Knee Joint Optimization Design of Intelligent Bionic Leg Based on Genetic Algorithm

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Abstract: *Intelligent bionic leg (IBL) is an advanced prosthesis which can maximum functionally simulate and approach the motion trajectory of human leg. Knee joint is the most important bone of human leg and its bionic design has great significance to prosthesis performance. The structural components of IBL are introduced and virtual prototype is given. The advantages of 4-bar knee joint are analyzed and are adopted in IBL design. The kinematics model of 4-bar knee joint is established. The objective function, constraint condition, parameters selection and setting of genetic algorithm are discussed in detail. Based on genetic algorithm, the optimization design of IBL knee joint is done. The optimization results indicate that the 4-bar mechanism can achieve better anthropomorphic characteristics of human knee joint.*

Keywords: *Intelligent bionic leg, Knee joint, Optimization design, Genetic algorithm.*

Introduction

Intelligent bionic leg [6] controlled by a micro processing unit (MPU) is an advanced intelligent prosthesis [3]. Thanks to precise MPU control, amputees with intelligent prosthesis can change their gaits according to their needs. 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 [2]. 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 [9]. As a civilized society, we have responsibility to provide the necessary technical support for the life of these people. Intelligent bionic leg which is close to human healthy leg both in appearance and function could maximum functionally simulate and approach the motion trajectory of human leg.

The virtual prototype of IBL developed by robotics project group at Northeastern University, China, is shown in Fig. 1. Its structure includes hip joint, thigh, bionic knee joint, shank and flexible prosthetic foot. Prosthetic foot is fixed to calf and ankle joint has no degree of freedom. The bionic knee joint is semi-controlled by MR damper to adjust rotation performance. MR damper can provide biggish damper force and lesser resilience to insure

IBL track human natural gait well. Six-axis force sensor is used to detect the information of ground reaction force (GRF).

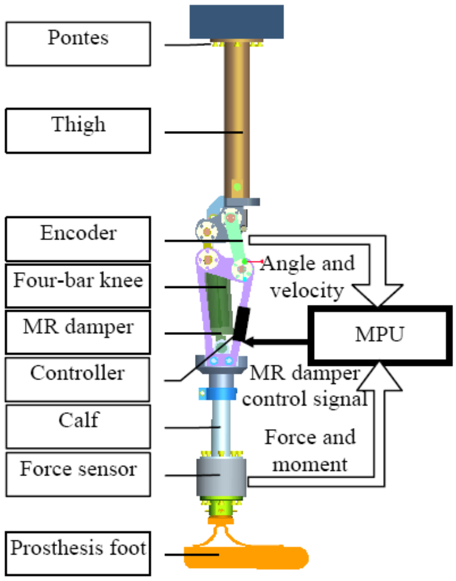


Fig. 1 Virtual prototype of IBL

Bionic design of IBL knee joint

The knee joint bears the largest weight and is the most complex joint of human body. Its main movement is flexion and extension. The structure of knee joint is directly related to the bionic characteristics and kinematic performance of IBL. The reasonable structure of knee joint can guarantee the stability in support phase and flexibility in swing phase. According to previous research of biomedicine [1], the human knee joint is composed of irregular shape of bones which are connected by ligament. The main bone structure of knee joint includes the femur, tibia and patella. Due to combined action of anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial ligament, lateral ligament, joint capsule and tendons, knee joint can move freely without dislocation. The contact surface between femoral bottom and tibial top is irregular. During flexion and extension activity of knee joint, 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 Fig. 2. Thus, the length of thigh and calf is variable and the distance between foot and ground is increased.

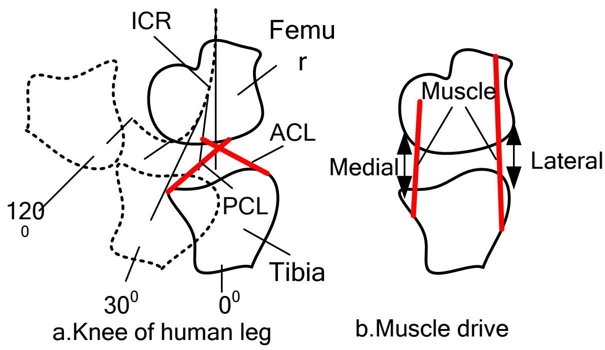


Fig. 2 Human knee joint

Now most of the humanoid robots and artificial limb joints adopt single axis knee mechanism and motor driver. Its rotation centre is fixed and has obvious difference from that of human knee joint. Bionic knee joint should adopt multiple axis knee mechanism (4-bar, 5-bar and 6-bar). The 4-bar bionic knee is adopted in the design of IBL because it has simple structure, low cost and excellent performance. Comparing with single axis knee mechanism, 4-bar closed-chain knee mechanism has many advantages such as "J" curve of ICR [7], higher foot clearance and good stability with GRF, as shown in Fig. 3. Virtual prototype of IBL knee joint is shown in Fig. 4.

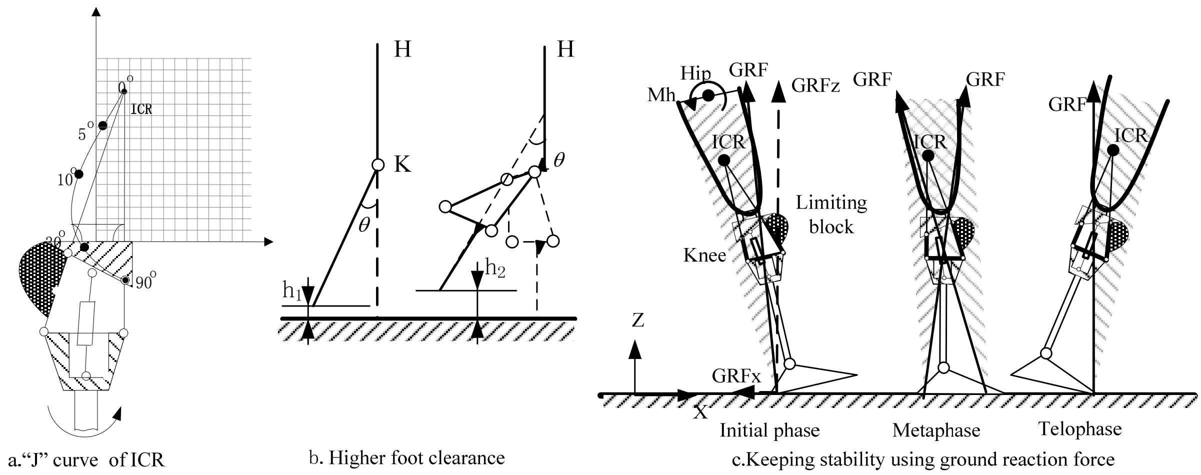


Fig. 3 Advantages of 4-bar knee joint

Fig. 4 Virtual prototype of IBL knee joint

Modeling of 4-bar knee joint

The schematic diagram of 4-bar closed-chain knee mechanism is shown in Fig. 5. K_2 is the origin of coordinates. l_i, $i = 1 \div 4$ is the length of ACL bar, down bar, PCL bar and upper bar respectively. θ_i, $i = 1 \div 4$ is the angle between l_i and horizontal line respectively. The thigh bar and calf bar are respectively fixed connection with upper bar and down bar. The extension node of ACL bar and PCL bar is ICR of 4-bar knee joint. In the modeling and analyzing process of the 4-bar knee joint, the down bar is fixed to study the relationship between ICR and other parameters of knee joint. The each point coordinates of 4-bar closed-chain knee mechanism can be written as:

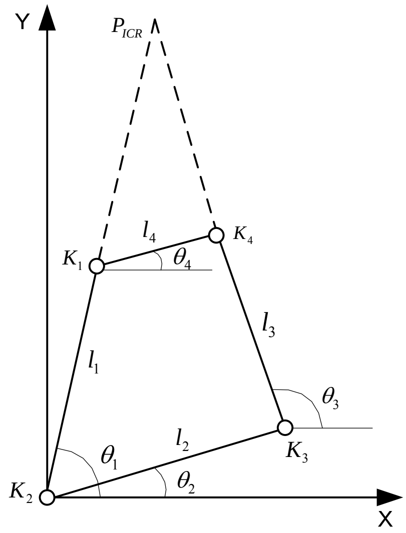


Fig. 5 Schematic diagram of 4-bar closed-chain knee mechanism

Coordinate of point K_1:

$$\begin{cases} x_{K_1} = l_1 \cos\theta_1 \\ y_{K_1} = l_1 \sin\theta_1 \end{cases}. \quad (1)$$

Coordinate of point K_3:

$$\begin{cases} x_{K_3} = l_2 \cos\theta_2 \\ y_{K_3} = l_2 \sin\theta_2 \end{cases}. \quad (2)$$

Coordinate of point K_4:

$$\begin{cases} x_{K_4} = l_1 \cos\theta_1 + l_4 \cos\theta_4 \\ y_{K_4} = l_1 \sin\theta_1 + l_4 \sin\theta_4 \end{cases}. \quad (3)$$

The calculation formula of θ_1 can be written as:

$$\theta_1 = \arctan\frac{y_{P_{ICR}}}{x_{P_{ICR}}}. \quad (4)$$

P_{ICR} is the intersection of $\overrightarrow{K_2K_1}$ and $\overrightarrow{K_3K_4}$. According to theory of slope equality, we can obtain:

$$\begin{cases} \dfrac{x_{K_1} - x_{K_2}}{y_{K_1} - y_{K_2}} = \dfrac{x_{P_{ICR}} - x_{K_1}}{y_{P_{ICR}} - y_{K_1}} \\ \dfrac{x_{K_4} - x_{K_3}}{y_{K_4} - y_{K_3}} = \dfrac{x_{P_{ICR}} - x_{K_4}}{y_{P_{ICR}} - y_{K_4}} \end{cases}. \quad (5)$$

The calculation formula of ICR coordinates can be written as:

$$\begin{cases} x_{P_{ICR}} = \dfrac{y_{K_2} - y_{K_3} + a x_{K_3} - b x_{K_2}}{a - b} \\ y_{P_{ICR}} = \dfrac{x_{K_2} - x_{K_3} + a^{-1} y_{K_3} - b^{-1} y_{K_2}}{a^{-1} - b^{-1}} \end{cases}, \tag{6}$$

where

$$a = \frac{y_{K_4} - y_{K_3}}{x_{K_4} - x_{K_3}}, \; b = \frac{y_{K_2} - y_{K_1}}{x_{K_2} - x_{K_1}}. \tag{7}$$

Knee joint optimization based on genetic algorithm

Genetic algorithm (GA) is one kind of stochastic method which simulates biological evolution process and is developed from biological evolution theory of natural selection. The optimization process based on GA mainly includes three basic operations: selection, crossover and mutation. The different operation method of these steps will lead to different optimization result. The operation process of GA is described in Fig. 6.

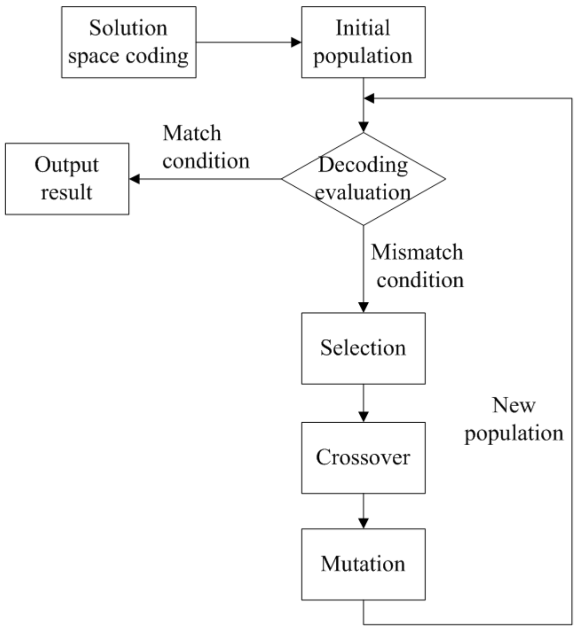


Fig. 6 Operation process of GA

Objective function

The degree of coordination between 4-bar knee mechanism and human body is better when the ICR trajectory similarity between 4-bar knee mechanism and human knee joint is higher. From this perspective, the square of coordinate difference between 4-bar mechanism ICR and human ideal ICR is selected as objective function. The ideal ICR coordinate values of human knee joint are shown in Table 1 [5].

Table 1. Ideal ICR coordinate values of human knee joint

Knee bending angle θ_i, [°]	$x_{p'}$, [mm]	$y_{p'}$, [mm]
0	2	133
10	5	133
20	7	132
30	9	132
40	11	131
50	12	130
60	14	129
70	16	127
80	18	124
90	21	118
100	26	107
110	31	87

In Table 1 θ_i is the bending angle of knee joint, namely relative rotation angle of thigh to calf. The angle range of knee joint movement is generally $0^\circ \sim 110^\circ$.

The objective function can be written as follows:

$$F(x) = \sum_{i=1}^{12} \left[(x_p^i - x_{p'}^i)^2 - (y_p^i - y_{p'}^i)^2 \right], \tag{8}$$

where $x_{p'}$ and $y_{p'}$ are ideal coordinate values of ICR, as shown in Table 1. Because $x_{p'}$ and $y_{p'}$ are known, the angle values of ACL bar can be obtained according to the Eq. 4, as shown in Table 2.

Table 2. Angle values of ACL bar

Knee bending angle θ_i, [°]	$x_{p'}$, [mm]	$y_{p'}$, [mm]	θ_1
0	2	133	89.138
10	5	133	87.847
20	7	132	86.960
30	9	132	86.099
40	11	131	85.200
50	12	130	84.725
60	14	129	83.806
70	16	127	82.820
80	18	124	81.740
90	21	118	79.908
100	26	107	76.341
110	31	87	70.385

Constraint condition

Kinematic constraint of linkage mechanism

The 4-bar mechanism of knee joint belongs double rocker mechanism and should meet the following requirements: i) The down bar is frame; ii) The length sum of the shortest and longest bar is less than that of the other two bars; iii) ACL bar is the longest and upper bar is shortest. As a result, the kinematic constraint conditions of 4-bar mechanism can be written as:

$$\begin{cases} l_1 > \max(l_2, l_3, l_4) \\ l_4 < \min(l_1, l_2, l_3) \\ l_1 + l_4 < l_2 + l_3 \end{cases}. \tag{9}$$

Bionic constraint

Before optimizing calculation, the size of 4-bar mechanism should be restricted to satisfy that the whole motion range of the mechanism would match the size of a real human knee joint, by limiting the length of the four bars within an appropriate scale. For example, the relative rotation angle of 4-bar knee mechanism in prosthesis socket should has normal and reasonable appearance. During stability phase, ICR of 4-bar knee mechanism should has higher position. Each bar and hinge point of knee mechanism must locate in activity range of healthy human lower limbs. According to published research of human knee joint structure [4, 8], size of the femur and tibia platform and its range of motion, the parameters of our 4-bar mechanism can be defined as follows:

$$\begin{cases} 40 < l_1 < 60 \\ 30 < l_2 < 55 \\ 35 < l_3 < 55 \\ 20 < l_4 < 40 \\ 0 < \theta_1 < 0.9 \end{cases}. \tag{10}$$

Dynamic appearance rationality condition

In order to make dynamic appearance of prosthesis knee match human normal knee, we should limit ICR position of knee joint, as follows:

$$x_{\text{icr}\min} \le x_{\text{icr}} \le x_{\text{icr}\max}, y_{\text{icr}\min} \le y_{\text{icr}} \le y_{\text{icr}\max}. \tag{11}$$

Constraint of 4-bar closed-chain mechanism

The constraint equation of 4-bar closed-chain knee mechanism can be written as:

$$\begin{cases} l_1 \cos\theta_1 - l_2 \cos\theta_2 - l_3 \cos\theta_3 + l_4 \cos\theta_4 = 0 \\ l_1 \sin\theta_1 - l_2 \sin\theta_2 - l_3 \sin\theta_3 + l_4 \sin\theta_4 = 0 \end{cases}. \tag{12}$$

Parameters selection and setting of genetic algorithm

Population scale setting

A larger population scale facilitates more searching points during the operation, without falling into local optimal solution too early. But, an oversized population also results in consuming more calculating time for each generation. The value of population scale in the paper is set 20.

Fitness calculation
Fitness is used to evaluate the superiority of the individuals. When the fitness is bigger, the individuals are better. The selection of individuals is according to the value of fitness to insure that the individual with bigger fitness has more chance to reproduce generation. The fitness value is related to the method of establishing objective functions. Generally, the individuals whose fitness values are higher than average fitness value are selected to implement crossover operation. The individuals whose fitness values are lower than average fitness value are selected to implement mutation operation. It can not only ensure excellent individuals are preserved, but also improve inferior individuals.

Selection operation
The purpose of selection is propagating the optimum individual directly to the next generation or through matching cross to produce new individual and then propagating to next generation. Select operation is established on the basis of fitness evaluation of individuals in the group. The uniform random function is selected in the optimization process.

Replication parameters setting
The genetic algorithm is based on controlling replication parameters to generate the next generation. These parameters are:

- *Elite count*: Elite count is the number of individuals with the best fitness value which should be copied to the next generation in the current population. The best fitness value decreases when the fine count is greater than 1. The fitness function is minimized due to the characteristics of genetic algorithm. Larger elite count makes the individuals with best fitness value controlling population, but it will reduce the effectiveness of search. The elite count is set as default value of 2.
- *Crossover fraction*: If the crossover probability equal to 1, it means all of offspring are crossover offspring; If the crossover probability equal to 0, it means all of offspring are variant offspring. The population size, elite count and crossover probability is 20, 2 and 0.8 respectively in this paper. It means that the next generation has 2 elite offspring and 18 individuals. The number of cross individuals can be calculated and rounded as 14: $0.8 \times 18 = 14.4$.

Mutation parameter setting
The genetic algorithm generates a new generation of individuals by changing the binary code of previous generation in a certain position according to certain regularity. In addition to generate excellent offspring, the algorithm must also reflect the randomness of variation. The selected mutation function is Gaussian function. The scale and shrink parameters are selected as 0.05 and 0.1 respectively.

Stopping criterion setting
It can change the final optimization results by increasing or decreasing the generations as well as the operation time. It always modifies and decides the stopping generation by means of observing the stability of fitness values. In this paper, the stopping generation and stall time limit are set as 1000 and 200s respectively on the basis of debug and observation. Other settings take default values.

Optimization results
The change curve of best fitness is shown in Fig. 7. It indicates that the best fitness value can be improved at a relatively fast speed in the early of each generation when individuals far from ideal value. In the subsequent change process, the population has been improved and the

best fitness value is closer to optimal value. Compared to the initial change speed, the change speed is slower and the overall trend is that fitness value is more and more small. The average fitness value has been rapidly and dramatically changed originally and kept stability subsequently. The outputs of the best individual values are shown in Fig. 8.

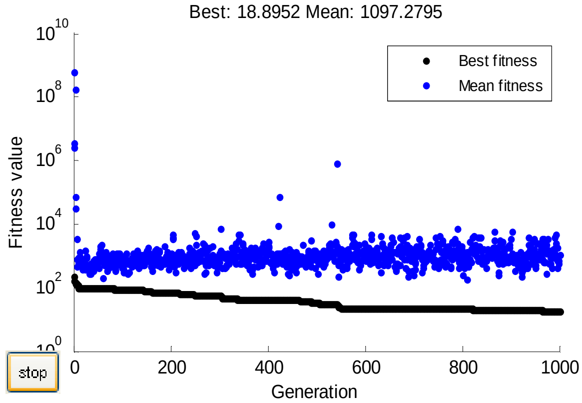
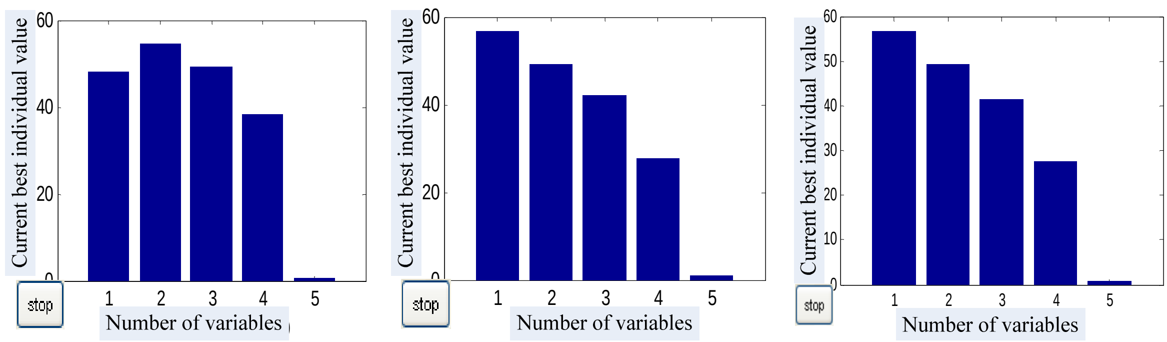


Fig. 7 Change curve of best fitness



a) 100th generation b) 900th generation c) 1000th generation

Fig. 8 Best individual values

At the beginning of optimization calculation, numerical change of the optimal individuals is frequent and great. It means that the algorithm is not mature and needs to continue operation to achieve stable numerical results. It can be seen from Fig. 8a and Fig. 8c that the numerical results of 1000th optimal individuals are far from that of 100th optimal individuals. With the operation of optimization, the optimal individuals are basically stable and the numerical changes are small. In addition, the average difference of individuals is shown in Fig. 9 which can reflect the effectiveness of the algorithm and the rationality of stopping criterion setting. It can be seen that the individual difference is large at first, rapidly decreases and tends to stabilization when the number of generation is increased. The individual difference reaches a minimum at the 1000th generations and it means that the algorithm tends to be mature. The optimization results based on genetic algorithm are shown in Fig. 10.

It can be seen from Fig. 10, l_1 = 57.01 mm, l_2 = 43.90 mm, l_3 = 41.82 mm, l_4 = 23.93 mm, θ_1 = 47°. Inputting above optimized parameter values into established kinematics model, ICR coordinate values can be obtained which is shown in Table 3.

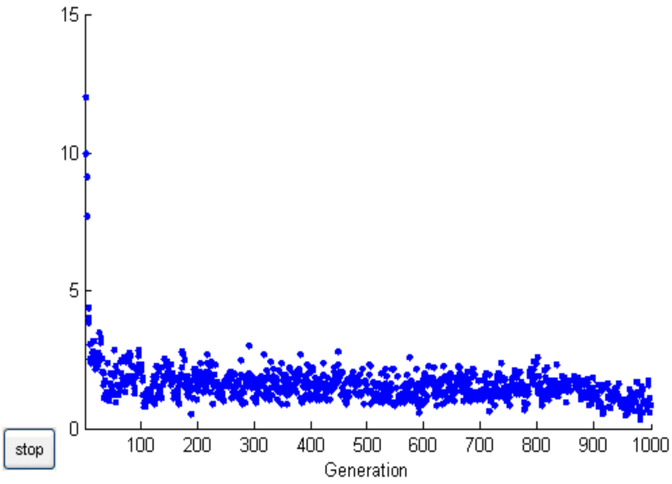


Fig. 9 Average distance of individuals

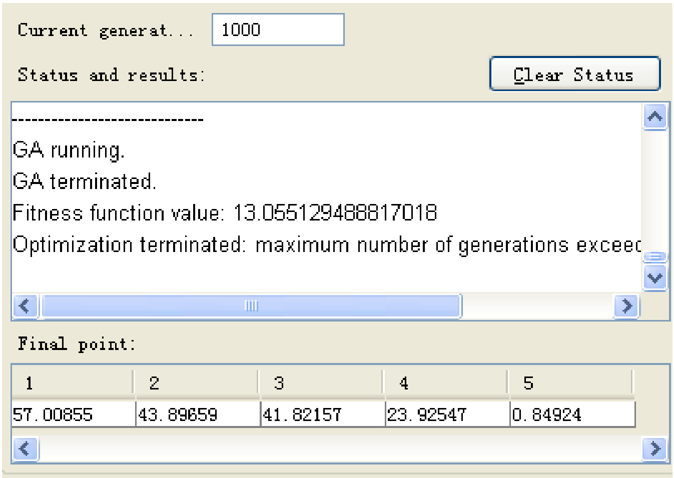


Fig. 10 Results of numerical algorithm

Table 3. ICR coordinate values after optimization

Knee bending angle θ_i, [°]	$x_{p'}$, [mm]	$y_{p'}$, [mm]
0	2.06	135.34
10	5.14	134.52
20	7.05	134.27
30	9.75	132.75
40	10.78	130.79
50	12.18	129.34
60	13.72	128.75
70	15.26	126.35
80	17.42	122.46
90	19.86	116.25
100	24.88	104.65
110	30.91	85.76

Compared with the ideal ICR coordinates of human knee joint, the difference between ideal and actual ICR coordinates are small. It means that the 4-bar mechanism can achieve better anthropomorphic characteristics of knee joint.

Conclusion

4-bar closed-chain knee mechanism has many advantages such as "J" curve of ICR, higher foot clearance and good stability with ground reaction force. It can simulate human knee joint well. Genetic algorithm has a good global search capability and is suitable to optimization of 4-bar closed-chain knee mechanism. The optimization results indicate that the 4-bar mechanism can achieve better anthropomorphic characteristics of knee joint.

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