	0	3	moderate
Patil et al., 2018 [63]	1	0	1	1	0	3	moderate
Ifukube et al., 1991 [24]	0.5	0	0	0	0	0.5	low
Meers and Ward, 2005 [25]	0.5	1	0	0.5	0	2	low
Pawar et al., 2022 [67]	0.5	1	1	1	0	3.5	moderate
Bai et al., 2019 [28]	1	1	1	1	1	5	high
Bhatlawande et al., 2014 [62]	0.5	0.5	0	1	1	3	moderate
Cardin et al., 2007 [22]	0.5	0	0	0.5	0	1	low
Hicks et al., 2013 [87]	0.5	1	0	0.5	0.5	2.5	moderate
Kaur and Bhattacharya, 2019 [64]	0.5	1	1	0	0	2.5	moderate
Lee et al., 2014 [90]	0.5	0.5	1	1	1	4	high
Ling et al., 2019 [91]	1	0	0.5	0.5	0	2	low
Kassim et al., 2016 [73]	0.5	0	0	1	0	1.5	low
Silva and Wimalaratne, 2020 [86]	0.5	0	0	1	0	1.5	low
Takefuji et al., 2020 [74]	0.5	0.5	0	1	0	2	low
Aguerrevere et al., 2004 [23]	0.5	0	0	0.5	0	1	low
Sainarayanan et al., 2007 [26]	0.5	0	1	1	0	2.5	moderate
Darwish et al., 2023 [106]	1	0	1	0	0	2	low

Notes Item 1, study reports on three key attributes of the device, namely, reliability, complexity, feasibility of further optimization; Item 2, study includes information with respect to the real-time feature of device in obstacle detection; Item 3, study provides a novel mechanism or algorithm to optimize the technique of obstacle avoidance; Item 4, study details the socio-demographic characteristics of participants in the trial; Item 5, Study outlines the three types of ergonomics-related experiences (effectiveness, user-friendliness, and wearing comfort / cognitive load) of participants during human-computer feedback. low-quality, < 2.5 points; moderate-quality, 2.5 ≤ score ≤ 3.5 points; high-quality, > 3.5 points.

covering Asia, Europe, North America, South America, and Oceania, reflecting the diversity of research regions (**Table 1**). The quality of this review is further enhanced by the multidisciplinary collaboration, with team members have diverse academic background in engineering, computer science, and health science. In addition, we appraised the quality of evidence for each included study in the light of a uniform evaluation tool (**Table 3**), which might enable a more robust and reliable reference for potential device manufacturers when translating evidence into production practice.

Albeit this review was carried out strictly in compliance with PRISMA guidelines [19] and APISSER guideline [20], some limitations should be acknowledged. First, this review has restrictions to publications in English or Chinese. Given the fact that the current included studies were geographically diverse in origin, it is likely that there are eligible studies published in other languages were not included, which may affect our current findings. In fact, at least three of the retrieved studies were excluded as the language limitation during the screening stage (**Figure 1**). Second, significant heterogeneity across the trials designed for test devices' validity hindered a quantitative synthesis of evidence. Some trials assessed the device's obstacle avoidance effects for overhanging obstacles [59], [61], [68], [96], while others focused on that of static obstacles below the knees [56], [63], [96], or dynamic movement obstacles [94], [96]. The different test scenarios and the lack of standardised outcome measures for appraising obstacle avoidance effects contributed difficulties in pooling the evidence for a meta-analysis (quantitative analysis). Finally, the instrumentation used for assessing the quality of included studies was self-developed, and its reliability and validity is yet to be tested. Such methodological shortfalls also suggest an urgent need for the development of a standardized systematic review guideline/expert consensus, including credible quality assessment tool, to facilitate future evidence-based bioengineering practice in the human-machine field.

C. A COMPARISON WITH PREVIOUS SYSTEMATIC REVIEWS

During the literature searching work, four systematic reviews with similar themes were identified [5], [18], [109], [110]. All four studies included a review of wearable obstacle avoidance ETAs. The similarities and differences between these four reviews and our systematic review were summarised in **Appendix 3**. Among them, Khan et al. [18] critically reviewed the articles involving navigation/pathfinder and obstacle avoidance devices published between 2011 and 2020. Tripathi et al. [110] analysed studies regarding indoor/outdoor obstruction avoidance assistants published from 2011 to 2022. The other two studies [5], [109] reviewed wearable devices for orientation and mobility, and outdoor navigation systems separately. As introduced in the "Eligibility criteria" section, the navigation for the BVIs is an umbrella concept, including ETA, EOA, and PLD [111]. Whilst Santos et al. claimed that their review focused on ETAs [5], they inappropriately included three studies involving development of orientation devices (belongs to EOA) [112]–[114]. Khan and colleagues adopted a table to summarise the hardware components proposed for obstacle avoidance, while some components without function of obstacle avoidance (e.g., QR code, GPS, etc.) were incorporated [18]. Such ineligible evidence synthesis caused by insufficiently rigorous screening can introduce substantial heterogeneities across the studies, and subsequently makes it difficult to interpret the results. Our review only targets devices for obstacle avoidance ETAs to reduce variability and better reflect the real progress and current status within this topic.

All four previous reviews searched English databases, and one of them also searched Portuguese databases [5]. By comparing the original studies that were eventually included in Santos et al. and our reviews, we found that at least eight eligible studies [21], [68], [76], [83], [84], [88], [97], [98] were missed by Santos et al. We also noticed that the majority of our included studies were not included in the systematic review by El-taher et al., which may be attributed to the fact that the latter searched literature in only one database (Google Scholar) [109]. The systematic review of Tripathi et al. [110] also suffered from an incomplete search. It restricted the search years between 2011 and 2022, and ultimately included 32 studies. However, we found 84 eligible studies in this period. Searching is a crucial part of conducting systematic reviews [115]. Therefore, errors made in the search process (including incomplete search) can potentially result in an incomplete or otherwise biased evidence-base for the review, which is detrimental in understanding of the research topic [115].

In addition, we summarised the part of body devices were worn on, processor types, and cost of these wearable devices in the results section. This information is pivotal in association with user experience, which further enriches our findings. In the following paragraphs of the current review, we suggest a standardized test-scenario construction protocol to assist future studies with relevant topics to validate the obstacle avoidance effects of devices. None of such information was provided in the prior four systematic reviews.

D. INTERPRETATION OF FINDINGS

Based on the rapid development of information technology, wearable devices assign both mobility and connectivity attributes to users so that users can access online information conveniently and communicate with others (or other things) while moving [116]. BVIs are also beneficiaries of this technology. Obstacle avoidance is well accepted as one of the top three needs of BVIs for assistive devices [37]. In recent decades, a variety of wearable obstacle avoidance ETAs have been developed to facilitate their daily travel [111]. However, given the considerable heterogeneity in but not limited to product appearance, core technologies used, features and performance parameters, it is hard to judge which product is the best. It also remains unclear whether the existing devices have met the obstacle avoidance needs among BVIs, and what requires to be further optimized. Hence, we conducted this review to address these research gaps.

ETAs make non-contact perception and trailing possible [111]. It enables the BVIs to receive directional indications and have strategic locations in the environment through vision substitution which involves input from one or more signal sources, processing the signal, and output in a non-visual form [111]. The first challenge in device development is the effective and accurate perception of environmental information, including range, direction, dimension, and height of the obstacles. Some devices detect and classify the obstacles through feature extraction and machine learning classifiers, such as support vector machines [11]. Whereas, other devices [30], [31], [49], [52], [74], [75], [88] adopted an array of deep learning algorithms based on convolutional neural networks, such as classical YOLO series. This may be explained by the fact that the latter generally offers higher accuracy, more robust performance and a higher level of scenario interpretation [117]–[119]. Depth data is a great merit of RGB-D cameras, which is powerful under any indoor lighting condition and can be utilized to determine the proximity of the potential obstacles with respect to the user and deliver warning messages [81], [120]. Some other devices employed ultrasonic sensors. This detection technology is unrestrained by the condition of light where cameras may fail [46], but it is usually affected by environmental temperature and/or other sensors [76], [121]. Obstacle avoidance generally comprises obstacle detection (detection of existence of an obstacle) and obstacle recognition (type recognition of obstacle) [109]. Apparently, ultrasonic technology is also unable to achieve obstacle recognition.

The trade-off between pros and cons appears to be unavoidable in the selection of processors. Local or remote computing are common options for processing signals, such as live video streams and ultrasonic echo [119]. Deep learning algorithms based on neural network excel in obstacle avoidance, but their application is hampered by their large computational and memory requirements [119], [122]. We found that devices with the system running close to real-time (more than 30 frames per second) often tended to adopt a laptop or a cloud computing unit because their powerful computational resources meet the needs [30], [87], [89]. However, remote computing heavily relies on a strong internet connection [65]. In the current review, the majority of the devices used local computing, involving laptops and portable computing units (**Table 1**). Laptop is larger, heavier, and less comfortable to wear [65], [68]; whereas portable computing unit is commonly limited in computational performance. Reassuringly, researchers have been aware of such limitations. For instance, Shen et al. and colleagues introduced a neural compute stick and compressed the model in the portable computing unit, aiming to speed the system up while maintaining its merits in low weight and portability [75]. The signal in the BVIs' surroundings needs to be presented and interpreted in real-time so as for a device to play an effective role in navigation [123]. This temporal problem is caused by the signal processing delay of the ETAs system and the delay in the presentation of the signal to the user [123]. The majority of studies missed the latency or real-time performance of their system in our findings. It is not a compromise on high latency [11], [124] though a BVI adult walked with a shorter stride length and slower walking speed [125], [126] than sighted individuals.

The interface between humans and computers is essential to facilitate the accessibility and usability of a system [71]. Amongst the devices we reviewed, haptic feedback was not highly adopted. This might attribute to its direct invasiveness to the skin, inadequate sensory information provided, and potential vibration-induced neurological hazards (particularly in BVIs with skin diseases or diabetes) [5]. Two of the reviewed devices interpreted environmental information to BVIs via the Braille interface [57], [83], which is a "language" more familiar to BVIs. This design was however significantly reduced the hands-free advantage of the wearable device. Furthermore, the delay in rendering images to the BVIs is usually created when these devices interpret complex information through stimuli [123]. In contrast, the acoustic interface was more popular. Both speech feedback and acoustic signals are used to deliver the obstacle and scene information [46], but speech feedback could more specific on the information of the obstacles even recommend a clear pathway. The merits of comfort and flexibility are significant, as the user only needs a pair of headphones. In seven studies, bone-conducting headphones were included in the devices to provide audio output [11], [45], [53], [54], [69], [71], [103]. BVIs are thus able to hear other sounds and are in lower risk of auditory overload. Complying with the sonification guidelines, Hu introduced three types of stereo sound effects to represent the detected environments, which improves the efficiency of information transmission [45]. Many auditory-based devices convert the signal or image into sounds through the temporal aspect as the left-right translation is also delayed, while this delay might be improved with enough experience [123], [127]. An interesting finding was that at least four devices reviewed used a hybrid (acoustic and tactile) interface, which was claimed to be user-friendly and intuitive [5]. However, all these devices contained multiple components and needed to be worn in multiple body parts simultaneously [11], [37], [81], [128], which obviously challenges user comfort.

According to our review, most of the devices were worn on the upper trunk and head (including the eyes). This might facilitate the precise alignment of the sensors with the direction where the user would face [128]. Nonetheless, wearing the device on the head poses a significant challenge to the correct reading of head-mounted sensors, as the natural turning of the head during walking is inevitable. Some other devices had to be worn on the upper extremity, such as arm, wrist or hand [72], [77], [94], [95], [101]. Although the users can easily detect medium-sized obstacles such as tables and chairs within a scene with these devices, the user has to continuously keep the upper limb facing forward to detect obstacles during travel. With these devices, the user has to keep the upper limb facing forward to detect obstacles during travel. This actually hinders the natural swing of the arm during human walking, and can also lead to user's failure in minimising torque loading on the joints and skeletal structure so that losing optimisation of the motion of the lower limb [129]. Devices worn on the lower limbs face a similar situation as upper limb devices, being proficient at detecting small and low obstacles while having to cope with substantial motion during walking.

As reported, approaching 90% BVIs live in low- and middle-income countries [130]. Visually impaired community is generally lower paid than others [131]. The cost is thereby a key issue for this population, and also one of the critical non-functional requirements that should be considered for a highly acceptable ETA [131]. After all, an unaffordable cost can directly dilute the acceptance of the device [72], [123]. More than half of the reviewed studies did not report cost-related information; and two studies acknowledged that the devices were expensive [59], [65]. Even though the latter shows excellent performance in obstacle avoidance, cost is destined to be a potential ''stumbling block'' in the conversion process from design to production.

Power consumption is a key parameter of the device, while most of the included studies (97.8%) did not seem to pay enough attention. The electronic components such as sensors and processors require power to operate. They are generally needed to be continuous operation over extended periods of time. If the battery dies or the device shuts down unexpectedly due to high power consumption, it could be a significant inconvenience for BVI people and even put them at risk.

Nearly 40% of included studies only recruited blindfolded-sighted healthy volunteers to validate the effects of the device, which is likely to cause potential measurement error [119]. Although BVIs are limited to access to environmental information by sensory channels other than vision, their ability to compensate for other senses is superior to that of sighted individuals. As reported, BVIs typically perform better in some auditory processing tasks, such as speech perception [132] and pitch discrimination [133]. Després et al observed that early-blind subjects spent shorter reaction times than sighted subjects for sound localisation at far-lateral locations [134]. Such supra-normal auditory ability in far-space was also identified in late-onset blind individuals [135], with even better ability [136]. With recruiting blindfolded-sighted, Gao et al. [56] and Yánez [84] confirmed the benefits of their device. However, both research teams highlighted that future re-evaluation of the device in real BVIs is still required to facilitate researchers to obtain accurate device evaluation efficiently with the minimisation of erroneous estimation. In addition, verification of the subject's visual abilities was often not mentioned, such as a hospital certificate.

User involvement in the design and development of assistive aids is imperative to ensure usability and eventual acceptance by the target users [128]. For obstacle avoidance ETAs, this involvement includes observing/understanding travelling characteristics, challenges encountered, reactions in an unfamiliar scenario, and various expectations for the device among BVIs [5], [37], [81], [97]. Unfortunately, the majority of studies did not use enough feedback from the intended end users (people with total or partial blindness of short and long duration), and did not include data associated with user experience, including effectiveness, user-friendliness and wearing comfort/cognitive load (**Table 2**).

Of those studies included feedback, user-friendliness (Ease of utilising the device) and comments for improvement received the least attention. It is noteworthy that many studies emphasized the necessary training time prior to the device use. However, there is in fact a consensus that obstacle avoidance ETAs should be user-friendly (easy to use) without extensive training [111], [121]. Comfortableness remains a top priority for the BVI communities, according to end-user experience-based reviews and comments [72]. The majority of the users in the studies favored a lighter and more compact device [28], [71], [72], [94], [100]. The reality, however, is that volunteers found those devices were heavy with wires and suggest that the wires be compressed or the devices be modified to be wireless [53], [137]. Additionally, the BVI people express concern with face and object recognition as they aspire to be more engaged with their environment [28], [54], [94].

E. IMPLICATIONS FOR RESEARCH AND DEVICE

1) IMPLICATIONS FOR RESEARCH

- **Lack of standard guideline and quality evaluation tool**

Systematic review has been a popular and common practice in medical field [119]. In contrast to narrative or other traditional review techniques, systematic review is a more structured approach [138], with striking superiorities lie in transparent, objective and reproducible methodology for including all available evidence in the review and unbiased appraisal of validity and relevance of each included study [119], [139]. In consequence, evidence derived from systematic review minimize the risk of subjective interpretation and inaccuracies because of chance error affecting the review results [138]. These strengths have also attracted researchers to introduce systematic review to more interdisciplinary and technology-oriented areas (e.g., engineering, IT and communications, artificial intelligence, etc.) to perform research [119]. Pooling disparate studies and identifying common trends that may be missed by individual studies is expected to help/guide designers and manufacturers of wearable obstacle avoidance ETAs in evidence-based engineering practice as well as justify future research direction in said area for relevant researchers. However, there is a significant loop hole in the structured practical execution of engineering/computer science-related systematic review in linked to tool support [20], including standardized guideline (similar to PRISMA statement) and instrument for critical appraisal (similar to Cochrane RoB tool).

Without such a structural framework (strict guideline and highly detailed priori approach), it would be difficult to ensure methodological rigor and quality reliability in the review [139], [140].

The current review was carried out adhere to PRISMA statement [19] and APISSER guideline [20]. The latter was adapted and developed on the basis of PRISMA by two researchers in power electronics-related fields [20]. Although the APISSER was claimed to be a guideline to facilitate practice in engineering-related systematic review by following a task-oriented engineering flow and supported by customized tools [20], it does not appear to be fully applicable to the subject of our review. This may partially attribute to the fact that the development of ETAs for BVIs is a topic with multidisciplinary [141] and interdisciplinary [142] nature, which might involve automatic control, computer science, biomedicine, industrial design, and human engineering. The APISSER also did not provide a tool for assessing the quality of literatures [20]. Besides, Torres-Carrión and colleagues formulated a guideline to conduct systematic review in engineering and education disciplines [143]. However, their guideline was compiled based on a previous review method for software engineering, and it was inapplicable to the subject we are currently focusing on as well [143]. Accumulative evidence strongly encourages engineers to perform a systematic review at the beginning of every research process in order to quickly establish what has been done and build on each other's work and knowledge [20]. This might be viewed as an evidence-based engineering philosophy with an aim —- providing the means by which current best evidence from research can be integrated with practical experience and human values in the decision-making process concerning the design and optimization of an engineering project [144]. We hence believe that the development of a more applicable and endorsed systematic review guideline with respect to the field of medical device engineering such as assistive technology for BVIs is warranted.

- **A need for wide-scope scene of trial assessment**

The huge heterogeneity across the device validation trials during the development and implementation phase of

APPENDIX 1. Search strategy.

Medline search strategy

No.	Search terms
1	blind [MeSH Terms]
2	blindness [Title/Abstract]
3	visually impaired [Title/Abstract]
4	visually Impaired Persons [Title/Abstract]
5	visual impairment [MeSH Terms]
6	vision disorders [Title/Abstract]
7	#1 or #2 or #3 or #4 or #5 or #6
8	obstacle avoidance [Title/Abstract]
9	wearable device [MeSH Terms]
10	wearable electronic device [Title/Abstract]
11	wearable technology [Title/Abstract]
12	wearable technologies [Title/Abstract]
13	wearable technique [Title/Abstract]
14	#9 or #10 or #11 or #12 or #13
15	#7 and #8 and #14

CNKI search strategy

No.	Search terms
1	避障 (篇关摘)
2	盲人 (篇关摘)
3	视障 (篇关摘)
4	视力障碍 (篇关摘)
5	#2 or #3 or #4
6	导盲 (全文)
7	导航 (全文)
8	#6 or #7
9	可穿戴 (全文)
10	#1 and #5 and #8 and #9

the prototypes impedes the standardised measurement and evaluation of the end-user experience [119]. It is difficult to objectively compare the performance of different prototypes using common criteria. The trials in the included studies often emphasized a narrow-scope scene in which the performance of a particular capability in obstacle avoidance such as hanging objects or ground objects, without consideration of the comprehensive functionality of the device. The representativeness of these prototypes is restricted to the lack of standardised assessment methods and potential reporting bias. These findings imply that there is an urgent need to develop or select standardised evaluation scenarios or assessment methods. We found a functional assessment, The Functional Low-Vision Observer Rated Assessment (FLORA), suitable for an ultra-low vision population [145], and it has been administered to evaluate a kind of retinal prosthesis system in clinical medicine [146]. Although this assessment was aiming to evaluate the impact of new vision-restoration treatments, most tasks for functional vision could be considered as a microcosm of the BVIs' daily life. We have selected 15 functional tasks that are relevant to obstacle avoidance as a reference of standardised measurement tool (**Appendix 4**). The researchers could calculate the percentage of four options (impossible, difficult, moderate and easy) through observing the performance of the subjects in all selected functional tasks, such that evaluate the prototypes objectively and comprehensively. Furthermore, Wiener et al. suggested that device should detect various obstacles that are ground level to head high and full body wide in the travel path according to the National Research Council's guidelines for ETAs [111], [147], which fills the gap in the description of obstacles in FLORA.

2) IMPLICATIONS FOR DEVICE

The obstacle avoidance scenarios are diverse and changeable as different types of obstacles might exist within multiple environments such as indoors or outdoors. It is essential that the solution of detecting environmental information is adaptive and independent of environmental modifications [119]. However, the available technologies used for perceiving the environmental information have their unavoidable limitations. For instance, computer vision-based methods fairly rely on the intensity of light and computational resources of the processor, which nearly leads to large power consumption. Ultrasonic-based approaches fail in detecting objects with smooth reflective surfaces and have a cross-talk with multiple sensors. Laser sensors are accurate at distinguishing small objects, but the laser beam must be pointed directly at the object [119]. Infrared sensors troubled by powerful natural light. Applying multiple environment detection techniques in combination can compensate for their respective shortcomings and enhance the performance of the ETA. However, engineers and researchers should consider addressing the cost, power consumption and wearer comfort issues result from these increased hardware requirements.

Similarly, engineers and researchers have to seek a trade-off among the computational resource, detection accuracy, latency, power consumption, weight and the dimension of an ETA. This is because the portable comput-

APPENDIX 2. **Tool for assessing quality of evidence in studies regarding developing a wearable obstacle avoidance device.**

No	Items	Score
1	Study reports on three key attributes of the device, namely, reliability, complexity, feasibility of further optimization (providing recommendations that can be used for device optimization or improvement) [**0 point**: no relevant information is provided; **0.5 point**: one or two attributes are reported; **1 point**: three attributes are reported]	
2	Study includes information with respect to the real-time feature of device in obstacle detection [**0 point**: no relevant information is provided; **0.5 point**: only the time required to analyze per frame is reported, e.g., the time required to detect/recognize per single video stream image; **1 point**: real-time performance, such as frames per second (FPS) of the device, is reported]	
3	Study provides a novel mechanism or algorithm to optimize the technique of obstacle avoidance [**0 point**: no relevant information is provided; **0.5 point**: only mechanism or program code (algorithm) is listed without detailed explanation; **1 point**: a novel mechanism or algorithm with detailed description and explanation is provided, such as the mathematical derivation is included]	
4	Study details the socio-demographic characteristics of participants in the trial [**0 point**: no specific information is provided or subject only is the designer of the device; **0.5 point**: subjects are blindfolded healthy-sighted volunteer; **1 point**: BVIs are invited outside the R&D team]	
5	Study outlines the three types of ergonomics-related experiences (effectiveness, user-friendliness, and wearing comfort / cognitive load) of participants during human-computer feedback [**0 point**: no relevant information is provided; **0.5 point**: one type of experience is reported; **1 point**: two or more types of experience are reported]	
Total scores		
Quality Assessment High-quality, Total scores > 3.5 points; Moderate-quality, 2.5 ≤ Total scores ≤ 3.5 points; Low-quality, Total scores < 2.5 points.		

APPENDIX 3. A comparison with previous systematic reviews.

	Items reviewed	Current review	Khan et al., 2021 [18]	El-taher et al., 2021 [109]	Santos et al., 2021 [5]	Tripathi et al., 2023 [110]
Range of years of included literature		Inception - 2023	2011 - 2020	2015 - 2020	Inception - 2021	2011 - 2022
Number of studies included		89	191	33 (Obstacle Avoidance)	61	32
Inclusion of literature in languages other than English		•			•	
Subjects' information	Wearable device	•	•	•	•	•
	Other forms of devices (e.g., robot, white cane, handheld device etc.)		•	•		•
	Obstacles avoidance (ETA)	•	•	•	•	•
	Other functionalities (EOA, PLD) (e.g., navigation, orientation etc.)		•	•	•	
ETAs' information	Sensor type	•	•	•	•	•
	Position of the sensor	•				
	Sensor characteristics	•				•
	Processor	•	•			
	User-system interaction (feedback)	•			•	
	Cost	•				
	Power consumption	•				•
	User socio-demographics	•			•	
	Use experience and feedback	•			•	
	Limitations of the device	•				
	A methodological quality assessment	•	•			

Abbreviations ETA, Electronic travel aids; EOA, Electronic orientation aid; PLD, Position locator device.

Notes The "•" symbol indicates that related item is reviewed in the previous systematic reviews.

APPENDIX 4. List of selected tasks from FLORA.

No.	Category	Task
1	Activities of daily living	Locate ordinary objects at various distance (familiar environment)
2	Activities of daily living	Identify ordinary objects at various distances
3	Activities of daily living	Identify top step/bottom step
4	Activities of daily living	Negotiate stairways independently
5	Interacting with others	Visually locate people in a non-crowded setting
6	Interacting with others	Determine when people walk by
7	Interacting with others	Detect the approach of another person
8	Interacting with others	Determine the direction of movement of people walking by
9	Interacting with others	Determine direction another person is facing
10	Mobility	Avoid obstacles while walking
11	Mobility	Estimate the size of an obstacle
12	Mobility	Detect curbs
13	Mobility	Avoid low-hanging branches, plants, head-high shelves, etc.
14	Visual orientation	Find doorways
15	Visual orientation	Recognize and use shapes for orientation and environmental information (e.g., stop sign)

ing units and embedded devices are sized in line with the expectations for wearable devices, whereas further improvements to real-time performance are eager. The latency contains two parts of delay from data processing and information rendering as aforementioned. A qualified device should be suitable for working in real-time in order to leave enough time for the BVIs to receive and react to the feedback information. In spite of the high accuracy, robustness, and efficiency of AI-based computer vision algorithms, the novel neural network-based models need significantly increasing computational resources [119]. A bulky laptop with high computational performance might not be the best choice for a wearable device. Cloud computing allows access to massive cloud resources to meet unpredictable demands, but signal instability while moving, unfamiliar scenes or network disconnection are inevitable and lethal topics for telecommunications and cloud computing.

In summary, the current findings suggest that further optimisation of existing wearable obstacle avoidance ETAs is required to meet the needs of independent travel among BVIs. An ideal user-friendly prototype is a cost-effective, user-centred and compact wearable ETA which detects obstacles in real time and has a trade-off among sensor characteristics, processor features and information feedback properties. This kind of balance can be dynamically adaptive to accommodate switching between scenarios. The feedback should be easy to understand without the need of extensive training. Of course, a switchable multiple-option of feedback interface is also encouraged to satisfy the diverse needs from the BVIs.

V. CONCLUSION

The current evidence indicates that many wearable obstacle avoidance ETAs have been designed to assist BVIs during independent navigation. These ETAs generally consist of different types of processors, environment detection techniques and human-computer feedback; and there are no studies comparing different ETA with each other. It is thereby hard to conclude which device is of optimum performance. Due to the limitations of various technologies or configurations, multiple environment detection techniques and human-computer feedback are proposed to be integrated into one ETA to provide optimal obstacle avoidance. Nevertheless, the increased hardware requirements of such combinations can inevitably lead to response latency, overloaded power consumption, increased device size and weight, as well as growing cost. Hence, finding the best trade-off between functional features (e.g., speed of detection, accuracy of detection, etc.) and non-functional features (e.g., cost, wearing comfort, etc.) remains a challenge to be solved in optimising this type of ETAs in the future. Considering the intrinsical differences in sensory compensation between BVIs and healthy people, user experience tests conducted with limited vision rather than blindfolded-sighted healthy volunteers can yield more accurate results. In addition, developing an applicable and standardised systematic review guideline with a credible quality assessment instrument for studies within the medical device engineering field is also warranted.

APPENDIX

See Appendices 1, 2, 3 and 4. The English search strategy in Appendix 1 was used for MEDLINE via pubmed while the Chinese one was used for CNKI; both two search strategies were also suitable for other electronic databases.

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