Abstract

In this paper, the effects of rigid-flexible coupling knees on the performance of the exoskeleton developed by us for power assist are mainly concerned. The work was conducted through a series of numerical simulation comparisons between rigid-flexible coupling models and pure rigid structure models of the exoskeleton under different loads. Before the dynamic analysis, a flat walking gait plan in sagittal plane was designed for the exoskeleton, and the coupling numerical model of the novel knee was verified through comparing with the experimental result. Compared with the pure rigid knees, the simulation results show that the rigid-flexible coupling knees exert a mixed influence on dynamics of the exoskeleton under different loads. Via the current study, a simple and practical gait plan is acquired for biped exoskeleton to imitate human level walking, and flexible parts utilized in the exoskeleton joints could lead to a vibration of joint driving torque without load, and on the contrary, it contributes to the lower impact ground reaction force and undemanding driving torque requirement with heavy load.

Keywords: Exoskeleton, Knee joint, Gait plan, Rigid-flexible coupling, Simulation

1. Introduction

The exoskeleton is an autonomous robotic device whose function is to increase the strength and endurance of a human pilot (Ghan and Kazerooni, 2006). These days, lots of lower-limb exoskeletons have been developed to assist human in various forms, such as, making load carriage easier by providing a parallel structure to ground, applying torques to the wearer’s body directly in order to assist impaired or able-bodied individuals (Asbeck et al., 2015). All around the world, the exoskeleton has attracted plenty of academic researchers and enterprises to work for it.

Despite the powerful functions and popularity of exoskeleton, there still remain some challenges for the researchers. For instance, the mechanical structure should be artful to achieve multiple movements as human; the construction of exoskeleton ought to be comfortable for its wearer; the safety of structure also needs to be taken seriously because of human-in-the-loop (Song et al., 2016), and some researchers even believe that the user safety is the top concern for exoskeleton developers, researchers, users and regulators (He et al., 2017). Most of traditional lower limb exoskeletons with hard structures along with complicated linkages were designed to resemble human ergonomics (Zoss et al., 2005; Deng et al., 2017; Kim et al., 2017), their joints were achieved through simple hinges without the anthropomorphic design of human joints. Besides, there is seldom research about the flexible material utilized in the joints of exoskeleton, and it is hard to verify whether the flexibility exerts positive or negative effects on the performance of exoskeleton during level walking. Meanwhile, there is a novel kind of exoskeleton which make use of soft fabrics to comfort the wearer (Asbeck et al., 2015). By a tendon actuated working principle, the soft exosuit is able to provide an additional torque to the wearer and move dexterously without disturbing the operator. However, due to the softness, it is impossible for exosuit to support the heavy loads on the back or the human body (Song et al., 2016), which will restrict its scope of application.
On the above analysis, flexible materials are considered to be added to create a hybrid knee joint for a better performance expectation of exoskeleton. Through comparing the simulation results of both Rigid-Flexible Coupling Models (RFCMs) and Pure Rigid Structure Models (PRSMs) of the exoskeleton, the influence of flexible materials on the exoskeleton performance in normal flat walking is studied. In addition, before the simulations, it is necessary to plan a level walking pattern for the models so that they are able to exercise like a human being.

Thus, the organization of this paper is as follows: Firstly, an exoskeleton with compliant knees made of rigid and flexible materials is constructed. The motion plan design of the exoskeleton is described in the next section. The third part introduces how to build the RFCMs and PRSMs. Then, the results of the simulations are obtained. Finally, the conclusions and future work are given.

2. Exoskeleton structure description

In order to achieve a better performance of human-machine coupled movement, a conventional powered exoskeleton which looks like a simplified biped robot is often composed of waist or back pack, thighs, shanks and shoes. On this basis, an anthropomorphic exoskeleton used for power assist with heavy load carrying is developed by us. On the one hand, the design of the exoskeleton named NE-105 (shown in Fig. 1) is similar to a traditional one with 6 Degrees of Freedom (DOFs) per leg, and the DOF allocations and movement angle restrictions of the joints are listed in Table 1. The 2 DOFs of the hip are accomplished by the conventional revolute pairs, one is placed at the side of human’s hip, the other is at the back; while the 3 DOFs of the ankle are realized by a rod end joint bearing as shown in the left of Fig. 1. Moreover, the lengths of the waist, thighs and shanks are adjustable for different wearers, and with the assistance of the soft belts mounted on the back, thighs and shanks, the wearer can blend in with NE-105 efficiently. For the convenience of design and manufacture, most of NE-105’s mechanical elements are designed to be tubular or cylindrical, it looks friendlier and is better for the wearer’s safety compared to a boxy one.

| Joints | DOF                  | Restriction   |
|--------|----------------------|---------------|
| Hip    | Flexion/extension    | 110°/20°      |
|        | Adduction/abduction  | 20°/20°       |
| Knee   | Flexion/extension    | 120°/0°       |
| Ankle  | Plantarflexion/dorsiflexion | 40°/40° |
|        | Varus/valgus         | 15°/15°       |
|        | Pronation/supination | 12°/12°       |

On the other hand, the knee joint of NE-105 is distinct from the ordinary which is usually set up by a rigid revolute pair. To our knowledge, human lower limb joints are complex and difficult for imitation through mechanical structure. The human knee joint is a synovial joint (Deng et al., 2017), inside which, there are two bones joined together: the femur and tibia. The ends of the bones are covered in a very smooth layer of a tough, rubbery substance known as cartilage. In the paper of Poole (1997), articular cartilage and extracellular matrix work synergistically to provide a hydro-elastic suspension mechanism which is able to absorb, redistribute and transmit physiological compressive and shearing forces to the subchondral bone. Meanwhile, the surface of articular cartilage is smooth, and the synovial fluid is flowing in the joint, and both of them make the joint have good anti-friction properties. As the great advantage of human joint, the imitated joint is designed shown in the right part of Fig. 1. Inside of NE-105’s knee, there are two pairs of flexible rings and rolling bearings. The flexible components can be regarded as articular cartilage to reduce the shock of the joint and cushion the impact between the linked parts. While the rolling bearings minimize the friction between exoskeleton thigh and shank. And the encoder is utilized as a detector to deliver the knee motion information to the control system, just like a knee nerve to a brain. And the knee is a core joint for the purpose of load carrying. Thus, there are two linear actuators made up of motors, gear reducers, and nut screw pairs to strengthen the knees to assist the wearer in supporting the load weight, and also to help with the locomotion of human lower limb.
Fig. 1 The full view of NE-105 and the knee joints. The left part is the assembling sketch and some explosive views of NE-105 with actuators. The middle part is the combination of human and NE-105 with belts. The right part is the internal organizations of human knee and NE-105’s knee.

3. Gait plan for level walking

On the basement of the mechanical structure of NE-105, the motion plan should be figured out for the input of the follow-up simulations.

In our daily life, the main and most repeated movement of human beings is walking (Huang et al., 2015), and the primary aim of this research is focused on the performance of exoskeleton in the process of level walking. To decrease the complexity of the motion plan, the motions of hip abduction/adduction, ankle varus/valgus and pronation/supination are not taken into consideration. To further simplify the kinematic model, the feet are parallel to the ground, and the waist as well as the other parts above the waist keeps intact. Besides, both the left hip and the right hip have the same route. In this way, the lower limb motion of exoskeleton can be regarded as a planar 4-links demonstrated in Fig. 2, including thighs, shanks in the sagittal plane.

Fig. 2 Kinematic simplification of NE-105 and the state of double support.

During the gait, the state of two legs staying at double support (Fig. 2) is a key position, and the leg changes from stance to swing or the opposite, and the movements of the hip and knee change rapidly. Figure 2 represents the state of double leg support (supposed that the right leg is in the front). At this moment, $\theta_{\text{rhs}}$ is the flexion angle of the right hip;
\( \theta_{rks} \) is the flexion angle of the right knee; \( \theta_{lhs} \) is the extension angle of the left hip; \( \theta_{lks} \) is the flexion angle of the left knee at this state. The lengths of thigh and shank are \( l_t \) and \( l_s \), respectively.

In this case, the right ankle is in front of the hip, and the length between them in the moving direction is \( l_f \), and the distance between the left ankle and the hip is \( l_b \). They can be calculated as followed:

\[
\begin{align*}
\begin{cases}
l_f &= l_t \sin \theta_{lhs} + l_s \sin (\theta_{lhs} - \theta_{rks}) \\
l_b &= l_t \sin \theta_{lhs} + l_s \sin (\theta_{lhs} + \theta_{lks})
\end{cases}
\end{align*}
\tag{1}
\]

The proposed model satisfies the following relationship:

\[
\begin{align*}
\begin{cases}
y_{hs} &= l_t \cos \theta_{lhs} + l_s \cos (\theta_{lhs} + \theta_{lks}) \\
y_{hm} &= l_t \cos \theta_{lhs} + l_s \cos (\theta_{lhs} - \theta_{rks})
\end{cases}
\end{align*}
\tag{2}
\]

where \( y_{hm} \) is the height from the hip to the ankle. When \( \theta_{lhs}, \theta_{rks}, \theta_{lhs} \) and \( l_t, l_s \) are all given, \( \theta_{lks} \) can be calculated with Eq. (2).

The motion plan method of ours follows the one proposed by Singh et al. (2016). Here, different from their method, the beginning of the gait is also concerned which is conducive to the driven setup of simulations. Therefore, the motion plan of exoskeleton is restarted from the beginning to the continuous of walk. In this case, the initial period of the walking design is standing still, and then the right leg takes the first launch step. After the right foot hits the ground to form the double support, the left leg steps the second, next the third step of the right, and then left leg repeats. Finally, the full gait is obtained as shown in Fig. 3. The time from the start of second step to the end of third step is named a gait cycle.

![Fig. 3 A level gait plan for the simplify model of NE-105.](image)

3.1 The first launch step

At first, the right leg starts to take a stride. When the right foot contacts the ground, it takes time \( T_1 \). The trajectories of the hips and ankles are shown in Fig. 4. Assuming that the moving direction is \( x_1 \), the position of the right ankle at \( 0s \) is \( o_1 \).
Fig. 4 The legs trajectories during the first launch step. The red represents the right leg while the black represents the left.

During the first launch step, the constraints of the right hip and ankle at critical moments are listed in Table 2. At the beginning, the position of the right ankle should be at point \( o_1(0,0) \), while the right hip is at the location of point \( h_1(0,L) \) (where \( L \) represents the full length of the leg, \( L = l + l_s \)), and both of the hip’s and ankle’s velocities should be \( 0 \) at both \( x_1 \) and \( y_1 \) direction. At time \( t_1 \), the right ankle is assumed to move to the highest place \( y_{am}^{1}\) while the \( x_1 \) direction has no restriction, and the same to the position of hip and its velocity. At time \( T_1 \), the ankle position is on the ground of \( o_1'(L_d,0) \) (where \( L_d \) is the stride length which can be calculated with \( l_f + l_b \)), so the velocity should be \( 0 \); at this time, the hip moves to the lowest position \( h_1'(l_b,y_{hm}) \), and the hip velocity in \( x_1 \) direction is supposed to be \( V_h \) (\( V_h = L_d/(2T_1) \)).

![Fig. 4 The legs trajectories during the first launch step. The red represents the right leg while the black represents the left.](image)

Table 2 The constraints of the right hip and ankle at critical moments in the first launch step

| Joints | Critical moments | 0s  | \( t_1 \) | \( T_1 \) |
|--------|-----------------|-----|-------|-------|
| Ankle  |                 | \( x_{an}(0) = 0 \) | \( y_{an}(0) = 0 \) | \( y_{an}(0) = 0 \) |
|        | \( \dot{x}_{an}(0) = 0 \) | \( \dot{y}_{an}(0) = 0 \) | \( \dot{y}_{an}(0) = 0 \) |
|        | \( y_{am}(t_1) = y_{am},\dot{y}_{am}(t_1) = 0 \) | \( x_{an}(T_1) = L_d \) | \( \dot{x}_{an}(T_1) = 0 \) |
|        |                 | \( \dot{y}_{an}(T_1) = 0 \) | \( y_{an}(T_1) = 0 \) |
| Hip    |                 | \( x_{hn}(0) = 0 \) | \( y_{hn}(0) = 0 \) | \( y_{hn}(0) = L \) |
|        | \( \dot{x}_{hn}(0) = 0 \) | \( \dot{y}_{hn}(0) = 0 \) |
|        | \( y_{hm}(T_1) = y_{hm} \) | \( \dot{y}_{hn}(T_1) = 0 \) |
|        | \( x_{hn}(T_1) = l_b \) | \( \dot{x}_{hn}(T_1) = V_h \) |
|        | \( \dot{y}_{hn}(T_1) = 0 \) |

Because of the constraints of hip and ankle at the key time, their trajectories can be obtained by third-order spline interpolation method. Then the knee trajectory is able to be computed via the following geometry constraints equations:

\[
\begin{align*}
    l_1 &= \sqrt{(x_{an} - x_{nh})^2 + (y_{an} - y_{nh})^2} \\
    l_2 &= \sqrt{(x_{hn} - x_{nh})^2 + (y_{hn} - y_{nh})^2}.
\end{align*}
\]  

For the left leg, the left hip has the same motion with the right hip, and the left ankle stays still, so the left knee can also be acquired by the geometry constraints.

3.2 The second step

During the second step from the right leg in the front to the left in the front, it takes time \( T_2 \). This time, the left leg is chosen as the plan design object with the trajectories shown in Fig. 5.
Fig. 5 The legs trajectories during the second step. The red represents the right leg while the black represents the left.

In the second step, the constraints of the right hip and ankle at critical moments are listed in Table 3. At the start of the left foot leaving the ground, the left ankle should be at \( \alpha_2(0, 0) \), and the velocity is \( \mathbf{0} \); the position of left hip is \( h_2(l_b, y_{hm}) \), and to ensure the continuity of the gait plan, the state of the left hip should be the same with the right hip at \( T_1 \) in the first step, thus the velocity should be \( (V_h, 0) \). The left ankle is assumed to move to the highest point \( y_{am2} \) at time \( t_2 \), and the left hip is presumed to get to the highest position \( (L_d, y_{hm}) \) at \( t_2 \), and the right leg is perpendicular to the ground at this moment, and the velocity of the left hip in \( x \) direction is \( V_h \). When the left foot is in contact with the ground at time \( T_2 \), the left ankle moves to point \( \alpha_2' (L_d, 0) \) and the velocity turns to \( \mathbf{0} \); at the same time, the velocity of the left hip in \( x \) direction is still \( V_h \), and in \( y \) direction, it moves to the lowest point \( h_2' (l_b + L_d, y_{hm}) \).

### Table 3 The constraints of the left hip and ankle at critical moments in the second step

| Joints | Critical moments | \( 0s \) | \( t_2 \) | \( T_2 \) |
|--------|------------------|---------|---------|---------|
| **Ankle** | \( x_{in}(0) = 0 \) | \( \dot{x}_{in}(0) = 0 \) | \( y_{in}(t_2) = y_{am2} \) | \( \dot{y}_{in}(t_2) = 0 \) |
| | \( y_{in}(0) = 0 \) | \( \dot{y}_{in}(0) = 0 \) | \( y_{in}(T_2) = 0 \) | \( \dot{y}_{in}(T_2) = 0 \) |
| **Hip** | \( x_{ih}(0) = l_b \) | \( \dot{x}_{ih}(0) = V_h \) | \( y_{ih}(t_2) = L \) | \( \dot{y}_{ih}(t_2) = 0 \) |
| | \( y_{ih}(0) = y_{hm} \) | \( \dot{y}_{ih}(0) = 0 \) | \( y_{ih}(T_2) = y_{hm} \) | \( \dot{y}_{ih}(T_2) = 0 \) |
| | \( x_{ih}(t_2) = L_d \) | \( \dot{x}_{ih}(t_2) = V_h \) | \( \dot{x}_{ih}(T_2) = l_b + L_d \) | \( \dot{x}_{ih}(T_2) = 0 \) |

With the same method of the first step, both the left and right hips, knees and ankles trajectories can be obtained. Changing the trajectories of the right leg to the left and the left to the right of the second step, the third step of the legs’ trajectories is gotten, and the third step spends the same time \( T_2 \). Then repeating the second and the third step, the model is able to walk continuously.

By varying the values of parameters \( l_l, l_r, \theta_{rhs}, \theta_{lhs}, T_1, T_2, t_1, t_2, y_{am1}, y_{am2} \), it is able to produce different walking trajectories easily for different quantitative researches or simulations.

### 3.3 Joint motion angle calculation

The joint motion angle of walking can be calculated by the geometry of the lower limb. For example, the hip and knee joints of the right leg can be obtained by the following formulas:
\[
\begin{align*}
\theta_{nh} &= \arcsin \left( \frac{x_{n} - x_{nh}}{l} \right), \\
\theta_{rk} &= \theta_{nh} - \arcsin \left( \frac{x_{rk} - x_{nh}}{l} \right). 
\end{align*}
\] (4)

As shown in Fig. 6, the right hip and knee motion angles are given when parameters are set as follows: 
\( l_{t} = 0.44 \text{m}, \) 
\( l_{s} = 0.4 \text{m}, \) 
\( \theta_{rhs} = 20^\circ, \) 
\( \theta_{rks} = 10^\circ, \) 
\( T_{1} = 0.5 \text{s}, \) 
\( T_{2} = 1 \text{s}, \) 
\( t_{1} = 0.1 \text{s}, \) 
\( t_{2} = 0.5 \text{s}, \) 
\( y_{am1} = 0.05 \text{m}, \) 
\( y_{am2} = 0.1 \text{m}. \) There are three seconds in this walking plan, including a half-second stand, a half-second launch step and two one-second normal steps.

Fig. 6 The right hip and knee motion angles of the designed level walking plan. Positive values indicate flexion.

### 3.4 The feasibility of the proposed gait plan

The gait plan for NE-105 is totally generated by the kinematic design. However, when discussing the gait of walking, the stability of the model should be taken into consideration. In fact, most of the imbalance of walking is caused by the loss of stability in the sagittal plane. Therefore, the dynamic stability in the sagittal plane is the core problem in the study of the dynamic stability of the gait. Thus, a simplified 7-linkage planar model is introduced to verify the feasibility of the proposed gait plan as shown in Fig. 7(a), link 1 and 7 represent the feet, link 2 and 6 are the shanks, link 3 and 5 denote the thighs, and link 4 is the upper body.

The stability index of the gait is defined as the distance between the Center of Gravity (COG) and the Zero Moment Point (ZMP) in \( X \)-direction (the walking direction) (Kim et al, 2018) shown in Fig. 7(a). The COG projection onto the \( X \)-axis is shown in Eq. (5). The definition of ZMP in \( X \) direction is given by Eq. (6).

\[
X_{\text{COG}} = \frac{\sum_{i=1}^{n} m_{i} x_{i}}{\sum_{i=1}^{n} m_{i}}, 
\] (5)

\[
X_{\text{ZMP}} = \frac{\sum_{i=1}^{n} m_{i} (z_{i} + g) - \sum_{i=1}^{n} m_{i} \ddot{x}_{i} z_{i} - \sum_{i=1}^{n} l_{i} \dot{\theta}_{i}}{\sum_{i=1}^{n} m_{i} (z_{i} + g)}, 
\] (6)

where, \( m_{i} \) is the mass of the body segment; \( x_{i}, z_{i} \) are the positions of the center of mass in each body segment. \( I_{y} \) (decided by mass and length of the segment) is the inertia moment about the \( Y \) axis (the lateral direction) depicted in Fig.7(a); \( \ddot{\theta}_{i} \) is the angular acceleration (\( \dot{\theta}_{i} \) is the movement angle of the \( i \)th link shown in Fig.7(a)). Thus, the stability index would be calculated by Eq. (7):
\[ X_{\text{sta}} = X_{\text{COG}} - X_{\text{ZMP}}. \]  

(7)

When the gait plan is defined as previously mentioned, it is easy to known that \( \dot{\theta}_1 = \dot{\theta}_2 = \dot{\theta}_3 = 0 \text{rad/s}^2 \), \( \theta_1 \), \( \theta_2 \), \( \theta_3 \) and \( \theta_4 \) can be calculated by the hip and knee movement angles of the plan; and if the mass of the segments are given as \( m_1 = m_4 = 0.5 \text{kg}, m_2 = m_5 = 0.4 \text{kg}, m_3 = m_6 = 0.5 \text{kg}, m_7 = 30 \text{kg} \) and the length are \( L_1 = L_7 = 0.24 \text{m}, L_2 = L_6 = 0.4 \text{m}, L_3 = L_5 = 0.44 \text{m}, L_4 = 0.6 \text{m} \). Then the stability index would be worked out as shown in Fig. 7(b). At the first step, because of the sudden start of the motion, the stability index changes rapidly at the zero line. However, when it comes to the normal gait, the \( X_{\text{sta}} \) returns back near the zero line, and after 1s, it stays close to 0 and the value is smaller than the foot length of an ordinary human. Thus, the simplified 7-linkage model is able to keep stable during the gait cycle. So, the designed gait plan is feasible for the dynamic simulation of NE-105.

4. The dynamic simulations specification of NE-105

The dynamic simulation of the simplified NE-105 model was established shown in Fig. 8, where the walking direction is \( X \), the upward direction of the vertical ground is \( Z \), and \( Y \) is determined by the right-hand rule. The gravity direction \( g \) is the opposite side of \( Z \). And in the simulations, the knee movement is actuated by the aforementioned gait plan instead of the actuator described in Part 2, thus, the actuators are ignored to simplify the models.

4.1 Theory model establishment of flexible ring

At the beginning of simulation, the computational model of flexible rings in NE-105 needs to be obtained. In this case, the material of the flexible rings is PA66, and the physical property is calculated by the data from Jin et al. (2016) within a linear interval: elasticity modulus \( E=1000 \text{MPa} \), poisson ratio \( \mu=0.28 \), density \( \rho=1.14 \text{g/cm}^3 \). Thus, the
The deformation of the flexible would be smaller compared to its size, and it can be regarded as assembly of nodes of FEM and the deformation can be regarded as linear superposition of mode of vibration (Luo et al., 2013).

In the rigid-flexible models, the position \( X = (x, y, z) \), orientation \( \Psi = (\psi, \theta, \phi) \) and modal \( q = (q_1, q_2, \ldots, q_n)^T \) (\( n \) is the number of modal coordinates) of the point on the flexible ring are taken into consideration, and the generalized coordinates can be expressed as:

\[
\xi = [x, y, z, \psi, \theta, \phi, q_i(i = 1, \cdots, n)]^T = [X \ \Psi \ q]^T.
\]  

Thus, for any point \( P \) on the flexible body, its position vector can be signified as:

\[
r_p = r_o + A(s_p + \Phi P q_f),
\]  

where, \( r_p \) is the vector of point \( P \) in the inertial coordinate (IC); \( r_o \) is the vector of the origin of the floating coordinate (FC) in the inertial coordinate; \( A \) is the orientation cosine matrix from FC to IC; \( s_p \) is the position of point \( P \) in FC before the deformation; \( \Phi P \) is the modal matrix of point \( P \); \( q_f \) is the generalized coordinates of deformation.

The generalized velocity of \( P \) can be obtained:

\[
v_f = \dot{r}_p = [I - A(s_p + \Phi P q_f)]B \ A \Phi P \xi^\dot{},
\]  

where \( I \) is the identity matrix, and matrix \( B \) is defined as a transformation matrix during solving the derivative of Euler angle.

Sequentially, the kinetic energy of the flexible ring is:

\[
T = \frac{1}{2} \int_v \rho v^T v dV = \frac{1}{2} \xi^T M \xi^\dot{},
\]  

where \( M \) is the mass matrix of the flexible.

And the gravitational potential energy and elastic potential energy form the potential energy of the flexible which can be expressed as:

\[
W = W_g(\xi) + \frac{1}{2} \xi^T K \xi = \int_\mu \rho r_p \cdot \mathbf{g} dW + \frac{1}{2} \xi^T K \xi^\dot{},
\]  

where \( K \) is modal stiffness matrix, and \( g \) is the gravitational acceleration equal to 9.8m/s².

Moreover, the energy loss caused by damping is:

\[
\Gamma = \frac{1}{2} \dot{q}^T D \dot{q},
\]  

where \( D \) is modal damping matrix.

As known well, the dynamic equation of small deformation can be calculated by Lagrange Equation:

\[
\begin{aligned}
\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\xi}} \right) - \frac{\partial L}{\partial \xi} + \frac{\partial \Gamma}{\partial \xi} - \frac{\partial \Gamma}{\partial \dot{\xi}} \lambda - Q = 0, \\
\end{aligned}
\]  

where \( C \) represents the constraints; \( \lambda \) is Lagrange coefficient of constraint equation; \( Q \) is the generalized forces.
associated with the generalized coordinates of flexible ring; \( L \) is Lagrange term defined as \( L=T-W \).

Combining Eq. (8) - (13) into Eq. (14), the flexible equation of motion can be obtained:

\[
M\dddot{\xi} + M\dddot{\xi} - \frac{1}{2} \frac{\partial M}{\partial \dot{\xi}} \dot{\xi} + K\dddot{\xi} + f_{\text{d}} + D\dddot{\xi} + \frac{\partial C}{\partial \dot{\xi}} \dot{\xi} = Q ,
\]

(15)

where \( f_{\text{d}} \) is generalized gravity.

### 4.2 Constraints of the models

The simplified model consists of back frame, waist, thighs, shanks, feet and the parts inside the knees shown in Fig. 8. The constraints and motivation of the model are set as followed:

1. the back frame is only able to move in \( X, Y, Z \) direction with a variable load (0kg, 30kg);
2. the waist is fixed on the bottom of the back frame;
3. two thighs are linked to the waist with rotation constraints to form the hips;
4. the flexible rings in knees are fixed at the terminal of the thighs, and they are connected with the shanks by revolute joints;
5. the feet and the shanks are linked by rotating pairs, and the feet are parallel to the ground with the contact force settings;
6. the hip and knee joints movements are driven by the gait plan designed above.

Before the dynamic simulations, the finite element model of the flexible ring and its modes are needed. Replacing the components in rigid multi-body system with flexible ones, RFCMs of the exoskeleton with hybrid knees occur. The total mass of simplified NE-105 is 7.787kg without loads, and the detailed segments’ mass and principal moments of inertia are given in Table 4. The procedure changing from RFCMs to PRSMs is only to transform the flexible rings into rigid ones, and it is quite convenient to switch back and forth between the RFCMs and PRSMs. There are four kinds of situations for the simulations: the PRSM with 0kg load (PRSM0), the RFCM with 0kg load (RFCM0), the PRSM with 30kg load (PRSM30), the RFCM with 30kg load (RFCM30).

| Part name               | Mass (kg) | \( I_1 \) (kg\( \cdot \)mm\(^2\)) | \( I_2 \) (kg\( \cdot \)mm\(^2\)) | \( I_3 \) (kg\( \cdot \)mm\(^2\)) |
|-------------------------|-----------|-----------------------------------|-----------------------------------|-----------------------------------|
| Back frame and waist    | 2.041     | 7.779\times10^4                   | 5.513\times10^4                   | 3.123\times10^4                   |
| Thigh                   | 0.521 6   | 1.078\times10^4                   | 1.076\times10^4                   | 90.60                             |
| Shank                   | 0.425 9   | 6.190\times10^4                   | 6.188\times10^4                   | 59.36                             |
| Foot                    | 1.911     | 1.301\times10^4                   | 1.155\times10^4                   | 2.216\times10^3                   |
| Flexible ring           | 7.500\times10^{-3} | 2.061                           | 1.046                             | 1.046                             |
| Load                    | 30.00     | 5.563\times10^3                   | 4.563\times10^3                   | 2.125\times10^3                   |

The simulations were run using the GSTIFF (Gear Stiff) implicit predictor-corrector integrator, and with the aim of increasing the stability and robustness of the solver, the SI2 (Stabilized Index 2) formulation was used. Usually, the SI2 allows to avoid the very short-duration numerical spikes for velocities and accelerations (D’Imperio et al., 2017).

### 4.3 The static simulation validation of the rigid-flexible coupling knee joint

Before the dynamic simulations, a static compression test of the real rigid-flexible coupling joint was carried out. In the experiment shown in Fig. 9(a), the red part was made of PA66, and the rest parts of the joint were made of 7A04 aluminum alloy, and the force on the joint was applied by the tensile and compression testing machine (TCTM), and the displacement of point P in the red area was captured and calculated with the DIC devices (Chu et al., 1985). While in the simulation shown in Fig. 9(b), the blue and yellow parts are rigid, and the red part is a flexible model obtained from the finite element method, the bottom of the joint is fixed and the top of the joint is applied by the \( F \) force. The load of the experiment and simulation were the same depicted in Fig. 9(c).
Fig. 9 The experiment and simulation illustration diagram of the rigid-flexible coupling joint. Part (a) is a description of the experiment consists of TCMT, joint and DIC devices; part (b) is a description of the simulation model of the knee; part (c) is the force applied to the real joint and the simulate model.

In Figure 10, the displacement of point P is shown, and the offset is linearly related to the load. The error between the simulation and experiment is very small and can be ignored, and the deformation of the flexible PA66 part is similar to the real one. Thus, the model of the joint is close to the real situation and the rigid-coupling method is reasonable for the RFCMs.

Fig. 10 The displacement of P in the experiment and simulation and their error. The green line is the result of simulation; the blue line is the result from experiment; the red line is the error between simulation and experiment. Compared to the displacement, the error is 10 times smaller, so it is negligible that the validity of simulation is proved.

5. Results and discussions

The gait states of the PRSMs and RFCMs are the same macroscopically during the walking process. The gait is a typical periodic motion, and its cyclic stage is more important than the start of gait for exoskeleton. Therefore, the discussions are mainly focused on the gait cycle period, and the right leg and the left are symmetric during this time, so the following results are just analyzed to the right leg.

5.1 The displacement of knee joint center in Z direction

Through the simulations, the translational displacement of knee joint center is obtained shown in Fig. 11(a). The center points of the knee trajectories in different models have a same curve trend in general. On the one hand, due to the parameters of the contact force on the feet with the ground, there is a deviation between different loads, and especially in the process of single leg support phase, the deviation is about 1 mm. On the other hand, the errors between RFCMs and PRSMs with different loads are drawn in Fig. 11(b), and it can be seen that the central position track errors are increased with the increase of loads owing to the deformation of the flexible rings in the knees.
5.2 Vertical ground reaction force

The percentage of the vertical ground reaction force against the gravity ($V_{GRF}/G$) of the model is shown in Fig. 12, and the variation of RFCMs and PRSMs are similar in general. At the time of standing still, it is 50% of the gravity; during the swing phase, it is 0; when it hits the ground, the force is larger than the gravity, and at the middle of the single support phrase, it is smaller than the gravity; when the foot is going to leave the ground, the force is increasing. Totally, the $V_{GRF}$ trend of RFCMs and PRSMs shows two peaks with an interjacent trough, and it is similar to human’s in normal walking (Nilsson and Thorstensson, 1989). However, there is a difference between PRSMs and RFCMs when the right foot is going to contact the ground. Compared to the PRSMs, the $V_{GRF}/G$ is smaller at about 1s and 3s, and when the load increases, the differences are growing shown in Fig. 12(b). Therefore, the flexible parts in the knees are beneficial to decrease the amplitude of the impact force when the feet hit the ground. However, none load situation turns out to be fluctuant at the single leg support phase (about 1.3~1.9s) depicted in Fig. 12(a).

5.3 Joint driving torque of the knee

The driving torque of the knee is shown in Fig. 13. Because of the constraints of the back frame, the line of gravity force applied to the knee gets through the center of the joint, and thus the torque is 0 at the beginning. When the right leg starts to move, the knee driving torque increases to flex the joint. It is easy to find that the torque when leg staying at support phase is greater than that at the swinging moment. And it also shows that the impact of NE-105 to the ground will cause great jitter and the driving torque changes rapidly. Fig. 13(a) illustrates that the driving torque of RFCM0 is oscillating, and the vibration amplitude of the first and second step is larger than the third step. In Fig. 13(b), as the load...
increasing, the vibration of RFCM decreases; and at about 1s, the driving torque change of PRSM30 is nearly 80N·m while that of RFCM30 is about 48N·m; what’s more, the change of PRSM30 is close to 75N·m and 15N·m larger than the change of RFCM30 at about 2s. That is, when the leg changes from swing phase to support phase or the opposite, the change of driving torque of RFCM30 reduces compared to the PRSM30. So, the RFCM has lower demand for the driving system when the NE-105 is utilized for heavy load carrying.

Fig. 13 The knee driving torque in PRSMs and RFCMs. Part (a) is the driving torque when the load is 0; part (b) is the driving torque when NE-105 is carrying a weight of 30kg.

6. Conclusions

The methods of walking plan and dynamic rigid-flexible coupling simulations for the designed exoskeleton NE-105 are presented. Through the study above, the following conclusions are drawn.

1) Through the aforesaid gait planning and simulation analysis, the results of \( V_{GRF}/G \) showed that the simulations are similar to human gait, and that’s to say, the walking plan design method is reasonable and correct to some extent for the imitation of human gait in sagittal plane.

2) The PA66 flexibility exerts positive an influence on the exoskeleton dynamic behavior in relation to the ideal case of rigid model. Because of the elasticity, the external force applied to the mechanical system of NE-105 can be reduced when it hits the ground. The flexible parts are good for exoskeleton to deal with the impact of the external environment.

3) The joint driving torque for load carrying calls for lower demand of the actuators shown in the RFCM30, while heavy load also leads to lower kinematic accuracy of the system and increases the complexity of control algorithm.

In the future, the prototype of NE-105 will be constructed and used in experiments to verify the dynamic simulations, and different flexible materials will also be studied through the experiments to select a better material for the improvement of NE-105’s performance.

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References

Asbeck, A. T., Schmidt, K., Galiana, I., Wagner, D., and Walsh, C. J., Multi-joint soft exosuit for gait assistance, Proceedings of the 2015 IEEE International Conference on Robotics and Automation (2015), pp.6197-6204.

Chu, T. C., Ranson, W. F. and Sutton, M. A., Applications of digital-image-correlation techniques to experimental mechanics, Experimental mechanics, Vol.25, No.3 (1985), pp.232-244.

D’Imperio, M., Pizzamiglio, C., Ludovico D., Caldwell, D. G., Genta, G. and Cannella, F., Advanced Modelling Techniques for Flexible Robotic Systems, International Conference on Robotics in Alpe-Adria Danube Region
Deng, J., Wang, P. F., Li, M. T., Guo, W., Zha, F. S. and Wang, X., Structure design of active power-assist lower limb exoskeleton APAL robot, Advances in Mechanical Engineering, Vol.9, No.11 (2017), pp.1–11.

Ghan, J. and Kazerooni, H., System identification for the Berkeley lower extremity exoskeleton (BLEEX), Proceedings of the 2006 IEEE International Conference on Robotics and Automation (2006), pp.3477-3484.

He, Y., Eguren, D., Luu T. P. and Contreras-Vidal, J. L., Risk management and regulations for lower limb medical exoskeletons: a review, Medical devices (Auckland, NZ), Vol.10 (2017), pp.89-107.

Huang, P., Zhong, H. M., Chen, B., Qi, J., Qian, N. D. and Deng, L. F., Three-dimensional gait analysis in normal young adults: temporal, kinematic and mechanical parameters, Journal of Clinical Rehabilitative Tissue Engineering Research, Vol.24 (2015), pp.3882-3888 (in Chinese).

Jin, T., Zhou, Z., Shu, X., Wang, Z., Wu, G. and Zhao, L., Experimental investigation on the yield loci of PA66, Polymer Testing, Vol.51 (2016), pp.148-150.

Kim S., Hirota, K., Nozaki, T. and Murakami, T., Human motion analysis and its application to walking stabilization with COG and ZMP, IEEE Transactions on Industrial Informatics, Vol.14, No.11 (2018), pp.5178-5186.

Kim, H., Shin, Y. J. and Kim, J., Design and locomotion control of a hydraulic lower extremity exoskeleton for mobility augmentation, Mechatronics, Vol.46 (2017), pp.32-45.

Luo, H. T., Chen, Z. C., Leng, Y. Q. and Wang, H. G., Rigid-Flexible Coupling Dynamics Simulation of 3-RPS Parallel Robot Based on ADAMS and ANSYS, Applied Mechanics and Materials, Vol.290 (2013), pp.91-96.

Nilsson, J. and Thorstensson, A., Ground reaction forces at different speeds of human walking and running, Acta Physiologica Scandinavica, Vol.136, No.2 (1989), pp.217-227.

Poole, C. A., Articular cartilage chondrons: form, function and failure, The Journal of Anatomy, Vol.191, No.1 (1997), pp.1-13.

Singh, R., Chaudhary, H. and Singh, A. K., Sagittal Position Analysis of Gait Cycle for a Five Link Biped Robot, Robotics and Factories of the Future (2016), pp.387-396.

Song, Q. Z., Wang, X. G., Wang, X., and Wang, Y., Development of multi-joint exoskeleton-assisted robot and its key technology analysis: an overview, Acta Armamentarii, Vol.37, No.1 (2016), pp.172-185 (in Chinese).

Zoss, A., Kazerooni, H. and Chu, A., On the mechanical design of the Berkeley Lower Extremity Exoskeleton (BLEEX), IEEE/RSJ International Conference on Intelligent Robots and Systems (2005), pp.3465-3472.