Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Novel Motor-free Passive Walk-assisting Knee Exoskeleton

Wei Zhang
School of Mechanical Engineering and Automation
Beihang University
Beijing, Beijing Province, China
shootgoals@163.com

Lei Sun
Beijing Institute Traumatology & Orthopedics
Beijing Jishuitan Hospital
Beijing, Beijing Province, China
dr_sunlei@263.net

Wuxiang Zhang* and Xilun Ding
School of Mechanical Engineering and Automation
Beihang University
Beijing, Beijing Province, China
{zhangwuxiang & xlding}@buaa.edu.cn

Abstract—In this paper, we present the design of a novel quasi-passive motor-free orthosis that realizing the compensation of knee joint supporting force during the weight acceptance phase and almost free motion during the swing phase. We explain that the normal knee landing motion is approximately a linear spring through the motion curve, so a suitable linear spring for the knee joint in parallel can achieve an approximate natural response. We show a compound mechanism based on ratchet and cam, which makes springs with different stiffness parallel in support and swing phases, and explain how to design mechanism parameters in switching process. This mechanism is a passive motor-free exoskeleton with automatic switching spring stiffness. It is lightweight and has no energy consumption.

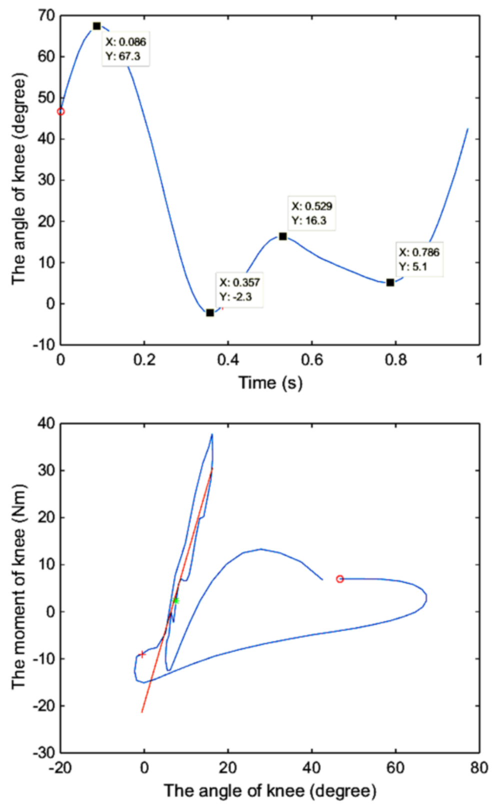
Index Terms - motor-free, variable stiffness, exoskeleton

I. Introduction

Lower limb exoskeleton is currently used for a variety of purposes, focusing on helping people with SCI stroke and other people who need force assistant [1-4]. In the research of exoskeleton mechanism, there are many kinds of drives [5-7]. Due to the high power of human motion, the large weight and limited working time of drives are still difficult problems in practical application. Therefore, some studies began to develop energy-saving and lightweight exoskeleton according to the particularity of human gait [8-10].

Considering that the main strength of knee joint is consumed during the support phase, this paper studies knee orthosis to compensate the support force for normal gait. For the compensation of support phase in some researches, the switching mechanism of driving stiffness is controlled by specific motor. The energy consumption and weight of the mechanism are optimized relative to the traditional assistant exoskeleton [8]. Even so, the weight is still large due to the use of motor for switching. Based on the study of human gait, a pure mechanical passive knee orthosis is designed by using ratchets and cams.

The mechanism can complete the key supporting role in the support phase, and barely interfere with human motion in the swing phase. Since the motor and controller are no longer used, the weight of the mechanism is smaller, the power consumption is zero, and the stiffness switching time can be shorter.



(a) Angle and time (b) Angle and moment
Fig.1 Angle and torque of knee joint

II. Method

A. A. Kinematic regularity of knee joint

According to human motion data [11], walking gait can be divided into two parts: support and swing. The support phase can be divided into landing phase, mid-support phase, end-support phase and pre-swing phase. There are two flexion actions of knee joint in the whole single leg movement, the motion angle of knee based on the data in [11] is drawing in Fig.1(a). Since the range of motion of the knee joint is mainly positive, it is about 0-120 degrees. The circle sign in Fig. 1 represents TOR (toe off of right), and the plus sign indicates HCR (heel contact of right). The smaller flexion/extension is in the landing phase of the support phase, while the larger flexion/extension includes a part of the support phase and the whole swing phase. The maximum angle of the smaller flexion/extension motion is 16.3 degrees, the minimum angle after extension is 5.1 degrees. The maximum angle of large flexion/extension motion is 67.3 degrees, and the minimum angle after stretching is -2.3 degrees.

The data of the knee joint are drawn. The horizontal coordinate is the angle of the knee joint and the longitudinal coordinate is the torsion of the knee joint. There are three note points in Fig. 1(b), including TOR, HCR and MSR (middle support of right). It is found that the landing torque is large, and the variation of the torque and angle is approximately a linear stiffness. Fitting the flexion/extension data from HCR, a straight line is obtained, as shown in the red line in Fig. 1(b). The torque of the knee joint is small in swing phase, and the whole process of the torque shows that stiffness vary from large to small.

B. Design Objectives

The motion curve of knee joint has two flexion/extension movements. According to the curve in Fig.1 (b), the mechanism should support the maximum landing torque and try not to affect joint movement during rest stages. Therefore, during the whole gait, the phase from landing to the later stage of support phase is a period of high stiffness, and from that period to the end of swing phase is a period of low stiffness. Fig. 1(a) shows that since the angle of the knee joint at the end of the high stiffness motion period is about 5 degrees, and the angle of the extension point is smaller at other motion speeds, the normal operation of the mechanism can be achieved only if the stiffness switching is completed above 5 degrees.

In this paper, a pure mechanical structure is designed to complete the realization and switching of different stiffness of knee orthosis in the gait. Combining the above motion characteristics and references[8], several design objectives are given here.

TABLE I
Target and Realized Values for the Design Parameters

Design parameter	Target	Realized
stiffness during land	176.34Nm/rad	176.34Nm/rad
stiffness during swing	~0Nm/rad	0.62 Nm/rad
angle of swich	≤ 6degrees	6 degrees
maximum angle	≥ 90 degrees	120degrees
swich delay	≤ 30ms	19.3ms
weight	≤ 3kg	1.7 kg

C. Functional Description of Mechanism

For the design requirements of mechanism, action switching can be accomplished by ratcheting mechanism. But it is more difficult to reach an arbitrary angle within the required range of flexion and complete switching at setting one. In order to meet the above requirements, this paper uses a special ratchet, which is only related to the start and end of the angle position. The design with the cams can achieve two kinds of stiffness switching independent actions within setting range. The ratchet types can be divided into tooth ratchet and friction ratchet. The friction ratchet has the problem of slipping, while the tooth ratchet transmission is accurate and simple. Although ratchet structure can achieve one-way angular/distance motion, it cannot achieve fixed angular/distance motion only related to the initial and end position. In this paper, a ratchet structure similar to that in the automatic ballpoint pen is used to achieve a wide range of reciprocating motion and a fixed step when back to setting position.

In this paper, the mechanism is mainly designed in six parts, including upper link part, lower link and push cam part, high stiffness spring part, switching ratchets part, compression spring, switching cam and locating rod part. The overall mechanism is shown in Fig. 2, where ratchets compression spring and switching cams are all inside the shell on the right side. The mechanism changes the rotation into translation, the translation into the rotation at the fixed angle, and then again turns the rotation into translation which moves the locating rod. The compression spring is the power source of switching stiffness. When the locating rod acts, the lower link connect with the high stiffness spring to produce high torque on the knee joint, the mechanism has less force on the knee joint during the swing phase. When the knee joint returns to zero position a small limit block on lower link will bring the spring disc back to zero position.

The mechanism first converts rotation into translation through the cam 1, and then drives the left ratchet. During this action the upper link part of the mechanism is connected with the thigh and the shell of the right mechanism, and the lower link is connected with the lower leg for relative motion. The rotating disc fixed on the lower link is between the cam 1 and the ratchets. When rotating, the pushing disc can rotate by sliding holes on the rotating disc, so that the pin can move along the trajectory slot on the cam 1. For smaller flexion motions, the range is 6-16 degrees. So if the spring at the ratchet is compressed in this range, the cam needs a very inclined chute. When large angle flexion motion occurs, the torque is large at first then small, and the cam needs a second slip slot with smaller inclination as its return trajectory to avoid large force back to knee. The design sketch of the trajectory expansion line is shown in Fig. 3. The two trajectories are divided into four sections L_1 L_2 L_3 and L_4. Small steps exist between L_1 and L_4, L_2 and L_3. The thick red line represents the deeper chute and the thin blue line represents the shallower chute. Because of the height difference between the deep chute and the shallow one, the follower can only move along the deep groove in the cross position. So where L_1 L_4 or L_2 L_3 intersects, it can only run in deep one. That means the follower can only follow the large inclined trajectory when it flex at a small amplitude, while after large flexion it could only follow the small inclined trajectory back. Meanwhile there are transition slopes between L_1 and L_2 , L_3 and L_4 . The follower is connected with the pushing disc through a spring, so it can be expanded in a smaller range to go through in one trajectory. In addition when the follower runs on L_2 , the torque will not be generated.

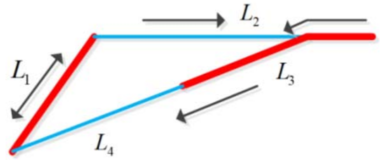


Fig.3 two trajectories on cam 1

By pushing the disc on the ratchets, the mechanism transforms the translation of different ranges into a rotating motion with a fixed angle. During this action the ratchet is similar to the automatic ballpoint pen ratchet. The ratchet of this mechanism consists of three parts: the left ratchet and the pushing rod, and the right ratchet. In addition, the right ratchet part is pushed to the left by a compression spring as the force source of ratchet switching action. The left ratchet has four open deep chutes and teeth on the right end, and the pushing rod slides along the chutes inside the left ratchet. The right ratchet contains two layers of teeth in different radius. The inner teeth can be inserted into the left ratchet and rotate at a small angle in the same direction as the outer teeth. The outer teeth can only pass through the open chute or contact the right end, and when contact with the right end one-way rotating torque will be generated. Each rotation angle during one step is 45 degrees. The accurate rotation angle of the ratchet has nothing to do with the flexion process, which guarantees the simplicity of the design of different spring compression amplitudes.

The rotational motion of ratchet acts on the cam 2 and converts the rotation into translation. In this process, the right ratchet and the cam 2 connect through the sliding rod. Each time the ratchet rotates 45 degrees, the cam 2 pushes the locating rod in one direction. The insertion or pulling out of the locating rod controls whether the high stiffness spring connect with the lower link. The moving distance of locating rod is designed to be 6 mm.

D. Mechanism Parameters and Function Realization

The mechanism needs to consider two forces that need to be calculated, one is the force of switching stiffness, which determines the switching time; the other is the reverse torsion generated by the mechanism, which affects the motion of the knee joint. In order to reduce the weight of the mechanism and reduce the friction coefficient, the contact parts are aluminum and steel, and the other parts are basically aluminum alloys. The friction coefficient is 0.17 in the absence of lubricating oil and 0.02 in the presence of lubrication.

From Sec. C, it can be seen that the mechanism mainly contains the following friction forces. In order to facilitate the analysis, the frictions can be divided into the friction forces on the inclined surface and the remaining friction forces. The friction on the inclined surface includes the inclined friction F_{f0} between the cam 1 and the follower, the inclined friction F_{f1} between the left and right ratchets and the inclined friction F_{f2} between the cam 2 and the locating rod. Other friction forces include the sliding friction F_{rf1} between the rotating disc and the pushing disc, the friction F_{rf2} between the pushing disc and the pushing rod, the sliding friction F_{rf3} between the right ratchet and the left ratchet under the action of the pushing rod, the friction F_{rf4} between the right ratchet and the cam 2, and the sliding friction F_{rf5} between the locating rod and the outer shell. For the force acting on the locating rod, it is necessary to consider F_{f1} , F_{f2} , F_{rf4} and F_{rf5} in turn. But the influence of stiffness of switching mechanism on knee joint needs to consider F_{f0} , F_{rf1} , F_{rf2} and F_{rf3} . The frictional force of the first inclined surface is F_{f0} , and the relationship model of the force is shown in the Fig. 4. The friction models of the other two inclined surfaces are similar.

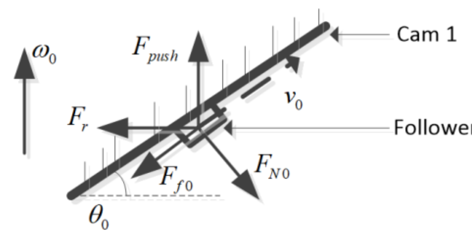


Fig.4 Friction Model of Inclined Surface

The force F_{r0} is tangential force, and the corresponding radius r_0 is used to calculate the torque τ_0 . Here we need to calculate the relationship between the pushing force F_{push0} and the tangential force F_{r0} , as shown in the first item in (1). Meanwhile the formulas of the other inclined surfaces models are deduced in (1).

$$\begin{cases} F_{r0} = F_{push0} \cdot \tan\left(\theta_0 + \varphi_0\right) \\ F_{r1} = F_{push1} \cdot \tan\left(\theta_1 - \varphi_1\right) \\ F_{r2} = F_{push2} \cdot \tan\left(\theta_2 + \varphi_2\right) \end{cases} \tag{1}$$

where φ_i (i=0,1,2) is the friction angle at each inclined plane. θ_i (i=0,1,2) is the helix angle at each inclined plane.

Because the mechanism has sliding friction between the rotating disc and the pushing disc, the right ratchet and cam 2, the two pushing forces need to offset the frictions, so the relations are deduced in (2).

$$\begin{cases} F_{push0} = F_{push1} + F_{r0} \cdot r_0 \cdot \mu_0 = F_{push1} + F_{rf1} \\ F_{push1} = F_{push2} + F_{r1} \cdot r_1 \cdot \mu_1 = F_{push2} + F_{rf4} \end{cases} \tag{2}$$

where r_i (i=0,1) are the radius at F_{r0} and F_{r1} . μ_i (i=0,1) are the friction coefficient at both places.

Because the cam 2 and the locating rod are synchronous, the running time of the cam and the locating rod is the same. Here, the initial angular acceleration of the cam during a switching motion is calculated. The forces are calculated from the contact of left and right ratchets until the moving of locating rod. The compression spring at the ratchet provides power F_{push1} and passes through friction F_{f1}, F_{rf2}, F_{rf4} and F_{rf5}. The initial angular acceleration can be obtained as (3):

$$\frac{\alpha}{F_{push1}}=\frac{\left(1-\tan\left(\theta_1-\varphi_1\right)\cdot r_1\cdot\mu_1\right)\tan\left(\theta_2+\varphi_2\right)\cdot\left(r_2-r_2\cdot\mu_4\cdot\tan\left(\theta_2+\varphi_3\right)\right)}{I_2+m_L\cdot\tan\theta_2\cdot r_2^{\,2}\cdot\tan\left(\theta_2+\varphi_3\right)} \quad (3)$$

$$\Rightarrow\frac{\alpha}{F_{push1}}=\frac{\alpha}{k\cdot\Delta l}$$

where I_2 is the rotational inertia of right ratchet and the cam 2, and m_L is the mass of the locating rod.

It can be seen from the formula that when the compression of compression spring varies, the acceleration is linear, that is, the motion is equivalent to a part of sinusoidal motion. Considering that the actual pushing force should not be too large, the stiffness may be chosen as 5000 N/m. The cam 2 rotates 45 degrees, the sinusoidal motion moves a quarter of the period, and the locating rod moves 6 mm. The stiffness of the mechanism, the angular velocity frequency of the equivalent sinusoidal motion, and the time required to run 45 degrees are expressed as follows.

$$\begin{cases} k_{\text{vib}}=\dfrac{I_2\cdot\alpha}{\pi/4} \\ \omega_{vib}=\sqrt{\dfrac{k_{vib}}{I_2}} \\ t=\dfrac{2\cdot\pi}{4\cdot\omega_{vib}} \end{cases} \quad (4)$$

where $\boldsymbol{k_{vib}}$ is the stiffness of vibration, $\boldsymbol{\omega_{vib}}$ is the angle frequency of vibration. So the relationship between time and acceleration is obtained as follows:

$$t=\frac{\pi\cdot\sqrt{\pi}}{4\cdot\sqrt{\alpha}} \quad (5)$$

Adding the initial constraint conditions, the inclination angle of the first cam should not be too large. Considering the suitable amplitude of compression spring is 0.010 m, and the minimum buckling angle is 10 degrees. The radius of cam 1 is 0.04 m. So the helix angle of the first cam is 55.08 degrees. The influence of radiuses of ratchet and cam 2 on angular acceleration is calculated. As shown in Fig. 5, the angular acceleration values at friction coefficients of 0.17 and 0.02 are calculated respectively. In order to consider the operation of the mechanism under poor working conditions, the friction coefficient is 0.17. The top curve in the figure shows that the ratchet radius is 0.01 mm, and the downward curve shows that the radius is increased by 0.01 mm in turn. It can be seen that with the increase of ratchet radius and the cam 2 radius, the angular acceleration of the cam decreases obviously.

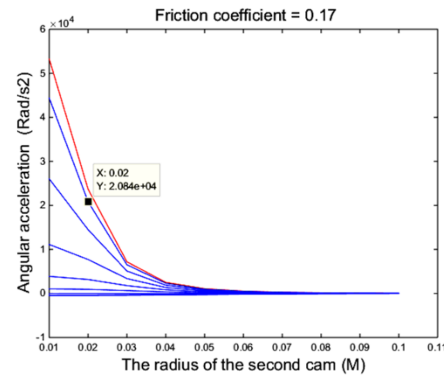
When considering the influence of mechanism on knee joint feedback force, F_{f0} F_{rf1} F_{rf2} F_{rf3} is considered. From (1) and (2) the relation between the force returned by the compression spring and the force of compression spring is shown in (6).

$$\frac{\tau_0}{k_2\cdot\Delta l}=\frac{F_{r0}\cdot r_0}{k\cdot\Delta l}=\frac{r_0\cdot\tan\left(\theta_0+\varphi_0\right)}{1-r_0\cdot\mu_0\cdot\tan\left(\theta_0+\varphi_0\right)} \quad (6)$$

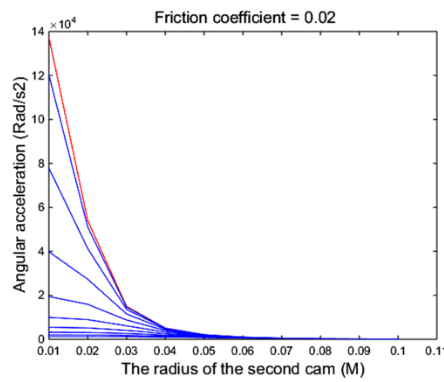
where k_2 is the stiffness of the compression spring. Therefore, the equivalent stiffness generated by the feedback force of the mechanism is as follows:

$$k_2\,'=\frac{\tau_0}{\theta_l}=\frac{k_2\cdot r_0^{\,2}\cdot\tan\theta_0\cdot\tan\left(\theta_0+\varphi_0\right)}{1-r_0\cdot\mu_0\cdot\tan\left(\theta_0+\varphi_0\right)} \quad (7)$$

where θ_i is the rotation angle of the leg.



(a) Friction Coefficients is 0.17



(b) Friction Coefficients is 0.02

Fig.5 Effect of Different Radius Parameters on Angular Acceleration

III. RESULT

Firstly, the initial angular acceleration of the cam 2 is calculated if the switching time in [8] is 30 ms. From (5) the initial angular acceleration should be 2153.2 rad/s2. From the acceleration diagram, we can see that many numerical points meet the requirements, so considering the actual mechanical condition and other factors, the ratchet radius and the cam 2 radius are selected as 0.02 m. When the friction coefficient is large, the initial angular acceleration value is 20840 rad/s2, which is much larger than the required angular acceleration value. The switching time is obtained as 9.6 ms from (5). The value of switching time is less than that of motor mode. At the same time, the measuring weight of the mechanism is 1.7 kg, which meets the set target.

The cam 1 design has two helix angles. The first large inclined trajectory can rotate 10 degrees to push 0.01 m, according to the radius of 0.04 m; the second large flexion motion can return through a small inclined trajectory when the leg rotates over 37.3 degrees, while the helix angle of the trajectory is 15 degrees. Equivalent stiffness of knee joint on two trajectories can be calculated by formula (7), which is 17.16 Nm/rad and 0.62 Nm/rad, respectively. It can be seen that the equivalent stiffness of the small inclined trajectory is very small. Equivalent stiffness of large inclined trajectory needs to be combined with large stiffness tension spring to produce red line stiffness value 176.34 Nm/rad in Fig. 1 (b). The large stiffness tension springs are uniformly distributed with a pulling radius of 0.05 m, as shown in Fig. 2 (a). In this way, the stiffness of the tension spring should be as follows:

$$k_s = \frac{176.34 - 17.16}{4 \times 0.05^2} = 15900\, N/m \tag{8}$$

According to the stiffness and (3) and (6), the torque of the mechanism to the knee joint can be calculated with the motion angle. By combining the data of torque in [11], the effect of the mechanism on the support force compensation and the swing process can be observed. As shown in the Fig. 6, during the swing phase, the mechanism torque is basically zero, the maximum value is 0.37Nm. The ratio of 15.1 Nm to the peak value of human joint torque is 2.45%, which has little effect on human body swing. During the support phase, the compensation torque is close to that of human body, and the compensation ratio of peak force is 88.68%. Meanwhile there are little effects on knee joint during other angles. It can be seen from the graph that the mechanism has basically achieved the design goal.

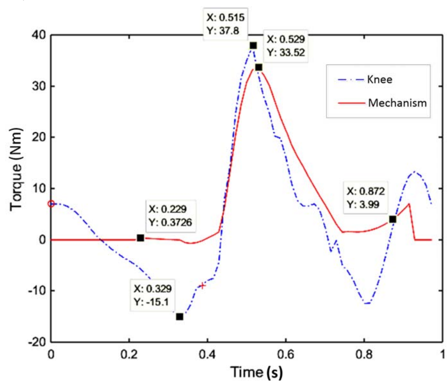


Fig.6 Contrast Diagram of Human Torque and Mechanism Torque

IV. CONCLUSION

According to the pattern of knee joint motion, this mechanism designs a pure mechanical lightweight assistant mechanism. Through analysis, it can be seen that the designed goal is basically achieved. Two patterns of flexion/extension motions are the key to the mechanism, which determines the mechanical process. Therefore, approximate leveling walk makes it easier for the mechanism to operate normally. In addition, the disadvantage of this mechanism is that it cannot adapt to walking on inclined terrain, so it can considered extending the operation modes by switching the locating bar in the future.

ACKNOWLEDGMENT

The authors thank the fundamental support provided by National Key R&D Program of China under grant No. 2016YFE0105000, National Natural Science Foundation of China under grant No.91848104.

REFERENCES

[1] R. Riener, L. Lünenburger, I. C. Maier, G. Colombo, and V. Dietz, "Locomotor Training in Subjects with SensoriMotor Deficits: An Overview of the Robotic Gait Orthosis Lokomat," Journal of Healthcare Engineering, vol. 1, pp. 197-216, 2010.

[2] G. S. Sawicki and D. P. Ferris, "A pneumatically powered knee-ankle-foot orthosis (KAFO) with myoelectric activation and inhibition," Journal of Neuroengineering & Rehabilitation, vol. 6, pp. 1-16, 2009.

[3] K. N. Winfree, P. Stegall, and S. K. Agrawal, "Design of a minimally constraining, passively supported gait training exoskeleton: ALEX II," in IEEE International Conference on Rehabilitation Robotics, 2011, pp. 1-6.

[4] J. Meuleman, A. E. Van, O. G. Van, J. Rietman, and d. K. H. Van, "LOPES II - Design and Evaluation of an Admittance Controlled Gait Training Robot with Shadow-Leg Approach," IEEE Transactions on Neural Systems & Rehabilitation Engineering A Publication of the IEEE Engineering in Medicine & Biology Society, vol. 24, pp. 352-363, 2015.

[5] N. Karavas, A. Ajoudani, N. Tsagarakis, and J. Saglia, "Tele-Impedance based stiffness and motion augmentation for a knee exoskeleton device," pp. 2194-2200, 2013.

[6] J. Morimoto, T. Noda, and S. H. Hyon, "Extraction of latent kinematic relationships between human users and assistive robots," in IEEE International Conference on Robotics and Automation, 2012, pp. 3909-3915.

[7] Y. LONG, Z.-j. DU, W.-d. WANG, L. HE, X.-w. MAO, and W. DONG, "Physical human-robot interaction estimation based control scheme for a hydraulically actuated exoskeleton designed for power amplification," Frontier of Information and Electronic Engineering: English Version, 2018.

[8] K. Shamaei, P. C. Napolitano, and A. M. Dollar, "A quasi-passive compliant stance control Knee-Ankle-Foot Orthosis," in IEEE International Conference on Rehabilitation Robotics, 2013.

[9] K. Shamaei, M. Cenciarini, A. Adams, K. Gregorczyk, J. Schiffman, and A. Dollar, "Biomechanical Effects of Stiffness in Parallel with the Knee Joint during Walking," Chinese Journal of Biomedical Engineering: English Edition, vol. 62, pp. 65-65, 2015.

[10] A. M. Dollar and H. Herr, "Design of a Quasi-Passive Knee Exoskeleton to Assist Running," in IEEE/RSJ International Conference on Intelligent Robots & Systems, 2008.

[11] D. A. Winter, Biomechanics and Motor Control of Human Movement, 1987.