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Design of an Unpowered Ankle-Foot Exoskeleton Used for Walking Assistance

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Abstract—**Enhance human walking and running is much more difficult compared to build a machine to help someone with disability. Unpowered ankle-foot exoskeletons are the current development trend due to their lightweight, wearable, and energy-free features, but the huge recognition and energy control system still affects their practicability. To refine the recognition and control system, we designed an unpowered soft ankle-foot exoskeleton with a purely mechanical self-adaptiveness clutch, which can realize the collection and release of energy according to different gait stage. Through switching and closing of this clutch, energy is collected when the ankle is doing negative work and released when the ankle is doing positive work. Results shows the unpowered ankle-foot exoskeleton at the stiffness of 12000 N/m could relieve muscles' load, with reduction of force by 52.3 % and 5.2%, and of power by 44.2% and 7.0%, respectively for soleus and gastrocnemius in simulation.**

***Clinical Relevance*—The proposed Unpowered Ankle-Foot Exoskeleton can both reduce muscle forces and powers. Hence, it can be used to assist walking of the elderly, others with neurocognitive disorders or leg diseases.**

I. INTRODUCTION

The global wave of aging is getting more and more serious. At present, the number of people over the age of 60 in China alone has exceeded 250 million. Muscle strength will decrease with age, which in turn affects the stability of gait of the elderly. Researchers hope to use some equipment to help the elderly walk. Compared to building a machine to help someone with a disability, it's very difficult from a design perspective to augment human walking and running. Because Humans are skilled walkers and our bodies have evolved well-suited to locomotion over generations [1][2]. Traditional medical auxiliary for the elderly (crutches, wheelchairs) cannot meet the needs of the elderly. More and more researchers begin to study how to enhance the walking function of the human body, such as exoskeleton [3], exosuits [4][5].

In recent years, soft exoskeletons are gradually replacing rigid exoskeletons in assisting walking due to their less restrictive and more biomimetic architectures. Nowadays Lower extremity exoskeleton robot is a wearable human-machine device combining artificial intelligence, mechanical power device and mechanical energy, which has the functions of improving the walking durability and loading capacity of human body [6]. Depending on whether there is a power source, the exoskeleton can be divided into powered and unpowered exoskeleton. The powered lower limb exoskeleton robot takes the motor, pneumatic or hydraulic drive as the power source, and transits the motion intention of the wearer to the exoskeleton robot with the help of bioelectric signal sensors and mechanical signal sensors. Under the guidance of the human gait, it assists the wearer at a proper time [7]. For example, Collins developed human in the loop optimization method for identifying the exoskeleton assistance which can minimizes human energy cost during walking [8]. It can assist human walking, but also exists some drawbacks such as large mass, bloated structure, short endurance, high operating cost. Some researchers want to invent a device based on the laws of gait which does not need external energy. The device converts the gravitational potential energy of human body to the elastic element, and assists the movement with the help of the energy switching device. Leclair and Pardoel both invented an ankle-foot exoskeleton, which can assist walking in push-off stage [9][10]. Due to less restrictive non-power and more biomimetic architectures, the unpowered exoskeleton is a new direction for the development of exoskeleton.

The key to the design of the unpowered exoskeleton is the clutch, which precisely controls the storge and release of energy. In human walking, the most work done by the ankle joint is about 45 percentage of the total work of the human joint [15]. In the design of unpowered ankle-foot exoskeleton, the key design is also clutch. Clutch controls energy collection and release by identifying the phase of human gait. Clutch mainly has electronic such as EMG sensor [11], foot pressure sensor [8], inertia sensor [12] and pure mechanical [3][5]. Sensors based on electrical signal need to be equipped with control and processing systems, increasing the weight, complexity and sometimes causing delays. Pure mechanical clutch, simple without power supply and delay characteristics. Both Collins and Xiangyang team adopted this approach, but it is still complicated and can only walk on level ground. Thus, this paper wants to design a new clutch placed on the sole to assist walk with less restrictive and ignore the impact of uphill and downhill.

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The paper aims to design an unpowered soft ankle-foot exoskeleton with a mechanical self-adaptiveness clutch. which can Through a clever four-bar clutch, the invented ankle-foot exoskeleton can precisely identify different gait stages and provide assistance at a proper time. Firstly, the walking experiments were conducted in order to study the biomechanics and energy conversion in walking and found the design criteria for clutch and elastomer. Secondly, unpowered ankle-foot exoskeleton with purely mechanical clutch was designed which can precisely identify different gait stages and provide assistance at a proper time, according the biomechanics and energy conversion. Then, a musculoskeletal model with the unpowered ankle-foot exoskeleton was set up and an simulation was conducted to demonstrate the effectiveness of the equipment.

II. METHODS

A. *Biomechanics and Energetics*

In order to explore the relations between unpowered ankle-foot exoskeleton design and human walking, a series of normal walking experiments were conducted. Gait data has two purposes: on the one hand, it is used to explore biomechanics and energy conversion and spring power changes; on the other hand, it is used to provide driving data for the human-exoskeleton coupling model. The experiment was approved by the Institutional Review Board of Shenzhen Institutes of Advanced Technology (SIAT-IRB-160915-H0113). Each subject experienced an acclimation session prior to data collection. They were instructed to walk using their normal speeds on level ground and two force plate were set two meters away from the start point. Kinematics data was recorded by a 3D motion optic capture system (Motion Analysis Eagle, USA) and the ground reaction forces were collected using two AMTI force plates (OR6-7, USA). 41 markers were attached to the body tracking the lower segments motion, as the Figure 1 shows.

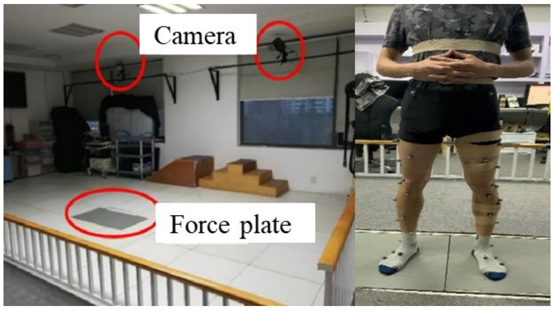

Figure 1. Kinematic data collection scene and marker set placement

Gait cycle was separated into stance and swing phase using the method of Pappas [13]. The stance phase comprises of three subphase that is load response, middle stance and terminal stance. Load response starts of heel strike (HS), while the middle stance commences at foot flat (FF), and terminal stance is corresponding to heel off (HO). The swing phase starts at toe off the ground (TO). The average ankle angle of right foot was calculated using kinematics data and separated it, as Figure 2a shows. The average ankle power of right foot was calculated using the kinematics and GRF data, Figure 2b. When the heel struck ground, the ankle joint firstly performed dorsiflexion motion and did negative work A1. The next it proceeded plantarflexion movement when reached the max angle until swing phase. It did a markable positive work in the A2 phase. Figure 2a shows, ankle joint swings back and forth between the heel off and swing (60% to 100% of the gait cycle) due to the inertia in motion and nonpower was done. Hence, an ideal ankle-foot exoskeleton is which stores energy in the negative work A1 and releases energy in the positive work A2. The dorxiflexion and plantarflexion in the swing phase should also be noticed which can product negative work and must be avoid.

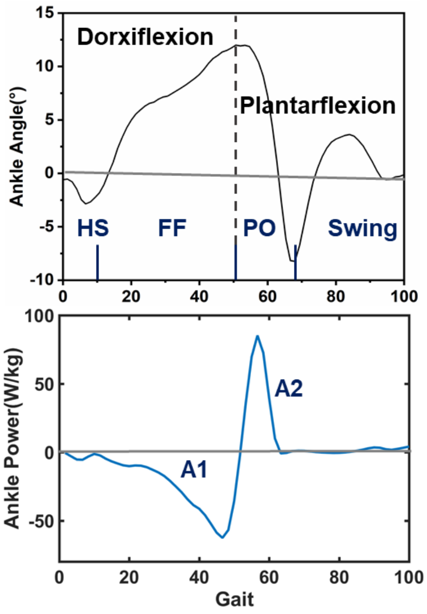

Figure 2. Instantaneous ankle angle and power of ankle joint on a gait cycle

B. *Unpowered Ankle-foot Exoskeleton and Clutch Design*

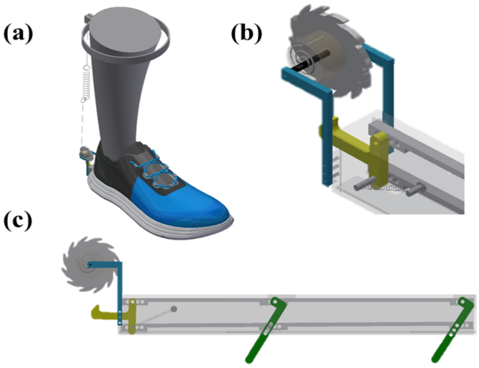

Figure 3. Unpowered ankle-foot exoskeleton. (a) Integrated Ankle-foot exoskeleton (b) Ratchet pawl mechanism (c) Clutch system

Based on the design points explored above, A non-powered ankle-foot exoskeleton was invented which can storge energy at A1 and release energy at A2. As Figure 3 shows, the exoskeleton consists of three parts: a mechanical sensor-controller system set in the sole (c), a mechanical executing part (b) and an energy storage unit(spring).

The sensor-controller system and executing part make up the clutch system, which is the key point of the design of the unpowered ankle exoskeleton and the most core part of the whole exoskeleton. It consists of induction rod, ratchet pawl mechanism and return spring, as Figure 3(c) shows. The induction rod was used to determine if the foot is on the ground, and if the foot is on the ground, that is stand phase, the ratchet and pawl are clutched by the link mechanism, and if the heel is off, that is Push-Off, the ratchet and pawl are opened. Its biggest function is to ensure the self-adaptation of the exoskeleton, that is, to identify the gait stage and perform different work according to gait stages and not affected by going up or going down. The main body of the clutch device is embedded in the shoes (Figure 3a). Meshing mainly occurs in the stage of forming a stance in the gait process, and separation mainly occurs in the stage of swing in the gait procession.

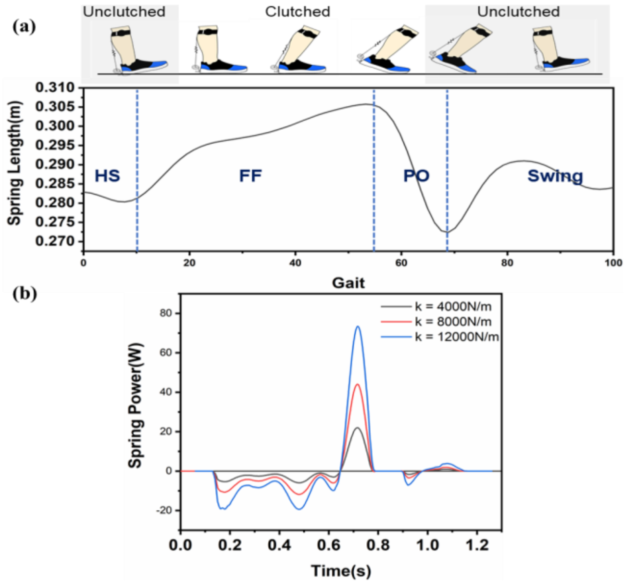

Figure 4. (a) State of the clutch during different gait phases (b) Spring power during gait cycle

Another important point is the design of the energy storage spring. A simulation was conduct to explore the power of different stiffness spring in walking using the normal gait data processed in A. Due to difference conditions between each person's muscles, the stiffness shall be determined according to the actual. In this case, three stiffness spring was adopted. Before the positive work, the spring firstly absorb energy, which most article only give the positive work stage, Figure 4. It is worth noting that from 0.8 to 1.2 seconds, there is still work due to the ankle wobble at this stage. So the range of angles should be avoided.

C. Exoskeleton Testing and Evaluation

Clutch state switching will significantly affect the function and effect of the assist, and as little as possible affect the normal gait law of the human body at the stage when the assist is not needed. A musculoskeletal with unpowered ankle-foot exoskeleton designed above simulation using OpenSim was conducted, to verify the feasibility of the unpowered soft ankle exoskeleton and find changes in muscles. Due to the aim muscles only refer to calf's and in order to simply the compute times, we made a trade-off on the model choosing. As Figure 5 shows, a model of eighteen muscle in OpenSim4.1 was selected. The pelvis_list, pelvis_rotation, pelvis_tz coordinates and the exoskeleton and cluchedPathSpring were added to the model using notepad++, respectively. The control signals of cluchedPathSpring were calculated according gait phase. And then a set of muscle forces that drive a dynamic musculoskeletal model to track the walking behavior has been calculated by the method of Thelen [14].

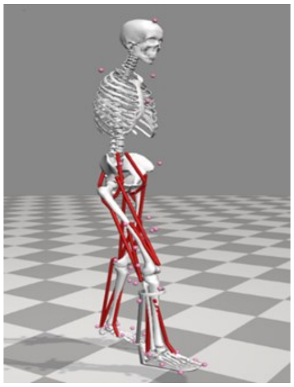

Figure 5. Human musculoskeletal model with the unpowered ankle-foot exoskeleton in OpenSim

III. RESULT AND DISCUSSION

In human walking, the main production work occurs at the stage of step- to-step transition, that is push-off stage. And in this stage, the main working muscles are soleus and gastrocnemius. Due to the start point of lateral gastrocnemius locates at knee, namely it is a cross-joint muscle, the middle gastrocnemius was selected as the research object. Figure 6 depicts variations of muscle force and power over time in a gait cycle with different spring stiffness. And the data of maximum muscle forces and range of powers are showed in Table 1. The forces and power present decrease trend with the spring stiffness increasing. So it can be sure using our unpowered exoskeleton can assist walking and make muscles producing less work during human walk. The maximum force of soleus reduced 223N on average while the 33.2 N of gastrocnemius, for each 4000N/m increase of stiffness. But the declined values of both maximum forces increased as the spring stiffness increases. Therefore, subjects should choose the maximum stiffness fitted to themselves on the exoskeleton.

TABLE I. MAXIMUM FORCE AND POWER RANGE

Stiffness (N/m)	Soleus		Gastrocnemius	
	Maximum Force(N)	*Range of Power(W)*	*Maximum Force(N)*	*Range of Power(W)*
no spring	1279.6	154.2	1912.5	235.0
4000	1056.5 (17.4%)	132.6 (14.0%)	1901.4 (0.6%)	231.1 (1.7%)
8000	840.9 (34.3%)	111.8 (27.5%)	1882.7 (1.6%)	225.4 (4.1%)
12000	609.9 (52.3%)	86.0 (44.2%)	1812.9 (5.2%)	218.6 (7.0%)

Number in brackets are the corresponding reduction

As the stiffness increase, the required force and power of muscles decrease, which is as the same as Collins, Quinlivan and Xiangyang. The decrease mainly occurs at stance phase. This maybe the spring produced negative work during dorsiflexion of ankle joint which declined the required power that muscles should provide. Due to the starts and ends points of gastrocnemius both earlier than the soleus and spring works latter, the exoskeleton mainly works on soleus. The clutch is the core component in the design of the unpowered ankle-foot exoskeleton. Compared to Collins and Xiangyang, we cleverly implemented the clutch design with the linkage mechanism and ratchet wheel, thus realizing the gait recognition and energy release.

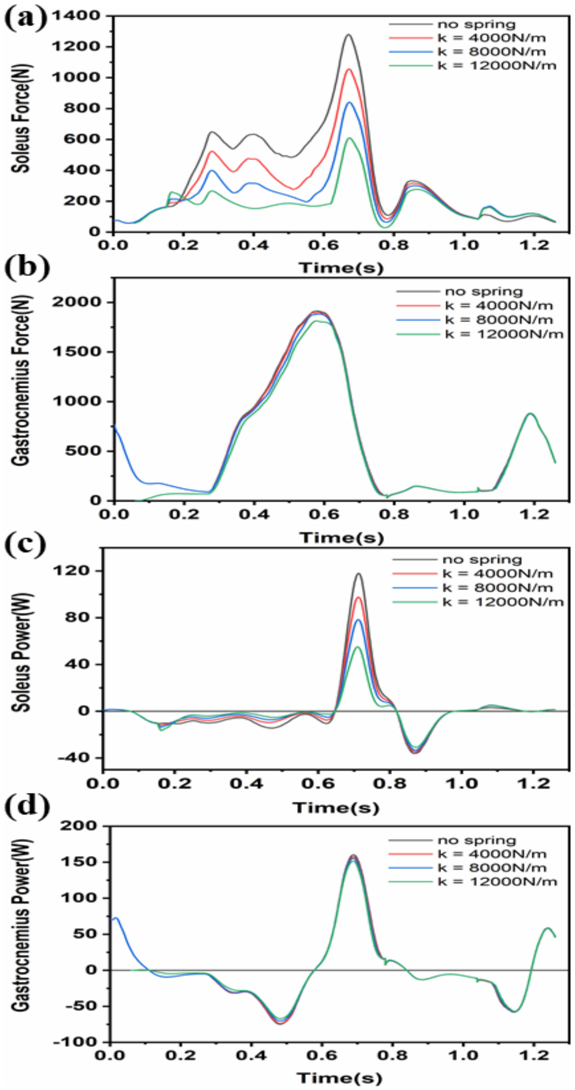

Figure 6. (a) Force of soleus (b) Force of gastrocnemius (c) Power of soleus (d) Power of gastrocnemius

There are also several limitations should be noticed. Due to differences of individual, exoskeletons are suitable for specific individuals mainly choosing of spring stiffness. In our case, the maximum stiffness is 12000N/m which is different from others. If a person's muscles are stronger, he can choose a spring with a greater stiffness factor. Another question is that is a musculoskeletal simulation in the verification and evaluation of exoskeleton, which maybe a little difference from reality. We have processed a mature product and will do more detailed research in the future. This work can give us guidelines for unpowered ankle-foot exoskeletons.

IV. CONCLUSION

In conclusion, this paper invented an unpowered ankle-foot exoskeleton consisting of smart clutch system, which can assist human walking and ignore the impact of uphill and downhill. Based on the analysis of the movement mechanisms and energetics during the gait cycle, we designed a four-link clutch which could be used to identify different gait stages and control the energy release and collection. Compared with existing unpowered ankle exoskeleton of other research groups, our exoskeleton has the advantages of low posture, low cost, simple structure, adaptability to different walking speeds, and more wearable. The prototype has been worked out, and we will do more test in the future work.

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