Analysis, Design, and Preliminary Evaluation of a Parallel Elastic Actuator for Power-Efficient Walking Assistance

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ABSTRACT

This paper introduces the analysis, design and preliminary evaluation of a self-integrated parallel elastic actuator (PEA) with an electric motor and a flat spiral spring in parallel to drive the hip joint of lower limb exoskeletons for power-efficient walking assistance. Firstly, we quantitatively analyze the reason why the parallel elasticity (PE) placed at the sagittal hip joint can reduce the motor power requirement during walking assistance, which contributes to the theory of PEA development and application. The design of the PEA is then introduced in detail. The novelty of the design is that the actuator is reduced in size by integrating the spring into the motor, and the requirement of spring stiffness is significantly reduced by placing the spring directly parallel to the motor shaft. Furthermore, both the simulation based on dynamic modeling and benchtop experiment are conducted preliminarily to evaluate the performance of the PEA with nine spring stiffnesses in a range from 0 – 5.29 mN-m/rad regarding two indexes including the average and maximum positive electrical power of the motor. Their results show that the two indexes become smaller when the PE is attached and decrease as the spring stiffness increases. When the PE with a stiffness of 5.29 mN-m/rad is attached, the actuator obtains the largest reduction rate of 11.99 and 16.84 % in the average (root mean square) and maximum positive electrical power of the motor in the simulation and 10.3 and 26.25 % in the experiment, respectively. Those results provide evidence for the applicability of the newly designed PEA in driving a lower limb exoskeleton with high power efficiency during walking assistance for paraplegic patients with complete loss in walking ability.

INDEX TERMS
Actuator design, compliant actuation, lower limb exoskeleton, parallel elastic actuator, power-efficient actuator.

I. INTRODUCTION

Traditional rigid actuators (RAs) (e.g. electric motors), as the key units of walking assistance devices such as lower limb exoskeletons (LLEs), consume a lot of power, leading to a high power requirement. An average power of nearly 600 W, for example, was required during level-ground walking at 1.3 m/s with the exoskeleton BLEEX actuated by motors [1]. Therefore, it is important to develop power-efficient actuators for walking assistance.

Since the gait is a periodic process, compliant elements can store the energy wasted as negative work in the period when the motor must brake the load actively and recycle it as positive work for accelerations in the opposite direction. Such characteristics of compliant elements can be used to enrich the dynamics of traditional electric motors [2], [3] for walking assistance [4]. Compliant actuation, such as elastic actuators (EAs), adding the elasticity element to the RA, is widely studied in robotic applications. This mimics biological solutions where muscle tissues and tendons act in parallel and serial with muscles [5], [6]. The EAs are generally divided into series (SEAs) and parallel EAs (PEAs), regarding the
connecting topology between the elastic element and the RAs. Researchers are interested in using SEAs to ensure friendly human-robot interaction, since the series elasticity can protect the motor from impacts [7]–[9]. However, regarding power efficiency, the PEAs have advantages over the SEAs in reducing motor torque and power in the periodic process [10]. In the simulation, [11] disclosed that the PEAs were strongly favored for a hopper regarding the elastic losses, and [12] also concluded that the PEAs were more power-efficient than the SEAs for typical legged animals and robots. The series-parallel or parallel-series EAs were proposed and developed to combine the advantages of both SEAs and PEAs [13]–[16]. However, these increase not only the complexity and weight of their mechanical structures but also the challenges concerning their control systems. Consequently, the concept of the PEAs is preferred to enhance the power efficiency for walking assistance in this paper.

The parallel elasticity (PE) was initially used to statically counterbalance the articulated robot for upper arms [17]. The applications of PEAs in recent years have been focused on walking robotics in multiple degrees of the human lower limb, such as hip flexion-extension [16], [18], hip abduction-adduction [19], knee flexion-extension [13], [20]–[25] and ankle dorsi-planter flexion [19], [26]–[28]. The simulation results during a normal walking gait showed that a unidirectional PE at the hip joint in the sagittal plane could reduce average (root mean square, rms) and peak motor power by 50 and 13.9 %, respectively [29]. An experimental study on nine healthy males also showed that the extension springs placed anteriorly across the hip joint can store proportions of the energy that would normally be stored in the Achilles tendon in the stance period and reduce the biological contribution to hip flexion in the swing period [30]. A series PEA [16] and a clutched PEA in our previous study [31] were the only two implementations of the PEA applied to drive the hip joint of the LLEs in the sagittal plane. However, those two PEAs each occupied a lot of space. Based on the investigations above, we proposed to a novel compact PEA with a unidirectional PE to assist the hip flexion-extension during walking.

The idea that the PE, placed in the sagittal hip joint, can reduce the motor power consumption needs to be proven in theory. References [32], [33] analyzed the reason why the power was reduced by adding the PE mainly in two ways. Firstly, the gravitational potential and kinetic energy are captured by the PE when the robot arm of the unmanned ground vehicle is lowered and then released when this arm is raised, which would be wasted if there was no PE. Secondly, reducing the torque over the cycle leads to a significant reduction of resistive losses. Reference [16] also analyzed that the reduction of the gravitational energy could be stored and released by the PE instead of being wasted by the motor. This increases the power utilization to assist the hip flexion-extension during walking. However, the energy analysis for the PEA above is qualitative. Herein, we not only qualitatively demonstrate the energy transformation but also quantitatively analyze why the motor power consumption is reduced in the PEA-driven hip joint.

There are various PE configurations that can be considered. In the literature, the extension coil spring is the most popular used in the PEAs, due to its low cost and good commercial availability. The knee joint is the most common application. Examples include a planar bipedal robot ERNIE [25], prosthetics and robotics [20], an exoskeleton for load-carrying augmentation [21] and the running robots SPEAR [22]–[24]. A clutch is needed to engage and disengage the PE during the gait for the knee joint because PEAs require large active torques to counter the elastic recoil for rapid stopping in stance or leg placement in swing [20]. In addition, the parallel extension spring is also utilized in the exoskeleton hip actuator [31], HAL for lumbar support [34], the hopping robot ETH Cargo for carrying load [35] and other cases [14], [15], [36]. The second type used widely is the torsion spring as it can provide the torque directly. Its applications include the bidirectional clutched PEA [37], [38], a passive-assist robot arm [32], [33] and a switchable clutched PEA [39]. The leaf spring is also commonly used as the PE due to its high stiffness, such as the parallel SEA-driven knee joint of the running robot Phides [13] and the series PEA-driven hip joint of the LLE [16]. Moreover, a few researchers adopted the spiral spring (see the STEPPR robot [19]), the compression coil spring [18], [27], [28], the magnetic non-linear torsion spring [5], the Belleville spring [26] and the bungee cord (see the hip joint for a back-support exoskeleton [40], [41]). There are two common characteristics summarized among these PEA designs. One is that the elasticity is placed in parallel with the unit of the motor-gearbox and connected directly with the load. The maximum torque of the load that the PEA-driven joint should carry or sustain is normally large and the deformation of the PE is normally small; this results in a high stiffness requirement for the PE. The volume and weight of the PE is, therefore, increased. The other is that PEAs are typically designed by considering the motor and the PE as two distinct components, except for [37], [38], [5]. This seems to cause bulky and heavy assemblies. In order to address the two challenges, on the one hand, the PE is placed parallel to the motor’s shaft instead of the output shaft of the motor-gearbox unit. Thus, the original stiffness of the PE is amplified by nearly the square of the reduction ratio to obtain the equivalent stiffness of the PE at the output of the PEA. Such a design can lower the stiffness requirement and lead to a smaller and lighter PE. On the other hand, the flat spiral spring is integrated into the motor design, which also reduces the size of the actuator.

The high requirement for power results in bulky motors, large battery packs and, eventually, a heavy walking assistance device. Following the predetermined reduction ratio of the PEA and gait of the hip joint from [29], the key point is to evaluate the effect of the PE on increasing the power efficiency of the motor. Various evaluation indexes are used, including electrical
work [19], [32], [33], [37], [42]–[44], positive electrical work [7], [11], absolute electrical work [45], [46], positive mechanical work [7], [11], resistive loss [7], [11], absolute mechanical work [25], [26], average (rms) mechanical power [4], peak electrical power [28], [43]–[46], peak torque [32], [33] and rms torque [4], [36] of the motor. The reversing power flow from the load is not regenerated by our motor. Therefore, only the positive part of the electrical power should be considered to measure the power consumption of the motor [47]. Two indexes, including the average (rms) and maximum positive electrical power of the motor, are used to evaluate the performance of the PEA.

We recently proposed a proof-of-concept design of a clutched variable PEA [48]. In this earlier work, the simulation was conducted and its results showed that the PEs can reduce the power of the motor over a gait cycle for the sagittal hip. The key assemblies of the clutched variable PEA include a self-integrated motor, a unidirectional flat spiral spring in parallel and a clutch to engage or disengage the outer end of the spring.

In this paper, we extend the previous study [48] in five aspects. Firstly, the working principle of the PEA, in which the energy transformation is quantitatively analyzed, is explained in more detail. Secondly, the structure of the PEA is simplified for conveniently conducting the benchtop experiment. The clutch assembly is removed, since the spring is always attached in each trial of the benchtop experiment in this paper. In addition, the structure to connect the motor and the flat spiral spring is changed to provide more stability. Moreover, the friction and the influence of the reversing power flow in the PEA are considered in the dynamic model to make the simulation more reliable. Finally, an experiment is added to validate the simulation result and preliminarily evaluate the actual performance of the PEA. For a proof of concept, a reduced body weight of the human subject, 10 kg was used, which can lower the maximum torque the flat spiral spring should sustain in the experiment.

The rest of this paper is structured as follows. Section II analyzes the working principle of the PEA. Section III illustrates the mechanical design of the PEA in detail. Section IV introduces the experimental setup and V gives the results of the simulation and experiment. The paper ends with a discussion in section VI and a conclusion in section VII.

II. THE WORKING PRINCIPLE OF PEA

This section analyzes the working principle of a general PEA-driven hip joint in the sagittal plane, i.e. why its power consumption can be reduced by the PE in theory. The power consumption of the motor consists of the resistive loss, which is obviously reduced since the motor torque over a cycle is reduced by the PE, and the mechanical power, which is quantitatively analyzed here. The rationality and benefits of adding a PE to the hip joint actuator are initially illustrated based on the gait analysis of the hip joint. Similar to the energy transformation of the RA or PEA driven ankle joint in [26], the energy transformation of the lower limb with the hip joint driven by a RA or PEA in a gait cycle will then be analyzed.

A. GAIT ILLUSTRATION OF THE HIP JOINT

The sagittal torque, velocity and angle of the right hip joint during a cycle were obtained from the gait of a healthy subject walking at 0.8 m/s [29], as shown in Fig. 1. The reference gait with the low walking speed was selected as the PEA-driven lower limb exoskeleton is intended to assist the paraplegic patients with a complete loss in walking ability in recovering the basic walking ability. Similar to the gait division in [30], the gait cycle is divided into three phases according to the sign of the joint power, as shown in Table 1.

FIGURE 1. Sagittal plane internal joint torque and velocity of the right hip from the gait of a healthy subject walking at 0.8 m/s [29]. The torque data was scaled to a body weight of 130 kg. Torques \( T_h \) and velocities \( \omega \) are defined as positive in hip flexion. HS, heel strike.

| Phase | Definition |
|-------|------------|
| 1     | From the time of heel strike (HS) to the time when the joint torque becomes zero in the stance period |
| 2     | From the end time of phase 1 to the time when the joint angular velocity becomes zero in the late stance period |
| 3     | From the end time of phase 2 to the time of next HS |

The motor generates the maximum torque to counteract the peak sagittal plane joint torque at the end time of phase 2. If the PE is designed to share the joint torque with the motor, the peak motor torque can be reduced.

Fig. 2 displays the curve of the sagittal plane internal joint torque-angle.

The positive joint torque over angles in a large range rationalizes a linear unidirectional PE being added, since it can provide positive torque. The slope of the spring torque-angle curve should be negative and the spring should reach its neutral position at the start of phase 1 (i.e. at the time of HS) to fit the torque-angle curve of the right hip joint.

B. ANALYSIS OF THE ENERGY TRANSFORMATION OF THE LOWER LIMB

The energy transformation of the lower limb during a gait cycle is analyzed based on the reference gait in Fig. 1 and 2.
Fig. 3 presents three phases of the right lower limb of a paraplegic patient in a gait cycle. The energy transformation of lower limb involved in the typical walking can be analyzed by approximating the human lower limb as an inverted-pendulum model [49], [50] based on those assumptions: 1) the lower limb is regarded as one rigid body with uniform mass; 2) only the dynamics of the hip joint in the sagittal plane is considered, while the dynamics of knee and ankle joints are ignored; 3) the friction and damper is ignored since their value is not certain in a general PEA; and 4) the gravity of the spring is ignored as it is negligible compared with that of the human lower limb.

Based on the model in Fig. 3, according to the theorem of kinetic energy, the relationship between the total work and the kinetic energy of the lower limb with the hip joint driven by the RA is then formulated by (1).

$$\int_{t_1}^{t_2} T_{RA}(t) \cdot \omega(t) \, dt + W_i = \Delta E_{ki}$$

(1)

where $i = 1, 2, 3$ and $t \in [0, T]$. $T$ is the gait cycle. Eq. (1) with $i = 1, 2, 3$ formulates the relationship between the total work and the kinetic energy of the lower limb with the hip joint driven by the RA in three phases, respectively. $T_{RA}$ is the torque that the RA produces on the rotation center of the hip joint and the direction of it in each phase coincides with Fig. 1 or 2. The integral term formulates the mechanical work of the motor, $W_i$ represents the work of all the other force on the lower limb in phase $i$, which is formulated by (2). $\Delta E_{ki}$ represents the change of the kinetic energy of the lower limb in phase $i$, which is formulated by (3).
from the propulsion from the opposite stance lower limb.

\[
\begin{align*}
\Delta E_{k1} &= J \cdot \omega (t_1)^2 / 2 + m \cdot (\omega (t_1) \cdot 1 / 2)^2 / 2 \\
\Delta E_{k2} &= -J \cdot \omega (t_1)^2 / 2 - m \cdot (\omega (t_1) \cdot 1 / 2)^2 / 2 \\
\Delta E_{k3} &= m \cdot (v_1 (t_3)^2 + v_2 (t_3)^2) / 2
\end{align*}
\]

(3)

where most parameters are explained in Table 2 except that \( J \) is the lower limb moment of inertia about the center of its mass, \( t_1 \) and \( t_3 \) is the end time of phase 1 and phase 3.

Based on Fig. 2 and (1-3), the motor in the RA-driven hip joint should do positive mechanical work \( (f_1 T_{R_A}(t) \cdot \omega (t) \ dt > 0) \), i.e. generate the mechanical power in phase 1, do negative mechanical work \( (f_2 T_{R_A}(t) \cdot \omega (t) \ dt < 0) \), i.e. absorb the reversing mechanical power flow from the positive work of the force that the torso applies on the lower limb and the reduction of the kinetic energy of the lower limb in phase 2 and do positive mechanical work \( (f_3 T_{R_A}(t) \cdot \omega (t) \ dt > 0) \), i.e. generate the mechanical power to swing the leg forward in phase 3.

It is hard for the motor to entirely regenerate the mechanical power in phase 2 in a simple actuator system [47]. The power absorption of the motor may be either wasted [16], [32], [33] or recaptured by a battery and then reused at an efficiency of 40% for the RA-actuated hip joint [37]. It is wasted in our case as the motor controller can only dissipate this power absorption. In order to recycle this considerable power, a unidirectional PE can be added to store it in phase 2 and release it in phase 3, which enriches the motor when actuating the hip joint. The change of hip motion direction at the end time of phase 2 corresponds with the recovery start of the spring. The deformation of PE changes from zero (at the time of HS) to maximum (at the end time of phase 2) and then returns to zero (at the time of the next HS). This means that its deformation should be \(|\theta_1| + |\theta_2|\) over a gait cycle and it remains the natural length at the time of HS. The scheme of utilizing the PE during a gait cycle corresponds with that of utilizing the hip spring in [30].

Hence, based on (1-3), the relationship between the total work and the kinetic energy of the lower limb with the hip joint driven by the PEA is similarly formulated by (4), but adding the work of the PE.

\[
\int \limits_{t} T_{PEA} (t) \cdot \omega (t) \ dt + W_{S1} + W_{i} = \Delta E_{k1} \quad (4)
\]

where \( i = 1, 2, 3 \) and \( t \in [0, T] \). \( T_{PEA} \) is the torque that the PEA produces on the rotation center of the hip joint. \( W_{S1} \) represents the work of the torque of the PE in phase \( i \), which is formulated by (5). Other terms and parameters are identical to those in (1).

\[
\begin{align*}
W_{S1} &= -K \cdot \left( |\theta_1| - |\theta_3| \right)^2 / 2 \\
W_{S2} &= -K \cdot \left( |\theta_1| + |\theta_2| \right)^2 - \left( |\theta_1| - |\theta_3| \right)^2 / 2 \\
W_{S3} &= K \cdot \left( |\theta_1| + |\theta_2| \right)^2 / 2
\end{align*}
\]

(5)

where \( K \) is the stiffness of PE at the output of the PEA and note that \( W_{S1} + W_{S2} + W_{S3} = 0 \).

By subtracting (1) from (4), the mechanical work of the motor in the PEA in three phases is formulated as follows.

\[
\int \limits_{t} T_{PEA} (t) \cdot \omega (t) \ dt = \int \limits_{t} T_{RA} (t) \cdot \omega (t) \ dt - W_{S1} \quad (6)
\]

where \( i = 1, 2, 3 \) and \( t \in [0, T] \).

Eq. (6) shows that the effect of the work of the PE on the mechanical work of motor in three phases. It is obvious that the motor in the PEA still does positive mechanical work with an increase by \( |W_{S1}| \) in phase 1. However, adding the PE may change whether the motor absorbs or generates the mechanical power in phase 2 or 3. Similar to the analysis in [27], three cases should be, therefore, analyzed here noting that \(|f_2 T_{RA}(t) \cdot \omega (t) \ dt| > f_3 T_{RA}(t) \cdot \omega (t) \ dt\) based on Fig. 2.

CASE 1: Adding a PE with a limited \( K \) does not reverse the direction of the motor torque, i.e. the direction of the motor power flow, in any phase. The value of \(|W_{S2}| \) or \( W_{S3} \) will be lower than the value of \(|f_2 T_{RA}(t) \cdot \omega (t) \ dt| \) or \( f_3 T_{RA}(t) \cdot \omega (t) \ dt\).

CASE 2: Adding a PE with a moderate \( K \) reverses the direction of the motor power flow only in phase 3.

CASE 3: Adding a PE with a high \( K \) which reverses the direction of the motor power flow in both phase 2 and 3.

For three cases, whether the motor in the PEA does positive or negative work in each phase is summarized in Table 3. The total positive mechanical work in a gait cycle done by the motor in the RA is \( f_1 T_{RA}(t) \cdot \omega (t) \ dt + f_3 T_{RA}(t) \cdot \omega (t) \ dt \). Comparing it with that in the PEA in each case, we can further obtain the reduction of the motor mechanical energy consumption during a gait cycle for three cases, which is also summarized in Table 3, as a result of adding a PE.

| Case | 1 | 2 | 3 | The reduction of the motor mechanical power consumption |
|------|---|---|---|----------------------------------------------------|
| 1    | P | P | N | \( W_{S1} \) |
| 2    | P | N | N | \( f_1 T_{RA}(t) \cdot \omega (t) \ dt + W_{S1} \) |
| 3    | P | P | N | \( f_1 T_{RA}(t) \cdot \omega (t) \ dt - W_{S1} \) |

Note: P means positive and N means negative. The reduction of the motor mechanical power consumption is positive in CASE 2 according to Fig. 2 and is assumed positive in CASE 3.

During a gait cycle, the PE stores some mechanical power from the motor in phase 1 for three cases, then continuously stores some mechanical power in phase 2 from only the lower limb for CASE 1 and 2 or from both the lower limb and the motor in CASE 3, and finally releases all the power in phase 3 into the lower limb for CASE 1 or into both the lower limb and the motor for CASE 2 and 3.

The result of the analysis explains theoretically why the PE can reduce the output of motor mechanical power for the reference gait. Even if this result can only suit the gait whose dynamics in three phases is similar to the reference
gait, the discussion above can also be referred to analyze the working principle of the PEA for other different gaits. Although our approximate model above may not completely coincide with the actual human walking due to the previous assumptions, the result of our analysis is referable for theoretically proving a power-efficient PEA during walking assistance and this theoretical basis motivated us to further develop the prototype of the PEA and evaluate the performance of the PEA through the software simulation and the hardware experiment.

III. MECHANICAL DESIGN OF PEA

This section illustrates the mechanical design of the PEA. The prototype of the PEA is shown firstly, the structure to connect the frameless flat brushless DC (BLDC) motor and the flat spiral spring is then clarified and the specific function of the flat spiral spring is finally explained in detail.

A. PROTOTYPES OF THE PEA

Fig. 4 shows the prototype of the PEA for the left hip in a side view.

![Prototype of the PEA for the left hip without housing.](image)

The PEA consists of six main assemblies: A self-integrated motor (see Fig. 6), a flat spiral spring, a housing (see Fig. 6) to hold the outer end of the spring, a synchronous drive (SD), a harmonic drive (HD) (see Fig. 5) and a support structure to fix the other parts. The SD is used to transmit power between the motor/spring and HD, which makes the PEA compact in axial width.

The hip joint requires a nominal speed, torque and power of over 31.96 rpm, 27.072 Nm, and 90.6 W, respectively, for a healthy subject with the weight of 120 kg walking at 0.9 m/s [51]. A pair of a high torque-density rotor and a stator with a nominal torque of nearly 1 Nm and the transmission were determined based on the technical requirements of the hip joint. An overview of the technical data of the PEA is summarized in Table 4. The selection of the motor and the HD, the design of the SD and other technical data of the PEA were introduced in detail in [52].

![Prototype of the PEA-driven exoskeleton hip module with an indication of the functionalities.](image)

B. STRUCTURE TO CONNECT MOTOR AND SPRING IN PARALLEL

Fig. 6 presents the internal structure of the self-integrated motor of the PEA for the right hip in a half-sectional view. Most components of the motor are self-designed, including the motor cover, rotary plate, motor shaft and bearing sleeve. The power of the motor can be transmitted from the rotor through a rotary plate to the motor shaft. The self-integrated motor shaft makes it convenient to test different parallel connection structures between the motor and the spring and to find out the most useful one among them.

In previous work, the inner end of the flat spiral spring was connected to the motor shaft by a round pin [48], [53], which had a poor effect in actual use. Based on the various practical test, a more feasible and simpler way to connect them was found, as clarified below. As illustrated in Fig. 7, a notch was cut on the end face of the motor shaft and a small threaded hole on the end surface of the motor shaft was machined. The inner end of the spring was placed in the notch and fixed onto the motor shaft by a set screw. This approximates the spring’s
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FIGURE 6. The half-section image of the self-integrated motor of the PEA for the right hip by SOLIDWORKS 2018 (Dassault Systèmes SolidWorks Corp., Vélizy-Villacoublay, France). CCW means counterclockwise.

FIGURE 7. Images clarifying the way the spiral spring is attached to the motor by SOLIDWORKS 2018. The images in the red circles are enlarged views of local parts pointed out by the arrows. Note that the image of the end of the motor shaft is a sectional view and other components of the PEA are not shown except the housing, the flat spiral spring and the end of the motor shaft.

The inner diameter to that of the motor shaft. The outer end of the spring was placed in the l-shaped groove of housing, which approximates the outer diameter of the spring to that of the blind hole of the housing. In this way, the motor and the flat spiral spring can produce power in parallel. It is convenient to engage or disengage the spring by manually taking its outer end in or out of the l-shaped groove of housing.

C. SPECIFIC FUNCTION OF THE FLAT SPIRAL SPRING

The specific function of the flat spiral spring in the PEA for the right hip is further clarified here. From the view of Fig. 6, the coil of the flat spiral spring is wound in the counterclockwise (CCW) direction (as shown in Fig. 7) so that the spring can produce torque in the CCW direction on the motor shaft when it is stretched. The joint rotation in the CCW direction labeled in Fig. 6 is defined as the right hip extension. The HD reverses the direction of the rotation between the wave generator and the flexible gear. As a result, the torque of the spring on the right hip joint should be in the clockwise (CW) direction for the right hip flexion. Similar to the bio-mechanic analysis in [26], based on the inverted-pendulum model and the analysis of three cases in section II-B, the actual working process of the PEA for the right hip in a gait cycle is detailed as follows.

1) In phase 1, for three cases, the motor shaft rotates in the CW direction so that the right hip joint rotates in the CCW direction to shift the center of mass of the lower limb forward. Meanwhile, the spring is stretched as the motor shaft rotates in the CW direction.

2) In phase 2, the sum of the torque of the force that the torso applies on the lower limb on the heel, the torque of the gravity of the lower limb on the heel and the moment of the inertia of the lower limb about the heel should be in the CCW direction, which can be transmitted and reduced onto the motor shaft in a CW direction by the SD and the HD since the assembly has a good back-drivability. For CASE 1 and 2, the torque above partly stretches the spring continuously and partly drives the motor. For CASE 3, the motor produces actively the torque in the CW direction on the motor shaft; all the torque above stretches the spring continuously.

3) In the majority of phase 3, the spring starts to recover and returns gradually to its original neutral position. For CASE 1, the motor shaft rotates in the CCW direction since both the motor and the spring output actively torque in the CCW direction on the motor shaft. This torque is reversed by the HD to flex the right hip joint. For CASE 2 and 3, the spring rotates in the CCW direction since only the spring produces torque in the CCW direction on the motor shaft. The torque of the spring partly reversed to flex the right hip joint and partly drives the motor.

IV. EXPERIMENTAL SETUP

This section describes the experimental setup for a preliminary evaluation of the performance of the PEA-driven hip joint with different spring stiffnesses. The design of flat spiral springs is demonstrated initially, then the dynamic model of the PEA is described and the experimental design and procedure are finally introduced.

A. DESIGN OF THE FLAT SPIRAL SPRINGS

Given the gait curve in Fig. 1, the total reduction ratio, $N = 55$, of the PEA and neutral position of the PE in Table 3, the stiffness constant, $k$, of the spring should be properly selected. The equivalent stiffness of the spring at the output of the PEA, $K$, can be calculated as follows.

$$K = \frac{Nk \Delta \theta}{\Delta \theta / N} = N^2 k \quad (7)$$

where $\Delta \theta$ is the hip angle range. The transmission of the torque of our spring was considered as symmetric and lossless for the purposes of calculating the equivalent PE, while noting that the relationship is more complicated for dynamic performance.

Eq. (7) shows that the $k$ is amplified by $N^2$ to obtain $K$, indicating the stiffness requirement for PE is significantly reduced. However, the maximum of $k$ is limited by the
strength of the spring material. Fig. 8 shows the non-contact flat spiral spring, made of the spring steel, 60Si2CrVA.

Given the specific width, \( b \), and thickness, \( h \), of the spring, \( k \) is considered inversely proportional to its working length, \( l \), as it is a linear spring in theory. \( k \) can be calculated by (8) \[54\],

\[
k = \frac{Ebh^3}{12l}
\]

The deformation of the spring required in a gait cycle, \( N \cdot \Delta \theta \), should not exceed the maximum deformation, \( \psi \), that such a structure of the spring could withstand, as formulated by (9).

\[
N \cdot \Delta \theta \leq \psi = T/k
\]

where \( \Delta \theta \) in Fig. 2 is 0.646 rad and the maximum torque that the structure of the spring could withstand, \( T \), was calculated by (10) \[54\].

\[
T = 0.8 \cdot c_a \cdot \sigma_b \cdot h^2 \cdot b/6
\]

The parameters of the flat spiral spring in (8-10) are summarized in Table 5.

**TABLE 5. Parameters of the flat spiral spring.**

| Symbol | Parameter | Value |
|--------|-----------|-------|
| \( b \) | Width | 7 mm |
| \( h \) | Thickness | 0.3 mm |
| \( E \) | Working length | - |
| \( \sigma_s \) | Young’s modulus of 60Si2CrVA \[56\] | 205800 MPa |
| \( c_s \) | Tensile strength of 60Si2CrVA \[56\] | 1492 MPa |
| \( c_a \) | Correlation for stiffness | 0.704 |
| \( c_p \) | Correlation for tensile strength | 1.5 |

Calculated from (8-10), the constraint condition of \( k \) was established as follows.

\[
0 \leq k \leq 0.8 \cdot c_a \cdot \sigma_b \cdot h^2 \cdot b/6N \cdot \Delta \theta = 5.29\, \text{mN} \cdot \text{m}
\]

Based on (11), springs with nine different stiffnesses were then designed: \( k = 1.85, 2.06, 2.20, 2.55, 2.89, 3.53, 4.44, 4.61 \) and 5.29 mN-m/rad, to test the performance of the PEA. These springs have an identical width and thickness but different working lengths. The mass of the spring is rather small (e.g. the heaviest spring at \( k = 1.85 \) mN-m/rad weighs 20.455 ± 0.0856 g and the lightest spring at \( k = 5.29 \) mN-m/rad weighs 7.348 ± 0.0371 g) and accounts for less than 1 % of the total mass of the PEA.

**B. DYNAMIC MODEL OF THE PEA**

The dominant friction of the PEA was experimentally determined to be Coulomb friction such that \( T_f = C_f \cdot \text{sgn}(d\theta/dt) \) \[32\]. The directionality of the mechanical efficiency of the transmission should be considered for the bidirectional power flows in the PEA \[56\]. In the case of direct power flow from the motor to the load, the physical system of the PEA was modeled by (12).

\[
-mT_h(t) - \left( \frac{1}{\eta_1}N^2 J_1 + \frac{1}{\eta_h} N h^2 J_2 + J_f \right) \ddot{\theta}(t) = -T_f = \frac{1}{\eta} NT_h(t)
\]

while in reverse power flow from the load to the motor, all the mechanical efficiencies are inversed \[47\], (12) therefore should be replaced by (13).

\[
-mT_h(t) - \left( \frac{1}{\eta_1}N^2 J_1 + \frac{1}{\eta_h} N h^2 J_2 + J_f \right) \ddot{\theta}(t) - T_f = \frac{1}{\eta} NT_h(t)
\]

where the first term on the left side is for both (12) and (13) the hip joint torque required. \( T_h \) is the scaled sagittal plane internal joint torque in Fig. 2 and \( m \) is the reduced body weight (10 kg). The second and third terms on the left side are the inertia torque and the friction, \( T_f = C_f \cdot \text{sgn}(d\theta/dt) \). The term on the right side is the torque of the motor and spring. The directions of both the speed and torque of the flexible gear, as the outputs of the PEA, are opposite to those of the motor shaft. The parallel torque input, \( T_{In} \), and the efficiency factor, \( \eta_1, \eta_h \), were calculated as follows.

\[
T_{In} = K_f \cdot \left( \dot{\theta}(t) + k \cdot N \cdot (\theta(t) - \theta_{max}) \right)
\]

\[
\eta_1 = \eta_h \eta_\theta \eta_p
\]

\[
\eta = \eta_h \eta_\theta \eta_p
\]

The parameters in (12-16) are summarized in Table 6.

**TABLE 6. System parameters of the PEA.**

| Symbol | Parameter | Value |
|--------|-----------|-------|
| \( N_5 \) | The reduction ratio of HD | 50:1 |
| \( T_6 \) | The scaled internal joint torque | - |
| \( K_f \) | Motor constant | 0.134 N-m/A |
| \( \dot{\theta} \) | Motor current | - |
| \( \theta \) | Hip angle | - |
| \( \theta_{max} \) | Maximum hip flexion angle | 0.452 rad |
| \( J_1 \) | The sum of motor and small pulley moment of inertia | 5781.1 g cm² |
| \( J_2 \) | The sum of the big pulley, the input shaft of HD and the wave generator moment of inertia | 416.2 g cm² |
| \( J_f \) | The flexible gear moment of inertia | 110.1 g cm² |
| \( \eta_\theta \) | The efficiency of a deep-groove ball bearing | 0.9 [58] (modified by the experiment) |
| \( \eta_p \) | The efficiency of the SD | 0.955 [58] |
| \( \eta_\theta \) | The efficiency of the HD | 0.8 (provided by the manufacturer of HD) |
Given the largest mass (20.5415 g) and the outer radius (3.406 cm) of the selected springs, the equivalent moment of inertia of those springs should be much smaller than 238 g·cm², which accounts for 4.5 % of the moment of inertia of the motor (5301 g·cm²). Therefore, the inertia torque of the spring was ignored in the dynamic model of the PEA.

The Coulomb friction is experimentally estimated by measuring the minimal current, \( I_0 \), required for a “steady and free” motion of the PEA without the PE attached. The value of friction, \( C_f \), was calculated as follows.

\[
C_f = N \cdot K_T \cdot I_0 \tag{17}
\]

where the efficiency factor, \( \eta \), was ignored here in order to make the result of the simulation closer to that in the experiment.

Regarding the PEA in the right hip, \( I_0 = \pm 0.6 \) A meaning that \( C_f = 4.422 \) Nm. Regarding the PEA in the left hip, \( I_0 = \pm 1 \) A meaning that \( C_f = 7.37 \) Nm. The different tightness of the timing belts of the two PEAs may cause the difference in their friction. The PEA in the left hip was chosen to study the effect of the PE on the average (rms) and maximum positive electrical \( P \) of its motor, therefore, the friction \( C_{f1} = 7.37 \) Nm in (12) and (13).

Based on (12-17), the necessary current, \( I \), of the BLDC motor in the PEA during a gait cycle can be obtained.

The motor speed, \( n \) (unit: rpm), at the time, \( t \), was calculated by (18).

\[
n(t) = -30N \cdot \dot{\theta}(t) / \pi \tag{18}
\]

With the current, \( I \), above, the necessary voltage, \( U \), and electrical power, \( P \), of the BLDC motor in the steady state at the time, \( t \), can be calculated as follows [43], [44], [44]–[46].

\[
U(t) = I(t) \cdot R + n(t) / K_S \tag{19}
\]

\[
P(t) = I(t) \cdot U(t) \tag{20}
\]

where the terminal resistance phase to phase of the motor, \( R = 0.266\Omega \), and the speed constant of the motor, \( K_S = 71.4 \) rpm/V.

The reversing power flow from the load can not contribute to the power regeneration for the motor as the it was dissipated by the motor controller we used, instead of being recharged by the battery. Consequently, the positive part of electrical power, \( P \), was used to measure the power consumption of the motor. To evaluate the performance regarding the power efficiency of the PEA, the two indexes including average (rms) and maximum positive electrical, \( P \), of the motor in a gait cycle were chosen based on (20).

C. EXPERIMENTAL DESIGN AND PROCEDURE

Inspired by the bench level validation in [19] and the experimental setup in [20], the experiment was designed as shown in Fig. 9. By four pairs each of a bolt and nut, two 3-D printed flanges made of ABS connected the output of the PEA for the left hip and the RA which is exactly the PEA for the right hip but without the spring attached.

During the clinical trials of the PEA-driven LLE, the target users, paraplegic patients with a complete loss in walking ability should exactly follow the reference trajectory predefined in the controller of the LLE. In the clinical trials, the hip joint actuator should produce a similar torque to the internal joint torque of the hip in the reference gait, though a small difference may occur between them as the mass distribution of the LLE is different from that of human. For the experimental validation of proposed PEA, a benchtop experiment can be firstly conducted before the clinical trials. In order to reflect the real application scenario in the clinical trials to a large extend, the sagittal plane internal joint velocity and torque of the hip from the reference gait (see Fig. 1) were used to approximate the dynamics that the hip joint actuators should generate in the clinical trials. The PEA was used to generate the hip joint motion, while the RA was used to generate the torque that the hip joint actuators should sustain in the clinical trials.

Fig. 10 shows the experimental hardware of the data acquisition and control system.

Two commercial motor controllers (type Escon modules 50/8, Maxon Motor AG, Sachseln, Switzerland) were used to control the two motors. The hall sensors were pre-integrated in the motors to obtain the precise absolute position feedback for the motor controller. A software named EPOS studio
run by a PC can set up the configuration of the motor and its controller based on their technical data and acquire the real-time feedback data from the motor through USB. Two DC power supplies (0-60 V and 0-10 A) provided 30 V (the nominal voltage of the motor) for two motor controllers.

Based on the gait curve in Fig. 1, the RA produced the torque desired by the current control mode of the motor controller, and, meanwhile, the PEA generated the motion desired by the speed closed-loop control mode of the motor controller. The ideal power flow in the whole system is demonstrated here to study the power harvest effect of the PE in three phases based on the analysis of three cases in section II-B and the description of the specific function of the spring in section III-C.

1) In phase 1, for three cases, the motor in the PEA should be driving and meanwhile the PE and the motor in the RA should be driven. Most of the power from the motor in the PEA would flow to the motor in the RA and a little of it would flow to the PE, leading to a slight increase in the electrical power of the motor in the PEA.

2) In phase 2, for CASE 1 and 2, the motor in the RA should be driving and, simultaneously, the motor and the PE in the PEA should be driven. A part of the power from the RA would flow to the PE and the rest of it would flow to the motor in the PEA. The mechanical power of the motor in the PEA is still negative and can’t be regenerated by our system and Joule heating losses is presumably reduced due to a reduced torque magnitude. As a result, for CASE 1 and 2, the electrical power of the motor in the PEA would be reduced or unchanged in phase 2. For CASE 3, both motors should be driving and the PE should be driven. The power from both motors would flow to the PE. Therefore, the electrical power of the motor in the PEA would be slightly increased in phase 2 for CASE 3.

3) In phase 3, for CASE 1, the motor and PE in the PEA should be driving, while the motor in the RA should be driven. The power partly from the motor in the PEA and partly from the PE, would flow to the RA. For CASE 2 and 3, the PE should be driving, while both motors should be driven. The power from the PE would flow to both motors. Therefore, the electrical power of the motor in the PEA would be significantly reduced in phase 3 for three cases.

The RA was governed by the following equation, which resembles the dynamic model of PEA in (21).

\[ mT_h(t) - \left( \eta_1 N^2 J_1 + \eta_2 N^2 h_1 J_2 + J_c \right) \dot{\theta}(t) - T_I = \eta N T_R(t) \]

where \( T_R \) is the electromagnetic torque of the motor, the value of friction \( C_{f_2} = 4.422 \text{ Nm} \), \( T_{I_2} = C_{f_2} \text{sgn}\left(\frac{d\theta}{dt}\right) \), and the two connecting flanges moment of inertia, \( J_c = 787.74 \text{ g cm}^2 \). The other parameters are identical to those in (12).

Based on (21), the motor current, \( I_R \), in the RA was determined by (22).

\[ I_B(t) = T_R(t)/K_T \]

The data of \( T_h \) in Fig. 1 was first fitted by Fourier equation with terms of 8 to become a smooth Fourier series and then transferred to obtain the \( I_B \) in the RA by (21) and (22). The data of the hip joint velocity, \( d\theta/dt \), in Fig. 1 was, firstly, fitted by Fourier equation with the terms of 7 to become a smooth Fourier series and then transferred to obtain the target motor speed, \( n \), in the PEA by (18). Both the \( I_R \) and \( n \) were mapped into a pulse-width modulation (PWM) wave signal, as the inputs of motor controllers. As shown in Fig. 10, an Arduino Uno R3 was used to generate the PWM wave signal desired. Before recording the data, 7 s of resting state (i.e. the PWM input is zero) were set. Filtered by a 1st order digital low-pass filter with a cut-off frequency of 5 Hz, the current and speed of the motor were recorded with a sampling time of 9.911 ms. Five trials were repeated for each case in the experiment to obtain the average value of the two indexes. The spring may not return to its original neutral position after a trial due to the control error on the motor position of the speed closed-loop controller. To address this problem, we labelled the initial position of the timing belt in order to manually adjust the timing belt to the initial position before starting each trial.

V. RESULTS

The simulation was carried out by solving (12-20) in MATLAB 2017b (Mathworks, Natick, USA) in the cases that PEs with \( k = 1.85, 2.06, 2.20, 2.55, 2.89, 3.53, 4.44, 4.61 \) and 5.29 mN-m/rad were attached or not attached. The results of the simulation and experiment are shown in this section.

Fig. 11 overlays the performance of the PEA in the light of two indexes, average (rms) and maximum positive electrical \( P \) of the motor in a gait cycle when springs with different stiffnesses were attached and no spring was attached.

The results of the simulation and experiment demonstrate that both indexes tended to decrease substantially with the increase of \( k \) and were smaller when the PEs were attached than when they were not. Both indexes reached the minimum at \( k = 5.29 \text{ mN-m/rad} \) in the simulation and experiment.
Moreover, even if the simulation consistently predicts a lower electrical power of the motor than the experiment, they both showed that the spring with the stiffness in the selected range was saving the electrical power of the motor. The standard deviations in the experiment for two indexes were rather small, which verifies that the PEA has a stable performance. The value of the two indexes in the experiment was rather close to that in the simulation.

Fig. 12 overlays the reduction rates in the two indexes when PEs with different stiffnesses were attached compared to those when no PE was attached in the simulation and the experiment, calculated from Fig. 11. Note that the reduction rates in the experiment were calculated in terms of the mean of each index.

The reduction rates of two indexes tended to increase with the increase of \( k \). With the PE of \( k = 5.29 \) mN·m/rad, the average (rms) and maximum positive electrical \( P \) were largest reduced by 11.99 and 16.84 % in the simulation and 10.3 and 26.25 % in the experiment, respectively. The reduction rate in the experiment was close to that in the simulation.

The results in Fig. 11 and 12 both show that the PEA with those springs of different stiffnesses can all reduce the power requirement for walking assistance.

As shown in Fig. 13(a), \( n \) in the experiment was close to that in the simulation overall, indicating that the system of the PEA has a good tracking precision in speed. In addition, \( n \) was nearly identical whether the PE was attached in the experiment or not, which indicates the system of the PEA has a good antijamming capability.

Fig. 13(b) shows \( P \) when the PE with \( k = 5.29 \) mN·m/rad was attached and not attached. The results of the simulation and experiment demonstrated that \( P \) with the PE attached was a little higher in phase 2 and significantly lower in phase 3 than that without the PE attached, which verifies the PE can store some power in phase 2 and recycles it in phase 3. According to Fig. 13(b), with the PE attached, the average (rms) positive \( P \) of the motor was reduced by 12.0 % (from...
3.51 to 3.0894 W/kg) in the simulation and 10.3 % (from 3.6682 to 3.2904 W/kg) in the trial of the experiment, compared to that without the PE attached. The maximum positive $P$ of the motor was reduced by 16.8 % (from 10.4527 to 8.6922 W/kg) in the simulation and 26.1 % (from 11.6360 to 8.5935 W/kg) in the trial of the experiment, compared to that without the PE attached.

In Fig. 13, $n$ and $P$ in the experiment both had a rather similar tendency over the gait cycle to those in the simulation, which proves that the experiment validates the simulation.

The results of the benchtop experiment preliminarily proved that the proposed PEA successfully achieved a power-efficient walking assistance, which indicates a promising effect of the PE in reducing power consumption during the clinical trials on paraplegic patients with a complete loss in walking ability.

**VI. DISCUSSION**

In this section, the differences between the results of the simulation and experiment are discussed initially. Then, we discussed the comparison between the new structure with PE placed on the motor-side and the traditional structure with PE placed on the load-side. Finally, a potential improvement of the proposed PEA is discussed.

**A. EXPLANATION OF THE DIFFERENCE BETWEEN THE RESULTS OF SIMULATION AND EXPERIMENT**

It is shown in Fig. 11 that the values of the two indexes in the experiment are a little higher than those in the simulation at each $k$ and the error between the simulation and experimental results regarding the values of both indexes reduces as $k$ increases. Figure 12 shows the error between the simulation and experimental results regarding the reduction ratio of both indexes is increased as $k$ increases. Fig. 13(b) also displays that the amplitude of $P$ in the experiment is a little higher than that in the simulation, and the phases of $n$ and $P$ in the experiment were both delayed compared to those in the simulation.

The differences above are probably attributed to the following reasons: 1) Nonlinear and varying friction (based on position) may exist in the powertrain of the HD and SD in the experiment, while this was not modeled and the friction is assumed to be constant in the simulation. This is also regarded as a reason for the difference between the model and actual experiment in [32]. It is important to note that the value of the friction in the system is comparable to that of the maximum motor torque with the reduced body weight, $m = 10$ kg. Consequently, smaller differences between the simulation and experimental results for the full body ($m = 90$ kg) could be expected as the overall influence of friction may be less. 2) The PE is ideally linear in the simulation, while the flat spiral springs are probably nonlinear and have hysteresis characteristics in the experiment, which is also reported in the leaf spring system of the PEA-driven knee joint for Phides [13] and in the nonlinear cam-spring mechanism of the PEA-driven ankle-Foot Prosthesis [28]. 3) Friction between the side of the spring and the housing and between the adjacent coils of the flat spiral spring in the experiment existed, which was ignored in the simulation. 4) Finally, controller errors, e.g. the motor position error, occurred in the experiment, while the simulation assumes perfect control. This is also reported in [32].

Therefore, those differences are the results of imperfect modeling of the physical system and the controller error, which are not problematic given the agreement between the trends in the simulation and the experiment. Additionally, the differences between the results of the simulation and the experiment are reported in other PEAs [25], [28], [32]. Exemplarily, the averaged power cost in the experiment is about three times that in [25], and there are some discrepancies in the profiles of the electrical power between the experiment and the simulation in [32].

**B. COMPARISON BETWEEN THE NEW STRUCTURE WITH THE PE PLACED ON THE MOTOR-SIDE AND THE TRADITIONAL STRUCTURE WITH PE PLACED ON THE LOAD-SIDE**

As mentioned in the introduction, the proposed PEA with the PE placed on the motor-side has advantages over the traditional PEAs with the PE placed on the load-side. According to (7), it can be inferred that a physical spring with a stiffness of $K = 16002.25$ mN-m/rad placed on the load-side can obtain the same effect as the flat spiral spring with a stiffness of $k = 5.29$ mN-m/rad placed on the motor-side. We can deduce that the stiffness requirement for the spring is significantly reduced by the new structure, leading to many benefits, including a lower strength requirement for the spring material, and a lighter and compact PE with such a low stiffness, the proposed PEA in our study still has a comparable reduction rate regarding the motor power consumption to other two.

| PEA applications                        | PE stiffness | Motor power consumption reduction in the experiment |
|----------------------------------------|-------------|--------------------------------------------------|
| The proposed PEA in our study          | 5.29 mN-m/rad | 10.3 and 26.25 % in the average (rms) and maximum positive electrical power, respectively |
| PEA-driven knee joint in a planar bipedal robot ERNIE [25] | 201300 mN-m/rad | 29.6 % in the mechanical power on average |
| Clutched PEA-driven hip joint in LLAs [31] | 30000 mN-m/rad | 29 and 24 % in the average (rms) and peak motor power on average |

The stiffness of the PE we used accounts for 0.0026 % of that in [25] and 0.018 % of that in [31]. However, attaching this light and compact PE with such a low stiffness, the proposed PEA in our study still has a comparable reduction rate regarding the motor power consumption to other two.
PEAs with traditional structures with PE placed on the load-side [25], [31].

C. POTENTIAL IMPROVEMENT FOR THE PROPOSED PEA

Since the power requirement of the motor can be reduced, the motor could be replaced with one of a lower assigned power rating and a smaller nominal torque. Consequently, the size and weight of the PEA would be reduced, leading to a lighter walking assistance device.

The successful validation of the current benchtop experiment in this study motivates us to conduct more experiments in order to evaluate the performance of the proposed PEA comprehensively. Firstly, similar benchtop trials but with PEs of greater stiffnesses can be conducted. Secondly, we will further conduct clinical trials of paraplegic patients (with a complete loss in walking ability) walking with the assistance of the PEA-driven LLE, based on the successful preliminary experimental validation of this LLE without the spring attached in [52]. It is important to improve the system effectiveness of the PEA. The work in the future will focus on improving its feasibility for the actual utilization in an exoskeleton and further increasing its power efficiency in the following ways.

1) The maximum stiffness of the PE is supposed to be higher to enable the PE to sustain a larger torque, which may further reduce the power consumption of the motor and support the patient with normal weight. A greater range of stiffness of the flat spiral spring can be realized by replacing the spring steel of 60Si2CrVA with others of a higher tensile strength or enlarging its thickness/width according to (8). For example, in order to support a patient with 120 kg, the material, the working length and the width of the spring remain the same, but its thickness can be enlarged by $2\sqrt{3}$ to build a spring with 12 times of the initial stiffness. An alternative way to increase the spring torque is employing a compact spring mechanism e.g. the cam-spring mechanism [27], [28]. In addition, the interface between the housing and the outer end of the spring, may need to be reshaped or fixed by a set screw to increase the friction, enabling the interface to sustain a higher load.

2) The user when wearing an exoskeleton with the current PEAs can not stand straight due to the existence of the spring torque in this status. To overcome this, we intend to firstly use a ratchet-pawl mechanism, by which an operator can help engage the spring at the time of HS if the user intends to start walking and disengage the spring at the time of HS if the user intends to stop walking. This manual clutch assembly consisting of the ratchet-pawl mechanism has been introduced in [48]. In addition, the operator can help replace the spring in the current design when different gait patterns are performed. Those operations are reliable and workable, although short of intelligence. In order to improve the practicality and intelligence of the manual clutch assembly, a bi-stable solenoid will be further utilized to replace the manual operation of switching the status of the parallel spring between engagement and disengagement owing to the low power consumption of the bi-stable solenoid and the low force required for status switching. A bi-stable solenoid has been used as a clutch actuator for another PEA and turned out to perform well in our previous study [31]. For the bi-stable solenoid-driven clutch, only a short current pulse with different polarities is required to trigger at the time of HS if the user intends to change his/her status between walking and standing and no additional current is required to maintain the status of the clutch after switching due to the force of the permanent magnet. Therefore, the power consumption of the bi-stable solenoid clutch will be rather small, which little influences the energy consumption of the whole PEA.

3) The optimization of the stiffness of the PE, the reduction ratio of the PEA and the executing hip trajectory will be studied to further improve the power efficiency of the PEA, since they all influence the power consumption of the motor. This could be a multi-objective optimization problem which can be solved by the optimization algorithm in [58]. Alternatively, it could be a single-objective optimization problem, such as that reported in [25], which optimized the walking gait for a variety of spring stiffnesses, or [32], which studied the gear ratio for a given spring and analyzed the spring design for different trajectories. In the future, on the one hand, the optimized PE stiffness for a determined reduction ratio of the PEA and a given hip trajectory will be determined by minimizing the average electrical power consumption of the motor in a gait cycle through both the simulation and experiment. Comprehensive optimization methods for the PE should be considered for the general operation of the PEA. An iterative optimization process, for example, has been developed for the nonlinear spring in the cable-driven parallel robots [59] and the combination of counterweights and springs in the static balancing serial and parallel mechanisms [60]. On the other hand, inspired by the analysis in CASE 1 of section II-B, it is worth studying the effect of different values of $\theta_1$, $\theta_2$ and $\theta_3$ on motor power consumption for the PEA with a limited spring stiffness during the gait whose dynamics in three phases is similar to that in Fig. 1.

4) The nonlinear and varying friction, e.g. the viscous friction, a more complex and nonlinear stiffness function and the equivalent inertia torque of the spring and other parameters with unprecise value, e.g. the inertia of the components and the transmission efficiency in the PEA should be comprehensively identified to establish a more precise dynamic model of the PEA. Based on the revised dynamic model of the PEA and hardware experiments, the undermined dynamic parameters can be identified by some algorithms.

5) An advanced controller should be designed to acquire a more precise control effect.

The proposed PEA with those improvements above is promising to be applied in the clinical trials. As inferred from the working principle of the PEA-driven hip joint in our case, the essential reason that the PE can increase energy efficiency is that the reversing power from the load is stored (instead
of wasted) during a phase with a unidirectional motion and recycled during the next phase with the reversed motion in a periodic process. Hence, the application of the proposed PEA is not limited to the exoskeleton hip joint but may be extended to other powered robots/devices (e.g., an industrial pick-and-place robot), which have a similar executing trajectory to the exoskeleton hip joint, in order to increase power efficiency. The executing trajectory should be periodic and contain a period when the power of the load flows back to the robots/devices but cannot be recaptured by it.

VII. CONCLUSION

In this paper, a novel PEA with a self-integrated motor and a flat spiral spring in parallel for power-efficient walking assistance was analyzed, designed, and preliminarily evaluated. As a theoretical basis, we quantitatively analyzed the working principle of the PEA-driven hip joint. The mechanical design of the PEA was illustrated in detail. Both the simulation and experiment were conducted to preliminarily evaluate the performance of the PEA with a selected spring stiffness range of 0 – 5.29 mN·m/rad regarding two indexes: The average (rms) and maximum positive electrical power of the motor over a gait cycle. The results from both showed considerable reduction in two indexes when the PE was attached compared with when no PE was attached. Consequently, the proposed PEA has a bright prospect to improve the energy efficiency for walking assistance and promising potential to replace the traditional rigid actuators. In addition, it can be applied in other powered robots/devices with a periodic executing trajectory containing a phase when the reversing power flow from the load cannot be regenerated.

In conclusion, this study focuses on the quantitative theoretical analysis, the novel mechanical design and a thorough examination through preliminary benchtop experiments and sufficient discussions regarding the power-efficient PEA-driven hip joint. There are two main novelties in this work: 1) In theory, the working principle of the PEA is quantitatively analyzed to explain the reason why the power requirement of the motor can be reduced by the PE; 2) In mechanical design, the parallel flat spiral spring is integrated into the motor design and placed on the motor-side instead of on the load-side, enabling the PEA to be compact and the PE to be smaller, lighter and less stiff. The clinical trials on paraplegic patients with a complete loss in walking ability are taken into consideration for future research.

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