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REVIEW

The development of anti-fall functional clothing for elderly

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ABSTRACT

Objective: The consequences of falls in the elderly are severe, ranging from skin abrasion to hip fracture, which is very easy to cause death. Using advanced technology to develop anti-fall clothing that meets the needs of the elderly can play a significant role in protecting the elderly. By reviewing and analyzing the existing literature on the importance of fall protection clothing in reducing falls and protecting the body of the elderly, it is hoped to explore further research that needs improvement.

Methods: Guided by the preferred reporting items for systematic reviews and meta-analyses, eight related studies were identified through Web of Science, Scopus and Chinese National Knowledge Infrastructure. The research objects, approaches, material and equipment, protection principle, and survey results are extracted.

Results: Two articles verified the fall detection algorithm adopted in the research through experiments, which significantly improved fall detection accuracy. Six papers found that selecting appropriate cushioning materials can effectively reduce the consequences of falls of the elderly through experimental comparative analysis. Finally, three attributes for significant design value are drawn: (1) size and fit; (2) cushioning materials; (3) wearable sensing elements.

Conclusions: Anti-fall clothing can effectively protect the elderly when they fall. Further design experiments are needed to select appropriate cushioning materials and wearable sensing elements based on anthropometry and aesthetics to design the style and structure of the garment to achieve the purpose of protecting the elderly.

1. Introduction

Falling is one of the most critical threats to the life and health of the elderly. The World Health Organization reports that 28% to 35% of elderly over 65 experience a fall each year, and that number rises to 32% to 42% for those over 70.[1] According to the *Global Burden of Disease Study 2019* survey results, the incidence of falls among the elderly in China grew dramatically between 1990 and 2019.[2] Additionally, according to the Zhejiang Provincial centre for Disease Control and Prevention of China, falls account for more than 50% of injuries sustained by elderly persons who seek medical attention, and about 40% of elderly people suffer fractures.[3] Falls are responsible for more than 90% of hip fractures, which can result in severe disability, longer hospital stays, higher medical costs, and even an increase in mortality.[4]

Falls damage the physical and mental health of the elderly, reduce the quality of life of the elderly, and increase the economic burden on individuals, families, and society.[5-7] Preventing falls is an essential health issue among elderly. Studies on fall intervention for the elderly has been focus on physical activity, home hazard modification, medical intervention, and psychological intervention.[8-11] Clothing serves as the second skin of the human body, inherently possesses advantages in healthcare treatment and physical protection.[12] Protective clothing is essential for safeguarding against physical harm and enhancing safety and security.[13] To reduce falls risks among the elderly, researchers have developed anti-fall products such as e-textile pants, garment with airbags, pants with cushion material and vest with intelligent wearable devices.[14-17] These studies have shown that these functional clothes can significantly lower the number of falls and injuries among the elderly. Therefore, it is of great significance to create anti-fall clothing for the elderly.

Based on previously published papers,[18,19] this review defines the concept of "fall protection" as the protective effect of clothing when the elderly unintentionally fall to the ground or some lower plane (excluding falls caused by violence, loss of consciousness, hemiplegia or seizures). This paper aims to explore the relationship between anti-fall functional clothing and human fall monitoring and fall protection. In order to exclude the impact of disease on falls in the elderly, this review did not include cases reported by other chronic diseases such as hypertension and diabetes. "Elderly" is defined as citizens aged 60 and over. In addition, the change of body shape of the elderly and the inadaptability of clothing are also the influencing factors of falls.[20]

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Therefore, the literature on the clothing preference of the elderly is relevant.

This review provides necessary information on styles, structure, materials, equipment, and protection principles of anti-fall clothing for the elderly. Furthermore, the gaps found in this review can provide direction for future research. This paper will benefit not only the elderly but also health practitioners and clothing manufacturers.

2. Methods

2.1. Bibliographic database

This systematic review was conducted and reported under the preferred reporting items for systematic reviews and meta-analysis statements (PRISMA). The databases searched include Web of Science and Scopus and China National Knowledge Infrastructure (CNKI). Web of Science, which includes journals, books, patents, proceedings, and datasets, is the largest and most comprehensive academic information repository in the world. It compiles the most esteemed academic publications in a variety of research areas, including the natural sciences, engineering technology, and biomedicine.[21] Scopus is one of the world's largest databases of literature abstracts and citations, with over 23 452 active journal titles, 120 000 conferences and 206 000 books from over 5 000 international publishers, separated into categories of science, social sciences, technology, arts, medicine, and humanities.[21] CNKI is the largest and most frequently updated academic database in China, integrating resources such as journals, doctoral theses, master's theses, conference papers, etc.[22] The most comprehensive and authoritative logical literature now available worldwide is almost entirely covered by the Web of Science and Scopus databases.[22] As the country with the largest population of elderly people,[23] researchers in China have conducted extensive research on anti-fall strategies and clothing design for elderly,[2,4,15,16] so the research findings published in Chinese are equally important. These three databases fundamentally include all authoritative literature, confirming the validity of the data and the applicability of the research.

2.2. Systematic search strategy

Medical and technical papers by subject selected for containing "elderly fall" or "falls-related factors" or "fall" or "fall protection" or "elderly garment" or "adaptive clothing" or "anti-fall clothing" or "anti-fall fabrics" or "elderly pants" or "anti-fall pants" or "fall monitoring" or "old adult clothing" or "clothing preference of the elderly" or "clothing demand of the elderly" in titles and abstracts.

2.3. PRISMA statement

PRISMA has been used to retrieve articles for review analysis. The PRISMA is an established standard often used in the systematic literature review to improve the systematic review and meta-analysis reporting. The PRISMA process is divided into four stages: identification, screening, eligibility, and articles selected.[24]

The original search yielded 389 articles, which was reduced to 334 after removing duplicates. Titles, keywords, and abstracts of each article were screened, and when the eligibility criteria were applied, 72 articles were included in the full-text review. A total of 64 articles were excluded from the full-text review for reasons. Typical factors for exclusion include an absence of factors of a garment related to falls in the research ($n = 29$), the study focused on physical fitness changes in older adults ($n = 14$), fall and injury sites ($n = 9$), fall detection and prevention system ($n = 7$). Some articles contain the theoretical knowledge of anti-fall clothing design. Part of the paper is irrelevant to this review. Finally, 8 articles were included in the narrative review. Full details of the screening process are available in Fig. 1.

Finally, 8 articles have been selected through the PRISMA method, which met the requirements most in terms of research content, research methods, and research relevance. Two articles use the method of qualitative research to summarize and analyze the fabric selection, color, style design, and the application of intelligent technology for intelligent fall prevention clothing for the elderly. The remaining six studies use quantitative research approaches such as modeling, simulation, and experimental comparison to focus on fall prevention monitoring and anti-fall garment. Summary table was created to report the research objects, approaches, material and equipment, protection principle, combination mode, and results of each papers. Through longitudinal analysis and horizontal comparison, a narrative review was conducted to explore the design values of anti-fall clothing and their practical role in preventing and protecting elderly people from falls.

3. Results

3.1. The functions of anti-fall clothing

The development of anti-fall clothing for the elderly focuses on prevention and protection. Among the eight studies, three are aimed at the function of prevention, using wearable devices to monitor the daily life and physical state of the elderly and setting corresponding indicators to judge whether the elderly fall.[25-27] It will be sending Global Positioning System (GPS) positioning and physical condition data to relevant relatives' mobile apps to ensure that the guardian can grasp the situation of the elderly in real-time. Another five studies focused on the function of protection.[28-32] Starting from the clothing, according to the change of human posture, design the clothing structure line in line with ergonomics, and select appropriate energy absorbing and cushioning materials to improve the impact resistance of clothing (Table 1).

3.2. Design principles of anti-fall clothing

Eight selected papers studied the anti-fall effect and development principle of older people's anti-fall clothes from different aspects. The study results show that anti-fall clothing plays a role in two aspects: fall prevention monitoring and fall protection for the elderly. There are two qualitative studies on anti-fall clothes for the elderly.[27,30] Through comparative observation, the selection of appropriate software, hardware, style structure, fabric, and color are described, and the design effect of intelligent clothing is evaluated. In these two articles, sensors are used to monitor human posture and realize the early warning function before the elderly fall. In terms of implantation methods, detachable methods are designed to facilitate clothing cleaning. However, there is a lack of corresponding experimental evidence in the specific effect evaluation.

The other six quantitative research literature mainly focuses on simulating the protective effect of protective clothing through experiments to find the materials and clothing structure most conducive to preventing and alleviating the fall injury of the elderly. In terms of fall prevention monitoring, Kang et al.[25] and Niazmand et al.[26] have proposed a fall detection algorithm according to the magnitude of the action range. By simulating the four movements of front fall, side fall, fast run, and squat, after 200 groups of experimental data and multiple groups of tests, Kang et al. obtained that the recognition accuracy and accuracy of anti-fall intelligent clothing for fast run and squat reached 100%.[25] The accuracy rates of anterior and lateral falls were 98.7%, respectively 7% and 97.2% conclusion. In Niazmand et al.'s experiment, the algorithm implemented on the microcontroller has a true-positive-rate of 97.50% (sensitivity) and a specificity of 96.92%.[26] These two papers discussed the different protective effects of different materials and equipment and their different ways of combination with the clothing through the experimental analysis. Therefore, the performance of cushioning materials and the position of their combination with clothing are the main factors affecting the anti-fall effect of the elderly.

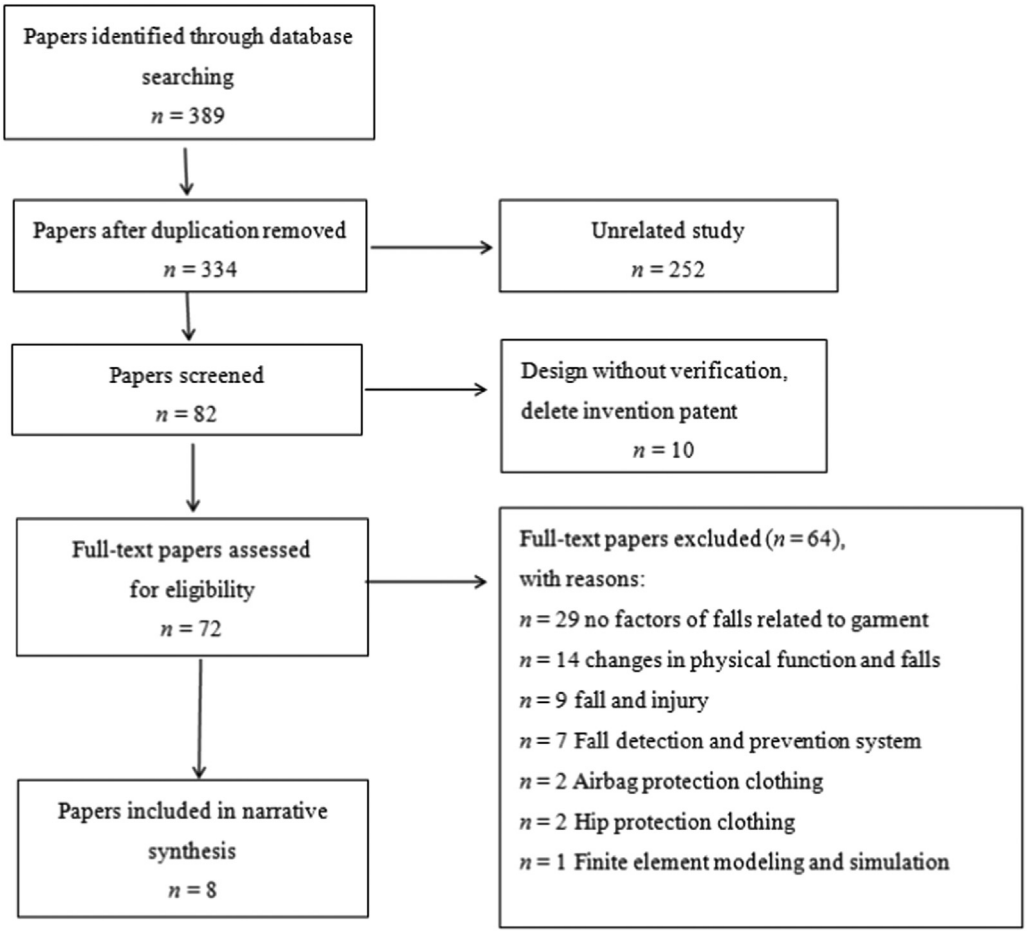

Fig. 1. Preferred reporting items for systematic reviews and meta-analysis statements diagram.

3.3. Protection methods of anti-fall clothing

In terms of protection methods, it can be divided into three categories. One is triggered protection based on monitoring. Li strictly considered the safety airbag's placement position after verifying the main impact parts of the human body when falling while creating the airbag fall protection garment.[31] However, only dummy experiments are carried out in the final test link, and the safety performance is unknown.

The second type of protection is based on non-triggered materials. Yu et al. tested the cushioning performance of six materials through experiments.[28] Finally, ethylene-vinyl acetate copolymer with a thickness of 20 mm was selected to create the protective pad. Park and Lee chooses the 5 mm thick chloroprene rubber foam with good cushioning and cushioning.[29] The protective pad designs three different forms of incision, punch, and sculpture while taking into account the surface and motion of the human body. The ergonomic structural design of trousers was presented by the two authors, who also evaluated the effectiveness of fall protection. The results show that the created trousers have a significantly better impact resistance effect.

The third type is to establish the model by the finite element method. Park and Nam proposes a finite element model of the hip joint in older women with virtual impact simulations that can replace actual fall and impact tests and examine the positions and characteristics of fractures resulting from falling.[32] The position of the proposed protective device matches the clothing baseline. With the support of virtual simulation, the protective performance of the clothing can be optimized in this study, reducing the risk of fractures caused by falls in the elderly and improving their quality of life and safety.

4. Discussion

The articles reviewed results show that some research has been done related to anti-fall functional clothing. Design characteristics are crucial in producing and designing ergonomic products that fit the elderly. Through the systematic literature review, 3 attributes for significant design value were drawn: ①size and fit—anthropometric study; ②cushioning materials—fabric properties; ③wearable sensing elements—electronic clothing device.

4.1. Size and fit—anthropometric study

Clothing, by its nature, has an inhibitory effect on the user's movement and activity.[33] Conventional clothing design will increase the resistance to physical activities of the elderly due to the lack of adaptability to the changes of the elderly. When the elderly have limited mobility or balance, wearing ordinary clothes can be challenging. For the elderly, the movements become restricted due to the reduction of muscular and articular flexibility, which can hinder the act of dressing. The elderly do not have enough strength to raise their arms high enough to pull a garment over the head. Ballak et al. emphasize that this progressive decline in muscle function is presumed to contribute to the increased incidence of falls.[34] The act of don and doffing pants, skirts, or other bottom clothing, for instance, requires flexibility of the torso and legs and the balance of the entire body. For older adults with physical body limitations, these behaviors can be very hard and even increase the risk of falls. One of the essential factors the elderly falls is their poor clothing.[20] Clothing for older people should be designed with their physical

Table 1
Material and design principle of anti-fall functional clothing.

Authors	Objectives	Research approaches	Material and equipment	Principle of protective	Combination mode	Results
Kang et al., 2021[25]	To design an anti-fall detection intelligent clothing	Modeling experiments; Comparative experiments	Damping and wear-resistant fabric, a joint angle measurement module	Detect alarm and send human body data to mobile app	Splice shock-absorbing fabrics and embed the joint angle measurement module	The anti-fall smart clothing achieved 100% accuracy in fast running and squatting,98.7%, and 97.2% accuracy in front and side falls
Niazmand et al., 2010[26]	To develop a washable garment for fall detection integrating acceleration sensors	Laboratory work	A washable pullover with integrated acceleration sensors	Eight acceleration sensors in the garment to detect the movements of the torso and the upper body	The electronics unit is integrated within the garment	The algorithm implemented on the microcontroller has a true-positive-rate of 97.50% (sensitivity) and a specificity of 96.92%
Wang et al., 2021[27]	To design intelligent fall alarm suit for the elderly	Inductive generalization, design evaluation	GSM module; GPS module; ADXL345Trip-angle acceleration sensor; Buzzer module; STM32 micro control unit	Achieve rapid alarm and immediately send location information	Sensor implantable design in a detachable way	The STM32 chip in smart clothing can achieve rapid alarm and send help information to the mobile phone when fall
Yu et al., 2020[28]	To design and develop a pair of anti-impact hip protection pants for elderly female	Interview, Comparative experiments	Material:sponge, elastic cotton, SBR, EPDM, CR, EVA Equipment: piezoelectric film sensor	Obtain the shape and data characteristics of the hip, and design cushion pad	The hip protection pad was inserted into the trouser suit based on the design of the side section line and the solid pocket	The fall impact force reduces by 29.92% compared with the case without protection, and increased by 12.67% compared with SHK-6010 underwear
Park and Lee, 2016[29]	To develop prototype of fall impact protective pants for elderly women	Interview; Comparative experiments	Material: chloroprene rubber foam. Fabrics: Tactel, Thermolite, Coolmax, Lycra. Impact protection pad	Design three types of cushions pad: cut type, the porous type, and the honeycomb type	Design A has protective pads in the hip, hip joint, and knee, while design B has protective pads in the hip and hip joint area	Proposed two kinds of design to develop protective pants. Design three kinds of pad types
Li and Wang, 2021[30]	To develop an intelligent anti-fall vest for the elderly	Inductive generalization, design evaluation	Impact-resistant fabric; MEMS inertial sensor	Elastic impact-resistant fabric is spliced at joints and airbag is embedded in the waist	Splicing	Design intelligent anti-fall vests should based on functional fabrics, ergonomic styles, and high-tech technologies such as intelligent warning, communication positioning, and airbags
Li, 2018[31]	To design the airbag anti-fall functional clothing	Observation research; Experimental measurement	600D polyester fabric; 1000D nylon fabric; Cooldry mesh breathable fabric; Warp knitted mesh	Connect the airbags in the neck, chest, shoulder, abdomen, pelvis, and waist	The airbag anti-fall vest is connected with the jacket through the zipper	An innovative design in terms of functional structure, fabric, and color
Park and Nam, 2020[32]	To proposes a finite element model of the hip joint for design protective clothing	Modeling experiments	Rhino 5.0; CATIA V5	Developed a finite element model to enabled a simple impact simulation	The position of the proposed protective device matches the clothing baseline	The model is readily applicable to designing protective devices to develop unique clothing for hip joint fracture prevention

GSM: Global System for Mobile Communications; GPS: Global Positioning System; STM: STMicroelectronics; ADXL: analog devices extra low power; SHK: Shan Hai Kang; SBR: styrene butadiene rubber; EPDM: ethylene propylene diene monomer; CR: chloroprene rubber; EVA: ethylene-vinyl acetate; MEMS: micro-electro-mechanical systems; CATIA: computer-aided three-dimensional interactive application.

characteristics in mind. All garments should be created to be easily don and doff, due to dizziness and loss of balance.[35]

There is a decline in sitting and standing height in old age due to vertebral compression, change in the height and shape of the vertebral discs, loss of muscle tone, and postural changes.[36] For older women, age affects stature and sitting height the most.[37] Women change their body shape with increasing age. The hips and waistline expand, the bustline and shoulders droop, the legs and face become thinner, and total height decreases. The dimension of a garment can be determined according to fashion or personal preference. It can be loose, irregular, or tight. For the clothing of the elderly, their requirements must be fulfilled concerning comfort while allowing them to perform tasks without any impedance or restriction. Under these circumstances, the fit is critical to the function of clothing and is often the only consideration in design. In addition, physical weakness and declining flexibility are often characteristics of advancing age. Clothing styles that are difficult to put on or move in can be an exceptional hindrance to an older adult. The existing standardized garment sizes, developed for body proportions typifying individuals aged 60 or less, can cause older women either wear ill-fitting clothes or make extensive garment alterations. Men, women, and children all have garment size standards, but there are no clear criteria for the elderly.[38] To design clothes suitable for the elderly, it is necessary to systematically measure the body shape and size of the target population, that is, anthropometry. Due to the physical constraints resulting

Table 2
The fabric property of cushioning materials.

Absorbing material	Strength	Weakness
Polymeric foams	Commonly used Several kinds Have good cushioning properties	Low air permeability Poor moisture transmission capability
Rubber	Large stretch ratio High resilience Extremely waterproof	Susceptible to vulcanisation Sensitive to ozone cracking
3D spacer fabrics	High breathability Good cushioning effect Excellent recovery property Very light in weight	Fraying edges Thicknesses, challenging to sew
Air cushion, airbag material	Strong protection performance Convenient to use Light quality Good Adaptation	Dress bloated Poor reproducibility Low practicability; Expensive
D3O material	Good protection performance Soft and curved Strong adaptability to human activities	Expensive Hard to acquire
Silicone	High-performance shock absorption Easy cutting Maximum flexibility Extremely comfortable	Expensive Hard to acquire

D3O: Delta Three Oscar.

from the stage of life, the elderly present difficulties in the act of dressing and the use of specific clothing products. In this sense, the integration of biomechanics, anthropometry, and ergonomics is essential for the correct sizing of the clothing since it protects its commitment to its users to satisfy their needs and expectations.

4.2. Cushioning materials—fabric properties

Cushioning materials can be applied to reduce the magnitude of impact when falls so that the subject will have fewer injuries. The application principle of cushioning material in protective clothing is that the material absorbs the impact force when the human body falls or disperses the impact load through the material to increase the buffer efficiency.[39] The cushioning material reduces the force created when one surface comes abruptly into contact with another by compressing or deforming to produce a gradual, rather than instantaneous, change in velocity. This property can reduce potentially high deceleration to more moderate values and minimize negative impact forces. Cushioning materials generally absorb kinetic energy under compression at relatively constant stress over an extensive displacement range to achieve cushioning. Typical cushioning materials include polymeric foams, polymeric solid elastomer, rubberized fiber cushions, air cushions, corrugated fibreboard, three-dimensional (3D) spacer fabrics, and Polymer energy-absorbing material. They have different fabric properties, shown as Table 2.[40]

Nowadays, different brands have started incorporating soft hip protective pads made from compressed foam pads into pants to produce hip protective pants for the elderly.[40] Because of the current situation that middle-aged and older women are vulnerable to waist and leg pain, Chen et al. proposed that soft, warm, breathable, and sweat-absorbing fabrics should be selected for the clothes of the elderly.[41] Wang analyzed the structure of human lower limbs and determined that the critical protective parts of female elderly fall protective pants are the hip and knee.[16] The 3D weft knitted fabric is woven as the cushioning material through the comparative analysis of the existing cushioning materials. The material is used in the design of trousers to protect the elderly. It can be seen that in the design of fall protection clothing for the elderly, the fabric itself should have softness, warmth retention, moisture absorption, and air permeability. It is important to choose cushioning materials that are lightweight, have good moisture absorption and breathability, and are highly compatible with clothing textiles.

4.3. Wearable sensing elements—electronic clothing device

Wearable devices mainly refer to electronic devices that can be directly worn on people.[42] They are electronic products that can be integrated into a garment or similar clothing. They are also wearable technology products that can use data interaction, cloud interaction, and software support to realize special functions on people's bodies. Wearable technology combines material technology and information technology and uses embedded sensor devices to monitor and analyze data in real-time to distinguish human action behavior.

There are two forms of wearable devices: one is rigid wearable devices, such as Google glasses, iWatch, and other consumer electronics, which can continuously provide people with continuous connection and data collection; the other is flexible wearable devices, designers develop clothing with unique functions such as medical care, safety protection and sports monitoring after interdisciplinary research on microelectronic components, chemistry, textile and garment ergonomics.[43] In order to integrate electronic components into textiles or clothing in a concealed manner, the design and sensing technology of flexible electronic circuits must complete the related work of circuit sensitivity optimization according to textile integration constraints and specific structural requirements.[44] The sensors in the early smart clothing are non-deformable hardware and electronic components, which are mostly used to collect the physical health data of severe patients with inconvenient movement, and are not suitable for adults who can move freely. The emergence of the flexible sensor makes sense of clothing of intelligent clothing and traditional clothing converge, and the operation is simple, and the aesthetics is increased. It makes up for its defects and extends the application range of clothing.

The research principle of protective clothing for the elderly is to embed sensing elements into clothing, wear them in various parts of the elderly's body, and monitor the movement state of the elderly in real-time, so as to judge the purpose of falling behavior. Wearable sensing technology design can be divided into early warning and positioning. When the sensing element detects the falling behavior, it will immediately send the fall early warning and then send the fall signal to the hospital or relatives through wireless transmission so as to realize real-time protection and timely treatment. The team of Virginia Tech University has developed an anti-fall electronic pant, which is equipped with electronic components containing communication devices, sensors, and microcontrollers for vulnerable parts of the human body such as the knees, waist, and head.[14] By detecting human gait stability, it can identify people with high fall risk, give early warning in advance, reduce the number of older adults injured by falling, and ensure the safety of older adults traveling alone. Tamura et al. developed a protective vest for the fall of the elderly.[45] The protective vest uses a triaxial acceleration sensor to judge the fall of the human body through the acceleration threshold.

The wearability and washability of most electronic devices have brought some problems. Vigorously developing sensing elements with excellent effectiveness, accuracy, miniaturization, waterproof, flexibility, and diversity, and adding sensing technology to protective clothing for the elderly is a significant development direction of fall protective clothing for the elderly in the future.

The physical and psychological consequences of a fall are serious: diminution of motility, less independence, limitation in daily life, less social, and loss of confidence.[6] Effective methods must be taken for prevention. Fall prevention is a significant issue in the aging society. According to Grave, dressing is a preventive act.[33] The recent literature on anti-fall clothing reflects the importance of such garment that benefits the elderly. The two themes of prevention and protection identified from the systematic literature review represented the impact of anti-fall garments in creating a healthy, comfortable, ergonomic living environment for the elderly.

5. Conclusions

Anti-fall clothing can effectively protect the elderly when they fall. Previous research has mostly focused on cushioning materials and intelligent wearable devices when design fall protection garments. The former pays attention to the protective performance of the material itself after design; The latter is mainly used in early warning and protection. Due to the emphasis on the development of anti-fall functions, clothing often has characteristics such as bulky appearance or inconvenient equipment operation.[28,31] Elderly people continue to participate in socially active activities as they age, which makes them more conscious of the aesthetics of clothing.[46] The height, weight, circumference, and physiological status of the elderly will change significantly compared with the young. Therefore, traditional ready-to-wear design approaches are no longer appropriate when creating functional apparel for the elderly. Future anti-fall clothing design must be more in line with the physiological and psychological changes of the aged, which includes doing research on the demands of anti-fall clothing and developing a sizing system for the elderly. In addition, future design should focus on the sustainability of material selection and manufacturing processes to reduce adverse environmental impacts, which will better meet the needs of future sustainable development.

In conclusion, the design of elderly anti-fall clothing in the future must take into account a wide range of variables, including functionality, comfort, aesthetics, sustainability, and diversity. This comprehensive design method will help meet the needs of the elderly, improve their quality of life, and promote the integration of fashion and functionality, providing them with more choices and freedom.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Chuan Tang: Conceptualization, Methodology, Writing – original draft. **Norsaadah Zakaria:** Supervision, Writing – review & editing. **Wan Syazehan Ruznan:** Writing – review & editing.

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