Design of lower limb fitness exoskeleton based on ergonomics

Lan Duan [1], Chengwei Bao [2, *], Dongwen Li [1], Xueming Qian [3]

[1] Xi'an Technology and Business College Xi'an, China

[2] Northwestern Polytechnical University Xi'an, China

[3] Xi'an Technological University Xi'an, China

* Corresponding Author Email: baocw@mail.nwpu.edu.cn

Abstract. The lower limb fitness exoskeleton can overcome the load and reach the exercise effect by human moving arms and legs. In this paper, the structural features of human lower limb joints, human gait, and degrees of freedom of lower limbs are analyzed from the perspective of bionics, and a lower limb fitness exoskeleton structure is designed by combining the operating principle and main structural components of the lower limb exoskeleton. The modeling and calibration of the human body and lower limb fitness exoskeleton are completed by Solidworks and ANSYS. Developing the count recorder could detect human movement information as well as remind people to prevent over-exercising.

Keywords: Wearing exoskeleton, bionics, human-machine integration, structural design.

1. Introduction

As living standards rise and many diseases caused by obesity increase, more people recognize the value of fitness. However, due to the fast pace of modern life, it is difficult for people to devote a certain amount of time to work out. In addition to the limits of gyms and equipment, many people exercise lasting fewer than 30 minutes every day, which directly affects human function [1]. The majority of current home fitness equipment is designed to exercise the upper body up to the waist, and very little is designed to exercise the lower limbs. It is challenging for people to undertake targeted exercises on lower limb muscle groups in their daily life because most lower limb training machines are bulky and require special sites, making them only configured in specialist places such as gyms [2]. In this regard, we developed a wearable fitness device based on the above background that specifically improves people's arm and leg strength, which resolves the contradiction between people's exercise time and fitness equipment.

Two aspects have been the primary focus of conventional research on fitness equipment: (1) the effect of fitness equipment is investigated based on the physiological aspects of fitness, including the energy consumption of various exercise modes and the efficiency of the exercise mode on various muscle groups. The energy consumption of exercise and alterations in the physiological characteristics of bodybuilders are then applied to the design of fitness equipment [3]. (2)Research on the functional realization of fitness equipment, such as the realization of force generation and changing functions, as well as the analysis of functional rationality based on satisfying functions. However, there hasn't been much research on the ergonomics of exercises' connection with home gym equipment [4]. According to market demand and purchasing psychology, many fitness equipment companies have improved the appearance and color of home fitness equipment. Many studies concentrated on the functional realization of fitness equipment design without evaluating the physiological and psychological features of local people (especially Chinese people) in order to investigate the functional combination, size, and exercise parameters of fitness equipment. Several academics have conducted some analysis and research on the rationale of the size and suitability of workout equipment, yet not systematically enough [5].

Wearable robotic exoskeletons have gradually gained popularity in recent years. Body augmentation, virtual reality, and sports rehabilitation are their primary applications [6]. The wearable fitness device is a flexible and intelligent drive system that interacts with a high-power density driving device, a non-rigidly connected set of the external human body, to assist with limb mobility. This paper achieves the reverse use of the exoskeleton mechanical system, namely, offering comparable resistance to the movement of the limb, which employs the least amount of space to double the purpose of training. This can be extensively used in common families to solve the problem of restricted alternatives for lower limb training equipment at home, allowing people with such demands to swiftly reach fitness objectives and enhance physical fitness.

2. Determination of human exoskeleton design parameters

2.1. Overview of human lower limb exoskeleton

Figure 1 depicts the composition and conceptual diagram of the lower limb exoskeleton. Its mechanical structure consists of two metal legs that walk-in collaboration with humans, feet that transmit gravity to the ground, a waist that allows for twisting motions, and back brackets that hold heavy goods. It includes sensors, power output devices and actuation components, control systems, and energy systems, all of which are essential to sports activity.

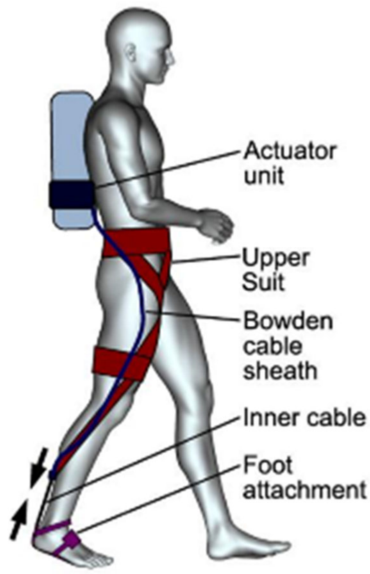

Figure 1. Human exoskeleton composition

2.2. Analysis of the human walking mechanism

The exoskeleton walks synchronously in parallel with humans, and the degrees of freedom for the lower limb exoskeleton is designed from a bionic standpoint based on the degrees of freedom for the human lower limb [7]. To achieve body bending/erectness, right and left rotations, and thigh abduction/adduction, the hip joint has three degrees of freedom. The knee joint is given one degree of freedom to permit bending motion between the lower leg and the thigh while disregarding slight rotating motion when the lower leg is buckled. At the exoskeleton’s ankle joint, three degrees of freedom can be configured to provide up-and-down rotation of the foot around the ankle joint, abduction/adduction, and rotational motion, respectively. Each leg has seven degrees of freedom, plus one in the foot, for a total of eight degrees of freedom in the lower limb exoskeleton.

Despite human's can walk flexibly and stably, bipedal locomotion is characterized by instability. An essential beginning in the study of bipedal walking mechanics is the investigation of human gait patterns and thus the identification of the conditions for stable bipedal walking. The coordination between the walker's limbs, as they move, is referred to as the gait. In order to maintain balance during walking and running, the legs alternately shift, the support points shift back and forth between the feet, and the upper body and upper limbs sway. Human walking and running gaits are depicted in Figure 2. Theoretically, to ensure stable bipedal stepping, it is necessary to satisfy the theory of stable bipedal walking proposed by McWormand Vukobratovic [8].

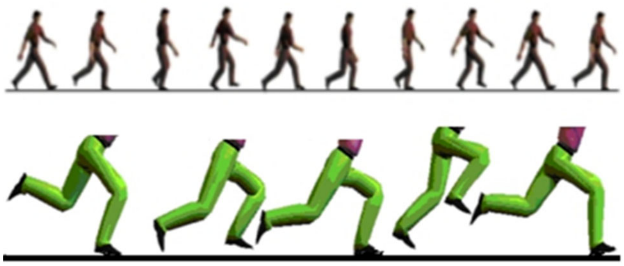

Figure 2. Human walking and running gait

2.3. Principle scheme design

The bionics concept is adopted to design the lower limb exoskeleton made of high-strength aluminum alloy material that resembles the structure of human legs. The following four factors required to be considered in the design:

1. The mechanical device matches the human body: The thighs and calves can be used without affecting the gas spring working parts, and the telescopic casing can be used in connection with the locking device to facilitate rod length modification allowing people with varying lower limb lengths to be used together.

2. The mechanical device is fastened to the body union: Belts or girdles can be used to tighten the waist, making it easier to wear and adjusting the breadth of the waist. The thighs and calves can be fixed with elastic bandages, which protect the leg muscles from rigid compression while maintaining comfortable to wear; The feet are secured with a buckle, allowing the entire bottom steel plate to be fixed with the shoes while facilitating disassembly.

3. Human joints and mechanism degrees of freedom are compatible: Six degrees of freedom are present in each leg, three at the hip, one at the knee, one at the ankle, and one at the sole. The hip joint has more degrees of freedom; therefore, it's connected with a spherical sub-joint; hinged connections have been used to satisfy the knee and ankle joints. The sole part of the foot contributes less to the lower limb muscles; therefore, it can be overlooked. This guarantees a tight connection and flexible rotation of the entire structure while maintaining a realistic feel.

4. Installation of fitness damping devices: Raising resistance when walking by shifting the angles of the thighs and calves, resulting in an effective workout. To enhance the resistance of the ankle movement and to exercise the calf section of the muscle, a pair of torsion springs are placed on the outside of the leg, and gas springs are connected at the size of the leg to ensure the leg muscles are not compressed when people stand still. The more robust the resistance, the more efficient the activity for fitness. The kinematic sketch of the mechanism of the lower limb fitness exoskeleton is obtained based on the foregoing considerations, as illustrated in Figure 3.

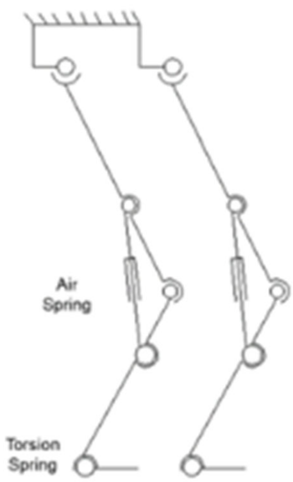

Figure 3. Kinematic sketch of fitness exoskeleton mechanism.

2.4. Structure design

The waist is fixed to the body with a double-layer belt made of outer cloth and inner cotton, with a wide band and thread gluing as the connecting technique; Using tension spring damping at the two ankle joints and connecting the left and right springs, which can both be retracted and fixed to the calf bar; The fabric waist joint is attached to the universal joint by steel nails and to the waist belt by sticking buckles; The thigh and calf rod is a combination of aluminum alloy and stainless steel rod, which is tightened to the thigh and calf by elastic band tacking and the rod length adjustment is locked. The aluminum alloy plate is fastened to the stainless-steel rectangular tube, the two stainless steel round rectangular tubes are nested, and the two stainless-steel rectangular tubes are finally locked with a locking mechanism; Joint hinges are selected for both the knee and ankle joints; The foot sole is made of a thin sheet of rubber plus aluminum that is fastened to the foot and attached with clips; Gas spring dampers are used at the knee joint and torsion springs are used as ankle joint dampers. Table 1 depicts the mobility ranges of the main joints of the typical human lower limbs.

Table 1. The motion range of the main joints of normal human lower limbs

Name	Joint Type	Maximum range	Walking range
Hip Joint	Flexion/Extension Abduction/adduction	-125~65 -45~20	-30~20 -6~4
Knee Joint	Flexion/extension	-130~0	-65~0
Ankle joint	Dorsiflexion/flexion	-20~45	-15~20

After consulting the national standard, we determine the male height size range as 160--180cm, and the female height size range as 155--175cm. And it can be demonstrated that the approximate range and fluctuation of each component of the human lower limb size, as well as the size difference of the human body parts in different age groups, can be obtained. According to the probability distribution study of ergonomic measurements, it is concluded that the dimensions of lower limb skeletal parts and the height of the human body of all ages in China have a directly proportional relationship. Accordingly, the mutual dimensions between each joint center of the lower limb skeleton model can be determined, as shown in Figure 4. As indicated in Figure 4, the connecting rod parameters of the simplified model of the lower limb skeleton are I0=0.039H; I1=0.246H; I2=0.245H; I3=0.191H. Therefore, we can calculate the dimensional range of lower limb length for Chinese males and females.

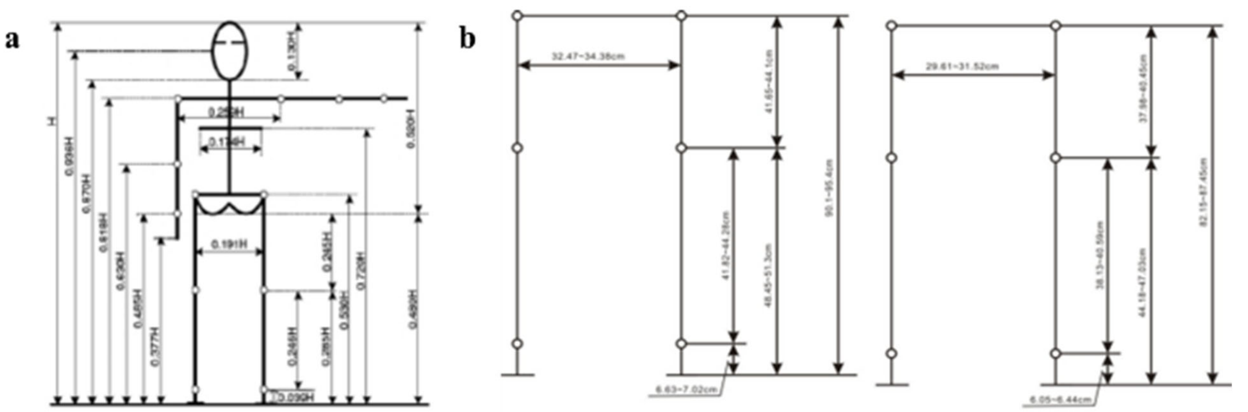

Figure 4. Dimensions of human body parts in proportion to height (a); Lower limb size parameters for men (left) and women (right) (b)

3. 3D Modeling and Structural Analysis

3.1. Modeling

The dimensions of individual model parts were obtained after the dimensional data collection of human lower limb parts was completed. Accordingly, the parts were modeled, and then the basic solid assembly model was established. The original solid assembly model was simplified and structurally optimized based on actual usage and processing and production conditions, and the following assembly model and appearance design were obtained as shown in Figure 5.

Figure 5. 3D model axonometric drawing, exterior design drawing

3.2. Structural analysis

Due to the excessive parts of the three-dimensional assembly model, the analysis requires significant resources, so the model must be simplified before structural analysis. Most of the parts are rods, and they can be viewed as pipe fitting. Therefore, a beam can be used for selecting unit types; Moreover, due to the left and right lower limbs having the same design structure, and bearing the same stress, only half of them may be chosen for analysis. The coordinates of each point: 1(0,0), 2(0,0), 4(350,200), 5(350,200), 8(125,600), 9(125,600), 10(125,650), 11(175,0), and connect the points 1 and 11, 2 and 4, 5 and 8, 9 and 10. The final simplified model is shown in Figure 6.

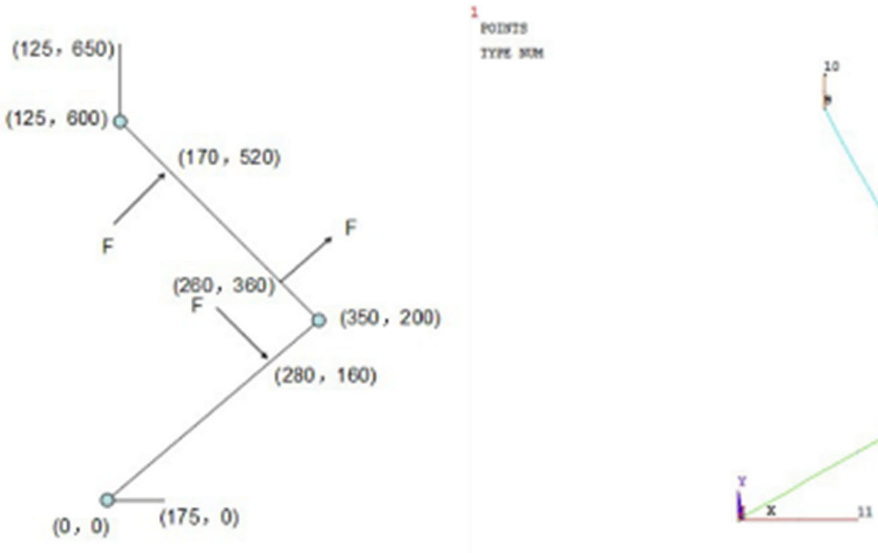

Figure 6. Simplified CAE model.

Due to the model being a tube, the entire model is defined with the unit type "Beam", selected as "2D elastic 3", and then select the nodal forces and nodal moments in the output unit in the output coordinate system. Four sets of real constants are needed to be set because the four rods have different lengths and therefore different rotational inertia. The cross-sectional area of the rods is 105 mm^2. The lengths of the four rods from top to bottom are L1 = 50 mm, L2 = 450 mm, L3 = 400 mm, and L4 = 100 mm, respectively. Their rotational inertia in order is $J1=7.17\times10^{-7}$ kg·m^2. $J2=6.44\times10^{-6}$ kg·m^2, $J3=5.74\times10^{-6}$ kg·m^2, and $J4=1.435\times10^{-6}$ kg·m^2. The elasticity modulus is set to 2.1e11 and Poisson's ratio is 0.3.

Since four sets of real constants have been specified, the cell properties of each rod should be assigned here, with different real constants allocated to separate rods. Set the model line division length to 10, then mesh all the lines.

The simplified model has three hinge points. Therefore, crucial points 1 and 2, 4 and 5, and 8 and 9 on the FEM model require to couple of degrees of freedom. These three places are coupled in the UX and UY directions for the degrees of freedom. However, the degrees of freedom in the UY direction are not in the same plane as the load, they are not subjected to the load, so the degrees of freedom coupling in the UY direction is also performed. After completing the degrees of freedom coupling, the load and constraints should be applied to the divided mesh FEM model.

(1) Applying load: The location where the load is to be applied can be seen by looking at the coordinates of the simplified rod model, and according to the division length of the line in the mesh division is 10, the nodes where the force needs to be applied can be selected as node 54, node 71 and node 103 respectively. In order to improve the reliability of the mechanism, a load of 100N is applied at all three bearing points. This provides sufficient safety margin to guarantee the reliability and safety of the machine when subjected to static and impact loads simultaneously; Node 54 is subjected to a load of 50 N in the X-direction and -90 N in the Y-direction decomposition; Node 71 and Node 103 are subjected to a load of 90 N on the X-axis and a load of 50 N on the Y-axis.

(2) Applying constraints: Before solving the model, constraints should be applied to the model. As for this model, the main load is applied to the thigh and calf rods. And the fixed parts are all at the waist and the foot sole, so the constraints are to be applied to the waist and the foot sole, i.e., the short lines at the upper and lower ends of the FEM model. And the fixed parts are all at the waist and the foot sole, so the constraints are to be applied to the waist and the foot sole. The constraint on the waist part can be approximated as a point constraint, and the point of the constraint is the key point10; the constraint on the foot sole part is a line constraint, where the line between key points 1 and 11. These two constraints are the full degree of freedom constraints. The FEM model with applied load and constraints is shown in Figure 7.

Figure 7. FEM model with applied load and constraints.

After successful solving, firstly check the deformation result to inspect the deformation amount. Check the stress distribution of the FEM model and observe whether the model is safe and reliable. The stress distribution of the model shows that the maximum stress is in the middle of the thigh rod and the minimum stress is at the ankle. The maximum stress is 152.848N, which is much smaller than the ultimate stress of the rod used in the model. Therefore, the model is safe and reliable. Then check the model bending moment diagram to ensure the model strength is reliable. The static structural strength analysis and calibration results indicate that the lower limb fitness exoskeleton fulfills the requirements in practical use. The strength is safe and dependable, and it can meet structural strength requirements.

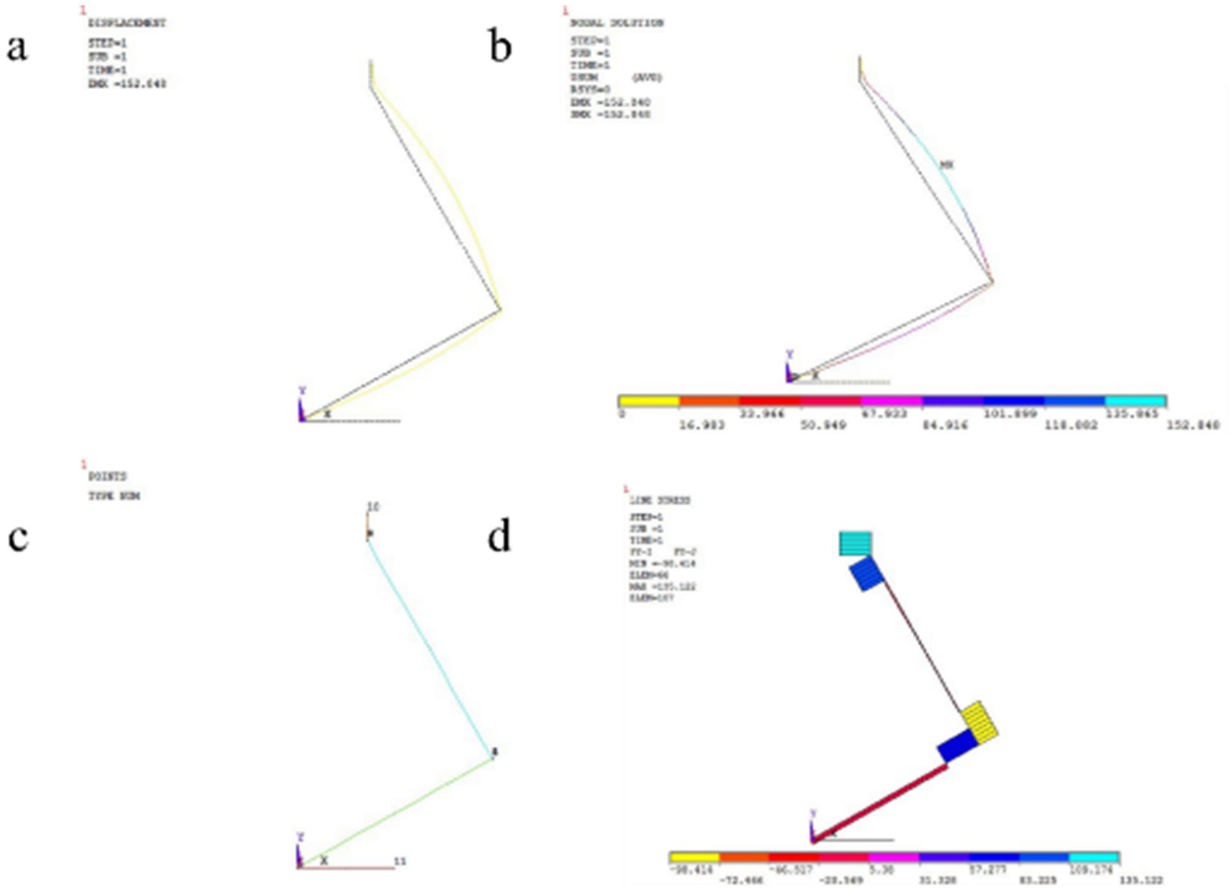

Figure 8. FEM analysis results. Deformation (a); stress distribution (b); bending moment diagram (c); shear diagram (d)

4. Count recorder design

In order to get the amount of exercise more accurately, its counting module is added, and its circuit diagram designed by Proteus is shown in Figure 8. The counter recorder has two functions, one is to record the number of individual daily exercises. At the same time, a certain upper limit can be set. When the upper limit is exceeded, an alarm will be given to remind the exercisers to end the exercise. For example, excessive exercise is not appropriate in the patient's rehabilitation treatment, so it is necessary to make prompt when exercising.

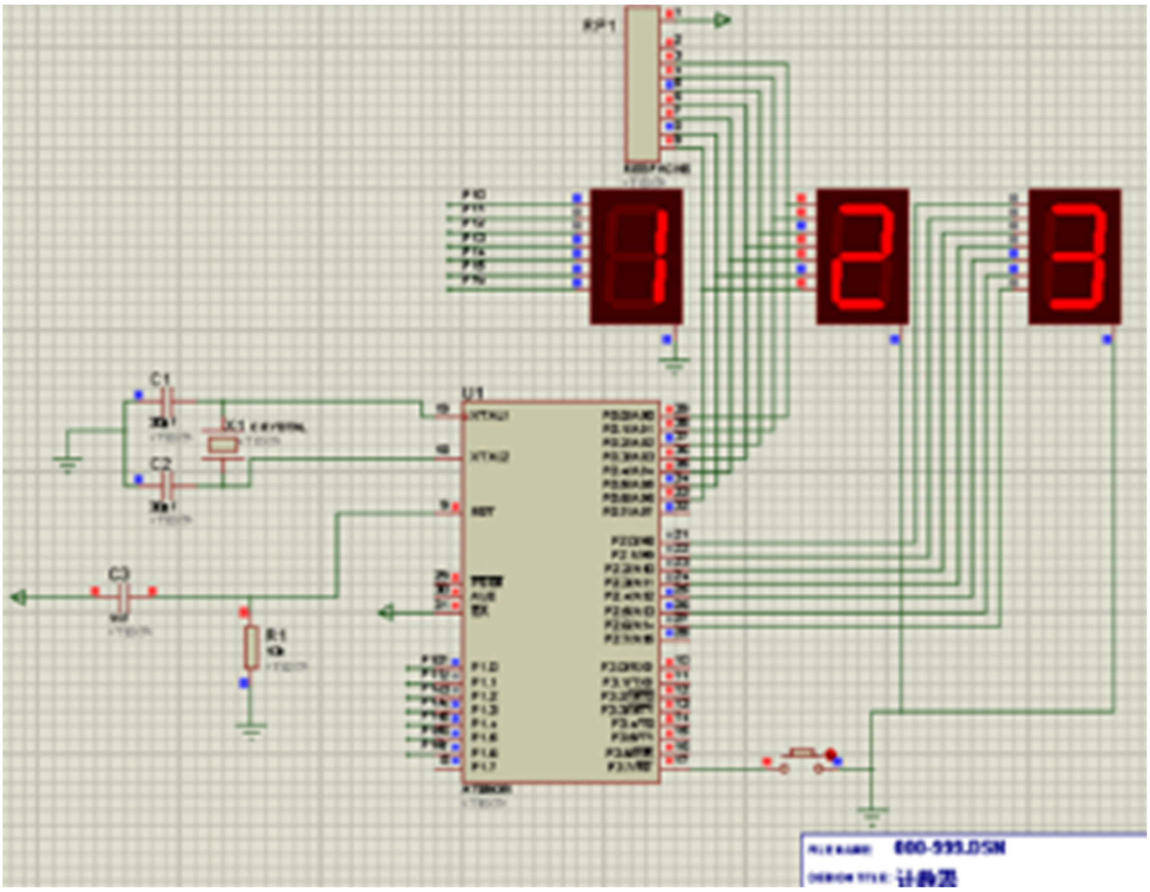

Figure 9. Counter circuit diagram.

5. Conclusion and Prospect.

People are paying more attention to their fitness now that a healthy lifestyle has become popular. We developed this household lower limb fitness exoskeleton based on market research and the concept of exoskeletons. The specific structure of the fitness device was determined by the questionnaire, relevant body size data, and the relationship between the amount of exercise and its intensity. The mechanism can fulfill the criteria of usage.

The future development of the lower limb fitness exoskeleton is fairly broad, as the developed lower limb exoskeleton fitness device and the human body can continue to optimize the relationship, to achieve a perfect combination. Future research should focus on improving and optimizing the shape, design, and ergonomics of the equipment. In the future, the fitness device can be combined with software and network. The daily amount of exercise and intensity of the human body can be transferred to the relevant APP of a mobile phone or computer via its built-in interface, allowing people to observe the amount of exercise, intensity of exercise, and various effects of exercise. You may even submit that data directly to the Internet to share your findings with others.

Acknowledgments

This work was financially supported by the Scientific Research Program of Shaanxi Provincial Department of Education (Grant: 21JK0667) fund.

References

[1] Copeland, JL, Currie, C, Walker, A, etc. Fitness Equipment in Public Parks: Frequency of Use and Community Perceptions in a Small Urban Centre [J], 2017, 14(5):344-352.

[2] Dedov, VN, Dedova, IV. A bilateral rehabilitation system for the lower limbs [J], Disability and Rehabilitation-assistive Technology, 2015, 10(1):75-80.

[3] Patton, RW, McGuire A, Greenleaf C, etc. SEX DIFFERENCES IN FITNESS EQUIPMENT USE [J], ACSMS HEALTH & FITNESS JOURNAL, 2011, 15(3):15-18.

[4] Cao, HB. Application of Smart Wearable Fitness Equipment and Smart Health Management Based on the Improved Algorithm [J], Computational Intelligence and Neuroscience, 2022, 1654460.

[5] Wan D, Xu Y, Bai Y. Research and development of lower extremity rehabilitation exoskeletons[J], Journal of Clinical Rehabilitative Tissue Engineering Research, 2011,15(52):9855-9858.

[6] Li JF, Zhang ZQ, Tao CJ, etc. Structure design of lower limb exoskeletons for gait training [J], CHINESE JOURNAL OF MECHANICAL ENGINEERING, 2015, 28(5):878-887.

[7] Amiri MS, Ramli R, Ibrahim MF. Hybrid design of PID controller for four DoF lower limb exoskeleton [J], APPLIED MATHEMATICAL MODELLING, 2019, 72:12-27.

[8] Westervelt, ER, Grizzle, JW, Koditschek, DE. Hybrid zero dynamics of planar biped walkers [J], IEEE TRANSACTIONS ON AUTOMATIC CONTROL, 2003, 48(1):42-56.