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ORIGINAL ARTICLE

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A Wire-Driven Series Elastic Mechanism Based on Ultrasonic Motor for Walking Assistive System

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Abstract

In order to improve the elderly people's quality of life, supporting their walking behaviors is a promising technology. Therefore, based on one ultrasonic motor, a wire-driven series elastic mechanism for walking assistive system is proposed and investigated in this research. In contrast to tradition, it innovatively utilizes an ultrasonic motor and a wire-driven series elastic mechanism to achieve superior system performances in aspects of simple structure, high torque/weight ratio, quiet operation, quick response, favorable electromagnetic compatibility, strong shock resistance, better safety, and accurately stable force control. The proposed device is mainly composed of an ultrasonic motor, a linear spring, a steel wire, four pulleys and one rotating part. To overcome the ultrasonic motor's insufficient output torque, a steel wire and pulleys are smartly combined to directly magnify the torque instead of using a conventional gear reducer. Among the pulleys, there is one tailored pulley playing an important role to keep the reduction ratio as 4.5 constantly. Meanwhile, the prototype is manufactured and its actual performance is verified by experimental results. In a one-second operating cycle, it only takes 86 ms for this mechanism to output an assistive torque of 1.6 N·m. At this torque, the ultrasonic motor's speed is around 4.1 rad/s. Moreover, experiments with different operation periods have been conducted for different application scenarios. This study provides a useful idea for the application of ultrasonic motor in walking assistance system.

Keywords Ultrasonic motor, Wire-driven, Series elastic mechanism, Walking assistive system, Pulley, Reduction ratio

1 Introduction

In recent years, a declining birthrate and an aging population become a serious social problem on the world scale [1, 2]. Aging and diseases cause the muscular weakness of the elderly and then lead to their poor physical activities. Meanwhile, the unsafe walking postures can increase the risk of dangerous falls [3]. Therefore, to improve the quality of life for the elderly and reduce the burden on their caregivers, developing the walking assistive devices is one promising technology [4]. The history of motion assistance studies can date back to the 1960s in the United States, mainly used in the military field [5, 6]. In the decades that followed, great deals of studies have been published in the literature on developing the walking assistive devices (also referred to as the lower limb exoskeletons (LLE)) for humans [7–10].

Depending on the joints, walking assistive devices can be divided into two main classes, which focus on the multiple joints [11–13] and the single joint respectively. In the multiple-joint-type, more than one of the lower limb joints are actuated, while in the single-joint-type, only one joint (hip [14], knee [15] and ankle [16]) is actuated. In addition, according to its purpose, walking assistive devices can be categorized into rehabilitative, aided

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and enhanced systems [17]. The aim of the rehabilitative type is to provide guided movement to restore the lower limb's function (e.g., after a stroke) [18]. The aided type is designed to be worn by people with a movement disorder (e.g., elderly, physically weak) to provide physical support for walking. The enhanced type is intended to help operators (e.g., soldiers, disaster relief workers, fire fighters, industry workers, etc.) do some strenuous work and repetitive training, such as carrying heavy loads with minimal effort, and increasing accuracy, power, velocity and endurance [19].

In terms of the actuation types, walking assistive devices can be classified as the active actuation, the passive or quasi-passive actuation, and the hybrid actuation. The joint actuators, belonging to the execution part of the walking assistive devices, are the key for the active actuation. They deliver the desired power to achieve the auxiliary movement. The movement performance is determined by critical characteristics such as the power effect, composition shape, and response speed of the actuators. Based on surveyed papers [20, 21], the joint actuators mainly can be divided into three aspects: electromagnetic drive [22–25], hydraulic drive [26–28] and pneumatic drive [29–31]. For the electromagnetic drive (i.e., the servomotor drive), the servomotors generally need additional reduction boxes so as to increase the torque by decreasing the revolving speed, which will expand the size and weight of the whole device. That is how the electromagnetic motors are limited by requiring transmission elements to convert their high-speed and low-torque output features to low-speed and high-torque features [21]. As for the hydraulic drive and the pneumatic drive, they both depend on the non-portable pressure supplies. Both the pumps and air compressors are too heavy and large to carry, making their applications limited to the platform-based fields with no or low portability [21]. Furthermore, there may be an inevitable hysteresis between the inflation and deflation process, which is a potential limitation. The passive types mainly comprise the elastic components (especially springs) [32, 33] and the quasi-passive types chiefly comprise the viscosity devices such as clutches, dampers or clutch–damper combinations [34–36]. The hybrid types are a combination of more than one type of active, passive or quasi-passive actuators [37, 38].

Different from the walking assistive devices mentioned above, a novel hip-joint-type mechanism of the walking assistive system for the elderly is proposed and investigated in this research. The proposed mechanism is mainly composed of an ultrasonic motor (USM), a linear spring, a steel wire, four pulleys and one rotating part. Different from the traditional actuation types, the innovative proposal is to utilize the USM, which is a novel type of actuators based on the vibration of the stator in the ultrasonic frequency band and the reverse piezoelectric effect of piezoelectric materials [39]. Its stator's vibration can generate driving force via friction to its rotor, which converts electric energy into mechanical energy. USMs have plenty excellent and attractive characteristics such as high torque at low speed, quick response, quiet operation, compact dimensions, light weight, self-locking when power is off, and favorable electromagnetic compatibility [40]. Firstly, due to the fact that USMs can achieve high torque at low speed, there is no need to add a big and bulky gear box, leading to its compact dimensions, light weight and high portability. It implies that USMs are suited to assist people with slow speed, which was appropriate for the disabled and the elderly. Secondly, considering the importance of the device's response time, the response time of the joint actuators is equally worthy of attention. Thus, the characteristic of quick response at the millisecond level promises USMs the attractive prospects in the application of walking assistive systems.

Moreover, the advantages of this research is not only installing the USM but also introducing the wire-driven method. As is known to all, the gears used in the devices may cause the problems of friction, backlash, torque ripple and noise [41]. To address this issue, a steel wire and pulleys, which are easily to assemble and disassemble, are utilized in this novel mechanism to replace the gears and other transmissions. What's more, it is worth mentioning that current walking assistive devices and cooperative robots usually utilize elastic components in series with stiff actuators (named as series elastic actuator, SEA) to guarantee safety in physical human-robot interactions [42–44]. Ning et al. [45] and Zhang et al. [46] have developed a SEA with an active-type continuously variable transmission for the exoskeleton design, which can meet the different requirements of daily life. Lee et al. [47] have proposed a tendon type of SEA for a knee assistive exosuit, which can offer power in the knee joint when walking up and down the stairs. Chen et al. [48] presented a novel SEA with a flat torsional spring to guarantee the safety and control accuracy of cooperative robots. Al-Dahiree et al. [49] applied a rotary SEA in a lumbar support exoskeleton to increase the level of assistance and exploit the human bioenergy during the lifting task. Given the advantages of the SEA, one simple linear spring is applied as the series elastic part in this study, achieving additional performances such as strong shock resistance, better safety, energy storage and high force/torque control ability. Hence, this active-passive walking assistive device is named as "a wire-driven series elastic mechanism based on ultrasonic motor". In this paper, the mechanical design and working principle of this device are detailedly discussed. A prototype is manufactured and its actual performance is verified by the experimental results. Experiments with different operating periods have been conducted for different applications such as normal walking, slowly walking and rehabilitation exercise.

The outline of this manuscript is organized as follows. Section 2 presents a detailed description of the mechanical design and theoretical model of the proposed mechanism. In Section 3, the experimental verification and analyses are discussed in detail. Finally, the conclusions of this study are given in Section 4.

2 Mechanical Design and Theoretical Model

As depicted in Figure 1, the proposed mechanism is mainly composed of an ultrasonic motor, a linear spring, a steel wire, four pulleys and one rotating part. This mechanism is mounted on the outside of the user's thigh and Pulley3 is located near the hip joint. About the four pulleys: Pulley1 is fixed on the base plate; Pulley2 is fixed on the rotating part; the center of Pulley3 is on the servomotor's rotation axis; Pulley4 is fixed on the USM's output shaft. One end of the steel wire is attached to pulley4 and the other end is connected to the spring. Before the working principle is introduced, it is worth mentioning that a simple assumption is made that the 'leg' (the rotating part) should be lifted up and put down at a uniform speed, which needs further improvement in the future.

Driven by a servomotor, the rotating part can rotate forward and backward to simulate the lift-up and put-down movement of one's leg. In this case, when the servomotor drives the rotating part to rotate forward at a certain speed, the USM simultaneously rotates clockwise to roll up the steel wire and then stretch the spring to reach the target torque as fast as possible. After that, the speed of USM should follow that of servomotor to keep the steel wire under the constant tension to provide the constant assistive torque through Pulley2 for the user when lifting the leg up. Once reaching the final position, the servomotor drives the rotating part to go back at the same speed, the USM simultaneously rotates anticlockwise to release the steel wire. During this process, the speed of USM should also follow that of servomotor to make sure that the steel wire is gradually in a slack state so as to reduce the torque to near 0 and then stay torque free until returning the initial position. This is because when the user wants to put the leg down, if there is still an additional torque, then it would be an obstacle. That is to say this wire-driven method is used to offer only one direction support, which can meet the design requirements.

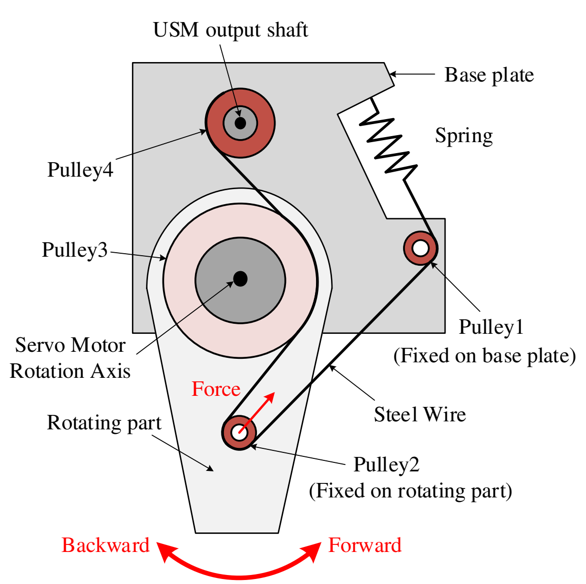

Figure 1 Structure diagram of the proposed mechanism

Regarding the role of the servomotor and ultrasonic motor mentioned above, it should be clearly clarified that the servomotor does not provide any torque but just drives the rotating part to rotate to simulate a human leg. The servomotor is not an integral part of the actual device. If installed on the leg, there will be no servomotor. This proposed mechanism only comprises one motor: an ultrasonic motor, which offers the final assistive torque.

In this mechanism, one simple linear spring is introduced as the elastic component, which can increase the shock tolerance, lower the reflected inertia and achieve the more accurate and stable force control. In addition, this mechanism is driven by the steel wire instead of the gears, which can avoid the disadvantages of friction, backlash, torque ripple and noise. That is to say, the spring, the steel wire, the pulleys and the USM together form a SEA. Therefore, this proposed mechanism is called as a wire-driven series elastic mechanism. To overcome the USM's insufficient output torque, the steel wire and pulleys are smartly combined to directly magnify the torque instead of using a gear reducer. To clearly reveal the principle of amplification, one theoretical model is built, as shown in Figure 2.

Figure 2 presents the mathematical model of the proposed mechanism at the initial position, corresponding to Figure 1. The xy-plane coordinate system is established with the center of Pulley3 as the origin. The center coordinates of Pulley 1, 2, 3 and 4 are respectively (x_1, y_1), (x_2, y_2), (0, 0) and (x_4, y_4). The radii of these 4 pulleys are respectively r_1, r_2, r_3 and r_4 ($r_1 = r_2$). R_1, R_2 and R_4 represent the distances from the centers to the origin. Therefore, the expressions for the four circles can be obtained as follows:

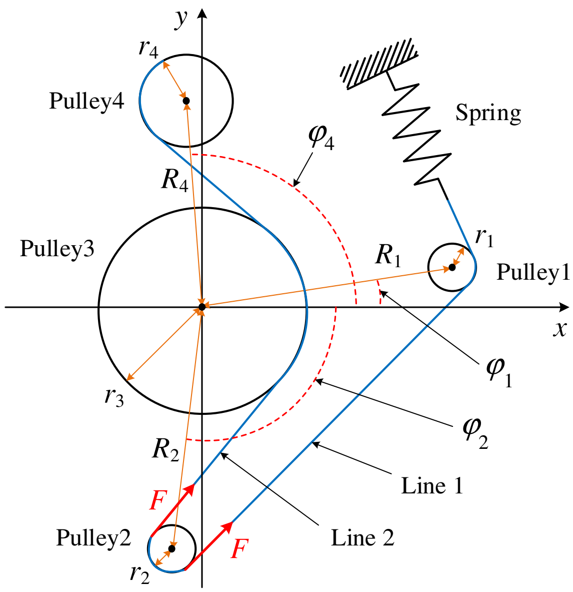

Figure 2 Mathematical model of the proposed mechanism

$$\begin{aligned}
&(x-x_1)^2+(y-y_1)^2=r_1^2, \quad \begin{cases} x_1=R_1\cos\varphi_1, \\ y_1=R_1\sin\varphi_1, \end{cases} \\
&(x-x_2)^2+(y-y_2)^2=r_2^2, \quad \begin{cases} x_2=R_2\cos\varphi_2, \\ y_2=R_2\sin\varphi_2, \end{cases} \\
&x^2+y^2=r_3^2, \\
&(x-x_4)^2+(y-y_4)^2=r_4^2, \quad \begin{cases} x_4=R_4\cos\varphi_4, \\ y_4=R_4\sin\varphi_4. \end{cases}
\end{aligned} \tag{1}$$

where φ_1, φ_2 and φ_4 are the angles. And the Line 1 can be expressed as:

$$\begin{aligned}
&(y_1-y_2)x-(x_1-x_2)y- \\
&r_1\sqrt{(x_1-x_2)^2+(y_1-y_2)^2}+x_1y_2-y_1x_2=0.
\end{aligned} \tag{2}$$

Then the distance from the origin to the Line 1 is:

$$\begin{aligned}
&\frac{r_1\sqrt{(x_1-x_2)^2+(y_1-y_2)^2}-x_1y_2+y_1x_2}{\sqrt{(x_1-x_2)^2+(y_1-y_2)^2}} \\
&=r_1+\frac{R_1R_2\sin(\varphi_1-\varphi_2)}{\sqrt{R_1^2+R_2^2-2R_1R_2\cos(\varphi_1-\varphi_2)}}.
\end{aligned} \tag{3}$$

Considering that the distance from the origin to the Line 2 is r_3, the output torque T_{output} of this mechanism (comes from Pulley2) can be obtained:

$$T_{output}=\left(r_1+r_3+\frac{R_1R_2\sin(\varphi_1-\varphi_2)}{\sqrt{R_1^2+R_2^2-2R_1R_2\cos(\varphi_1-\varphi_2)}}\right)F, \tag{4}$$

Table 1 Parameters of the designed mechanism

Parameter	Value
Radius of Pulley1 r_1 (mm)	9.5
Radius of Pulley2 r_2 (mm)	9.5
Radius of Pulley3 r_3 (mm)	25
Radius of Pulley4 r_4 (mm)	15
Distance from Pulley1 to the origin R_1 (mm)	75
Distance from Pulley2 to the origin R (mm)	40
Distance from Pulley4 to the origin R_4 (mm)	70
Angle of Pulley1 φ_1 (°)	15
Angle of Pulley4 φ_4 (°)	105

where F is the rope tension. Hence, the reduction ratio i of this mechanism should be:

$$i=\left(r_1+r_3+\frac{R_1R_2\sin(\varphi_1-\varphi_2)}{\sqrt{R_1^2+R_2^2-2R_1R_2\cos(\varphi_1-\varphi_2)}}\right)\frac{1}{r_4}, \tag{5}$$

where r_1, r_3 , r_4, R_1, R_2 and φ_1 are all constants in the initial design, as shown in Table 1. So the reduction ratio i is a function of φ_2, which means that as the rotating part rotates, the reduction ratio i changes, i.e., the output torque is not constant. Based on Eq. (5), the reduction ratio curve is given in Figure 3. It can be noted that as the angle increases from − 120° to − 40° (the motion range is about 80°), the reduction ratio increases from 3.6 to about 5.0, which is not in line with the expectation. It is worth mentioning that, considering the mechanism's scale and the USM's performance, the ideal reduction ratio is determined to be 4.5 (as a compromise considering the torque and speed).

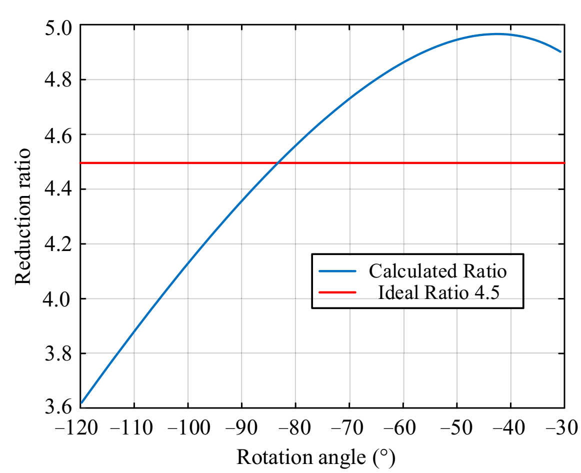

Figure 3 Reduction ratio curve of the mechanism

In order to address the issue of unstable output torque and keep the reduction ratio as 4.5, one special pulley with variable radius is designed to replace the original Pulley3, as shown in Figure 4(a). And its radius curve is given in Figure 4(b). With the angular variation, the reduction ratio can remain 4.5 constantly by using this new Pulley3.

For the walking assistive system, how long it takes to reach the final output torque is a key point. Namely, the startup response time is an important research target. To estimate the startup response time t of the proposed mechanism, a further study is conducted as follows. During the operation of this mechanism, the length of the Line 1 is changed. The line's initial length l_0, the after-t-time length l_t and the changed length Δl can be obtained:

$$\begin{aligned} l_0 &= \sqrt{R_1^2 + R_2^2 - 2R_1R_2\cos(\varphi_2 - \varphi_1)}, \\ l_t &= \sqrt{R_1^2 + R_2^2 - 2R_1R_2\cos(\varphi_2 - \varphi_1 + \theta t)}, \\ \Delta l &= l_0 - l_t. \end{aligned} \tag{6}$$

One ultrasonic motor (named PSM60S-E2T) shown in Figure 5(a), manufactured by Piezo Sonic (Piezo Sonic Co., Ltd, Japan) is utilized in this research. Based on its product manual, this USM's performance curve is presented in Figure 5(b). Its no-load speed and stalling torque are about 18.8 rad/s and 1.4 N·m respectively.

Considering that the USM's speed is roughly from 17.8 to 18.8 rad/s during the mechanism's start-up stage, a linear fitting curve (shown in Figure 5(b)) is given to fit the USM's performance curve. Combined with Figure 2, the rotate speed $v_{\mathrm{rad/s}}$ can be given as:

$$\begin{aligned} v_{\mathrm{rad/s}} &= 18.8 - 2.85T = 18.8 - 2.85Fr_4 \\ &= 18.8 - 2.85(k \cdot \Delta x)r_4, \end{aligned} \tag{7}$$

where T, F, k and Δx respectively represent the USM's output torque, the tension of the steel wire, the spring's elastic constant and the spring's extended length.

Changing the unit of Eq. (7) from rad/s to m/s, the Pulley4's rotate velocity $v_{\mathrm{m/s}}$ can be written as:

$$\begin{aligned} v_{\mathrm{m/s}} &= \frac{18.8 - 2.85(k \cdot \Delta x)r_4}{60} \cdot 2\pi r_4 \\ &= 0.627\pi r_4 - 0.095\pi k r_4^2 \cdot \Delta x = A \cdot \Delta x + B, \end{aligned} \tag{8}$$

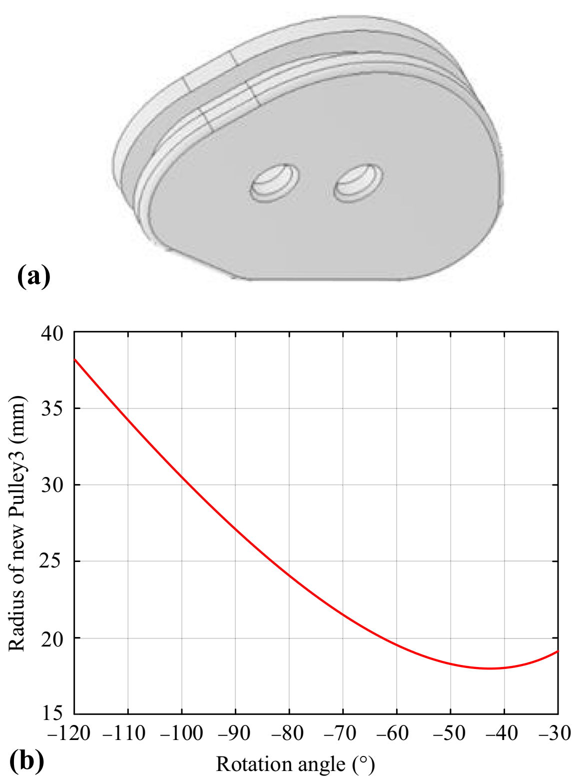

Figure 4 Designed special Pulley3: (**a**) 3D model, (**b**) Radius curve

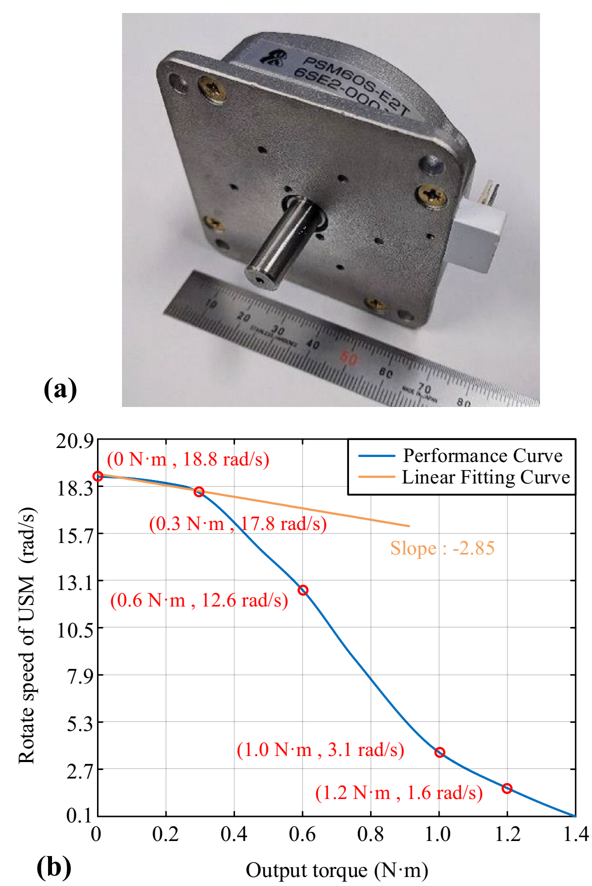

Figure 5 PSM60S-E2T: (**a**) Prototype, (**b**) Performance curve

where $A = -0.095\pi k r_4{}^2$ and $B = 0.627\pi r_4$. For this proposed mechanism, its equation of motion is:

$$v_{\mathrm{m/s}} \cdot t = \Delta x + \Delta l. \tag{9}$$

Substitute Eqs. (6) and (8) into Eq. (9), the relationship between the spring's extended length Δx and the response time t can be obtained as follows:

$$\Delta x = \frac{\Delta l - Bt}{At - 1} = \frac{l_0 - \sqrt{R_1^2 + R_2^2 - 2R_1R_2\cos(\varphi_2 - \varphi_1 + \theta t)} - Bt}{At - 1}. \tag{10}$$

Based on Eq. (10), a numerical curve for t and Δx can be plotted. For one certain spring with the elastic constant of k, the extended length Δx is a constant once the tension is given. Then, for this Δx, a corresponding time t that needed to reach the extended length Δx can be observed from the numerical curve. With this method, the response time respectively corresponding to the elastic constants from 500 to 4000 N/m can be obtained. For this mechanism used for walking assistive system, setting 1.6 N·m as a proper output torque (the corresponding tension is about 25 N), the calculated response time with different elastic constants is plotted in Figure 6. It can be easily found that the harder the spring is, the shorter the response time is. However, at this curve's last part, the response time decreases slowly as the spring constant increases.

In order to reduce the startup response time and reach the target torque as soon as possible, utilizing a harder spring could be a better choice. For the walking assistive system, the startup response time lower than 100 ms is expected. Therefore, several springs have been tested in this research, as shown in Figure 7. As illustrated in Figure 6, the calculated response time of Spring1 ($k_1 = 580$ N/m), Spring2 ($k_2 = 1840$ N/m), Spring3 ($k_3 = 2230$ N/m) and Spring4 ($k_4 = 3200$ N/m) are 346 ms, 109 ms, 89 ms, and 63 ms respectively.

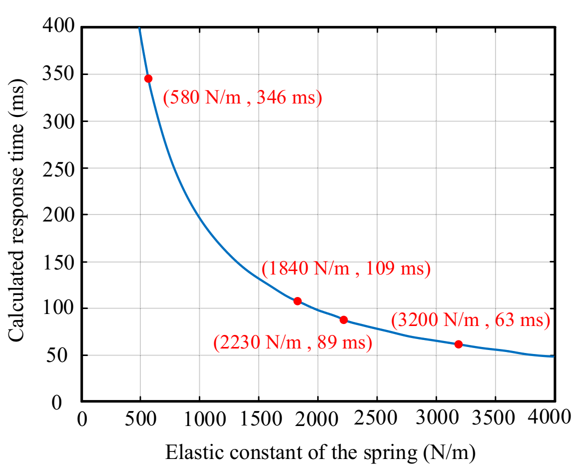

Figure 6 Calculated response time with different elastic constants

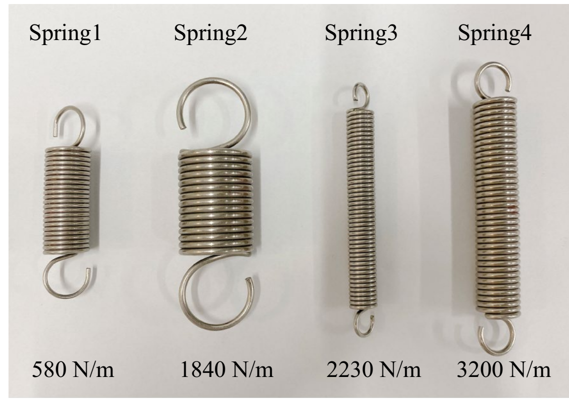

Figure 7 Springs with different elastic constants

3 Experimental Verification and Analyses

Based on the above design process, the 3D model and the final prototype are presented in Figure 8. Considering that the parts (the rotating part and the base plate) made of stainless steel can be replaced by 3D printed ones, the overall weight of the prototype can be limited in 800 g, which is superior to other existing assistive mechanisms. Figure 9 shows a picture of the experimental setup used to measure the mechanical properties of this proposed mechanism. The rotating part's shaft of the proposed mechanism is connected to an electromagnetic

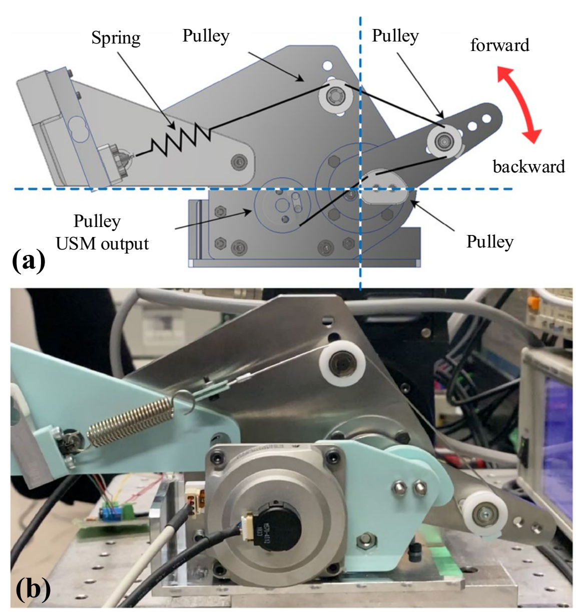

Figure 8 Proposed mechanism: (**a**) 3D model, (**b**) Prototype

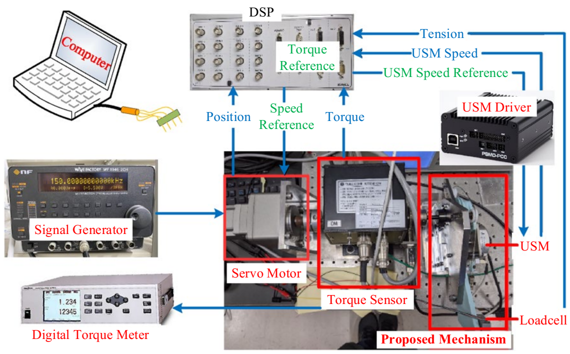

Figure 9 Experimental setup for the mechanism

servomotor (NX920AA-PS5-3; Oriental Motor Co., Ltd, Japan) through a torque sensor (SS-050; Ono Sokki Co., Ltd, Japan).

Regarding the role of the servomotor and USM mentioned above, it should be clarified again that the servomotor does not provide any torque but just drive the rotating part to rotate to simulate a human leg. The servomotor is only used for the experiments, not an integral part of the actual device. If installed on the leg, there will be no servomotor. This proposed device only comprises one motor: An ultrasonic motor, which offers the output torque. The measured output torque is shown by the Digital Torque Meter (TS-3200A; Ono Sokki Co., Ltd, Japan). The driving signals of the servomotor are generated by the signal generator (WF 1946 2CH; NF Co., Ltd, Japan). The tension of the steel wire is measured by a loadcell (SCI133-2kg; Sensor and Control Co., Ltd, China). In addition, the USM (PSM60S-E2T; Piezo Sonic Co., Ltd, Japan) is controlled by a USM driver (PSMD-PCC; Piezo Sonic Co., Ltd, Japan). Meanwhile, a digital signal processor (DSP) (DS1104; dSPACE Co., Ltd, Germany) is utilized to record all the measured data (rotation angle, output torque, rotation speed and tension) and control both the servomotor and ultrasonic motor by torque reference and speed reference. The servomotor's rotation speed is given to make the rotating part rotate forward and backward at a constant velocity. As for the ultrasonic motor, based on the given torque reference and the measured torque, the DSP outputs the speed reference in real time to the USM. Finally, the collected data is displayed on the monitor of a computer. Considering that the normal walking frequency of elderly people is about 1 Hz, one operating cycle (lift the "leg" up and then put it down) of this mechanism is set as 1 s. The rotating part of this mechanism rotates forward at a constant speed in the first half of the period and then it rotates backward at the same speed in the second half. An assistive output torque is provided in the first 0.5 s and then the torque decreases sharply to about 0. It is worth mentioning that the final output torque is enlarged to 1.6 N·m with the reduction ratio 4.5.

To verify the accuracy of the above calculated response time shown in Figure 6, experiments with the four springs (shown in Figure 7) have been conducted, whose results are depicted in Figure 10 and listed in Table 2. To reach the torque of 1.6 N·m, Spring1 ($k_1 = 580$ N/m), Spring2 ($k_2 = 1840$ N/m), Spring3 ($k_3 = 2230$ N/m) and Spring4 ($k_4 = 3200$ N/m) respectively took 228 ms, 152 ms, 119 ms, and 86 ms. Compared with the calculated data, the margin of error is approximately one third. In view of the USM's nonlinear performance and the control system's delay time, it is safe to say that the experimental results agree with the theoretical results in terms of the trend and the order of magnitude. That also proves that using a stiffer (within limits) spring would be better. Hence, the spring with the constant of 3200 N/m is chosen for this mechanism. Furthermore, it's also important to mention that using a stiffer spring can lead to a torque rebound after changing the rotation direction, at about 0.6 s. The Pulley2 pull on the steel wire may account for this phenomenon. Although the torque rebound has been greatly reduced by adjusting the control parameters (for now, only a simple PI controller is used), it still cannot be completely eliminated. Even so, the torque rebound of roughly 0.18 N·m is still acceptable. For further research, a better closed-loop controller is needed to completely remove the torque rebound.

Figure 11 presents the experimental results of the mechanism with the period of 1 s. The intention is to lift the leg up to a certain angle (for example, 26° shown in Figure 11) at a constant speed in the first 0.5 s and then

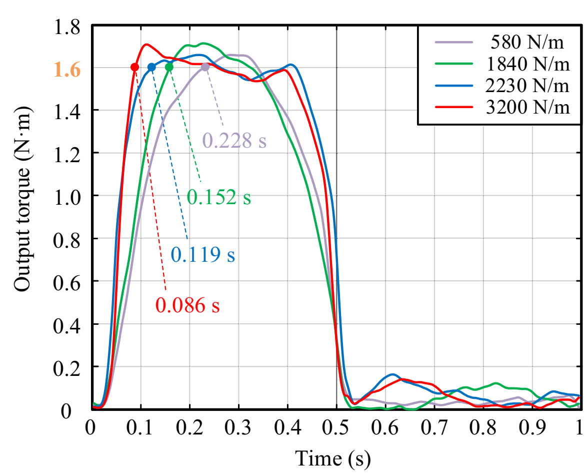

Figure 10 Measured response curves with different springs

Table 2 Response time with different springs

Springs	Elastic constant k (N/m)	Extended length Δx (mm)	Calculated time (ms)	Measured time (ms)	Error (%)
Spring1	580	44.0	346	228	− 34.1
Spring2	1840	13.9	109	152	39.4
Spring3	2230	11.4	89	119	33.7
Spring4	3200	8.0	63	86	36.5

put it down at the same constant speed to the initial position in the second 0.5 s. Hence, the servomotor should drive the rotating part to rotate at 52°/s (about 0.91 rad/s) for 0.5 s and then rotate reversely at 52°/s for another 0.5 s.

During the first 0.5 s, once the servomotor starts, the USM should simultaneously start to roll up the steel wire and stretch the spring to reach the target torque as soon as possible. It can be noted from Figure 11(a) that it only takes about 86 ms to reach the output torque of 1.6 N m, which starts to help the user lift his/her leg up. Afterwards, the speed of USM is supposed to follow that of the servomotor (0.91 rad/s $\times$ 4.5 $\approx$ 4.1 rad/s) to keep the steel wire under the constant tension so as to continue providing the constant assistive torque through Pulley2 for the user when lifting the leg up.

During the second 0.5 s, the servomotor rotates reversely, then the USM should also rotate reversely to release the steel wire immediately so as to reduce the torque to near 0 as soon as possible. The torque should drop rapidly ahead of time in order not to give resistance to the backward motion. Then the USM follows the servomotor's speed to stay torque free until returning the initial position. In other words, this mechanism only provides the assistive torque when the user wants to lift his/her leg up, and after that it must make sure the leg should be put down naturally without any external torque. In order to make the torque zero at the beginning of the second 0.5 s as much as possible, we adjust the reference torque curve, i.e., in advance (before the beginning of the second 0.5 s) to make the reference torque curve reduce to near 0.

Besides, although the shape of the measured tension curve in Figure 11(b) is quite similar to that of the measured torque curve in Figure 11(a), the delay can be easily observed. The tension curve is roughly 30 ms ahead of the torque curve, which may due to the properties of the measuring equipment. From Figure 11(c), it can be found that the USM's steady speed is around 4.1 rad/s but it outputs a final torque of 1.6 N·m (more than the USM's original stall torque), which verifies the amplification of the wire and pulleys. It can also be noted that the measured maximum speed of USM is near 25.2 rad/s (larger than the no-load speed 18.8 rad/s shown in Figure 5(b)), which may account for the errors between the experimental data and the calculated results.

In addition, experiments with the periods of 2 s and 3 s have been conducted, whose results are shown in Figures 12 and 13. For the case of 2 s, the "leg" is lifted up about 47° in 1 s, which means the rotating part's velocity is 47°/s (about 0.82 rad/s). The USM's steady speed is around 3.7 rad/s. This working mode of 2 s period (walking frequency is 0.5 Hz) can help older people walk slowly in some special situations.

For the case of 3 s, the "leg" is lifted up about 44° in 1.5 s, which means the rotating part's velocity is roughly 29°/s (about 0.51 rad/s). The USM's steady speed is around 2.3 rad/s. This working mode of 3 s period (walking frequency is about 0.33 Hz) could be utilized in the application of rehabilitation exercise for patients. In general, the response time of the proposed mechanism is about 0.1 s, which is superior to those of the other mechanisms (most are higher than 0.5 s) [28, 30, 44, 49]. This also highlights the advantages of using an ultrasonic motor as the driving source.

From the design parameters listed in Table 1, it can be found that the radius of Pulley4 is 15 mm. Therefore, with the reduction ratio 4.5, the designed equivalent radius of this mechanism should be 67.5 mm based on Eq. (5). Figure 14 collects the measured equivalent radius (the measured torque divided by the measured tension) of the mechanism during the first half of one period (1 s, 2 s and 3 s). When the output torque is stable (after reaching 1.6 N·m), the measured equivalent radius is very close to 67.5 mm, which verifies the effectiveness of the designed special Pulley3.

4 Conclusions

In order to improve the elderly people's quality of life, supporting their walking behaviors is a promising technology. Therefore, based on ultrasonic motor, a wire-driven series elastic mechanism for walking assistive system is proposed and investigated in this research. It innovatively utilizes an ultrasonic motor and a

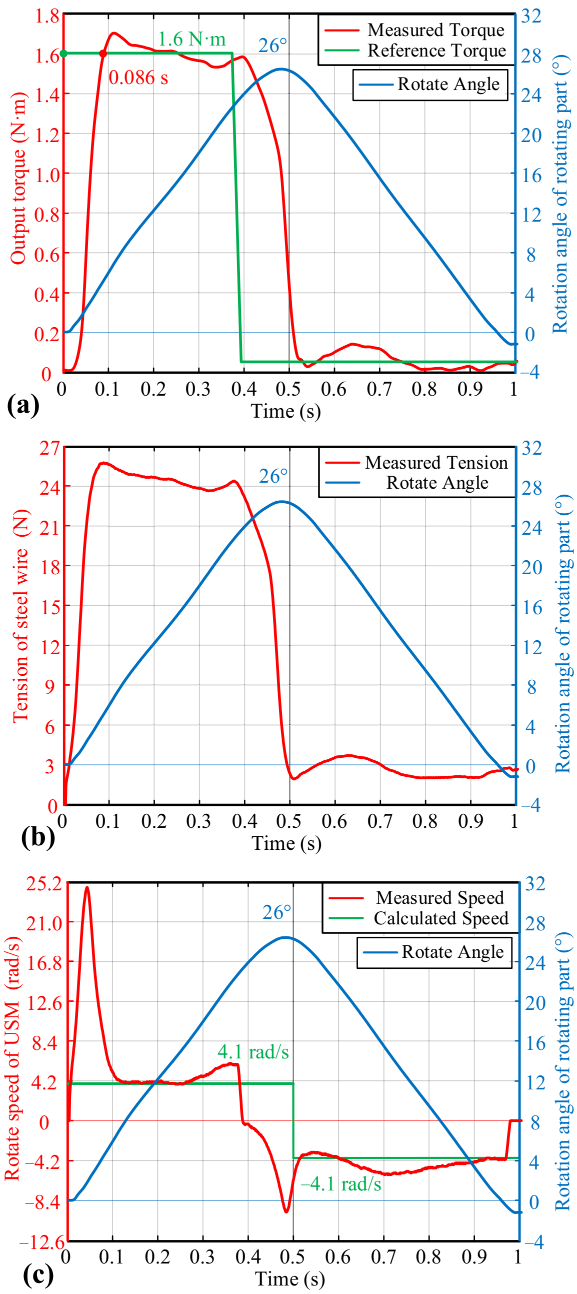

Figure 11 Experimental results with the period of 1 s: (**a**) Prototype's output torque response curve, (**b**) Steel wire's tension response curve, (**c**) USM's rotate speed curve

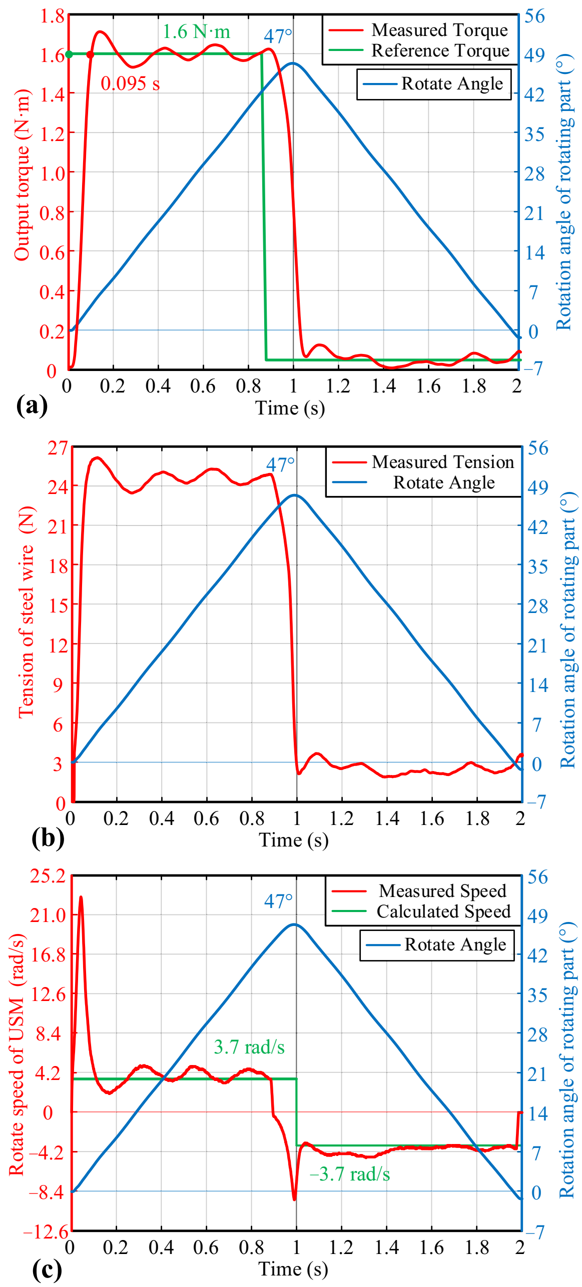

Figure 12 Experimental results with the period of 2 s: (**a**) Prototype's output torque response curve, (**b**) Steel wire's tension response curve, (**c**) USM's rotate speed curve

wire-driven series elastic mechanism to achieve system performances in aspect of simple structure, light weight, quiet operation, quick response, strong shock resistance and accurately stable force control. The proposed mechanism is mainly composed of an ultrasonic motor, a linear spring, a steel wire, four pulleys and one rotating part. USMs have plenty excellent and attractive characteristics such as high torque at low speed, quick response, quiet operation, compact dimensions, light weight, and no electromagnetic interferences. They imply that USMs are suited to assist people with slow speed, which was appropriate for the disabled and the elderly. To overcome the ultrasonic motor's insufficient output torque, a steel wire and pulleys are smartly combined to directly magnify the torque instead of using a traditional gear reducer.

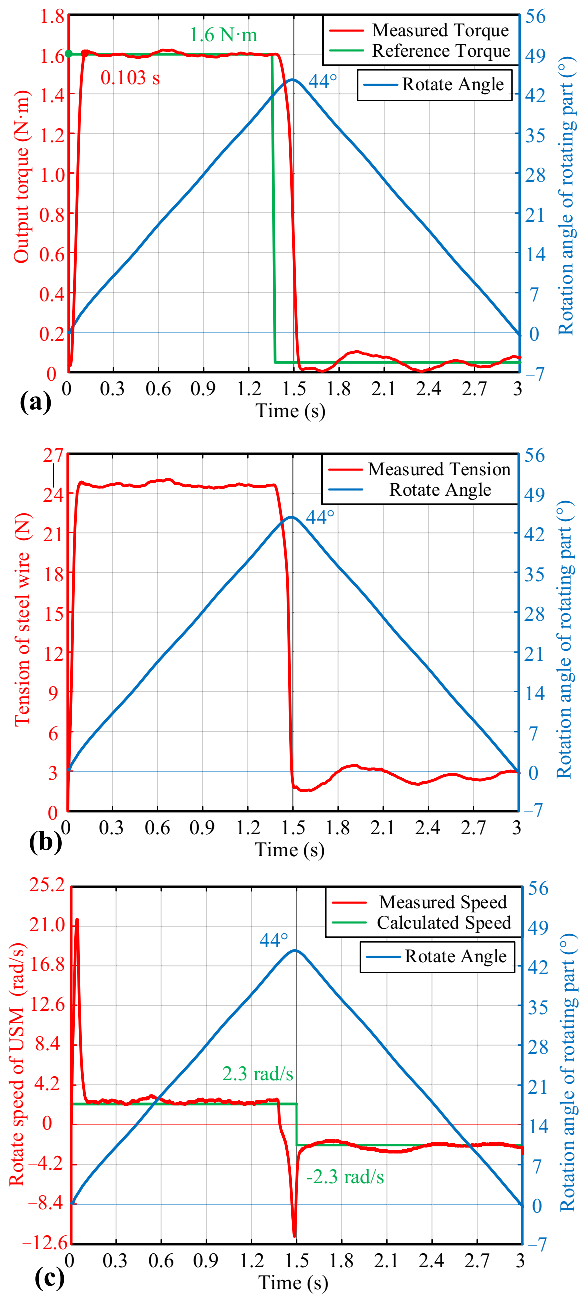

Figure 13 Experimental results with the period of 3 s: (**a**) Prototype's output torque response curve, (**b**) Steel wire's tension response curve, (**c**) USM's rotate speed curve

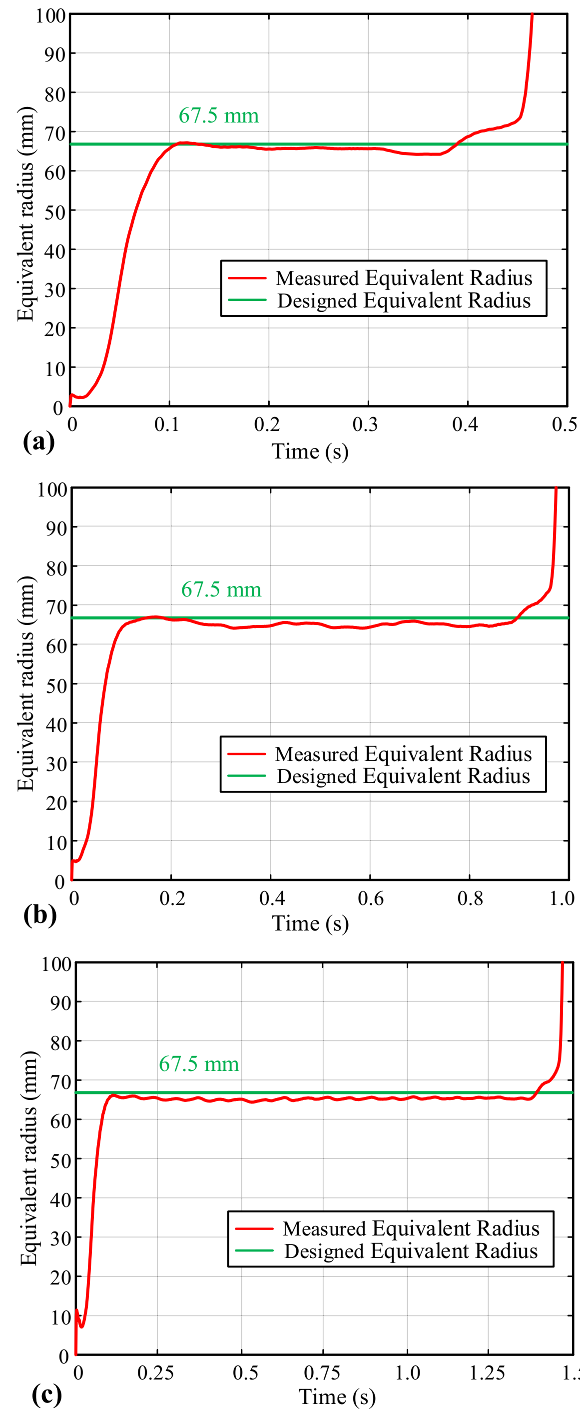

Figure 14 Equivalent radius of the mechanism during the first half of one period: (**a**) With the period of 1 s, (**b**) With the period of 2 s, (**c**) With the period of 3 s

Among the pulleys, there is one tailored pulley playing an important role to keep the reduction ratio as 4.5 constantly. The mechanical design and working principle of this device are discussed in detail. Meanwhile, the prototype is manufactured and its actuation performance is verified by the experimental results. In a one-second operating cycle, it only takes 86 ms (superior to other mechanisms) for this mechanism to output an assistive torque of 1.6 N·m, which is larger than the USM's stall torque. At this moment, the ultrasonic motor's speed is around 4.1 rad/s. Experiments with periods of 1 s, 2 s and

3 s have been conducted for different applications such as normal walking, slowly walking and rehabilitation exercise. In addition, it is worth mentioning that this mechanism has the characteristic of light weight, only about 800 g.

Admittedly, due to USM's properties of the relatively low output torque and low efficiency, the application of this proposed mechanism is limited. Besides, if its portability is fully considered, the battery problem still needs to be solved. Based on the ultrasonic motor, there is still a long road to transfer the wire-driven mechanism from lab to commercialization.

In the future, we will devote ourselves to improve the performances of the proposed mechanism, especially improving the control system to make its operation more suitable for the actual situation of walking. For example, biomechanically adjust the time of "leg" lift-up and put-down instead of the fixed fifty-fifty. Meanwhile, better USMs with larger torque will be used and tested in this mechanism. After that, we will attempt to install this mechanism on the user's leg to conduct further research.

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Author's Contributions
WR and TM were in charge of the whole trial; WR wrote the manuscript; HY and LY assisted with sampling and laboratory analyses. All authors read and approved the final manuscript.

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Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing Interests
The authors declare no competing financial interests.

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