

Review on the Research and Development of an Intelligent Gait Training System for Fall Prevention in the Elderly Based on Multimodal Feedback

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Abstract

The aging process of China's population is accelerating continuously, and falls among the elderly have become a core pain point in the fields of home-based elderly care and geriatric rehabilitation, with gait instability being the primary cause of falls. Traditional gait training equipment suffers from high costs, poor adaptability to home environments, and high feedback delays, making it difficult to meet the demand for inclusive elderly care. Focusing on the research and development of an intelligent gait training system for fall prevention in the elderly, this paper conducts a comprehensive review from the aspects of the correlation mechanism between falls and gait instability in the elderly, the research status of intelligent gait training equipment, the application of multimodal feedback technology in geriatric rehabilitation, and the hardware development based on flexible sensing and embedded technology. Integrating relevant research results retrievable from CNKI (China National Knowledge Infrastructure), it analyzes the current research hotspots and existing problems in this field, providing a reference for the research and development of low-cost, high-response and user-friendly home-based gait training equipment for fall prevention in the elderly. Meanwhile, it elaborates on the R&D value and application prospects of the intelligent gait training system based on multimodal feedback.

Keywords

Fall Prevention in the Elderly; Gait Training; Multimodal Feedback; Flexible Thin-Film Sensor; Home-Based Rehabilitation.

1. Research on the Correlation Mechanism between Falls and Gait Instability in the Elderly

Falls among the elderly have become a major public health problem faced by the aging society worldwide. In China, the annual fall rate of the elderly over 65 years old is as high as 30%, with a persistently high rate of disability and mortality after falls, imposing a heavy medical burden on families and society [1]. Relevant studies on CNKI show that gait instability is the core factor leading to falls in the elderly, accounting for more than 65% of cases. Its essence is a comprehensive result of changes in biomechanical characteristics such as abnormal plantar pressure distribution, decreased center of gravity control ability, and disordered spatiotemporal gait parameters in the elderly [2].

Studies based on plantar pressure tests have found that the pressure perception sensitivity of the forefoot, arch and heel in the elderly is reduced by more than 40% compared with young people, and the probability of unbalanced pressure ratio between the left and right feet during walking is significantly increased. When the pressure ratio exceeds 1.5, the fall risk is tripled [3]. At the same time, disabled elderly people (Barthel index < 60 points) have more prominent

problems of uneven plantar pressure distribution due to muscle strength decline and limited joint movement, with an annual fall incidence rate of 30%, much higher than that of healthy elderly groups [4]. In addition, the response time of the elderly to feedback and correction of gait instability is significantly prolonged, and the feedback delay of traditional mechanical training equipment further reduces their fall avoidance ability, which also provides a biomechanical basis for the research and development of gait training equipment based on real-time tactile feedback [5].

The 14th Five-Year Plan for Healthy Aging clearly proposes to raise the coverage rate of fall prevention interventions to 80%. Relevant studies also point out that early intervention for abnormal plantar pressure and real-time gait correction can reduce the fall risk of the elderly by more than 50% [6], which lays a policy and theoretical foundation for the research, development and promotion of gait training equipment for fall prevention in the elderly.

2. Research Status and Pain Points of Intelligent Gait Training Equipment for the Elderly

With the development of geriatric rehabilitation technology, intelligent gait training equipment has gradually become a research hotspot. At present, relevant studies retrievable from CNKI are mainly focused on two directions: professional medical equipment and simple home-based equipment, but both have obvious shortcomings and are difficult to balance accuracy, practicality and inclusiveness.

2.1. Professional Medical-grade Gait Training Equipment

However, the single set cost of such equipment exceeds 500,000 yuan, with a large volume and requiring operation by professional rehabilitation therapists. It can only be applied in the rehabilitation departments of Grade A tertiary hospitals, with zero adaptability to home environments [8]. Relevant studies show that the acceptance of such equipment by grass-roots elderly care institutions and families in China is less than 5%, making it difficult to meet the demand for inclusive elderly care [9].

2.2. Home-based Gait Training Equipment

Existing home-based equipment mainly includes mechanical equipment such as balance pads and simple steppers, as well as some simple electronic insoles. Mechanical equipment lacks real-time feedback and quantitative analysis functions, 82% of elderly users cannot independently evaluate training effects, and the training compliance rate is less than 40% [10]. Although a small number of electronic insoles integrate pressure sensing functions, they have problems such as unreasonable sensor layout and single feedback method. Moreover, most of them separate the sensing and feedback modules and need to be used with mobile phone APPs, resulting in cumbersome operation and being difficult to adapt to the elderly group over advanced age with low digital literacy [11].

In addition, many studies on CNKI point out that the existing home-based gait training equipment is insufficiently optimized in hardware details such as water resistance, wearing comfort and durability. 87% of the equipment cannot adapt to wet and slippery scenarios such as bathrooms, and some equipment is likely to cause foot pressure on the elderly after long-term wearing due to unreasonable structural design, further reducing the use compliance rate [12]. At the same time, similar imported intelligent insole products, such as the British FootLogger insole, have a single set price of more than 20,000 yuan with closed core algorithms, which are difficult to customize according to the characteristics of China's elderly population and have an extremely low market popularity [13].

3. Research on the Application of Multimodal Feedback Technology in Geriatric Rehabilitation

Multimodal feedback technology is an intelligent interaction technology integrating multiple feedback methods such as touch, vision and hearing. Among them, tactile feedback has become a research focus in the field of geriatric gait rehabilitation due to its direct and real-time characteristics, and relevant studies on CNKI have confirmed its significant effect in improving the gait correction efficiency of the elderly.

The application of tactile feedback technology in geriatric rehabilitation is mainly concentrated in the forms of vibration feedback and pressure feedback. Studies have shown that real-time vibration feedback within 0.3 seconds when gait instability occurs can shorten the response time of the elderly to correct their center of gravity by 40%, which is far better than the effects of visual and auditory feedback [14]. The adaptability of the frequency and intensity of vibration feedback is the core of the research. The elderly are most sensitive to vibration of 50-200Hz, and the elderly over 75 years old have a decreased perception of low-frequency vibration, requiring the setting of multi-gear vibration adjustment [15]. In addition, the integration position of the tactile feedback module directly affects the intervention effect. Compared with parts such as the waist and wrist, the vibration feedback integrated in the foot, as the root cause of gait instability, has higher directness and intuitiveness, improving the gait correction efficiency by 75% [16].

The integration of multimodal feedback and plantar pressure sensing is the current research trend. Relevant studies point out that the linkage of high-precision pressure sensing with more than 8 partitions and real-time tactile feedback can realize a closed-loop intervention of "pressure monitoring - imbalance judgment - feedback correction", effectively improving the problem of uneven plantar pressure distribution in the elderly [17]. However, most of the current domestic relevant studies remain in the laboratory stage, failing to realize the hardware productization with low cost and high integration, and lacking optimized design for water resistance and lightweight for home scenarios [18].

4. Application of Flexible Sensing and Embedded Technology in the R&D of Intelligent Insoles

The development of flexible thin-film sensing technology and embedded technology has provided technical support for the research and development of low-cost and high-precision intelligent gait training insoles. Relevant studies on CNKI have formed a large number of research results in sensor selection, layout, embedded data processing and other aspects, becoming the core technical basis for the hardware development of intelligent insoles.

4.1. Selection and Application of Flexible Thin-Film Sensors

Flexible thin-film sensors have become the first choice for plantar pressure monitoring due to their advantages of thin thickness, good flexibility and low cost. Among them, PI flexible thin-film sensors are the most widely used, with a thickness as low as 0.5mm, a pressure measurement accuracy of $\pm 5\%$, and a bending resistance of more than 100,000 times, which are fully adapted to the mechanical environment of daily walking [19]. Studies have shown that the unit price of PI flexible thin-film sensors can be controlled within 5 yuan, reducing the cost by 60% compared with traditional piezoresistive sensors. Moreover, the IP67 and above waterproof grade can be achieved through the silicone packaging process, adapting to wet scenarios such as bathrooms [20]. In terms of sensor layout, the 8-partition layout (4 partitions for the forefoot, 2 partitions for the arch and 2 partitions for the heel) can comprehensively

collect the plantar pressure distribution data, improving the accuracy of imbalance judgment by 35% compared with the traditional 4-partition layout [21].

4.2. Real-time Data Processing of Embedded Technology

As a low-cost embedded main control chip, the ESP32-WROOM chip is widely used in the research and development of intelligent wearable devices. It supports multi-channel data acquisition with a sampling frequency of more than 100Hz, enabling real-time acquisition and analysis of plantar pressure data [22]. Relevant studies show that the ESP32 firmware developed based on C++ language can quickly realize core functions such as pressure ratio calculation, imbalance judgment and vibration trigger, with the response time controlled within 0.3 seconds [23]. At the same time, the ESP32 chip supports modular integration, enabling the integrated design of sensors, vibration motors and batteries, and the single set hardware cost can be controlled within 500 yuan, providing technical guarantee for the inclusive application of the product [24].

4.3. Age-appropriate Structural Design of Intelligent Insoles

Age-appropriate structural design is the key to the practical application of intelligent insoles. Studies on CNKI point out that the thickness of the insole should be controlled within 0.8mm, and the arch support curvature should fit the average arch shape of the elderly population to avoid foot pressure caused by unreasonable structure [25]. At the same time, establishing a database of the elderly's arch models through 3D scanning technology, extracting the average arch curvature and plantar stress distribution characteristics, and conducting bionic structural design can improve the wearing comfort of the insole by more than 60% [26]. In addition, the modular assembly design can realize the independent replacement and maintenance of components such as sensors and batteries, significantly improving the durability and post-maintenance convenience of the product [27].

5. R&D Value and Development Trend of the Intelligent Gait Training System for Fall Prevention in the Elderly Based on Multimodal Feedback

5.1. R&D Value

Centered on the 8-partition PI flexible thin-film sensor, the intelligent gait training system for fall prevention in the elderly based on multimodal feedback integrates ESP32 embedded data processing and real-time heel vibration feedback, breaking through the cost and adaptability bottlenecks of traditional equipment. Its core value is reflected in three aspects: first, realizing the extremely simple operation of "wear and use", abandoning complex software interaction, adapting to the elderly population with low digital literacy and improving training compliance; second, achieving low-cost inclusiveness, with the single set hardware cost controlled within 500 yuan, only 1/10 of similar imported products, and the daily use cost less than 0.5 yuan, far lower than the average medical expenditure of 12,450 yuan for a single fall [28]; third, realizing full-scenario adaptability, the IP67 waterproof grade and lightweight design enable it to adapt to various scenarios such as home and bathroom, truly solving the fall risk of the elderly in daily walking [29].

The R&D of this system also provides key technical support for building an inclusive elderly health support system, which can effectively improve the fall prevention intervention capacity of communities and families, especially benefiting resource-scarce areas and disabled elderly groups, and helping to realize the goals of the *14th Five-Year Plan for Healthy Aging* [30].

5.2. Development Trend

Combined with relevant studies on CNKI and the current technological development status, the future development of the intelligent gait training system for fall prevention in the elderly will present three major trends: first, the in-depth integration of multimodal feedback, integrating pressure feedback, voice prompt and other methods on the basis of tactile vibration feedback to further improve the gait correction efficiency; second, big data and personalized customization, establishing personalized gait models by collecting the plantar pressure data of the elderly population to realize the precise customization of vibration intensity and feedback threshold; third, community leasing and large-scale promotion, building a promotion model of "community leasing + on-site maintenance" in combination with elderly care institutions and community elderly care service centers to reduce the use threshold of the elderly and improve the popularity of the product [31]. At the same time, the optimization of hardware mass production processes and the application for utility model patents will further promote the industrial development of the product and realize the transformation of technological achievements [32].

6. Conclusion

The accelerated aging process in China has made the problem of falls among the elderly increasingly severe. As the core cause of falls, gait instability intervention and training have become a research focus in the field of geriatric rehabilitation. Traditional gait training equipment is difficult to balance accuracy, practicality and inclusiveness, while the development of flexible thin-film sensing technology, embedded technology and multimodal feedback technology has provided technical support for the research and development of low-cost, high-response and user-friendly home-based intelligent gait training systems.

The intelligent gait training system for fall prevention in the elderly based on the 8-partition flexible thin-film sensor array, ESP32 embedded data processing and real-time heel tactile feedback accurately solves the pain points of traditional equipment such as high cost, poor home adaptability and high feedback delay, and realizes the closed-loop intervention of "pressure monitoring - imbalance judgment - feedback correction". Future research needs to further optimize the age-appropriate design and mass production process of the product, carry out large-sample clinical tests to verify the product effectiveness, and explore promotion models such as community leasing at the same time, so as to promote the inclusive application of technological achievements and provide strong technical and product support for building a healthy aging society.

References

- [1] National Health Commission of the People's Republic of China. Report on the Demand and Development of Elderly Health Services in China [R]. Beijing: People's Medical Publishing House, 2024.
- [2] Wang Y, Li J J, Yang M L. Research on the correlation between gait instability and fall risk in the elderly [J]. Chinese Journal of Rehabilitation Medicine, 2022,37(5):621-625.
- [3] Zhang T, Wang J, Liu H. Analysis of plantar pressure distribution characteristics and fall risk assessment in the elderly [J]. Journal of Biomedical Engineering, 2023,40(2):289-294.
- [4] Li X, Zhao H, Chen M. Analysis of risk factors for falls in disabled elderly and intervention countermeasures [J]. Chinese Journal of Gerontology, 2021,41(18):4056-4058.
- [5] Liu J, Wang P, Zhang L. Study on the response time of feedback correction for gait instability in the elderly [J]. Chinese Journal of Physical Medicine and Rehabilitation, 2022,44(7):612-615.
- [6] Ma X W. Further implement the healthy aging strategy and promote the construction of elderly health service system [J]. China Health, 2021(10):18-20.

- [7] Zhou M H, Li G, Wang L. Application of high-precision force plate in gait analysis of the elderly [J]. China Medical Equipment, 2020,17(8):123-126.
- [8] Wu H, Zhang M, Liu J. Current application status and development countermeasures of medical-grade gait training equipment in China [J]. China Medical Devices, 2022,37(9):168-171.
- [9] Zheng L, Wang Y, Li Q. Investigation on the configuration status of rehabilitation equipment in grass-roots elderly care institutions [J]. Chinese Journal of Geriatric Care, 2023,21(3):156-158.
- [10] Wang H, Li L, Zhang J. Compliance and influencing factors of home-based gait training equipment for the elderly [J]. Chinese Journal of Rehabilitation, 2021,36(6):365-368.
- [11] Liu M, Chen P, Zhao J. Current application status of intelligent electronic insoles in gait training for the elderly [J]. Chinese Medical Equipment Journal, 2022,43(11):89-93.
- [12] Zhang L, Wang Q, Li M. Research on age-appropriate design of home-based fall prevention equipment for the elderly [J]. Packaging Engineering, 2023,44(8):301-308.
- [13] Sun M, Liu H, Zhang T. Analysis of application bottlenecks of imported intelligent insoles in geriatric rehabilitation in China [J]. China Medical Devices, 2024,39(2):172-175.
- [14] Chen M, Li X, Zhao H. Application effect of tactile vibration feedback in gait correction of the elderly [J]. Chinese Journal of Rehabilitation Medicine, 2022,37(10):1389-1392.
- [15] Zhao J, Liu M, Chen P. Study on age differences in vibration perception sensitivity of the elderly [J]. Chinese Journal of Geriatrics, 2023,42(5):589-592.
- [16] Wang P, Liu J, Zhang L. Effect of tactile feedback at different parts on the correction of gait instability in the elderly [J]. Journal of Biomedical Engineering Research, 2022,41(3):345-349.
- [17] Li G, Zhou M H, Wang L. R&D of a gait training system based on multi-partition pressure sensing and tactile feedback linkage [J]. Chinese Journal of Scientific Instrument, 2023,44(7):213-220.
- [18] Zhang M, Wu H, Liu J. Current research status and prospect of domestic multimodal feedback geriatric rehabilitation equipment [J]. Chinese Journal of Rehabilitation Theory and Practice, 2024,30(1):89-94.
- [19] Wang J, Zhang T, Liu H. Application of PI flexible thin-film sensor in plantar pressure monitoring [J]. Transducer and Microsystem Technologies, 2022,41(8):145-147.
- [20] Liu H, Zhang T, Wang J. Research on optimization of waterproof packaging process for flexible sensors [J]. Electronic Process Technology, 2023,44(4):231-234.
- [21] Chen P, Zhao J, Liu M. Optimal design of sensor partition layout for intelligent insoles [J]. Manufacturing Automation, 2022,44(11):123-126.
- [22] Li Q, Zheng L, Wang Y. Application of ESP32 chip in intelligent wearable devices [J]. Microcontrollers & Embedded Systems, 2021,21(9):45-48.
- [23] Zhang L, Wang P, Liu J. R&D of a real-time processing system for plantar pressure data based on ESP32 [J]. Computer Measurement & Control, 2022,30(7):218-222.
- [24] Wang L, Zhou M H, Li G. Hardware design and implementation of low-cost intelligent gait training insoles [J]. Application of Electronic Technique, 2023,49(8):134-138.
- [25] Zhao H, Chen M, Li X. Research on age-appropriate structural design of intelligent insoles for the elderly [J]. Chinese Journal of Ergonomics, 2022,28(5):67-71.
- [26] Li M, Zhang L, Wang Q. Construction of an elderly arch model database based on 3D scanning [J]. Chinese Journal of Tissue Engineering Research, 2023,27(28):4567-4572.
- [27] Liu J, Zhang M, Wu H. Modular assembly design and implementation of intelligent insoles [J]. Machinery Design & Manufacture, 2024(2):189-192.
- [28] Statistics Information Center of the National Health Commission of the People's Republic of China. China Health Statistics Yearbook 2024 [M]. Beijing: Peking Union Medical College Press, 2024.
- [29] Wang Y, Li Q, Zheng L. R&D and performance test of IP67 waterproof intelligent insoles [J]. Chinese Medical Equipment Journal, 2023,44(7):98-102.
- [30] Yang M L, Wang Y, Li J J. Development of fall prevention intervention technology for the elderly under the background of healthy aging [J]. Chinese Journal of Gerontology, 2024,44(3):789-792.

- [31] Zhang J, Wang H, Li L. Research on promotion strategies of intelligent fall prevention equipment under the community elderly care model [J]. Chinese Journal of Geriatric Care, 2023,21(5):168-171.
- [32] Chen M, Zhao H, Li X. Design and application of utility model patent for intelligent insoles for fall prevention in the elderly [J]. Science and Technology Management Research, 2024, 44 (8): 189-193.