The bionic design, virtual prototype modelling and motion simulation of biped robot with heterogeneous legs

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Abstract

The research of humanoid robot and intelligent prosthesis is integrated and a new-style humanoid robot named biped robot with heterogeneous legs (BRHL) is proposed to provide an ideal test-bed for intelligent bionic leg (IBL). The research background and concept of BRHL are introduced. The existed problems of common humanoid robot leg are analysed in detail. Based on bionics, the joint structure and driving scheme of artificial leg with pneumatic muscle actuator and bionic leg with magneto-rheological damper are designed. Using Pro/E, the virtual prototypes of artificial leg, bionic leg and BRHL are established. The bionic characteristics of artificial leg and bionic leg are analysed and the motion simulation of BRHL using ADAMS is done. The simulation indicates that BRHL can simulate amputees with IBL well and is an ideal test-bed for IBL.

Keywords: biped robot with heterogeneous legs, intelligent bionic leg, artificial leg, pneumatic muscle actuator, motion simulation

1 Introduction

In the process of human social development, it has led to a lot of people of physical disabilities as a result of natural disasters, accidental injury, traffic accident and war, and many other factors. The 2nd national sampling investigation of the disabled indicates that it has at least 24120 thousand people with physical disabilities in china and the lower limb amputees are about 440 thousands [1]. In the US, around 1.6 million people live with limb loss. About 97% of all vascular limb loss is lower-limb amputations, of which 25.8% are above-knee amputations [2]. The main research challenges in the design of trans-femoral prostheses are the efficiency with respect to the metabolic/external energy consumption and the adaptability to various walking conditions [3].

Intelligent bionic legs (IBL) controlled by a micro processing unit (MPU) is an advanced intelligent prosthesis (IP) [4, 5]. Thanks to precise MPU control, amputees with IP can change their gaits according to their needs. The prosthesis gait of amputees used in everyday life could include running, walking on slope, riding a bicycle, etc. To guarantee the IBL control performance, repetitive walking test of amputees with IBL is necessary. However, IBL test will exhaust the amputees. It is not only costly but also painful to human subjects. It may even lead to accidental harm to amputees.

Currently, a leg simulator is generally used in IBL tests, as shown in Figure 1. This leg simulator can produce human hip motion and drive IBL to test swing and stance performance. But it cannot be used to test the walking stability, dual-leg coordination and IBL's gait tracking to the healthy leg of amputees.

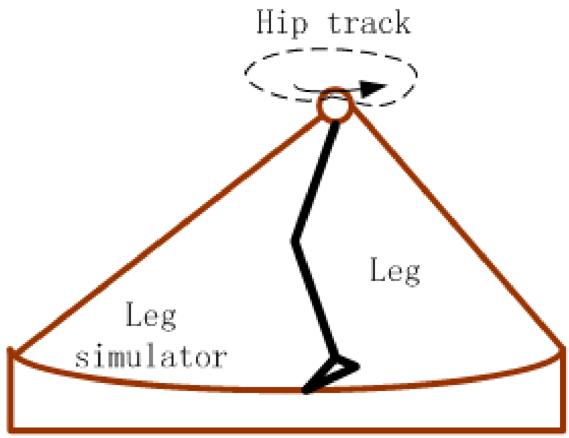

FIGURE 1 Sample leg simulator

The study of humanoid robot can help human understand own walking mechanism and use these characteristics for serving itself. At present, some devices, such as endoskeleton and exoskeleton prosthesis, have adopted certain technology of the humanoid robots:
1) The dynamic walking study of humanoid robots can help us design reasonable prosthesis mechanism which would make leg disabled people liberate from wheelchair or help hand disabled people restore life self-care ability.
2) The limbs coordinated motion study of humanoid robots can help us develop the exoskeleton prosthesis which would increase the strength and speed of human. For example, the BLEEX robot leg belongs to

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exoskeleton prosthesis and has important military significance.

The ultimate research goal of humanoid robots is to achieve a full range of anthropomorphism. In order to provide an idea test-bed for IBL, the research of humanoid robot and intelligent prosthesis is integrated and a new-style humanoid robot named biped robot with heterogeneous legs (BRHL) is proposed by the robotics group at Northeastern University, China [6]. A BRHL model is shown in Figure 2.

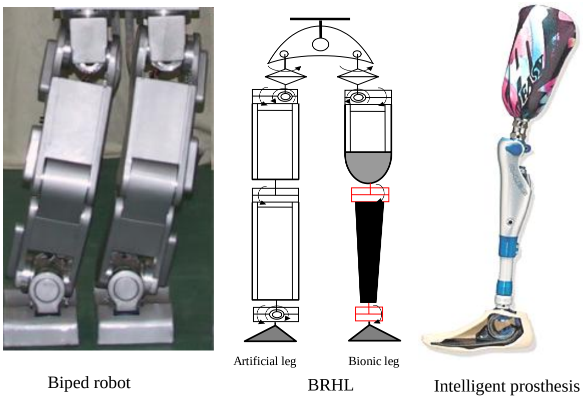


FIGURE 2 A BRHL model

BRHL is composed of two legs. One is artificial leg (AL) and the other is above-knee bionic leg (BL). AL has 6 degrees of freedom (3 DOF hip, 1 DOF knee and 2 DOF ankle). BL includes an artificial leg hip joint, intelligent bionic leg and flexible prosthetic foot. The artificial leg is corresponding to amputee's healthy leg and bionic leg corresponding to intelligent prosthesis used by amputees. So BRHL can simulate amputees' walking with IBL well and is an ideal test-bed for intelligent prosthesis. Since BRHL mainly orients area of rehabilitation medicine, its design focuses on personification. In the paper, the bionic design, virtual prototype modeling and motion simulation of a simplified BRHL which can walk forward are done.

2 Bionic analysis of common humanoid robot leg

The bionic design of knee joint is the key problem of BRHL development. Its design mainly refers the structure of common humanoid robot leg. Though the humanoid robots have been further studied and human basic movements, such as stable walking, up and down stairs, turn and dance movements have been realized, many problems still exists in the developed of humanoid robots:

1) Its walking gait is unnatural and has a larger difference from that of human leg.

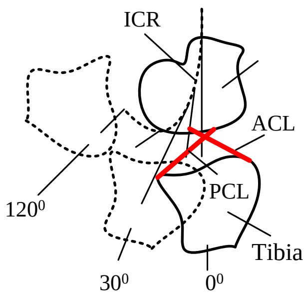
2) Limited to own mechanism structure, the impact between feet and ground is large and walking speed is slow.

3) The energy consumption and rigidity of drive are larger and go against the realization of joint flexible movement.

The bones of human leg are the result of natural selection and evolution for a long time and are most suitable for human walking. At present, knee joints of humanoid robot most adopt uniaxial axis mechanism and motor drive which have essential difference with joint structure, motion mechanism and driving mode of human leg. It results in the difference of leg gait between human and humanoid robot. The main differences can be summarized in the following three aspects.

2.1 KNEE JOINT STRUCTURE

The human knee joint is mainly composed of the femur, tibia and patella. The contact surface between femoral bottom and tibial top is irregular. During flexion and extension activity, the knee joint is driven by expansion motion of medial and lateral muscles. There are both rolling and sliding between the two contact surfaces. The outstanding feature of knee joint is that its instantaneous centre of rotation (ICR) is not fixed and similar a "J" curve, as shown in Figure 3 [7]. Thus the leg has alterable thigh and calf length and high obstacle negotiation performance. At the same time, the change of knee joint ICR and leg length can adjust the torque applied by the ground reaction force on joint and reduce the needed muscle extension force of hip joint, which can improve the walking stability and efficiency of the legs.



a.Knee of human leg

FIGURE 3 ICR of human knee joint

Now most joints of the humanoid robot and artificial limb adopt uniaxial knee mechanism which is shown in Figure 3. Its ICR is fixed and has obvious difference from that of human knee joint. To maintain stability during support phase, the robot generally keep legs bend when stand and walks slowly which would cause walking gait is unnatural.

2.2 MECHANISM RIGID-FLEXIBLE CHARACTERISTIC

The human leg is a flexible system as an organic whole. Depending on foot arch and ligaments adhered, human leg can generate flexibility, reduce impact and collision between feet and ground when walking, protect joints and increase ability of bearing human weigh and pressure. The flexibility of human feet can store energy and contribute to realize running and jumping. The knee joint of human has ligaments and meniscus mechanism, which can play a buffer action and protect joints from injuries in the process of human movement, as shown in Figure 4.

In contrast, the most legs of common humanoid robot are connected by rigid bars and its joints are driven by motors. Thus common humanoid robot would has large rigidity and poor flexibility which easy to cause unstable walking especially under uneven road. To solve above problems, the feet of common humanoid robot are usually designed as rectangular plates to increase contact area with ground. At the same time, the speed when foot contacts ground is limited and buffer devices are installed to reduce impact and collision between foot and ground when walking. Although above methods can reduce the impact and collision to insure robot walking steadily, but cause its gait unnatural.

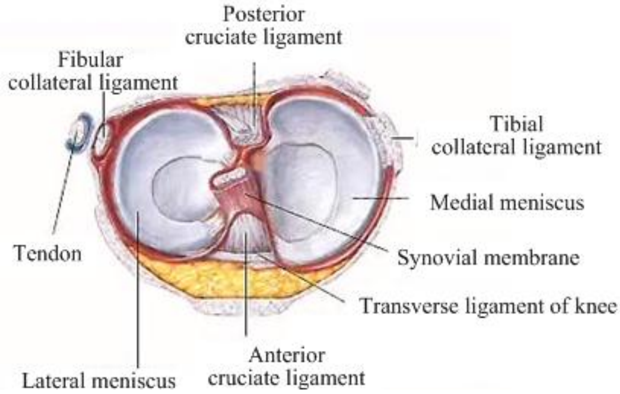


FIGURE 4 Ligaments and meniscus mechanism of human knee joint

2.3 JOINT ACTUATOR

When human walks in normal gait, muscles connected with ligaments on both sides of joints would accept neural signal and its expansion motion would drive joints to rotate and slide. The muscles and ligaments with good flexibility can effectively buffer impact and collision of ground and the walking is steady. Currently, most joints of legs are driven by electric or hydraulic actuator, etc. The actuator of common humanoid robot has obvious difference with that of human. Humanoid robot joints can be distinguished as three categories, including active, semi-active and passive, by the types of actuators that were used in the according mechanism.

1) Active joint: Joint is always driven by electromotor, pneumatic or hydraulic device and can swing optionally if actuator is allowable. Its energy consuming is much larger.

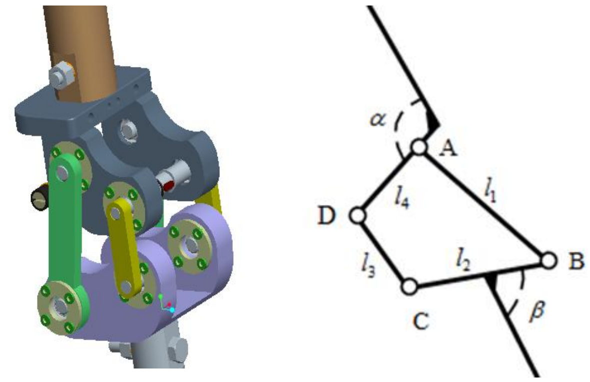
2) Passive joint: Joint without actuator basically consumes no energy and has ability of storing some energy by mechanism design. It can walks only depending on its gravity. Its walking gait is natural, but road condition is limited.

3) Semi-active joint: Joint is always driven by intelligent damper, such as electro-rheological or magneto-rheological damper, etc. It can provide large damping force, but active force is less.

3 Bionic design and modelling of artificial leg

3.1 MECHANISM DESIGN OF KNEE JOINT

Currently, there are some kinds of knee joint configurations, mainly including uniaxial and multiaxial knee joint. Since artificial leg simulates human healthy leg to generate natural gait for intelligent bionic leg, its design emphasizes particularly on humanoid performance. To achieve that, 4-bar multiaxial knee mechanism which is shown in Figure 5 is adopted. In order to ensure that the artificial leg can keep balance in support phase, limit stop is added to avoid the shank excessive extension. All joints adopt bearing support and each rod is connected by shaft bossing. At the same time, in order to guarantee walking stability, 4-bar mechanism with both sides is adopted. The parameter values of 4-bar knee mechanism obtained by mechanism optimization are shown in Table 1 [8].



a) b)
FIGURE 5 4-bar multiaxial knee joint: a) Virtual prototype, b) Schematic diagram

TABLE 1 Values of 4-bar knee parameters

l_1	l_2	l_3	l_4	α	β
0.089m	0.079m	0.04m	0.059m	2.49rad	1.57rad

The calculation formula of ICR coordinates can be written as:

$$\begin{cases} x_{ICR} = \dfrac{y_C - y_B + ax_B - bx_C}{a-b} \\ y_{P_{ICR}} = \dfrac{x_C - x_B + a^{-1}y_C - b^{-1}y_B}{a^{-1} - b^{-1}} \end{cases}, \quad (1)$$

$$a = \frac{y_A - y_B}{x_A - x_B}, b = \frac{y_C - y_D}{x_C - x_D}.$$

The ICR of 4-bar multiaxial knee joint is calculated, as shown in Figure 6.

Compared with uniaxial knee mechanism used by common humanoid robot, it has many advantages as follows:

1) ICR of 4-bar multiaxial knee joint is not fixed and similar to "J" curve. It can effectively simulate normal movement of human knee joint.

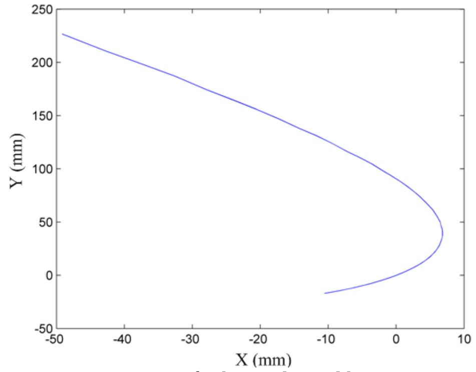


FIGURE 6 ICR of 4-bar multiaxial knee joint.

2) During swing phase, it can effectively reduce the length of thigh and shank under the same swing angle which is shown in Figure 7. Thus it has good obstacle-surmounting performance.

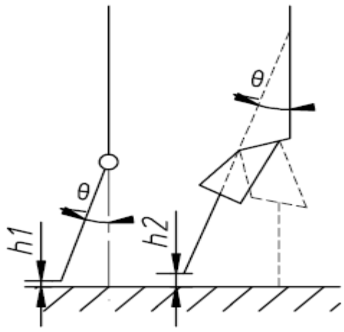


FIGURE 7 Contrast of obstacle-surmounting performance for uniaxial and multiaxial knee joint.

3) During mid-swing phase or sitting down, its ICR would down to the normal position and effectively improve sitting posture.

4) It can effectively improve the stability of support phase which is shown in Figure 8.

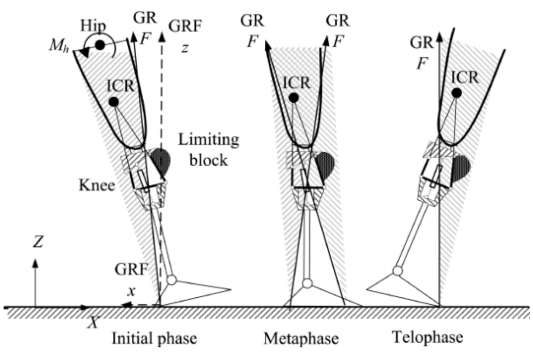


FIGURE 8 Stability of 4-bar multiaxial knee joint during support phase

3.2 DRIVING SCHEME DESIGN OF KNEE JOINT

The human knee joint is driven by antagonistic muscles which not only can provide driving force for precise position control, but also have good flexibility to absorb vibration and buffer impact. Pneumatic muscle actuator (PMA) has advantages of light weight, simple structure, large output force, good flexibility and similar force-length characteristics to human muscle, etc. In the paper, PMA is selected as actuator of knee joint.

The knee joint with 4-bar mechanism has four drive shafts. The control torque analysis of each drive shaft is shown in Figure 9. The needed control torque of shaft A is minimum and shaft D takes second place. From the view of energy saving, shaft A or D should be selected. Restricted by its own structure of 4-bar mechanism, the space of axis A is less and goes against to install sprocket drive system. Shaft D is selected as drive shaft which can not only meet the requirements of actual mechanical structure, but also can reduce energy consumption.

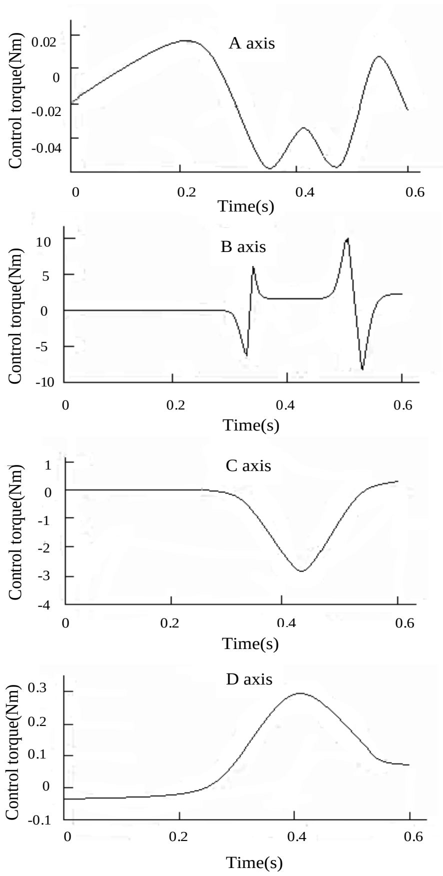


FIGURE 9 Control torque analysis of each drive shaft

Two sets of placement schemes for PMA are designed. The first scheme with single drive is shown in Figure 10, that is to say, through a shaft to drive the movement of knee joint with two sides. The second scheme with separating drive is shown in Figure 11, that is to say, two parallel 4-bar linkages are driven respectively with two drive shafts.

Compared with the first scheme, the second scheme require rotation angle of two axes synchronous and consistent. Thus its control system is complicated. The first scheme, which has simple structure and can simplify control is adopted.

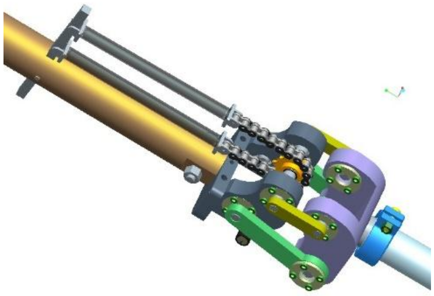


FIGURE 10 The first placement scheme of PMA

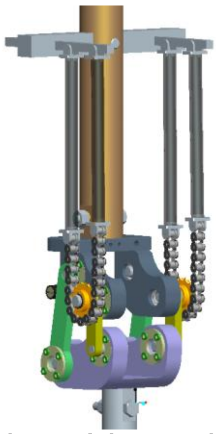


FIGURE 11 The second placement scheme of PMA

The shaft D is driven by a couple of pneumatic artificial muscles through sprocket installed and provides a driving force for 4-bar knee joint. Ends of the shaft are supported by bearings. The sprocket drive is adopted because it has advantages of high transmission accuracy, simple structure, strong bearing capacity, easy maintenance and long service life, etc. The sprocket is connected with drive shaft by key. In order to prevent axial movement of sprocket, sprocket is fixed by shaft shoulder and clasp on both sides separately.

3.3 MODEL SELECTION OF PNEUMATIC ARTIFICIAL MUSCLE

The model selection of pneumatic artificial muscle is mainly determined by two parameters: diameter and length. The working principle of knee joint driven by pneumatic artificial muscle is shown in Figure 12. The load which is connected with pneumatic artificial muscle by sprocket and chain can be considered as a uniform and thin rod with length l and quality m. The rotation angle of knee joint is described using θ and its initial value is zero. The initial length and diameter of pneumatic artificial muscle are described by L_0 and D_0.

According to moment balance, the following relationships can be obtained.

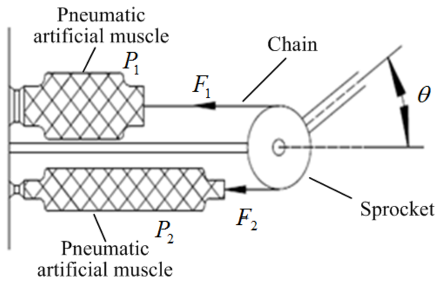


FIGURE 12 Working principle of knee joint driven by PMA

$$T = mg\frac{l}{2}\sin\theta, \tag{2}$$

$$T = (F_1 - F_2)\frac{D_0}{2}, \tag{3}$$

Then the tension difference can be derived by simultaneous Equations (2) and (3).

$$F_1 - F_2 = \frac{mgl}{D_0}\sin\theta, \tag{4}$$

With reference to the human body parameters [9], shank length is 0.48*m*, shank weight is 3.225*kg*, foot weight is 1.125*kg*, and flexion-extension angle range of knee joint is $0^\circ \sim 135^\circ$. The sprocket diameter is 0.368*m*. When θ is equal to 90°, the tension difference is maximum. Input above parameters values into Equation (4), the tension difference can be calculated as 685.6*N*.

In order to determine the length of pneumatic artificial muscle, the contraction length ΔL of pneumatic artificial muscle when human knee bends to the maximum angle should be calculated first. The ΔL can be calculated as follows:

$$\Delta L = \pi D_0 \frac{\theta}{360^\circ}, \tag{5}$$

Input $\theta = 135^\circ$ and $D_0 = 36.8mm$ into Equation (5), the ΔL can be calculated as 43.3mm. Since the maximum shrinkage rate of pneumatic artificial muscle produced by FESTO is about 25%, the needed length of pneumatic artificial muscle is about 200 mm.

The characteristic curve of FESTO-MAS-20-200N-AA-MC-O-ER-EG adopted in the paper is shown in Figure 13. In the picture, "1", "2", "3" and "4" denote maximum output force, maximum working pressure, maximum shrinkage rate and maximum preload respectively.

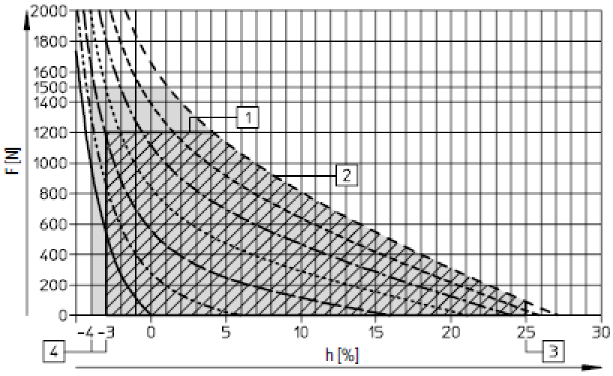


FIGURE 13 The characteristic curves of FESTO-MAS-20-200N-AA-MC-O-ER-EG

3.4 VIRTUAL PROTOTYPE OF ARTIFICIAL LEG

The virtual prototype of artificial leg established using software Pro/E is shown in Figure 14. The hip joint of artificial leg is driven by dc servo motor with harmonic gear reducer. Its advantage is that hip join has simple transmission mechanism and high transmission efficiency. The ankle joint of artificial leg is driven by dc servo motor with harmonic gear reducer and spur gear transmission. The horizontal structure of ankle joint is more compact and transmission accuracy is better.

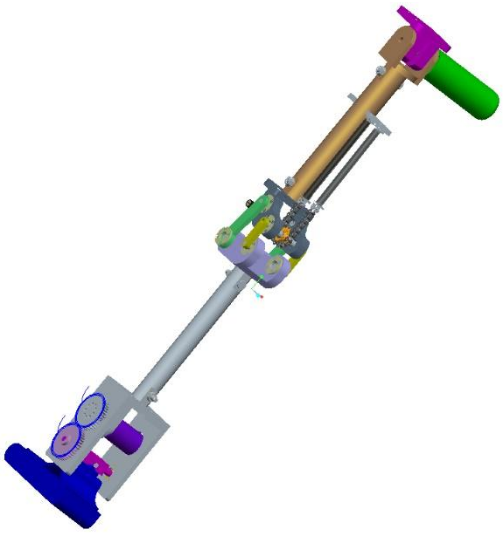


FIGURE 14 Virtual prototype of artificial leg

4 Bionic design and analysis of bionic leg

4.1 BIONIC DESIGN OF BIONIC LEG

The virtual prototype of bionic leg established using software Pro/E is shown in Figure 15. The knee joint of bionic leg is also adopts the same 4-bar multiaxial knee mechanism. Compared with artificial leg, the knee joint of bionic leg is semi-controlled by magneto-rheological damper to adjust rotation performance. MR damper has a series of advantage, such as simple structure, small volume, smart response, low energy demand and large resistance etc. Prosthetic foot is fixed to BL, so its ankle joint has no degree of freedom.

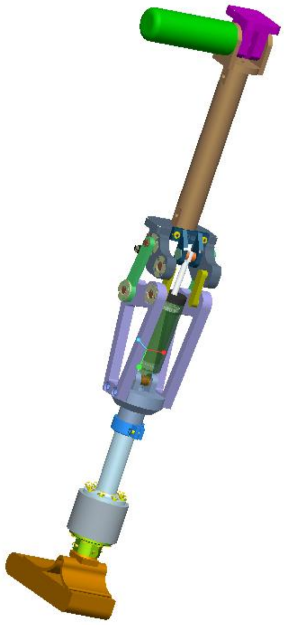


FIGURE 15 Virtual prototype of bionic leg

4.2 PERFORMANCE ANALYSIS OF BIONIC LEG

The parameters which describe stability of bionic leg are shown in Figure 16.

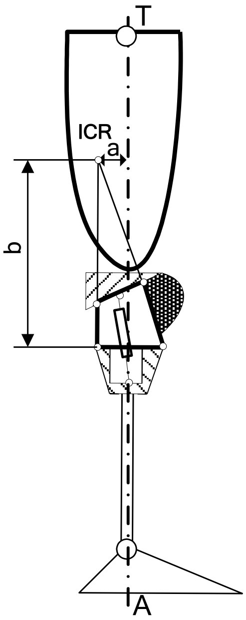


FIGURE 16 The stability parameters of bionic leg.

Here "a" denotes the distance between knee joint ICR and load line at full extension position. "b" denotes the distance between knee joint ICR and hinge point of down bar and shank along load line at full extension position. The static stability of bionic leg is described using γ which denotes bending angle of knee joint when "a" is equal to zero. It can be obtained from Figure 15,

$a = 35.28mm$, $b = 293.71mm$, $\gamma = 4.74^{\circ}$. The stance phase stability of 4-bar mechanism is very good.

The dynamic stability of bionic leg is determined by the relative position of knee joint ICR and load line. According to flexibility of swing phase, the prosthetic knee joint of four bar mechanism can be distinguished as three categories, including absolute stable, coordinated and flexible. Absolute stable 4-bar knee joint refers that its ICR always after load line, whether the heel touches or tiptoe leaves the ground. Thus the knee bend is difficult and gait is unnatural during transition from support phase to swing phase. But it has strong stability and is suitable for patients with weak muscle strength of residual limb. Coordinated 4-bar knee joint refers that its ICR locates stable coordination area and has higher position. It has relatively good stability and doesn't need big hip joint torque to ensure ICR in stable coordination area. So it is suitable for patients who need not only better stability, but also certain flexibility under weak muscle strength of residual limb. The ICR of flexible 4-bar knee joint is also locates stable coordination area. But it has less distance and higher position relatively. So its stability is less than that of coordinated 4-bar knee joint and needed hip joint torque is higher. But it has good flexibility and can easily realize knee bend during support telophase. It is suitable for patients with strong strength of residual limb and sport prosthesis.

For 4-bar knee joint designed in the paper, the relationship between ICR and load line from initial phase to telophase of support is shown in Figure 8. It can be seen that it belongs to flexible 4-bar knee joint.

5 Motion simulation of BRHL

The software of ADAMS integrates with the latest theory results of multi-body dynamics, a variety of convenient modelling tools, efficient solver, powerful post-processing modules and visual interfaces. It can automatically establish and solve equations of system model which is almost impossible to be achieved manually. So ADAMS can be used for system simulation of particularly complex robot system. In the paper, the virtual prototype of BRHL is established using Pro/E and imported into ADAMS. The virtual prototype of simplified BRHL is shown in Figure 17. The auxiliary vehicle is used to keep walking stability of BRHL.

Based on virtual prototypes above, the motion simulation of BRHL is done by adding joint angle curves which are previous planned. The continuously walking simulation of BRHL under flat environment is shown in Figure 18. The simulation indicates that BRHL can simulate amputees with intelligent prosthesis well and is an ideal test-bed for IBL.

FIGURE 17 Virtual prototype of simplified BRHL

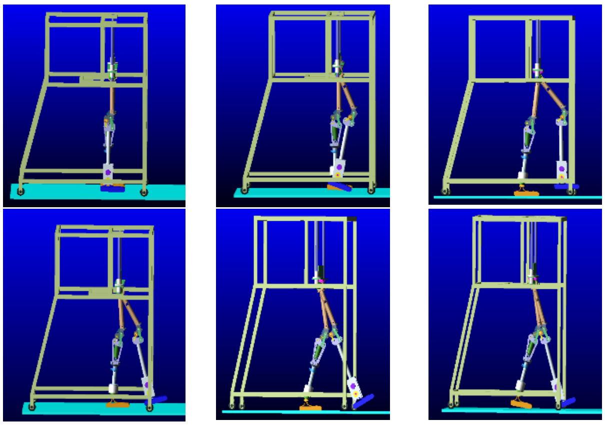


FIGURE 18 Continuously walking simulation of BRHL

6 Conclusions

The ICR of 4-bar multiaxial knee joint is similar to "J" curve and is consistent with that of human leg. The artificial leg driven by PMA can simulate the control mode of human knee joint by antagonistic muscles. IBL semi-controlled by magneto-rheological damper which consume less energy has good stability and flexibility. BRHL has good humanoid characteristics and is an ideal test-bed for IBL.

Acknowledgments

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