The structural design, simulation analysis and parameter optimisation of the cheetah robot's leg components

Qingsheng Luo* and Jianfeng Gao

School of Mechatronical Engineering,
Beijing Institute of Technology,
Beijing, 100081, China
Email: luoqsh@bit.edu.cn
Email: wyngjf@yeah.net
*Corresponding author

Chenyang Zhou and Yansong Huang

School of Mechanical Engineering,
Beijing Institute of Technology,
Beijing, 100081, China
Email: zhou_cybit@163.com
Email: hys18611113607@gmail.com

Abstract: The design and analysis of the cheetah robot's leg is directly associated with the bionic shape, bionic structure, bionic function and the bionic materials, even the bionic control. Adopting the essences of the cheetah skeleton system, we finish the design, the simulation and the optimisation of the bionic cheetah leg. After the strength, stiffness, stability, reliability and the durability are ensured, the basic shape and size are constructed according to the properties of functions and connections. After applying load, a finite element analysis (FEA) is carried out. According to the results of FEA, the design is well optimised. The methods described herein combines the advantages of CAD and CAE technology, which can significantly enhance not only the accuracy, rationality and speed during the design of the bionic cheetah robot's leg, but also the level of optimisation of biomimetic robots.

Keywords: bionic robot; CAD; CAE; finite element analysis; FEA; parameter optimisation; robot legs.

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Biographical notes: Qingsheng Luo is Professor and Doctoral Tutor in Beijing Institute of Technology, and the tutor for this program. He researches into the technology of special robot and technology of mechatronics. He is the author of over 180 theses and ten monographs, and has obtained ten or so national patents for invention.

Jianfeng Gao is an undergraduate major in Mechatronics in Beijing Institute of Technology. He is the leader of the team in charge of the program, who works at the structural design of robots, FEA and motion control technology.

Chenyang Zhou is an undergraduate major in Vehicle Engineering in Beijing Institute of Technology. He is a member of the team in charge of the program, who works at gait plan and dynamic stability control using CPG method.

Yansong Huang is an undergraduate major in Vehicle Engineering in Beijing Institute of Technology. He is a member of the team in charge of the program, who works at structural design and FEA.

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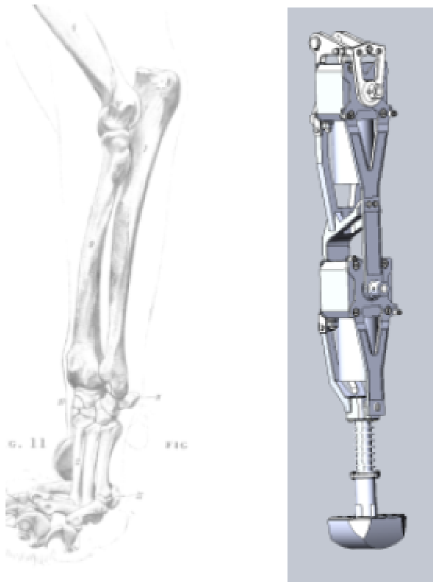
1 Introduction

In the research of bio-robot, the design of skeletal system is not only the focus, but also a difficulty, because the quality and the optimisation can directly affect the kinematic and dynamic performances. In the medical field, artificial bones and the finite element analysis (FEA) of skeletons has made significant progress. However, these achievements are not widely applied to the bionic robot design (Cheng et al., 2010; Penguin et al., 2010; Wu et al., 2012). The method described herein develops the analysis method in the medical research. FEA is used in the design and optimisation. Also, the materials, the processing technology, the cost, the maintenance as well as the aesthetic value, especially the reliability, stability and the durability are taken into consideration. As we all know, for any kind of bionic robots, reasonable stable reliable and durable mechanism and structures play a fundamental role in improving the robustness of the control system. So the bionic robot design should be given great concentration and scientific analysis. The excellent biological structures and functions after long-term evolution can be reasonable referred. The four-legged robot showed in Figure 1, which is under research by the author's team, is a robot with supple spine and elastic legs. This robot can run and jump excellently, whose skeletal system combines a large number of bionic research findings.

Figure 1 Bionic cheetah robot (see online version for colours)

Figure 2 Tibia, fibula and design for robotic leg (see online version for colours)



2 Choose the reasonable biomechanical model

In the field of biomechanics research, biomechanical model can be divided into the phenomenon model and anatomical model (Kong, 2010–2012). The phenomenon transfers the complex biological structures into a simplified mechanism in order to simplify the analysis and help people recognise the structure's mechanical essence. Anatomical model is a highly imitative physical model, which is based on strict anatomical principle and can help with static and dynamic simulation. From the subtle of the biological characteristics, the optimal design can be reached. Considering the particularity of the bionic cheetah's design and function, the special skeleton model is established mainly based on the phenomenon model and supplemented by anatomical model.

Using FEA, the virtual prototype and load cases can be fully simulated, which can approximately reflect the force condition, thus helping people to optimise the design and improve the solution in aspects of materials mechanics. Referred to the idea of Jacob and Patil (1999) and Cheung et al.'s (2005) FEA of human foot, the bionic cheetah robot's leg skeleton is firstly divided into micro unit and then applied with external load. After that, the experiments can be simulated on the computer and the physical features on any cross are known.

The FEA began to be applied to biomechanics in the 1970s, of which the biological solid mechanics is an important branch. The biological solid mechanics uses the basic principles and methods of the material mechanics, fracture mechanics, elastic-plastic theory to study the mechanical problems associated with biological tissues and organs. The most important application lies in the research and practice of the bone's mechanical properties. The bone can stand the forces with minimal anisotropic materials, which cannot be calculated by tradition methods. But the FEA is able to solve this problem successfully. FEA plays an important role in designing the bionic robot's skeleton system Xiong and Fan (2004). It should be noted that isotropic material is adopted to simplify the skeletal model (Xiao, 2008).

3 Scientifically determine the principles in the bionic design

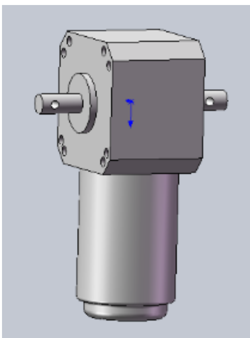
Humanity itself is a treasure, from which we can learn a lot. We get the idea from the combination of the tibia and fibula of human leg and come up with the 'Master-Slave Splints Structure' (seen in Figure 2). The drive device is placed between the splints. At the same time, the following principles are drawn up to improve the robustness of the bionic cheetah robot:

1. different kinds of materials, different cross for supporting to get lightest weight and optimise the force condition
2. using metal materials as the connection part to strengthen the leg and prevent the thermal deformation
3. ability to withstand forces from any directions to enable the leg to move forward, backward, to the left and right (Zhao and Xu, 2008).
4. Using shape constraints to simplify the leg skeleton.

4 Selection of robot's drive device

In order to achieve the precise control of movements, the servo control system should be scientifically selected. To meet the requirements in dynamics, the torque should be more than 10 N * m. To ensure the condition above and the concentricity of revolute joints, the industrial dual-biaxial servos (seen in Figure 3) are used as the drive device. To adjust to the 'Master-Slave Splints' design, the device is fixed to the upper unit to avoid gearings and bearings between units and reduce the weight as well as improve the utilisation of energy. In addition, dual-axis output mode can avoid the problems on concentricity when the accuracy of process is low.

Figure 3 Industrial servos (see online version for colours)



5 The design of the size of skeleton robot's leg and numerical analysis

After the research of bionics, the overall structure of the robot is determined: 26 kg weigh; 1,075 mm long (excluding head and tail); 480 mm wide; 780 mm high. The front legs are 280 mm + 360 mm (thigh and calf) long; the back legs are 300 mm + 390 mm (thigh and calf); its waist is 200 mm wide. These sizes are all based on the anatomic findings of cheetah and ADAMS simulation.

5.1 The design of the size of skeleton robot's leg and 3D modelling

- Parts to be designed: Fibula, tibia, tibia flange.
- Preparation of materials: Metal, nylon, metal are used for each part separately.

The design of the individual parts' size and construction of 3D mode are as follows:

5.1.1 Design and 3D modelling of the tibia

As the main component to receive forces, the tibia suffers huge load. Its size, weight and volume are also big. Considering bionic findings and machining process as well as the shape of the servo and the connections with other parts, we designed the tibia, which is shown in Figure 4. Its bifurcated structure can divide the force along the leg axial into the left and right sides. Also, the screws on the flange of servos are distributed on two sides. The results of FEA are showed in Figure 5. In the left two figures, the end of tibia yields. The next two figures indicate that the yield is eliminated after partly thickening and adding stiffener. The stress is adjusted to the allowable range by structure optimisation. From the second one in Figure 6, the stress in the middle of the tibia is very small, causing a waste of materials. Thus the middle of the tibia is thinned to reduce weight. After research, Nylon 66 is adopted for the tibia.

Figure 4 Tibia design (see online version for colours)

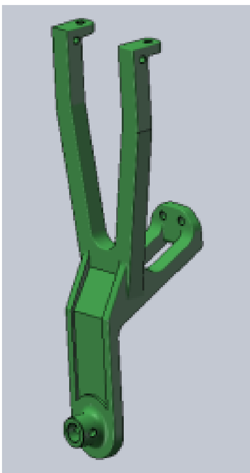


Figure 5 Figure for FEA of tibia (see online version for colours)

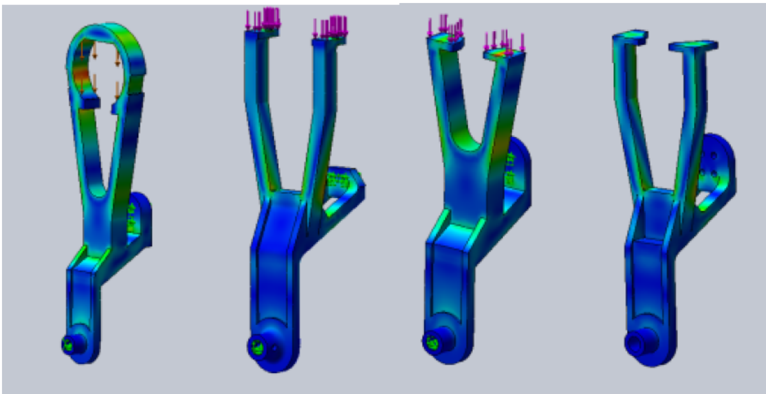
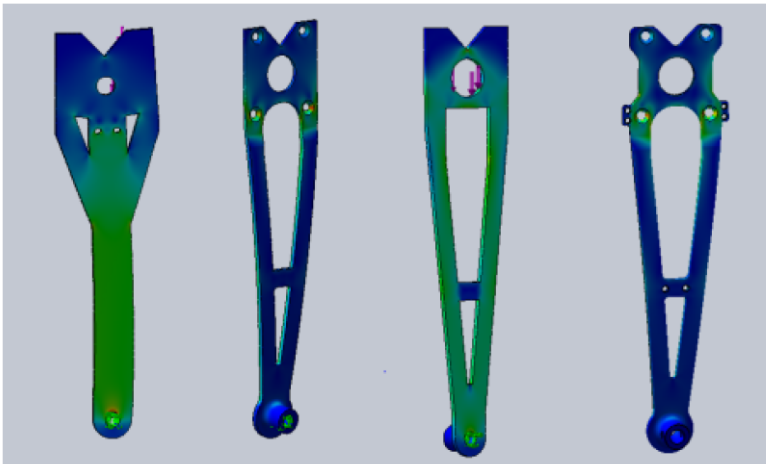


Figure 6 Fibula design (see online version for colours)



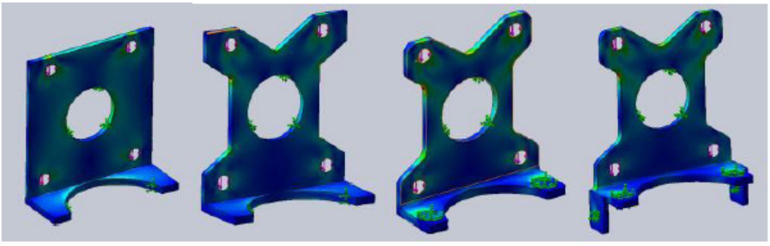
5.1.2 The design and 3D modelling of fibula and tibia flange

These two components can also be designed according to the ideas and methods above, which can be described in this way: the places which stand greater force and concentrated stress should be strengthened by supporting bar or stiffener, while the places which support lighter force should be lightened. Considering that the legs often suffer mutations of forces and impacts, the safety factor is decided as 2. The design of fibula is showed in Figure 6.

5.2 Numerical analysis and optimal design of robot's leg skeleton

After the basic shapes and related sizes are decided, the FEA can be done after applying the load. Designers can improve the original scheme based on the results of analysis. Take the design of tibia flange, for example, we can obtain the result (Figure 7) through FEA. From the left figure of Figure 7, the original scheme is too conservative. L-shaped flange stands very small stress in the most joint area, causing a big waste of materials and a huge weight. So, the materials should be thinned or cut off. Figure 7 shows the process of structural optimisation. From the first object to the fourth object the thickness of the L-shaped flange is reduced from 5 mm to 3 mm, and the shape is changed according to the analysis.

Figure 7 Design and analysis of tibia flange (see online version for colours)



Because of the concentrated stress at the bent, the right angle and the stiffener filled are rounded. The final flange's maximum stress is less than 1/8 of the material's yield strength, which meets the Von Mises strength criterion.

6 FEA and optimisation of parameters of the robot's leg assembly

6.1 Set of parameters

The finish of individual parts does not mean the perfect design of the overall system. The reasonableness of parts should be also examined according to robot's functions and the assemble relationships among the parts. The assembly of the bionic cheetah robot's leg is shown in Figure 8. The blue part is fibula, the green part is tibia, the part on the tibia and connected to the servo is the tibia flange. The middle white part represents the industrial dual-axial servo. To simplify the model, the servo is firstly removed. Figure 9 shows the analysis model of the leg. Tables 1 to 4 show the necessary set of parameters during FEA.

Figure 8 Assembly model for leg (see online version for colours)

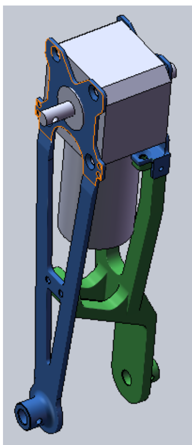


Figure 9 Analysis model for leg (see online version for colours)

Table 1 Basic information

Study name	*FEA of robotic leg*
Type of analysis	Static stress analysis
Type of grid	Grid for entity
Thermodynamic effect	Opened
Thermal option	temperature load
Non-deformation temperature	298 Kelvin
incompatible joining option	Automatically
Calculate the body forces	Opened
Friction	Closed

Table 2 Unit setting

System of units:	*Metric (MKS)*
Length/displacement	mm
Temperature	Kelvin
The angular velocity	Radians/sec
Pressure/stress	N/m^2

Table 3 List of load (see online version for colours)

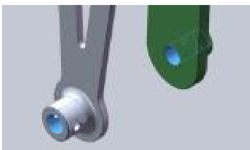
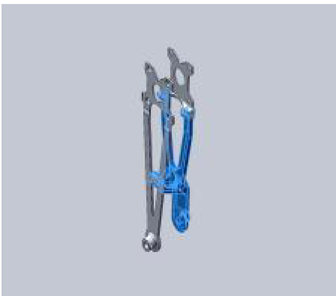
Name of tongs	*Image of tongs*		*Details*	
Fixing-1			Entity: surface Fixed geometry	
The parts	X	Y	Z	Composite force
Reaction force (N)	29.5994	599.227	–0.03	599.958

Table 3 List of load (continued) (see online version for colours)

Name of load	*Image of load*	*Details*	
Force		Entities:	2 surface
		Reference:	Edge < 1 >
		Type:	Force
		Values:	0, 0, 300 N

Table 4 Material properties (see online version for colours)

Model	*Property*	
	Name:	2,024 alloy
	Type:	Linear elastic isotropic
	The default failure criterion:	von Mises criteria
	Yield strength:	7.58291e + 007 N/m^2
	Tensile strength:	1.86126e + 008 N/m^2
	Modulus of elasticity:	7.3e + 010 N/m^2
	Poisson's ratio:	0.33
	Density:	2,800 kg/m^3
	Shear modulus:	2.8e + 010 N/m^2
	Coefficient of thermal expansion	2.3e-005/Kelvin
	Name:	Nylon 66
	Type:	linear elastic isotropic
	The default failure criterion:	von Mises criteria
	Yield strength:	8.3e + 007 N/m^2
	Modulus of elasticity:	5.4e + 009 N/m^2
	Poisson's ratio:	0.41
	Density:	1140 kg/m^3

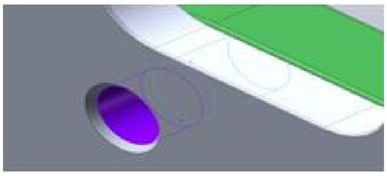
Given the materials of each part in the leg, the total weight of the robot's skeleton is 25 kg. Taking the auxiliary equipment into consideration, the whole weight of the bionic cheetah robot will reach up to 30 kg. It is easily imagined that the robot will be supported only by one leg, causing the static load reaches 300 N. With the help of symmetry characteristic of the leg, the 300 N load will be shared equally between the two connection surfaces of the servo.

6.2 *Definition of joints*

At the bolt connections between two parts, the connectors are defined, which is easy to call the software's library to process such joints. Because the method, which is used to solve the stress and the strain at the axle holes and shafts, is the same in different engineering problems, the connector definition can not only shorten the time but also ensure sufficient accuracy.

Figure 10 shows a bolted joint.

Figure 10 Joints (see online version for colours)



6.3 Contact information

The assembly will no longer retain the original assembly relationships during FEA. Thus, the relationship must be reset. In the material mechanics of, the mutual penetration is not allowed between the contact surfaces. If two parts are fastened, the displacement between surfaces is quite small and the connections of them can be simplified as rigid during the analysis in the direction of perpendicular to the surfaces. If there are forces in the surfaces, the relevant joints constraints must be defined. Specific settings are shown in Table 5.

Table 5 Tangency information (see online version for colours)

Tangency	*Image*	*Property*	
Surface set 1		Type: Entities:	Bonding 2 surface
Surface set 2		Type: Entities:	Bonding 2 surface
Surface set 5		Type: Entities:	Bonding 2 surface
The global tangency		Type: Entities:	Bonding Compatible grid

6.4 Grid information

High precision mesh contributes to a more scientific simulation results. The finer the mesh is, the closer to the reality the analysis is, however, the more time the simulation costs. So, the grid control technology should be adopted. Firstly, the stress concentrated sites can be prejudged with experience. Then, the mesh can be refined. Also, the automatic transition should be planted to deal with the rounded corners and curved surfaces. Specific parameters' settings are listed in Tables 6 and 7.

Table 6 Meshing (see online version for colours)

Total number of node	1,843,539
Total number of units	1,156,062
Maximum aspect ratio	126.84
Unit(%), aspect ratio < 3	97.2
Unit(%), aspect ratio > 10	0.0186

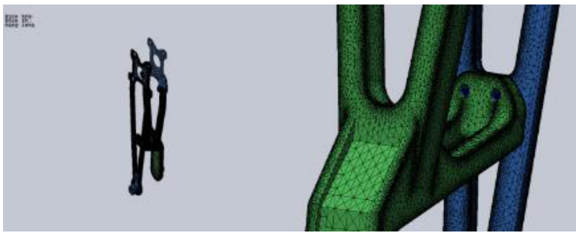


Table 7 The type of grid

The type of grid	Grid for entity
The grid tool	the curvature-based grid
Jacobi point	4
Quality	High quality

6.5 *Grid control information*

When the shape has mutations or the radius of curvature and the mesh is in the same magnitude, the grid control strategy should be used to refine the necessary part to get a better mesh, which ensure the accuracy of analysis. Specific measures are shown in Table 8.

Table 8 Grid control

Grid control	*Image*	*Details*	
Control strategy		Entity:	10 surface
		Unit	mm
		Size:	2.01415
		Ratio:	1.5

6.6 *FEA results and followed analysis*

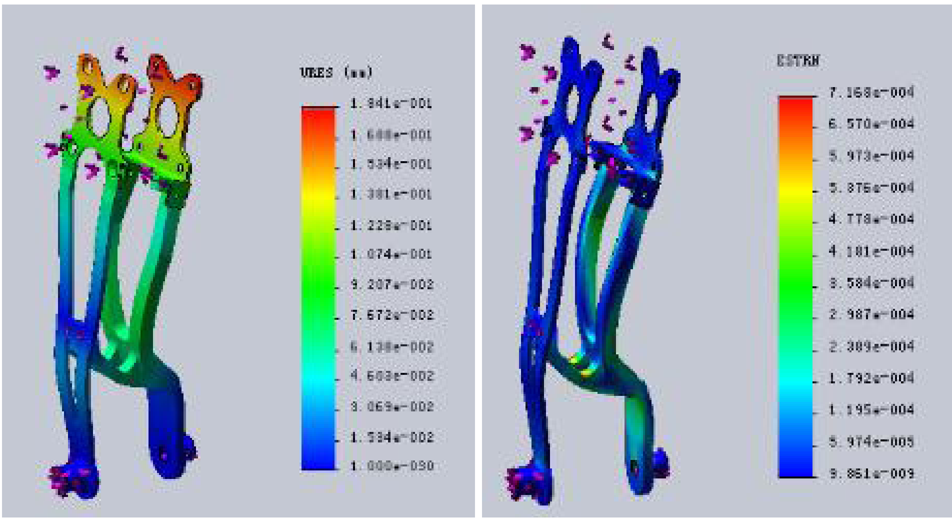
Using FEA, the results are shown in Table 9 and Figure 11. With the theory in material mechanics, when the equivalent stress reaches to a certain limit (the limit has nothing to do with the state under forces), the materials yield. That is to say that the material in plastic state has a constant equivalent stress, which follows the criterion of strain energy density corresponding to distortion (the fourth theory). The maximum shearing stress criterion holds the view that the maximum shear stress is the main reason for the failure. This theory explains the reason for the plastic deformation of plastic materials. Its form is simple and its requirement is stricter than the fourth theory (Mei, 2009). The fourth theory explains that density of distortion energy is the main reason for failure, whose results are more realistic. We use the plastic material – Nylon, aluminium alloy and steel for the leg. The tensile strength of nylon is 83 MPa, Elongation at break is 60% yield extension 8% shear strength 80 MPa strength of flexure > 100 MPa and safety factor n is 2. After calculation, we get: $\sigma = 22.433$ Mpa < $[\sigma]$. According to the materials properties and the stress-strain analysis chart, the maximum stress is 22.5 MPa. It can be safely drawn that this design is able to meet the fourth strength theory and the Von Mises criterion.

Table 9 FEA results

Name	*Type*	*Min*	*Max*
Displacement	URES: composite displacement	0 mm node:20,222	0.180942 mm node: 340
Deformation	ESTRN: equivalent stress	2.59506e-008 Unit: 201,038	0.00143311 Unit: 676,508
Stress	VON: von Mises stress	1,020.94 N/m^2 node: 322,974	2.24331e + 00 7 N/m^2 node: 1,434

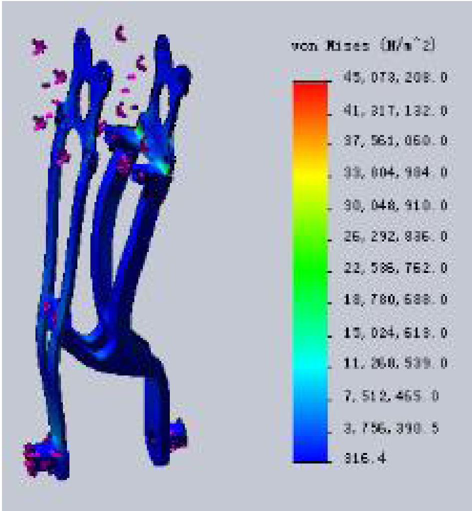
It is can also be seen through the analysis that the stress concentration points are easily appeared at the sharp points and edges. So, the designers should set the safety factors individually according to the functions of different parts. With the help of the four strength theory in material mechanics and Von Mises Criterion, the strength of each part is checked. When the parts are in danger, corrections should be made to meet the allowable range. At the same time, the working environment, including the temperature and the humidity, as well as the special condition should also be taken into consideration, such as the unsteady impact, unexpected load.

Figure 11 FEA results, (a) displacement (b) deformation (c) stress (see online version for colours)



(a) (b)

Figure 11 FEA results, (a) displacement (b) deformation (c) stress (continued) (see online version for colours)



(c)

7 Conclusions and future work

The design and analysis of the cheetah robot's leg is directly associated with the bionic shape, structure, function and the materials, even the control, which plays a very important role in the robot design. This article uses the phenomenon model-based, anatomical model-supplemented method to construct the bionic cheetah robot's skeleton. Adopting the essences of the cheetah skeleton system, strict structure design, detailed simulation analysis and careful optimisation of parameters have been achieved. After the strength, stiffness, stability, reliability and the durability are ensured, the basic shape and size are constructed according to the properties of functions and connections. After applying load, the FEA is carried out. Using FEA, the design is well optimised. The methods described herein combine the advantages of CAD and CAE technology. This shows that with the aid of professional software during the design and optimisation, the accuracy, the rationality and speed are significantly enhanced, which contributes to the progress in the optimisation of biomimetic robots.

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