Journal of Engineering Mechanics and Machinery (2023)
Clausius Scientific Press, Canada

DOI: 10.23977/jemm.2023.080414
ISSN 2371-9133 Vol. 8 Num. 4

Structural Design and Dynamics Simulation of Lower Limb Fitness Exoskeleton

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Keywords: Lower limb exoskeleton; human integration; structural design; kinematic analysis

Abstract: Human beings have given more attention to health as civilization has progressed. In this study, the structural properties of human lower limb joints and degrees of freedom in the lower limbs were investigated from a bionic perspective. The fitness exoskeleton structure of lower limbs was designed for exercising people's lower limb muscles and cardiorespiratory function by combining the functions, operating principle, and structural composition implemented by the exoskeleton. The fitness effect was obtained by applying loads to the elbow and knee joints and then overcoming them with leg movement. This exoskeleton, like any other typical human-computer integration system with bipedal walking characteristics, depends on human motion information to control the structure.

1. Introduction

The modern urban hectic life has made it impossible for individuals to take out physical exercises on a regular schedule, and the human body status will always be sub-health in the long term [1]. Furthermore, the limitations of fitness venues and equipment make it difficult to achieve the goal of 30-min daily fitness per capita, which not only directly leads to a linear decline in human function, but also indirectly affects human psychological health. Traditional fitness equipment research mainly focuses on the realization of its function. Fitness equipment is often referred to or obtained from almost similar brands, without investigating the functional combination, functional size, and movement limits of the equipment, according to the physiological characteristics and psychological characteristics of local people - especially Chinese people [2]. Currently, there are studies on the dimensional rationality and the suitability of fitness equipment, but not systematically enough; the scientific and sensible design of fitness equipment can not only produce a more efficient effect on people's fitness exercise from the aspect of exercise physiology but also better suitability for users from all aspects [3].

Therefore, based on the above background, we designed a simple piece of fitness equipment - a wearable fitness device, specifically to exercise human arm strength and leg strength, solving the contradiction between human exercise time and fitness equipment. Unlike the concept of the traditional exoskeleton, the objective of maximizing fitness with minimal space and a shorter time is accomplished through the use of a reverse exoskeleton mechanical system, which adds corresponding resistance to the movement of the limb. It can be widely used in common households, solving the current problem of almost no home lower limb segment fitness machinery to help people with such needs rapidly achieve fitness goals and quickly improve physical fitness[4].

2. Lower Limb fitness exoskeleton structural features and parameters

2.1 Structural characteristics of human lower limbs

From the perspective of bionics, the exoskeleton is paralleled with humans to achieve synchronous walking, and the degrees of freedom are designed for the exoskeleton following the human lower limb degrees of freedom [5]. The hip joint consists of three degrees of freedom to enable body bend/upright, left/right spin, and thigh abduction/adduction, respectively. The knee joint is set with one degree of freedom which enables the bending motion between the lower leg and the thigh, disregarding the small rotational motion after the calf is flexed. Three degrees of freedom can be established at the ankle joint of the exoskeleton which enables up and down rotation of the foot around the ankle joint, abduction/adduction, and rotation, respectively [6]. The lower limb exoskeleton has seven degrees of freedom for each leg, plus one on the foot for a total of eight degrees of freedom. Figure 1 displays the ideal degree of freedom for the lower limb exoskeleton configuration.

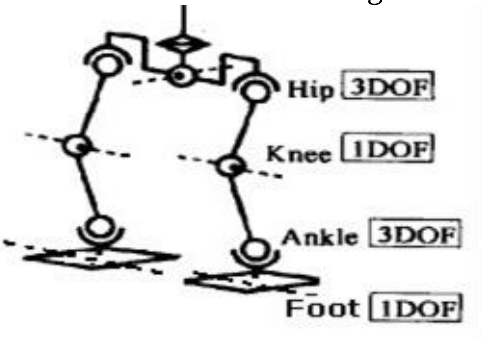

Figure 1: Degrees of freedom for lower limb exoskeletons

2.2 Lower limb exoskeleton shape and design parameters

As the fitness equipment shape is designed in the form of the human exoskeleton, the dimensions of its parts need to match the human body, so the parameters needed are:

(1) The measured human body dimensions are selected and the approximate dimensions of each structural part of the mechanical exoskeleton are obtained, as shown in Table 1.

Table 1: Range of major joint movements of the lower limbs of normal people

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

Illustration: Hip and knee joints: forward motion as flexion, backward motion as extension; Ankle joint: the movement of the foot from the neutral position to the top is dorsiflexion, and the movement of the foot to the bottom is stumbling flexion.

(2) Determining the muscle groups to be exercised: The muscle groups that need to be exercised at each step of the exercise are determined for this design and feedback into the design scheme. During

the body exercise, the exerciser has a strong stimulation of the entire lower limb, which can work out the gluteus maximus, biceps femoris, semitendinosus, and semimembranosus, and has a strong effect on the erector spine, pear-shaped muscles, large retractors, gluteus medius, gluteus minimus, and calf muscles.

(3) Understanding the measurement of exercise, the relationship between the intensity and amount of exercise and energy consumption, and finally measuring the amount of exercise, and the energy consumed, to clarify the accurate correspondence between them. Lower limb fitness exoskeleton through increased damping of the legs, achieving the effect of exercise. Normally, a person walking slowly at a speed of 4 km/h consumes 255 calories, wearing an exoskeleton is equivalent to walking carrying 8 kg of weight, which adds extra 2400 calories consumption. And the integration of the absolute value of the body movement acceleration against time is linearly related to energy or oxygen consumption, thus, the faster the movement, the more energy consumed per unit of time, and the more muscles can be exercised. In determining the above outline parameters and requirements, the mechanism design parameters are then determined, as shown in Table 2 below.

Table 2: Mechanism design parameters

Item	Parameter
Total Weight	3.2kg
Leg length range	965——1085 mm
Maximum leg hip swing angle	40 °
Leg knee rotation angle range	20 °——85 °
Maximum leg ankle swing angle	40 °
Leg spring load range	-75N——+75N
Leg spring adjustable force range	0N——40N
Applicable height range	155——180cm

3. Lower limb fitness exoskeleton design

In this design, high-strength aluminum alloy is used, and the whole structure is based on a bionic design, similar to the human legs structure. In the principle scheme design, the following issues need to be considered: (1) the size of the mechanical device to match the human body; (2) the fixed mechanical device combined with the human body; (3) the degree of freedom of the mechanical device to match the joints of the human body; (4) placement of the fitness damping device. Combining the above considerations, a skeleton of the mechanism of the lower limb fitness mechanical exoskeleton is derived as shown in Figure 2.

3.1 Structure scheme design

(1) waist structure

The waist structure should be selected to achieve the purpose of wearing comfortable, breathable, with a certain degree of toughness, and could provide effective fixation. When considering people's actual fitness, they tend to sweat, and the use of outer cloth and inner cotton design will absorb the human sweat, so that the body remains dry and comfortable, while the leather belt will not have such a function. In terms of the fixing method, both buckle and sticking buttons can be used when the belt is thin, whereas it is preferable to choose the sticking button when the belt is wide because the excessive volume of the buckle will lead to sliding displacement.

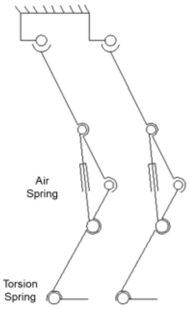

Figure 2: Sketch of mechanism movement

(2) Hip joint structure

The hip joint has three degrees of freedom, and the hip joint rotates frequently during body movement, therefore, the addition of a four-bar mechanism at the hip joint can easily lead to interference. And during movement, the human body has a swinging arm action, which makes the arm pass the outside of the hip joint. If this four-bar mechanism has excessive volume, it will also lead to interference between the upper and lower limbs during human movement.

When the ankle joint of the fitness machine is placed in the damping tension spring, the tension spring can be retracted and fixed on the calf bar, when the two ankle joints will be connected through the tension spring. This can be effective in exercising the muscle groups at the thighs and buttocks, and these muscle groups can be exercised separately, without the need to exercise at the same time as other muscle groups.

(3) Thigh and calf parts structure

Thighs and calf parts of the structure need to play a role in addition to the frame and pillar, but also subject to the role of damper forces and moments, here mainly subject to bending stresses. Taking the common rectangular tube (25mm * 13mm), and round tube (Φ20mm), both wall thickness of 1mm structural members as an example, using the formula (1) (2) to calculate the maximum bending stress of the two kinds of rods respectively. It is found that the maximum bending stress of the rectangular bar is higher than that of the round tube under the same force, so the thigh and calf part of the bar is selected as the rectangular tube.

$$\sigma_{max\,1}=\frac{F_{max}\times L}{\frac{I_{z1}}{y_{max\,1}}}=\frac{F_{max}\times L}{\frac{b_{outter}h_{outter}^{3}-b_{inner}h_{inner}^{3}}{12}\times\frac{2}{h}}=2.16\times10^{-3}F_{max}\times L \tag{1}$$

$$\sigma_{max\,2}=\frac{F_{max}\times L}{\frac{I_{z2}}{y_{max\,2}}}=\frac{F_{max}\times L}{\frac{\pi d_{outter}^{4}-\pi d_{inner}^{4}}{64}\times\frac{2}{d}}=3.70\times10^{-3}F_{max}\times L \tag{2}$$

(1) Footbed structure

The choice of footbed structure needs to fully consider the wearing comfort. If there is insufficient comfort with a poor user experience, the design is not considered successful. Therefore, when selecting the footbed structure, apart from the structural strength and fixation method as the selection conditions, comfort should also be an important factor.

When the sticking button fixed the sole with the body, it can have good flexibility, ensuring a good rotation characteristic of the ankle joint when exercising, and a high level of fit with the body, with good comfort. However, it is prone to get dirty when moving as it is close to the ground, and requires frequent disassembly and cleaning, which is more troublesome, and the user experience is not good in this regard. While buckle fixing and removal are very convenient and do not easily get dirty, without deliberate cleaning. When fixed with the body, the buckle has enough rigidity, with the only disadvantage of poor flexibility. Yet, when making the part that connects the buckle to the alloy sheet of the footbed, the material with good flexibility can be used to ensure the flexibility of the entire footbed structure, thus ensuring sufficient comfort. In the production, adding soft plastic to connect the alloy sheet with the buckle, and the whole footbed structure shows good flexibility. Finally, the buckle structure was chosen.

3.2 Model Design

After checking the national standard, we determine the Chinese male height size range as 160--180cm, and the female height size range as 155--175cm. And it can be seen the approximate range and the variation amount of the human lower extremity parts' dimensions, and can also obtain the differences of the human body parts' dimensions at different ages.

According to the study of the probability distribution of ergonomic measurements, it is concluded that there will be a directly proportional relationship between the size of each part of the lower limb skeleton and the height of the human body at various ages in China [7]. Accordingly, the mutual dimensions between the joint centers of the lower limb skeletal model can be determined, i.e., the rod parameters of the simplified lower limb skeletal model are I0=0.039H; I1=0.246H; I2=0.245H; I3=0.191H.

Once the dimensional data collection of each part of the human lower limb was completed, the dimensions of each part of the model were also obtained. Based on this, each part is modeled, and then the basic solid assembly model is established, the engineering structure is optimized, and the assembly structure and the final object are finally determined, as shown in Figure 3.

3.3 Dynamics analysis

The motions of the human body are mainly reflected by the joints' movements, therefore, it is essential to analyze the hinges that are used in the human model [8]. As shown in Figure 4 left, blue represents connecting rod 1, purple stands for connecting rod 2, white and red is the gas spring, green for the thigh rod, yellow for the calf rod, red for the belt connector, and brown for the belt, silver and white for foot parts, and the rest of Marker points are located as shown in the figure. The 3D model built by Solidworks was saved into x_t format and imported into Adams, after defining the material of each part as STEEL, to facilitate analysis and viewing, the model was then simplified into 8 modules, with the same modules displayed in the same color. After defining the kinematic pair of the given parts, 10 rotating pairs, 1 moving pair, and 1 spherical pair, the belt part is connected to the Earth (fixed pair) to highlight the main parts, and the belt is fixed to the thigh, as shown in Figure 4 right.

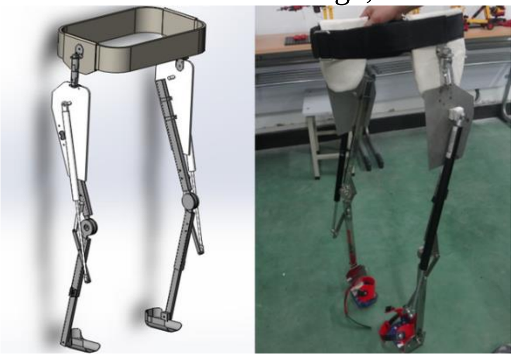

Figure 3: Lower limb fitness exoskeleton assembly diagram and physical picture

Figure 4: ADAMS simulation: axonometric view

Motion 1: moving pair, Joint Type: translational; Function(time): 25*sin(time); Motion 2: rotating pair, Joint Type: revolute; Function(time): 25.0d* sin(time). Define damping (including friction) to the moving pair, due to friction F=μmg, according to the table: 0.1≤μ≤0.4, take μ=0.2, then F=μmg=0.2×1×9.8≈2N, set the damping added by the drive is 8N, assign the total damping=10N. The damping is set to 10N, and the damping friction F=1N is defined for each rotating pair. In the post-processing module, the End time is set to 12 and the Steps are set to 200.

(1) Ankle joint analysis: Motion 2 was applied to Jiont9 at the ankle as Joint Type: revolute, Function(time): 25.0d* sin (time), which is a sinusoidal function. The applied friction force is 1N constant force, and the output angle-time graph should also be a sinusoidal function with no rotation in the X and Y axes, so it should be a straight line. From Fig. 5 left, it can be seen that the overall turning angle can reach 50 °, and the design requires the maximum angle of leg limb ankle joint swing to be 40 °, so the requirement is satisfied. Further analysis shows that joint 9 only receives the gravitational force of the model as a whole on the Y-axis, as well as a small force upward on the X-axis during rotation, and without force change on the Z-axis, so it should be a straight line. From Figure 5 right, it can be seen that the Y-axis force is 2.4N. As the selected material is stainless steel pipe, it is known that the tensile strength of 304 stainless steel plate is 520MPa. The diameter of the pressurized axis is 5mm, and it is calculated that F=12.246KN≫2.4N, so the requirement is satisfied.

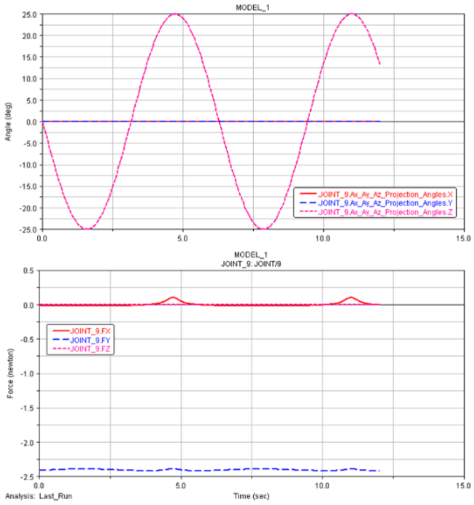

Figure 5: Ankle angular displacement-time diagram (left) and force-time diagram (right)

(2) Knee joint analysis: The friction force applied to joint 8 at the knee joint is 1N constant force,

which moves under the action of the gas spring. Applied to Motion 1 as Joint Type: translational, Function(time):25*sin(time), the output angular displacement- time graph should also be similar to a sinusoidal function, and there is no angle of rotation in the X and Y axes, so it should be a straight line. From Figure 6a, it can be seen that the total turning angle is 45 °, and the design requires the knee joint swing angle to be 20 °~85 °, so the requirement is satisfied. Since the friction force exerted by joint 8 at the knee joint is 1N constant force, which moves under the action of gas spring, applied to Motion 1 as Joint Type: translational, Function(time):25*sin(time). Analysis shows that joint 8 is subject to the gravity of the model as a whole on the Y axis, and the force of the gas spring on the knee joint, which will produce a small force upward in the X axis during rotation, and no forced change in the Z-axis, so it should be a straight line, and the force in the Y axis is shown in Figure 6b. From the figure 6, Fmax = 35N, as the selected material is stainless steel pipe, the same calculation has F = 24.492KN ≫ 35N, so the requirements are met.

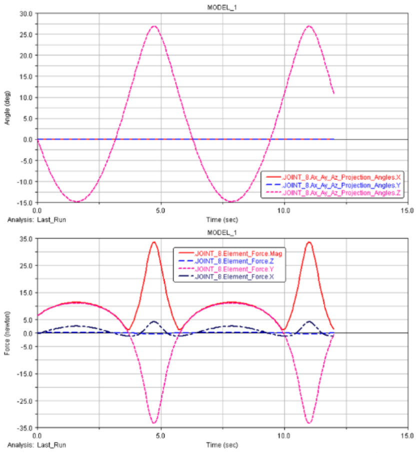

Figure 6: Knee joint Angular displacement-time diagram (left) and force-time diagram (right) of

(3) Gas spring analysis: The damping (including frictional force 2N) of the moving pair is defined as 10N. Applied to the moving pair Motion 1 as Joint Type: translational, Function (time): 25*sin (time), the output acceleration-time graph should also be similar to the sinusoidal function. From Fig. 7, we can see that amax=25mm/s, which meets the design requirements. The damping (including frictional force 2N) of the moving pair is defined as 10N. Applied to the mobile pair Motion 1 as Joint Type: translational, Function(time):25*sin (time). The analysis shows that joint 10 is subjected to driving force and frictional force, and the geometric mean Mag force matches the figure 7. Due to the gas spring being a standard part, the requirement is satisfied.

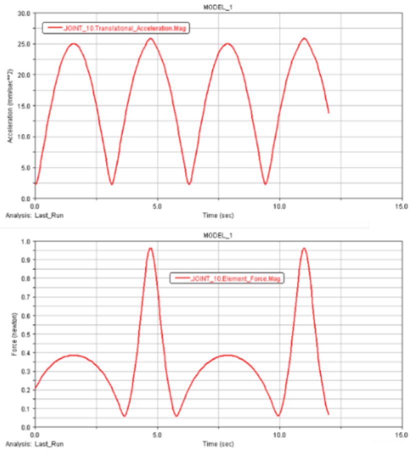

Figure 7: Gas spring acceleration-time graph (left) and force-time graph (right)

4. Conclusion

Based on the market research, we designed this household lower limb fitness exoskeleton in combination with the popular exoskeleton concept. According to the data obtained from the questionnaire and reviewing the relevant body size data and parameters such as the relationship between the amount and intensity of exercise, the relevant design task was formulated. The mechanism kinematic sketch of the fitness device was subsequently determined in principle, and in accordance with this sketch, the structural scheme was designed to determine the specific structure of the fitness device. The dynamic simulation analysis shows that the design is reasonable and feasible, and provides a reference for the preparation of the exoskeleton device for home fitness of lower limbs.

Acknowledgments

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

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