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Research article

A predictive walking energy model based on gait phase with suspended backpack

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ABSTRACT

Walking with heavy loads is a common task in military affairs and daily life. Considering that the shoulder and leg muscles fatigue will be caused during walking, which will affect the walking endurance and physical health. However, the suspended backpack is found to improve the energy efficiency of walking with a load. In this study, A lightweight suspended backpack is designed and proposing a model for estimating the metabolic cost of a suspended backpack based on gait phase. In this study, four inertial measurement units (IMUs) are fixed on the thigh and shank, six flexible pressure sensors are mounted on the soles of the feet and shoulders, respectively. The gait is defined as four successive phases. For each phase, the muscle tension is solved based on the muscle moment balance theory. Based on the phase segmentation method, the ECCF index is calculated by adding the gait phase constraint and backpack data calculation into the energy prediction model, and the relatively accurate data is obtained. In addition, In order to study the effects of the suspended backpack with different parameters on the cost metabolism, gait phase and biomechanics, the subjects need to carry the same load of 16.5 kg to walk 400 m at the different speeds, respectively. A group of seven healthy subjects in the same walking condition need to conduct two experiments: suspended backpack work (SB) and ordinary backpack (OB). The experimental results show that the suspended backpack can reduce plantar pressure and shoulder pressure in the SB condition. And at the speed of 5.0 km/h, ground reaction force (GRF) and shoulder reaction force (SRF) were reduced by 11.59 % and 13.22 % in the SB condition compared to the OB condition, respectively.

1. Introduction

The Transportation equipment has developed rapidly in recent years and is widely used in daily life and military work in remote areas. Although these transportation devices can greatly improve transportation efficiency, they are suitable for relatively flat or spacious transportation scenes. Human transportation is still an irreplaceable mode of transportation in complex environments and special application scenarios, such as hiking, mountain surveys, disaster relief and individual combat, etc [1]. It is worth noting that backpacks are considered to be the most common means of transport by humans, and backpacks can release both hands. It is reported that the wearer show increased metabolic costs, larger GRF and more muscle activation during the load-bearing period [2,3], which will accelerate muscle fatigue and increase the risk of injury.

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In order to improve the individual transport capability, some individual transport equipment has been developed and gradually applied to the wearer. Some researchers transfer the weight of the load to the ground through the designed exoskeleton robot, which can greatly alleviate the wearer's fatigue [4–6]. Although exoskeleton has high load transfer efficiency in individual transportation, these exoskeleton robots are limited by their heavy mechanical structure and energy supply requirements, and are difficult to apply to long-distance missions or complex field scenes. Since ancient times, backpacks have been widely used as traditional tools to carry loads and carry goods due to their convenience, flexibility and diversified application scenarios. In addition, human movement has abundant kinetic energy, which can be used in the design of wearable devices [7]. Some researchers have combined the advantages of the backpack and the kinetic energy of the body to invent a suspended backpack [8–10]. The suspended backpack has gradually attracted the interest of researchers because of its convenience and comfort, and has become one of the research hotspots.

The suspended backpack allows relative movement of the load relative to the wearer's back and reduces the vertical movement of the load relative to the ground. In addition, the suspended backpack can reduce the dynamic peak force acting on the wearer and reduce the wearer's metabolic cost during the activity [11]. In order to evaluate the impact of suspended backpack on the wearer, some researchers have established a spring-mass-damper model to explore the hidden internal relationship, and on this basis to establish an energy assessment model. For example, Xie et al. [7] developed a suspended backpack device based on adjustable frequency to obtain part of the human body's kinetic energy during walking and relieve part of the backpack's acceleration load on the wearer. At the same time, the designed backpack can achieve 0.20–0.353 W of electricity produced per unit of external load mass, and the maximum peak acceleration load is reduced by 15 %. Huang et al. [12] verified that the suspended backpack can reduce the muscle activity of the lower limbs and the work of biological joints, and reduce the metabolic cost of walking by 12.53±2.39 % through the designed experiment. Yang et al. [13] developed a load suspended backpack based on a friction nanogenerator to collect energy generated by human movement. Through related theoretical analysis and field experiments, the backpack can reduce the vertical oscillation of the load by 28.75 % and the wearer's vertical force by 21.08 %. Leng et al. [10] reported how the wearer affects the GRF of each leg when carrying a suspended backpack under 12 walking conditions, and proposed an extended biped walking model with a spring-mass damping system (EBW) to predict the GRF of each leg.

In this paper, we designed a suspended backpack with a spring-mass-damping model. We compare the experimental data of the suspended backpack in the SB state with the another load state (OB) to evaluate the performance of the model. In order to explore the effect of speed on the performance of the suspended backpack, we designed and set three different walking speeds in the experiment. In addition, this paper installs membrane pressure sensors on the shoulders of the backpack and the heels of the soles to measure the SRF on the shoulders of the straps and the GRF on the heels. Furthermore, In order to explore the influence of the suspended backpack on the walking gait of the wearer, this paper collects the angle signals of the knee and hip joints. We collected the angle signals of the knee and hip joints during the experiment to explore the influence of the suspended backpack on the walking gait of the wearer. Finally, we use a smart bracelet to collect the wearer's heart rate. These results can help us explore the performance of the suspended backpack in relieving muscle fatigue and increasing energy efficiency.

The rest of the manuscript is organized as: In section 2 materials and methods are discussed followed by the testing protocol explanation in section 3. Section 4 shows the experimental results and gives a discussion in Section 5, and the manuscript is concluded in Section 6.

2. Materials and methods

In this study, we only focus on the load which is not fixed in the vertical direction and is constrained to move in the horizontal direction. The designed suspended backpack is shown in Fig. 1(a). The suspended backpack system consists of three parts: the backpack frame, the load and the elastic damping element. And the suspended backpack system consists of three parts: the backpack frame, the load and the elastic damping element. The suspended backpack model can be simplified as a spring-mass-damped vibration system, as shown in Fig. 1(b). In the process of walking, the suspended backpack frame is closely attached to the human body and moves together with the human body, and the load can also move in the vertical direction relative to the frame through the rolling slide rail on the frame. Ignoring the relative movement of the load relative to the backpack frame in other directions, applying Newton's Law, the governing equation for this mass-spring-damped oscillation system of the suspended backpack can be written as follows:

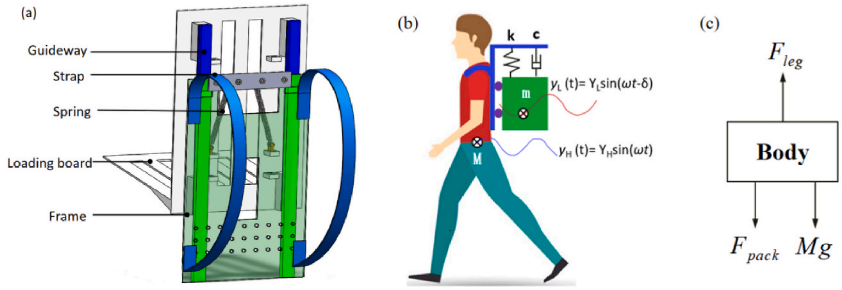

Fig. 1. A simple model of human walking with a suspended backpack. (a) Suspended backpack prototype. (b) Proposed backpack mode. (c) The free body diagram of the body.

$$m\left(\ddot{y}_L - \ddot{y}_H\right) + c(\dot{y}_L - \dot{y}_H) + k(y_L - y_H) = -m\dot{y}_H \tag{1}$$

where m is the load weight, c is the system damping coefficient, y_L is the displacement of the swing load, y_H is the displacement of the backpack frame, and k is the elasticity coefficient.

Introducing $u = y_L - y_H$ represents the relative displacement between the suspended backpack frame and the load. Eq. (1) can be expressed as follows:

$$m\ddot{u} + c\dot{u} + ku = -m\dot{y}_H \tag{2}$$

During normal walking, the motion state of the lower limbs of the human body changes back and forth between single-leg support and double-leg support. When the lower limbs change from double-leg support to single-leg support, the center of mass (COM) of the human body will move upward; And when the lower limbs are changed from single-leg support to double-leg support, the center of gravity of the human body will move downward, The vertical movement of the human's center of gravity can provide energy storage opportunities for the suspended backpack. The movement amplitude y_H in the vertical direction of the COM can be expressed as a sinusoidal function of walking frequency ω, as shown in Eq. (3) [8,14]:

$$y_H(t) = A \cdot \sin(\omega t) \tag{3}$$

where A is the amplitude of the vertical displacement during walking, and can be approximated as a function of walking speed (V) and walking frequency [15], as shown in Eq. (4). Where R is the equivalent length of the leg. And walking frequency can be approximated as a function of walking speed and leg length [16], as shown in Eq. (5).

$$A = \frac{R}{2}\left(1 - \sqrt{1 - \left(\frac{0.963\pi V}{R\omega}\right)^2}\right) - 0.0157R(\mathrm{m}) \tag{4}$$

$$\omega = 9.45\left(\frac{V}{R}\right)^{0.57}(rad/s) \tag{5}$$

According to the vibration theory, the dynamic response $u(t)$ of the suspended backpack will be a sinusoidal function with the same frequency as the excitation $y_H(t)$ [7], as shown in Eq. (6). Inserting Eq. (6) into Eq. (2), the corresponding amplitude U and phase φ can be obtained by Eqs. (7) and (8), respectively.

$$u(t) = U \cdot \sin(\omega t - \phi) \tag{6}$$

$$U = A\frac{\mu^2}{\sqrt{(1-\mu^2)^2 + (2\xi\mu)^2}} \tag{7}$$

$$\phi = \tan^{-1}\left(\frac{2\xi\mu}{1-\mu^2}\right) \tag{8}$$

Where, $\omega_\mathrm{n} = \sqrt{k/\mathrm{m}}$ is the natural frequency of the oscillating backpack, $\mu = \omega/\omega_n$ is the frequency ratio, and $\xi = C/(2M\omega_n)$ is the total damping ratio of the system.

Fig. 1(c) shows the force state of the body in the vertical direction during the motion, and the torque balance Eq. (9) in the vertical direction of the body can be calculated. Where $y_{\ddot{H}}$ is the acceleration in the vertical direction of the body COM, M is the carrier weight, F_{leg} is the actuating force that help carrier achieve the vertical motion of body COM. F_{pack} is the difference between the weight-bearing gravity and the oscillating force [9], as shown in Eq. (11). Substituting Eqs. (10) and (11) into Eq. (9) to calculate the force of the lower limb muscles, as shown in Eq. (12).

$$F_{leg} - F_{pack} - Mg = M\ddot{y}_H \tag{9}$$

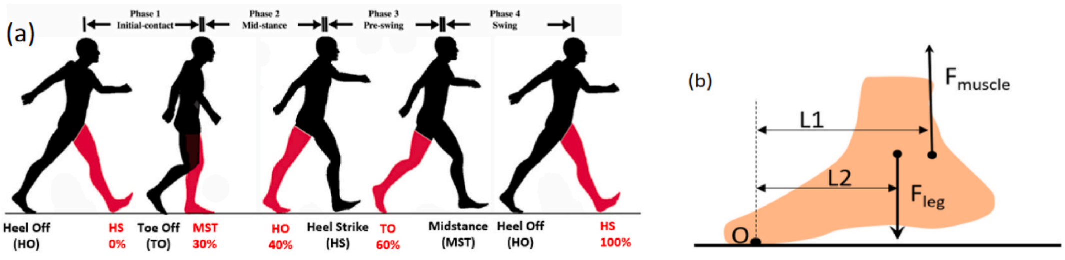

Fig. 2. (a) Phase diagram of walking gait. (b) Force diagram when the toes are on the ground.

$$\ddot{y}_H(t) = -\omega^2 A \bullet \sin(\omega t) \tag{10}$$

$$F_{pack} = mg - (ku(t) + cu(t)) \tag{11}$$

$$F_{leg} = Mg + mg - (ku(t) + cu(t))M\omega^2 A \bullet \sin(\omega t) \tag{12}$$

Considering that the different vertical motion directions of the human body COM will lead to different efficiency of muscle work (η), Li et al. [8] proposed a new energy cost calculation method, but did not further explore the influence of phase on muscle tension. Fig. 2(a) shows a complete gait phase [17]. It can be found that during the period from the HO event to the TO event (Pre-swing Phase), the lower limbs are in double-support phase, and the contact point between the lower limbs and the ground is near the toes, as shown in Fig. 2(b). In a gait cycle, both lower limbs will experience the Pre-swing phase, that is the support point of one foot is in the front half of the sole. The flexion and extension of the ankle joint is mainly done by the calf triceps, and the F_{leg} is not always equal to the tension of the triceps when the contact point is near the toe. The muscle tension F_{muscle} can be calculated by the moment balance Eq. (13). Combined with the energy cost calculation method proposed by Li et al. [8], the energy cost W_{energy} of a walking cycle is calculated as:

$$F_{muscle} = \begin{cases} F_{leg} \cdot L_2/L_1 & \text{Pre} - \text{swing} \quad \text{phase} \\ F_{leg} & \text{Other} \end{cases} \tag{13}$$

$$W_{energy} = \int_{t=0}^{2\pi/\omega} F_{muscle} \bullet \dot{y}_H \bullet \eta \mathrm{d}t, \eta = \begin{cases} 25\% & F_{leg} \bullet \dot{y}_H > 0 \\ -120\% & F_{leg} \bullet \dot{y}_H < 0 \end{cases} \tag{14}$$

Based on the measured data and previous excellent experimental work [6,7], this study determines that the final stiffness value of the suspended backpack is 3800 N/m. The load weight of the suspended backpack designed in this paper is set to16.5 kg.

3. Testing protocol

A total of seven subjects (7 male), mean age 22.71 years (SD: 2.69 years), mean height 175 cm (SD 4.9 cm), and mean weight 66.53 kg (SD: 6.45 kg), participated in the experiment. The detailed data of the subjects are shown in Table 1.

Subjects need to complete three different walking speed experiments on a treadmill: 3.0 km/h, 4.2 km/h and 5.0 km/h. Two different backpacks at each walking speed with two different conditions were used in the experiment: (1) The suspended backpack works (SB), in which the load can move relative to the wearer's back by rolling the slide rail; And (2) The ordinary backpack (OB). The subjects participating in the experiment have no any disease that affects walking gait, and are healthy in all aspects of their bodies. The load used in the experiment is mainly marble cube with uniform mass distribution. It is worth noting that the weight of the suspended backpack is 1.7 kg, while the weight of the ordinary schoolbag in the experiment is 0.2 kg. In order to ensure the uniqueness of the experimental variables, the subjects need to carry a load of 14.8 kg in the SB condition, and the subjects had to carry a load of 16.3 kg in the OB condition. In the experiment, all subjects were required to walk on a con Figured treadmill for at least 400 m at the set speed, and the equipment and related settings used in the experiment were the same. The experiment requires each subject to rest for at least 5 min after the end of each experiment to prevent the participants from affecting their walking gait due to fatigue. In addition, only when the running speed of the treadmill reaches the set speed can the data is allowed to save. When the experiment stopped and the speed of treadmill started to slow down, we stopped collecting data. Finally, each subject is required to perform the same experiment in the same conditions to ensure the reliability and effectiveness of the collection process.

The plantar pressure sensor MD30-60 (Jinke Electronic Technology Co., Ltd, Shenzhen, China) is used to measure the pressure of the sole and the shoulder, and explore whether BFU-SB can reduce the vibration force and peak force acting on the shoulder and heel respectively, which helps to relieve the muscles fatigue and improving energy efficiency [17]. It should be noted that the pressure value in the experiment is the analog value collected by the sensor, not the real pressure value, but the analog value can indirectly reflect the real pressure. Plantar pressure is measured by foot pressure insole, as shown in Fig. 3. The analog value of plantar pressure in this study is defined as the average value of two plantar pressure sensors. The inertial sensor JY901 (Witt Intelligent Technology Co., Ltd., Shenzhen, China) is used to measure the movement angle information of the lower limbs, and explore the influence of the suspended backpack on the wearer's walking gait. Moreover, the smart bracelet (Xiaomi Technology Co., Ltd, Beijing, China) is also used to record the wearer's heart rate during the motion, which can help analyze whether the suspended backpack can reduce the wearer's metabolism. The details of the wearing experiment are shown in Fig. 3.

Table 1
Demographic data of subjects.

Subject	Gender	Age	Weight(kg)	Height(cm)
A	Male	22	66.5	173
B	Male	23	64.7	170
C	Male	28	54.0	168
D	Male	24	73.0	180
E	Male	21	72.3	179
F	Male	21	70.0	180
G	Male	20	65.2	175

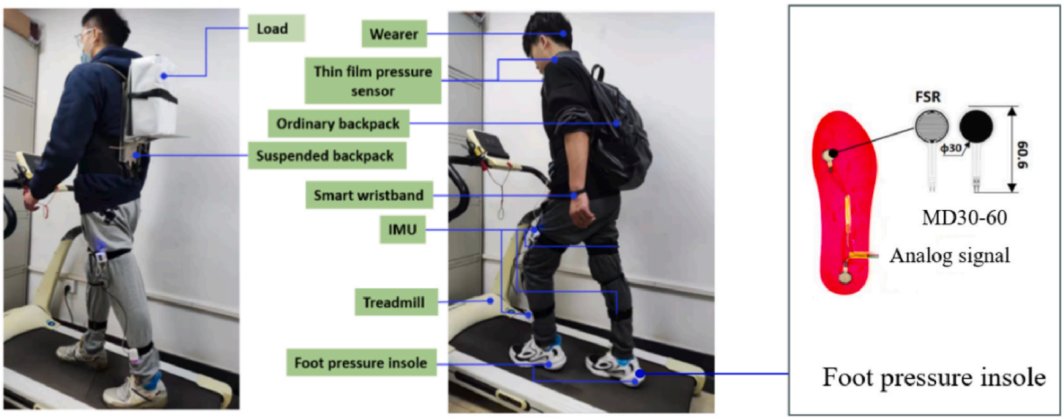

Fig. 3. Schematic diagram of load-bearing experiment.

The four pressure sensors are respectively used to measure the shoulder pressure signals and heel pressure signals on the left and right sides of the sagittal plane of the human body. These pressure signals are filtered using a second-order low-pass Butterworth filter (cutoff frequency: 10Hz), and then the filtered inertial signal and pressure signal are transmitted to the smart terminal through a wireless device (NRF24L01) at a frequency of 100Hz. The second-order low-pass Butterworth filter is shown in Eq. (15), where $a1$, a2, $b0$, $b1$ and $b2$ are the correlation coefficients of the filter, $x(n)$ and $y(n)$ sequences are the signal sequences before and after filtering, respectively.

$$y(n) = b0^*x(n) + b1^*x(n-1) + b2^*x(n-2) - a1^*y(n-1) - a2^*y(n-2) \tag{15}$$

4. Experimental results

The energy cost calculation method proposed in this paper is used to evaluate the performance of the suspended backpack relative to the ordinary backpack in terms of metabolic cost. The results are shown in Table 2. The prediction difference is less than 6 %, and the prediction result of the proposed method is closer to the experimental result than the method proposed by Li et al. [8]. Fig. 4 shows that within a certain range, higher mass loads will expand the difference in energy costs in different walking conditions during walking. The maximum point of ECCF appears when walking speed is near the mass of load is around 46 kg. When the walking frequency is equal to the natural frequency of the backpack system (Resonant walking frequency), the energy cost of the system will change suddenly, especially when the load mass changes. Generally speaking, when the walking frequency is lower than the natural frequency of the system, the suspension backpack saves the metabolic cost compared with the ordinary backpack [19].

In addition, this paper used the membrane pressure sensors to measure the wearer's pressures of the heel and shoulder, respectively. Shoulder and heel pressure can indirectly reflect the muscle strength of the shoulders and legs and reducing muscle strength can reduce the energy consumption of the body. Fig. 5(a and b) shows the curve of heel pressure and shoulder pressure of a subject in OB and SB conditions. It should be noted that due to factors such as the position of the weight and the error of the strap length, which will cause different pressure on the left and right shoulders, so this paper uses the average value of the pressure on both sides of the left and right shoulders as the reference value. It can be seen from Fig. 5(a and b) that the peak pressure of the average heel pressure and the average shoulder pressure in the SB condition is smaller compare to OB condition, and the pressure on the shoulder is relatively smooth and supple.

The influence of walking speed on the SRF and GRF of the wearer are shown in Fig. 6(a–c) and Fig. 7(a–c), which show the changes in pressure on the heel and shoulder at three different walking speeds. It can be found that both GRF and SRF are generally lower in the SB condition than that in the OB condition. Moreover, both GRF and SRF will gradually increase with the increase of walking speed. The GRF and SRF in the SB condition will be significantly smaller than that in the OB condition when walking at a higher walking speed. Among them, when the walking speed was 5.0 km/h, the GRF and SRF received by all subjects in SB condition were 11.59 % and

Table 2
Comparison of the energy cost of carrying a suspended backpack and a ordinary backpack.

Energy cost comparison	Percentage increases		
Walking speed (km/h)	3.0	4.2	5.0
From experimental results	−1.42 %	−4.98 %	−5.71 %
Predicted by Li et al.	−2.54 %	−0.35 %	3.52 %
Predicted in this paper	−1.44 %	−4.81 %	−10.89 %

The percentages in this table are calculated with the follow equation: ECCF = (energy cost of carrying a suspended backpack-energy cost of carrying a ordinary backpack)/energy cost of carrying a ordinary backpack × 100 %. The predicted results are calculated with the method in this paper and in Li et al. [8], respectively.

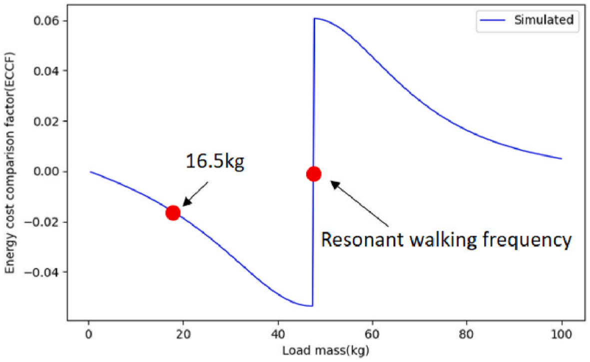

Fig. 4. Energy cost comparison coefficient under different walking speed.

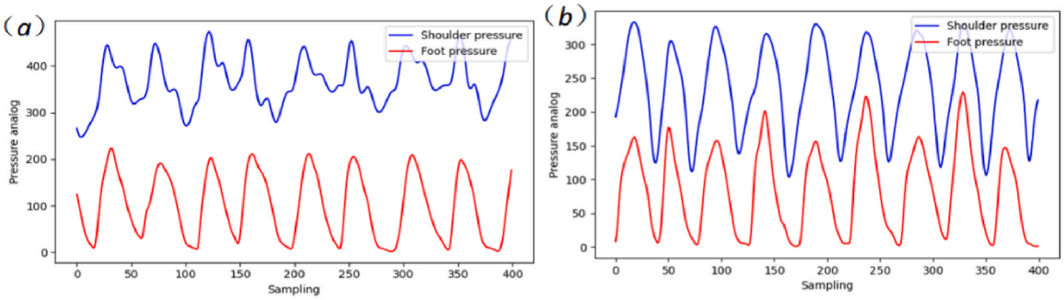

Fig. 5. Average pressure change curve. (a) Average heel and shoulder pressure in OB condition. (b) Average heel and shoulder pressure in SB condition.

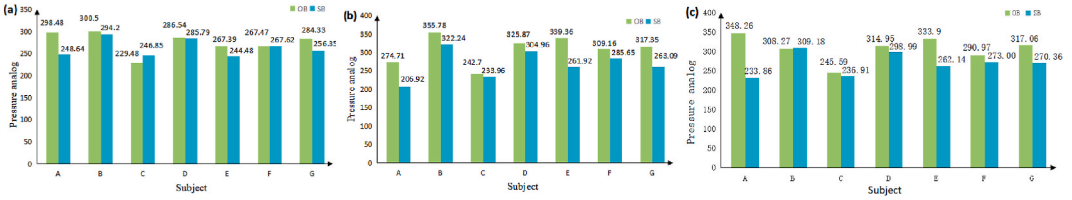

Fig. 6. Shoulder pressure at different walking speeds: (a) walking at 3 km/h, (b) walking at 4.2 km/h and (c) walking at 5 km/h.

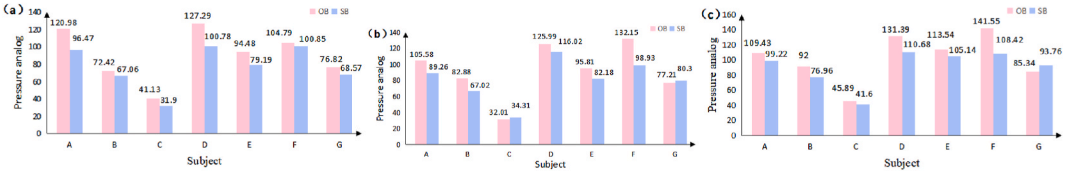

Fig. 7. Heel pressure at different walking speeds: (a) walking at 3 m/h (b) walking at 4.2 km/h (c) walking at 5 km/h.

13.22 % lower than those in the OB condition, respectively.

It can also be found from Figs. 6 and 7(a–c) that the two characteristic forces will increase with the increase of walking speed, but the growth characteristics of the two types of characteristic forces are not the same. When the walking speed increased from 3.0 km/h to 5.0 km/h, the average GRF growth rate and average SRF growth rate of subjects in the SB condition were 19.26 % and 1.53 %, respectively. The average GRF growth rate and average SRF growth rate of the subjects in the OB condition were 14.09 % and 12.03 %, respectively. It can be found that the change rate of the average GRF is greater when subjects change from low-speed walking to high-speed walking in the SB condition than that in the OB condition.

For gait parameters, it can be seen from Fig. 8(a–c, e) that the average value of the knee joint angle in the SB condition will decrease with the increase of the walking speed within a certain range of pace. However, in the OB condition, there is only a 42.86 % probability that the average knee angle will decrease when the walking speed increases from 3.0 km/h to 5.0 km/h, which means that the walking speed has little effect on the average knee angle in the OB condition. In the SB condition, the influence of walking speed on the average knee angle is relatively consistent. From the knee joint variance line chart in Fig. 8(a–c, e), it can be seen that there is no significant difference in the knee joint variance between the SB and OB conditions in the lower walking speed scene, and the average knee angle in the SB condition is higher than that in the OB condition. In addition, it can be found that the variance of the knee joint in the SB condition is generally lower than that in the OB condition at a higher walking speed, and the average knee joint angle in the SB condition is generally lower than that in the OB condition.

Fig. 8(b–d, f) also shows the influence of different walking conditions on the hip joint of the wearer. When the walking speed is within the range of 3.0 km/h to 5.0 km/h, the average value of the hip joint angle in the SB condition will decrease with the increase of the walking speed; While in the OB condition, the average hip angle only has a 57.14 % probability that it will increase with the increase of the walking speed, which means that the average hip joint angle is also insensitive to the walking speed in the OB condition. It can be seen from the hip joint variance line chart in Fig. 8(b–d, f) that the hip angle variance in the SB condition is lower than that in the OB condition. Moreover, in the experiment, the probability that the average hip angle in the SB condition is lower than that in the OB condition is 47.62 %, which means that the suspended backpack has little effect on the wearer's average hip joint angle.

Fig. 9 shows the joint angle curve of a subject the walking speed of 5.0 km/h. From Fig. 9(a), it can be seen that there is no significant difference in the swing phase between the knee joint angles in the SB and OB conditions, and the knee angle in the SB condition is slightly larger than that in the OB condition from the heel contact phase to the swing phase. From Fig. 9(b), it can be seen that there is no significant difference in the hip joint angle in the SB and OB conditions in the whole phase. In addition, it can also be seen from Fig. 8 that the suspended backpack has no obvious effect on the stride frequency and stride length.

5. Discussion

In this study, a suspended backpack was designed, and improved the corresponding energy cost model based on the work of Li et al. [8] In order to explore the impact of the suspended backpack on the wearer compared with the ordinary backpack, this paper designs related experiments and compares the suspended backpack with the ordinary backpack to verify the effectiveness of it.

Heart rate can characterize the wearer's metabolic cost in a short period of time,. But the heart rate is easily disturbed by external factors, such as emotions, noise, exhaustion, wearing style, etc. Although the wearers were required to keep their emotions as stable as possible and not to communicate with anyone during the experiment, it is still difficult to completely eliminate the interference of external factors on the heart rate. Taken together, when the walking speed is 5.0 km/h, the heart rate in the SB condition is 5.71 % lower than that in the OB condition on average. In addition, some studies have proven that suspended backpacks can significantly reduce the metabolic cost of subjects. For example, Huang et al. [12] designed a suspended backpack to reduce the metabolic cost by 8.81 % compared to the OB condition during walking. Rom et al. [18] reported that a suspended backpack can reduce the metabolic cost by 6.5 % compared to an ordinary backpack during walking (5.6 km/h). Foissac et al. [11] reported that the designed flexible backpack can reduce the metabolic cost by 1.4 % and 3.8 % when the walking speed is 3.7 km/h and 4.5 km/h compared to the rigid backpack. From the research results of Huang et al., Rom et al., and Foissac et al., it can be found that the change of the heart rate is almost consistent with the change of metabolic cost during a short walking. It can also be seen from Table 2 that within a certain range

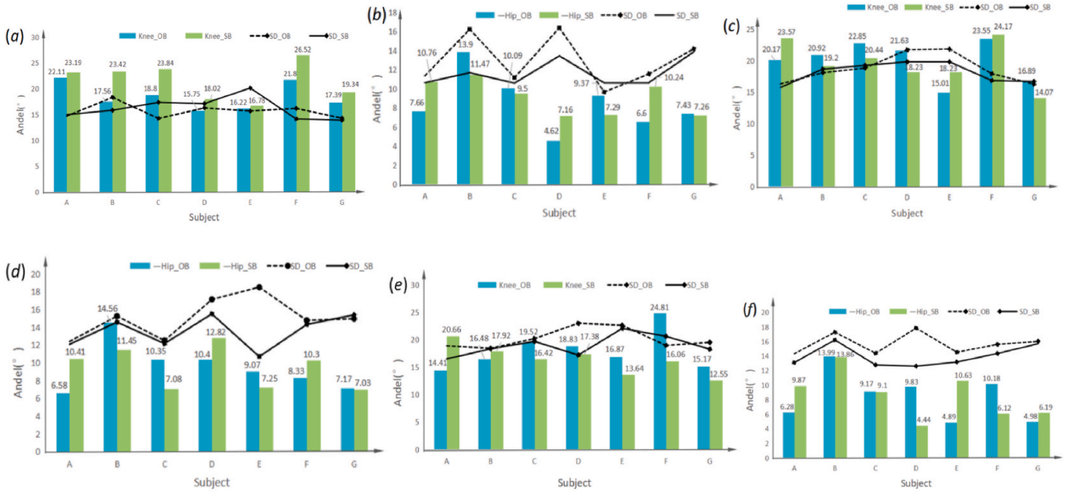

Fig. 8. The average joint angle under different walking speed: (a) 3.0 km/h (knee joint angle). (b) 3.0 km/h (hip joint angle). (c) 4.2 km/h (knee joint angle). (d) 4.2 km/h (hip joint angle). (e) 5.0 km/h (knee joint angle). (f) 5.0 km/h (hip joint angle). Knee_OB represents the angle of the knee joint in the OB condition. Knee_SB represents the knee joint angle in the SB condition. Hip_OB represents the hip joint angle in the OB condition. Hip_SB represents the hip joint angle in the SB condition. SD_OB represents the variance of the angle on the OB condition. SD_SB represents the variance of the angle in the SB condition.

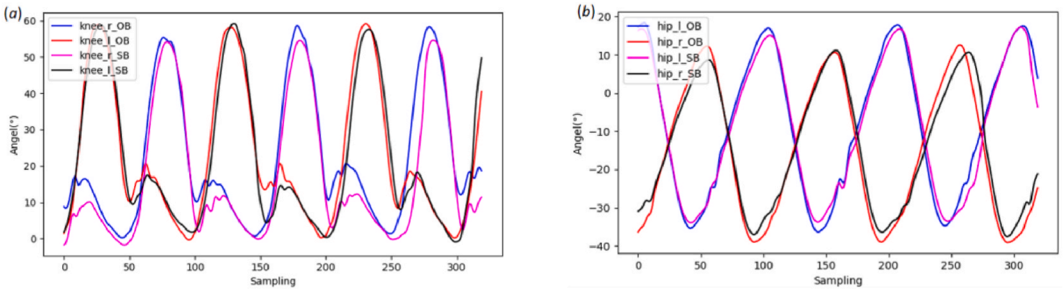

Fig. 9. Joint angles in SB and OB conditions: (a) knee joint and (b) hip joint. knee_r(l)_OB and knee_r(l)_SB represent the knee joint angle of the right leg (left leg) in the OB state and the SB state, respectively. hip_r(l)_OB and hip_r(l)_SB represent the hip joint angle of the right leg (left leg) in OB state and SB state, respectively.

of walking speed, accelerating walking speed is conducive to increase ECCF, which is consistent with the results of Ackerman et al. [20] and Xu et al. [21]. However, it should be noted that because the suspended backpack frame is a rigid body, a faster walking speed may cause serious discomfort and instability of the center of gravity to the wearer, which is worthy of further study.

In addition, some power-assisted exoskeletons are starting to be used in weight-bearing scenarios and can significantly reduce metabolic costs. For example [22,23], designed a flexible exoskeleton robot, which can reduce metabolism by 7.8 % and 15.28 % respectively under load-bearing and normal walking conditions. Cao et al. designed a load-bearing exoskeleton robot and reduced its metabolism by 12.8 % under experimental conditions of load-bearing [24]. In the future, combining suspended backpack with exoskeleton robots could reduce metabolism even more.

Besides, the heel pressure and shoulder pressure signals can also indirectly reflect the subjects' metabolism. It should be noted that due to the height and body shape of the subjects, the shoulder pressure sensors can only be installed in approximately the same position of different subjects, and it cannot be ensured that the sensor can be installed in the same relative position every time. In order to adjust the installation position of the sensor, we use the Velcro to stick the sensors to the strap of the backpack. It can be seen from Fig. 6(a) that the average shoulder pressure of subject C in the OB condition during the experiment is slightly smaller than that in the SB condition, which may be caused by a large error of the sensor installation position. By observing Figs. 5(a) and 6, it can be found that the average value and peak value of the wearer's shoulder pressure can be significantly reduced in the SB condition compared to the OB condition. When pedestrians carry heavy loads for a long time, the backpack straps of the backpack will cause the soft tissue of the arm plexus to deform [25], and the sensitivity of the arm is impaired, which make the characteristics of the suspended backpack to reduce shoulder pressure becoming very meaningful. In addition, the different burden-relieving effects of the suspended backpack on different subjects may be related to the length of the strap. This is because previous studies have shown that placing loads close to the body's center of gravity reduces metabolic costs [26]. The heel pressure signal is measured by the membrane pressure sensors installed in the insole. It can be seen from Fig. 8 that in most cases, the heel pressure in SB condition is smaller than that in OB condition. In rare cases, the heel pressure in OB condition is smaller than that in SB condition. This may be related to personal walking habits, the size of the insole, etc.

In this study, the inertial sensor modules need to be placed at the designated position of each subject to measure the joint angle during exercise. However, due to the body shape and walking habits of each subject, the sensors cannot be accurately placed at the designated location, and can only be installed at the approximate designated location, which requires further research. It can be seen from Fig. 9(a) that the minimum value of the knee joint angle collected by the sensor is slightly lower than 0° and cannot be completely equal to 0°. Other data collected may have greater deviations, especially at the end of the experiment. The sensor should be installed in a firmer way in the future. Furthermore, we can try to use deep learning methods to replace traditional modeling methods to predict metabolic cost, which may further improve the accuracy of prediction [27–29].

6. Conclusions

In this study, a method for calculating the metabolic cost of a suspended backpack based on gait phase is proposed. This model is used to predict the ECCF index in different walking speed, and obtain precise results. In addition, this paper also explored the influence of suspended backpacks on plantar pressure, shoulder pressure and walking gait parameters. Combining the relevant experimental data, it can be obtained that the suspended backpack can reduce the peak and average values of plantar pressure and shoulder pressure. Among them, the average value of shoulder pressure and plantar pressure at a walking speed of 5.0 km/h can be reduced by 11.59 % and 13.22 %, respectively, which helps delay leg muscle fatigue and optimize energy consumption. Moreover, the average knee joint angle in the SB condition is larger than that in OB condition, and the hip joint angle is not sensitive to the way of backpacking. In this study, the gait cycle is simplified into two phases to establish the energy consumption model, which brings some errors. In the future, energy evaluation models based on more phases should be developed to reduce prediction errors.

Consent for publication

The picture materials quoted in this article have no copyright requirements, and the source has been indicated.

Compliance with ethical standards

This article does not contain any studies with human participants performed by any of the authors.

Data availability

The data that supports the findings of this study is available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Tao Zhen: Writing – review & editing, Writing – original draft. **Qiuxia Chen:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

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.

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References

[1] L. Ren, R.K. Jones, D. Howard, Dynamic analysis of load carriage biomechanics during level walking, J. Biomech. 38 (4) (2005) 853–863.
[2] S.A. Birrell, R.H. Hooper, R.A. Haslam, The effect of military load carriage on ground reaction forces, Gait Posture 26 (4) (2007) 611–614.
[3] K.M. Simpson, B.J. Munro, J.R. Steele, Backpack load affects lower limb muscle activity patterns of female hikers during prolonged load carriage, J. Electromyogr. Kinesiol. 21 (5) (2011) 782–788.
[4] Z. Zhou, et al., Design and experimental evaluation of a non-anthropomorphic passive load-carrying exoskeleton, in: 2021 6th IEEE International Conference on Advanced Robotics and Mechatronics (ICARM), 2021.
[5] H. Li, et al., UCAS-hand: an underactuated powered hand exoskeleton for assisting grasping task, in: 2021 IEEE International Conference on Real-Time Computing and Robotics (RCAR), 2021.
[6] R.L. Medrano, E.J. Rouse, G.C. Thomas, Biological joint loading and exoskeleton design, IEEE Transactions on Medical Robotics and Bionics 3 (3) (2021) 847–851.
[7] L. Xie, M. Cai, Increased energy harvesting and reduced accelerative load for backpacks via frequency tuning, Mech. Syst. Signal Process. 58–59 (jun) (2015) 399–415.
[8] D. Li, et al., A simple model for predicting walking energetics with elastically-suspended backpack, J. Biomech. 49 (16) (2016) 4150–4153.
[9] J. Hoover, S.A. Meguid, Performance assessment of the suspended-load backpack, Int. J. Mech. Mater. Des. 7 (2) (2011) 111–121.
[10] Y.Q. Leng, et al., A model to predict ground reaction force for elastically-suspended backpacks, Gait Posture 82 (2020) 118–125.
[11] M. Foissac, et al., Characterization of the mechanical properties of backpacks and their influence on the energetics of walking, J. Biomech. 42 (2) (2009) 125–130.
[12] L.D. Huang, et al., Physiological and biomechanical effects on the human musculoskeletal system while carrying a suspended-load backpack, J. Biomech. (2020) 108.
[13] Z. Yang, et al., Power backpack for energy harvesting and reduced load impact, ACS Nano 15 (2) (2021) 2611–2623.
[14] J.B. Saunders, V.T. Inman, H.D. Eberhart, The major determinants in normal and pathological gait, J. Bone Jt. Surg. Am. Vol. 35-A (3) (1953) 543–558.
[15] Al, R.E., Xu, XU. “An investigation on the interactivity between suspended-load backpack and human gait”. (Under the direction of Dr. Simon M. Hsiang.)[J]. [2024-10-08].
[16] D.W. Grieve, R.J. Gear, The relationships between length of stride, step frequency, time of swing and speed of walking for children and adults, Ergonomics 9 (5) (1966) 379–399.
[17] X.T. Jiang, et al., A wearable gait phase detection system based on force myography techniques, Sensors 18 (4) (2018).
[18] A. Rom, ousFynn, A. Yoo, Biomechanics: rubber bands reduce the cost of carrying loads, Nature (2006).
[19] J. Ackerman, J. Seipel, A model of human walking energetics with an elastically-suspended load, J. Biomech. 47 (8) (2014) 1922–1927.
[20] J. Ackerman, K. Potwar, J. Seipel, Suspending loads decreases load stability but may slightly improve body stability, J. Biomech. 52 (2017) 38–47.
[21] Keren, et al., Energy performance analysis of a backpack suspension system with a timed clutch for human load carriage, Mech. Mach. Theor.: Dynamics of Machine Systems Gears and Power Trandmissions Robots and Manipulator Systems Computer-Aided Design Methods (2018).
[22] W. Cao, Y. Ma, C. Chen, J. Zhang and X. Wu, "Hardware circuits design and performance evaluation of a soft lower limb exoskeleton," in IEEE Transactions on Biomedical Circuits and Systems, vol. 16, no. 3, pp. 384-394.
[23] W. Cao, C. Chen, H. Hu, K. Fang and X. Wu, "Effect of hip assistance modes on metabolic cost of walking with a soft exoskeleton," *in* IEEE Trans. Autom. Sci. Eng., vol. 18, no. 2, pp. 426-436.
[24] W. Cao et al., "A lower limb exoskeleton with rigid and soft structure for loaded walking assistance," *in* IEEE Rob. Autom. Lett., vol. 7, no. 1, pp. 454-461.
[25] A. Hadid, et al., The effect of mechanical strains in soft tissues of the shoulder during load carriage, J. Biomech. 48 (15) (2015) 4160–4165.
[26] D. Abe, S. Muraki, A. Yasukouchi, Ergonomic effects of load carriage on energy cost of gradient walking, Appl. Ergon. 39 (2) (2008) 144–149.

[27] T. Zhen, J.L. Kong, L. Yan, Hybrid deep-learning framework based on Gaussian fusion of multiple spatiotemporal networks for walking gait phase recognition, Complexity 2020 (2020) 8672431.
[28] Jianlei Kong, Chengcai Yang, Jianli Wang, et al., Deep-stacking network approach by multisource data mining for hazardous risk identification in IoT-based intelligent food management systems, Comput. Intell. Neurosci. 2021 (2021) 1194565.
[29] Xuebo Jin, Weizhen Zheng, Jianlei Kong, et al., Deep-learning forecasting method for electric power load via attention-based encoder-decoder with bayesian optimization, Energies 14 (6) (2021) 1596.