Design of Wearable Walking Assist Device Based on Ergonomics Principles

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Abstract. To develop a wearable walking assistance device for the elderly that enables stable walking in complex scenarios with high wearing comfort, this study completed the dimensional, structural, and functional design of the device based on ergonomic principles, integrating the body shape characteristics and gait movement patterns of the elderly. The 3D modeling, hardware control circuits, and software design of the device were also finalized. Subsequently, modal analysis was adopted to investigate the vibration modes and natural frequencies of key components of the device. Simulation results were compared with the walking step frequency, muscle autonomous contraction frequency, ground impact frequency, and motor operating frequency of the elderly, verifying the rationality of the structural design. This study provides a reference for the design of similar wearable health and rehabilitation equipment.

Keywords: *Ergonomics; Wearable Walking Assist Device; 3D Modeling; Modal Analysis; Elderly Care*

1. Introduction

With the rapid development of the social economy, population aging continues to deepen, and the demand for elderly health and rehabilitation equipment is growing steadily. It is widely recognized that the probability of high fall risk among adults aged 60–79 years old reaches 10.5%, which is highly correlated with leg muscle strength and walking patterns [1]. Therefore, developing a walking assistance device adapted to the needs of the elderly is of great significance.

In recent years, domestic universities and enterprises have carried out extensive research on walking assistance devices for the elderly and achieved certain progress. For example, in 2023, Feng Kaixiang and Zhang Ting from Soochow University designed a flexible-joint-driven 4-degree-of-freedom hip exoskeleton robot, which effectively improved the walking balance of the elderly and reduced the probability of falls [2]. In 2024, Guo Zhanlong from Shaanxi Institute of Technology developed a control scheme for elderly walking assistants using a Proportional-Integral-Derivative (PID) control method based on a 3D human gait model, enhancing control performance and walking stability [3]. In 2025, Chen Yong and Zhao Junfeng from Dalian Jiaotong University adopted bionic design principles and a flexible design approach to develop a lower-limb exoskeleton robot capable of stable walking on complex terrain [4].

While existing studies focus on improving walking stability and preventing falls through device assistance, factors such as the adaptability between the device and the user's legs and wearing comfort are rarely addressed. Therefore, guided by ergonomic concepts, this study aims to design a structurally stable wearable walking assistance device adapted to the legs of the elderly while ensuring core functions, so as to improve wearing comfort and enable stable walking in complex scenarios.

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2. Overview of Ergonomics Principles

Ergonomics, also known as Human Factors Engineering or Human Engineering, is an interdisciplinary field that studies the interactions among humans, machines, and the working environment. Based on anthropometry, biomechanics, and human physiological and psychological characteristics, it aims to adapt products to the human body through rational design, thereby achieving the unity of safety, efficiency, and comfort in the human-machine-environment system [5]. In the design of wearable walking assist devices, it is necessary to match structural dimensions and driving parameters with the range of motion of lower limb joints, the force characteristics during the gait cycle, and the physiological degradation of the target users, so as to improve wearing compliance and prevent secondary injuries [5].

3. Data Sampling for the Walking Assistance Device

To ensure high adaptability between the wearable walking assistance device and the legs of elderly users, as well as to enhance wearing comfort and operational safety, this study adopts ergonomic principles as the core guideline. It places significant emphasis on the meticulous collection and comprehensive analysis of lower limb morphological parameters specific to the elderly population. Given the considerable individual differences in thigh length, calf length, and foot length among older individuals, fixed-size devices are insufficiently accommodating for the diverse range of body types. Such rigidity can lead to discomfort or even compromise the overall assistive performance of the device, ultimately hindering its effectiveness. Therefore, a tailored approach is essential for optimal user experience.

In this research, a carefully selected sample group comprising 1,000 elderly participants was utilized. The study employed precise anthropometric methods to accurately measure three key dimensional parameters—thigh length, calf length, and foot length. This comprehensive approach enabled the acquisition of statistically representative distribution characteristics of human body dimensions within this demographic. The resulting data will serve as a crucial geometric foundation for subsequent three-dimensional modeling, dimensional optimization, and the thoughtful design of wearing schemes for the device. Ultimately, these efforts will ensure that the final product aligns effectively with the unique lower limb morphology of the target population, enhancing comfort and usability.

Partial collected data are shown in Table 1.

Table 1. Partial data of sampling for the walking assistance device.

Measurement item	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Sample 6**	**Sample 7**	**Sample 8**
Thigh (cm)	42.5	44.2	41.8	43.6	42.1	42.5	44.2	41.8
Calf (cm)	32	35	34	36	37	36	35	37
Foot length (cm)	23.4	24.3	24.3	24.1	24.5	24.6	24.3	24.2

4. Hardware Design of the Walking Assistance Device

4.1. 3D Modeling of the Walking Assistance Device

According to the anthropometric data presented in Table 1, the mean thigh length of the sampled elderly participants was 42.8 cm (range: 2.4 cm), the mean calf length was 35.3 cm (range: 5.0 cm), and the mean foot length was 24.2 cm (range: 1.2 cm). Based on the statistical analysis of these measurements, the wearable walking assistance device was structurally divided into four primary components: a thigh support mechanism measuring 45.0 cm, a calf support mechanism measuring 35.0 cm, a foot sole support plate measuring 24.24 cm, and a connecting adjustment mechanism.

Each support mechanism incorporates a sophisticated slide rail–type continuously adjustable structure that is seamlessly integrated with elastic straps to achieve dual fixation and enhanced stability. The major dimensional parameters were carefully derived directly from an extensive anthropometric dataset, thereby ensuring compatibility with a broad range of lower limb morphologies within the target population. Furthermore, the anterior section of the device is equipped with an advanced infrared sensor along with an ultrasonic ranging sensor, enabling real-time detection of forward obstacles in various environments. This innovative configuration not only facilitates active obstacle avoidance but also provides a crucial early warning function against potential falls, significantly improving user safety and mobility [6].

The 3D models of the main components of the wearable walking mechanism are shown in Figures 1–4.

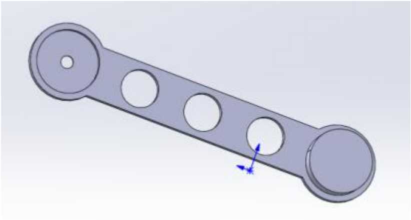

Figure 1. Thigh support mechanism.

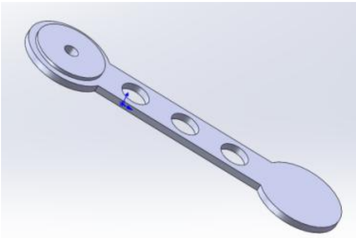

Figure 2. Calf support mechanism.

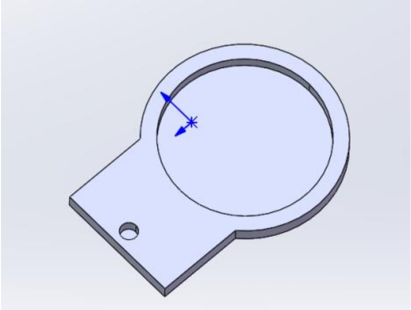

Figure 3. Knee joint assembly.

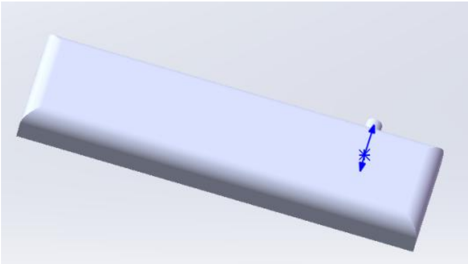

Figure 4. Pedal mechanism.

The general assembly 3D model of the walking mechanism is shown in Figure 5.

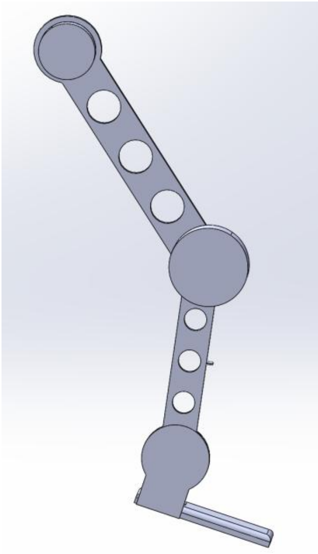

Figure 5. General assembly drawing.

4.2. Design of the Control System of the Walking Assistance Device

4.2.1. Main Controller Design

To achieve effective and precise control over each module in the system, this paper selects the STM32F103C8T6 microcontroller as the core component. This highly capable 32-bit enhanced microcontroller is built on an ARM Cortex-M3 core, operating at a maximum frequency of 72 MHz. It integrates a generous 64 KB of Flash memory and 20 KB of SRAM, making it suitable for various applications. Additionally, the microcontroller offers a wealth of peripheral interfaces, including a multi-channel 12-bit ADC, advanced timers, USB connectivity, CAN bus support, and SPI communication. Its three primary advantages are as follows:

(1) Extremely high cost-performance ratio, with strong performance and controllable cost, widely used in teaching and industrial mass-produced products [8];

(2) Complete peripheral resources, with hardware support for USB and CAN communication, greatly reducing the development difficulty of complex systems;

(3) Mature development ecosystem, with official CubeMX tools and a large community resource base significantly shortening the R&D cycle [9].

With its stable and reliable performance, this chip has emerged as the preferred solution for those venturing into embedded systems, particularly for beginners and designers working on small-to-medium-sized control system applications. Its versatility and ease of use make it an excellent choice for various projects in this field.

The minimum system of STM32F103C8T6 is shown in Figure 6.

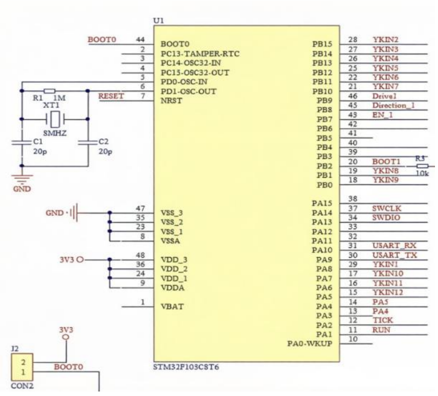

Figure 6. Minimum system circuit diagram.

4.2.2. Design of HC-SR04 Ultrasonic Ranging Module

Ranging module is recommended [10]. The module operates at a supply voltage of 5 V, offers a measurement range of 2 cm to 4 m, and achieves an accuracy of approximately ±3 mm. It can be directly interfaced with the GPIO ports of the STM32F103C8T6 microcontroller via its Trigger (Trig) and Echo pins [11].

The key advantages of this module include:

(1) Simple interface, only four connections are required to perform non-contact distance measurement, facilitating straightforward implementation in both hardware and software designs.

(2) High-cost performance ratio, the module is inexpensive, widely available, and well suited for large scale deployment in walking aid systems.

(3) Fast response with minimal blind zone, it enables rapid detection of forward obstacles, allowing timely activation of audiovisual alarm signals to enhance user safety [10–11].

The PCB of the HC-SR04 ultrasonic ranging module is shown in Figure 7.

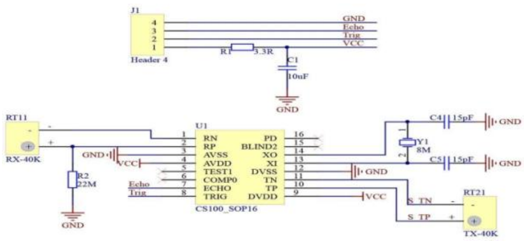

Figure 7. Ultrasonic eanging module circuit diagram.

4.2.3. Design of OLED12864 Display Module

For the elderly walking assistance device, a 0.96-inch OLED display module with an I²C interface (model OLED12864, driven by the SSD1306 controller) is recommended [12]. The module features a resolution of 128 × 64 pixels and is available with yellow blue or white emission options. Communication with the STM32F103C8T6 microcontroller requires only two signal lines—Serial Data Line (SDA) and Serial Clock Line (SCL)—enabling the display of critical information such as walking speed, battery status, obstacle proximity, and fall alert notifications [13]. The principal advantages of this module include:

(1) High contrast self-emissive display, the screen does not require a backlight, offers a viewing angle approaching 180°, and ensures clear readability for elderly users.

(2) Low power consumption, with a static current ranging from 0.02 mA to several milliamperes, it is well suited for battery powered, portable walking aids.

(3) Efficient interface utilization, The I²C communication protocol minimizes the number of occupied GPIO pins and benefits from extensive driver library support, facilitating streamlined integration with STM32 based systems [12–13].

The PCB of the OLED12864 display module is shown in Figure 8.

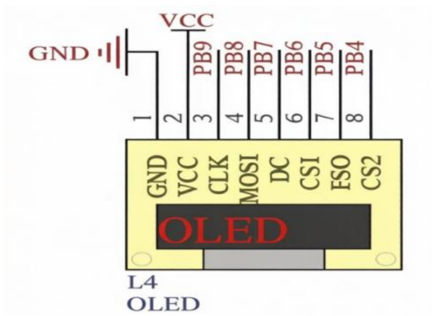

Figure 8. OLED12864 display module circuit diagram.

4.2.4. Design of Bluetooth Module

For the elderly walking assistance device, the HC 05 Bluetooth serial module—an integrated master slave device based on the BC417 chip—is recommended [14]. The module operates at a supply voltage range of 3.3 V to 5 V and interfaces directly with the USART peripheral of the STM32F103C8T6 microcontroller via a UART connection. It enables wireless transmission of critical data—such as fall alerts and obstacle distance measurements—from the walking aid to the caregiver's mobile application [15].

The main advantages of the HC 05 module include:

(1) Switchable master/slave modes, it supports direct interconnection between two HC 05 units or pairing with Android smartphones, thereby accommodating diverse networking requirements.

(2) Comprehensive AT command set and extensive documentation, Serial pass-through functionality is supported without the need for complex protocol stacks, reducing system development complexity.

(3) High-cost performance ratio, the module is low cost, widely available, and features an onboard status LED to indicate connection status, making it well suited for educational purposes and rapid prototyping [14–15].

The PCB of the HC-05 master-slave integrated Bluetooth serial module is shown in Figure 9.

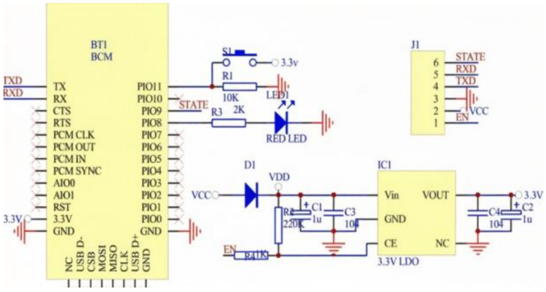

Figure 9. Bluetooth module circuit diagram.

5. Software Design of the Walking Assistance Device

5.1. Software Design Flow of the System

Upon system startup, the STM32 microcontroller first initializes its core peripherals, including the system clock, GPIO ports, timers, I²C bus, and USART interface. Following this essential initialization step, the OLED display module is configured, allowing for visual output, after which the HC SR04 ultrasonic ranging sensor is sequentially set up to enable accurate distance measurements. Next, the HC 05 Bluetooth serial module is initialized to facilitate wireless communication with other devices. Finally, the obstacle detection alarm threshold is established, ensuring that the system can effectively respond to potential obstacles in its path [16].

Within the main execution loop of the system, ultrasonic distance measurements are periodically triggered to ensure accurate monitoring. The acquired raw data from these measurements undergoes processing through a mean filtering algorithm, which effectively computes the actual distance. If the measured distance falls below a carefully predefined threshold value, the system promptly activates an audible alert via the onboard buzzer to notify users. Simultaneously, the updated distance value and overall system status are displayed on the OLED screen for easy visualization and monitoring. Additionally, this information is transmitted wirelessly through the HC-05 module to the caregiver's mobile application via serial communication, ensuring timely updates and efficient oversight [16].

The system operates in a continuous cyclic manner, which not only ensures real-time environmental monitoring but also facilitates prompt remote alarm notifications. This seamless process enables timely responses to any changes in the environment, enhancing overall safety and efficiency.

The flowchart of the system software design is shown in Figure 10.

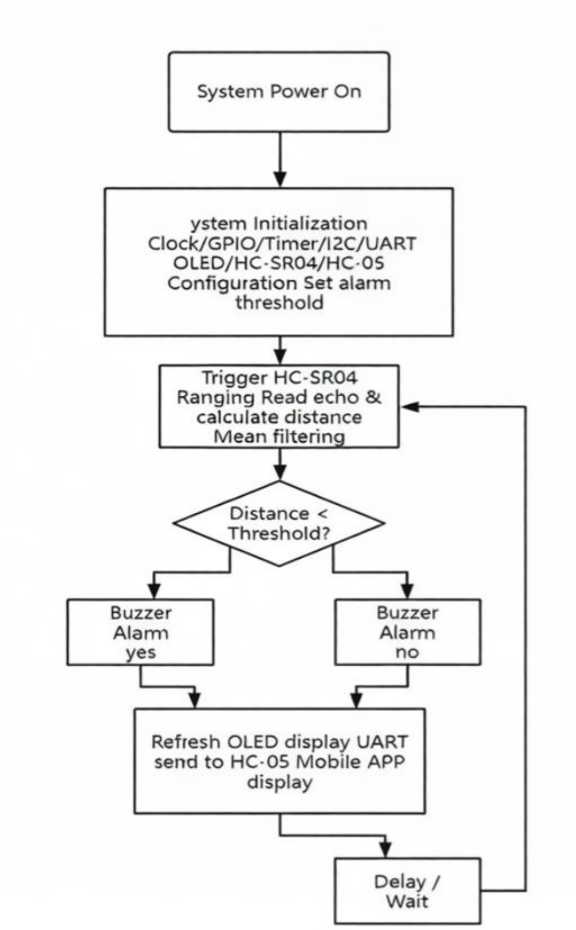

Figure 10. System software design flowchart.

5.2. Upper Computer Design of the System

The function of the upper computer is mainly to facilitate human-computer interaction with the wearable walking assistance device, allowing the elderly to manage the device appropriately during use according to actual conditions, and to keep track of the device status in time (such as thigh angle, calf angle, ultrasonic distance, motor assistance intensity, etc.). The upper computer design mainly includes modules for joint posture, environmental perception, driving assistance, safety protection, and obstacle warning threshold setting. The design flowchart is shown in Figure 11.

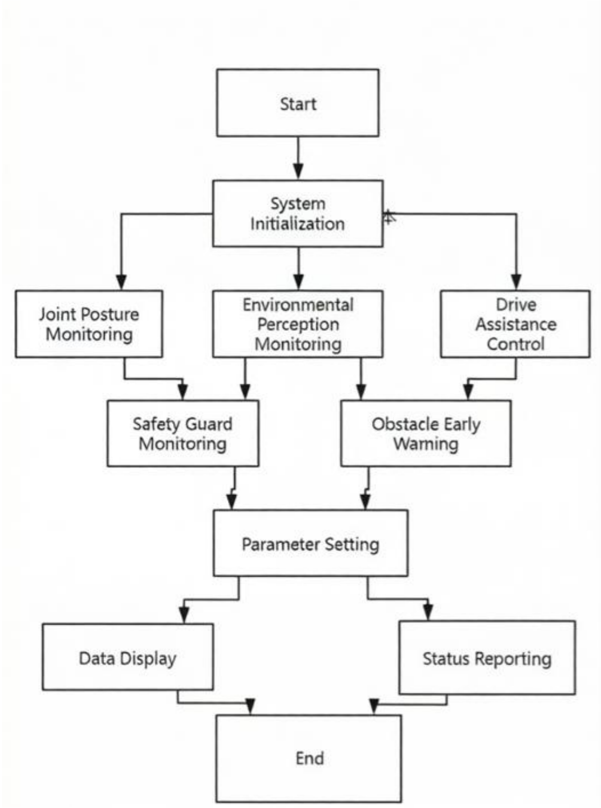

Figure 11. Host computer design flowchart.

The upper computer design interface is shown in Figure 12.

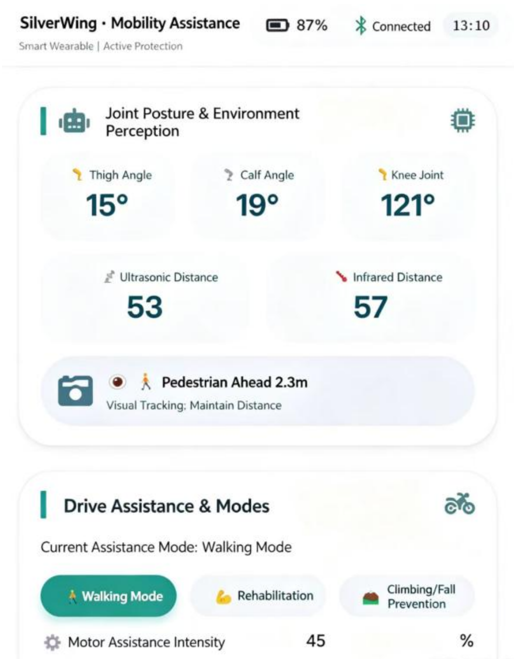

Figure 12. Wearable walking assistive device management system.

6. Performance Verification

Considering that safety and stability are the key indicators of the walking assistance device, this paper uses the finite element modal analysis method to evaluate its performance. The specific operation process is as follows:

(1) Material setting: Considering the safety of use by the elderly, high-strength and lightweight materials should be selected, so the main structure of the device is determined to be alloy steel.

(2) Fixed geometry setting: The fixed end during device operation is set as a fixed geometry.

(3) Meshing: Since the shape of the main structures (thigh and calf) of the model is relatively regular, solid meshing can be adopted; near fillets and weight-reduction round holes, mesh refinement can be performed to ensure high mesh quality.

(4) Iterative calculation: The FFEPlus solver is selected for iterative calculation, with the calculation order set to 6 orders. This solver is based on the conjugate gradient method, has good performance in solving linear problems, can effectively shorten the solution cycle, and achieve good solution accuracy. The calculation expression is:

$$\alpha_k = \frac{r_k^T r_k}{p_k^T K p_k}$$

The 6-order modes of the thigh structure are shown in Figures 13–18.

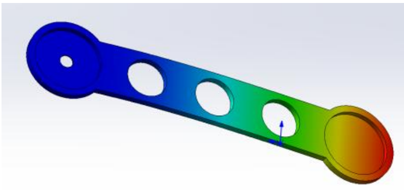

Figure 13. 1st Mode shape.

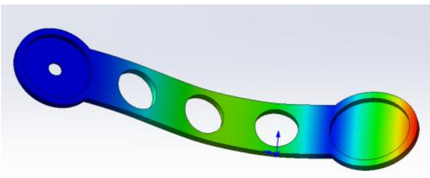

Figure 14. 2st Mode shape.

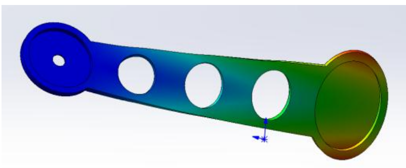

Figure 15. 3st Mode shape.

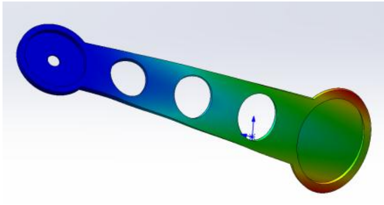

Figure 16. 4st Mode shape.

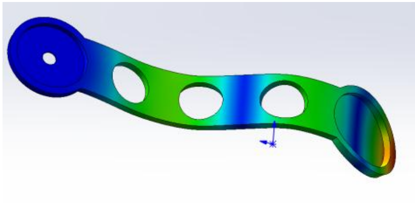

Figure 17. 5st Mode shape.

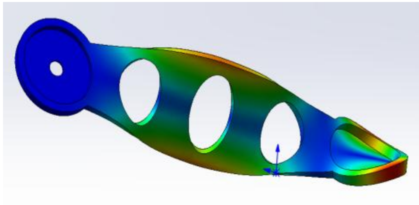

Figure 18. 6st Mode shape.

The mode shapes of each order are shown in Table 2.

Table 2. Mode shapes of each order.

Order	**1st order**	**2nd order**	**3rd order**	**4th order**	**5th order**	**6th order**
Mode	Swing	Flap	Flap	Swing	Flap	Torsion

Based on the analysis of the six-order modes of the thigh structure presented in Table 2, it is evident that the predominant mode shapes are primarily characterized by swing and flap motions, with torsional vibrations observed only at the sixth order. This observation allows us to conclude that the structure exhibits a strong resistance to torsion, underscoring its excellent overall stability and robustness under various dynamic conditions.

The 6-order modes of the calf structure are shown in Figures 19–24.

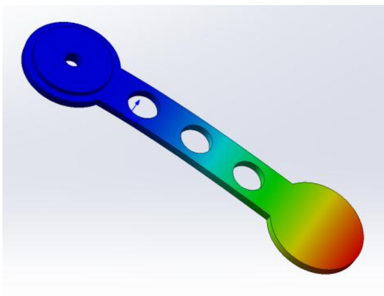

Figure 19. 1st Mode shape.

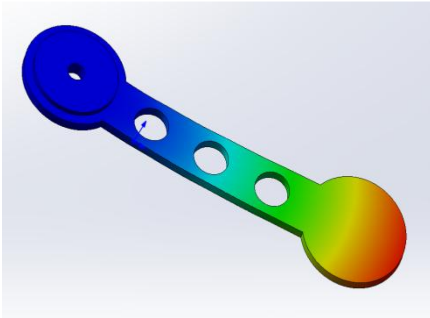

Figure 20. 2st Mode shape.

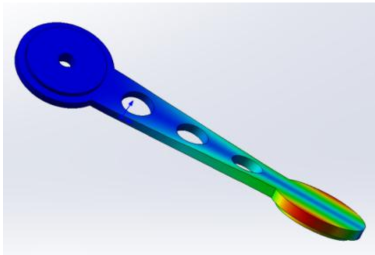

Figure 21. 3st Mode shape.

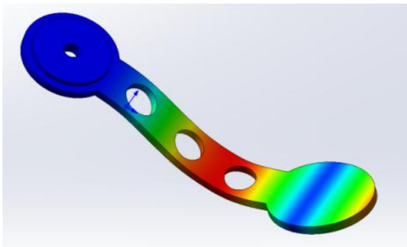

Figure 22. 4st Mode shape.

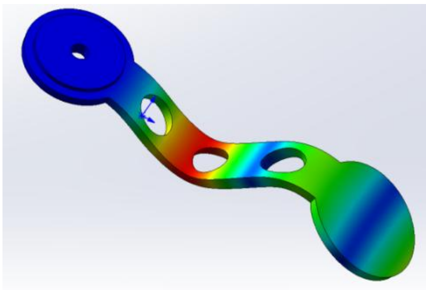

Figure 23. 5st Mode shape.

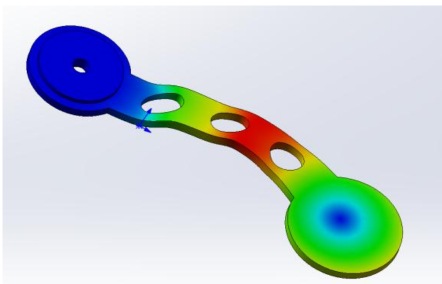

Figure 24. 6st Mode shape.

The mode shapes of each order are shown in Table 3.

Table 3. Mode shapes of each order.

Order	1st order	2nd order	3rd order	4th order	5th order	6th order
Mode	Swing	Swing	Torsion	Flap	Flap	Swing

From the 6-order modes of the calf structure in Table 3, the mode shapes are similar to those of the thigh structure, also dominated by swing and flap, with torsion only appearing at the 3rd order. It can be seen that the calf structure also has good stability.

The comparison between the natural frequencies of the thigh and calf structures of the wearable device and other relevant frequencies is shown in Table 4.

Table 4. Natural frequencies of thigh and calf structures and comparison with other frequency values.

Order	1st order	2nd order	3rd order	4th order	5th order	6th order
Thigh frequency (Hz)	33.737	205.91	285.98	306.13	555.65	934.6
Calf frequency (Hz)	35.391	233.01	290.63	335.59	1063.1	1584
Elderly walking step frequency (Hz)	1–2 (60–120 steps/minute)	1–2 (60–120 steps/minute)	1–2 (60–120 steps/minute)	1–2 (60–120 steps/minute)	1–2 (60–120 steps/minute)	1–2 (60–120 steps/minute)
Human muscle autonomous contraction frequency (Hz)	5–20	5–20	5–20	5–20	5–20	5–20
Ground impact frequency (Hz)	6	6	6	6	6	6
Motor operating frequency (Hz)	50	50	50	50	50	50

As shown in the results, all orders of natural frequencies for both the thigh and calf structures lie well outside the critical frequency ranges, including the elderly walking step frequency, human muscle contraction frequency, ground impact frequency, and motor operating frequency. Consequently, under normal operating conditions, the device is effectively isolated from resonant risks induced by external excitation. This indicates that the structural design possesses sufficient dynamic stability, thereby validating the rationality and reliability of the proposed design.

7. AI-Driven Adaptive Control Strategy

To overcome the rigidity of fixed-threshold triggering, an intelligent control module is proposed. Utilizing IMU and plantar pressure sensors, the system captures high-fidelity gait time-series data. A lightweight neural network—specifically a Temporal Convolutional Network (TCN)—is deployed to identify gait patterns and predict anomalies (e.g., pre-fall symptoms). This allows the device to dynamically adjust its assistance strategy, shifting from static alerts to context-aware adaptive responses.

8. Conclusion

In the design of the wearable walking assistance device, this study adopts a human-centric approach grounded in ergonomic principles. Structural optimization was achieved using extensive anthropometric data, significantly enhancing wearing adaptability. A high-performance control system based on the STM32 microcontroller was developed, integrating multi-sensor fusion to enable obstacle avoidance and real-time remote monitoring. However, limitations remain regarding the device's overall mass and operational endurance. Future work will focus on structural topology optimization utilizing lightweight materials such as carbon fiber, alongside the implementation of adaptive control algorithms, to further reduce physical load and extend battery life, thereby comprehensively improving the user experience.

Acknowledgements

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