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Bionics Design and Dynamic Simulation for Lower Limbs Prosthesis

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Bionics shape design of lower limbs mechanism is an important aspect of the design of humanoid robot and rehabilitation prosthes. Based on the measurement of the gait properties and the analysis of the structure shape of human lower limbs, a bionics shape design of lower limbs mechanism is presented. In the research project, the bionics shape design combined the outline design and parts shape design using the similarity principle. The methods have significant theoretical and practical values to the study of humanoid robot design and experiment study.

Keywords: Lower limbs prosthesis; Bionics shape; Structure design, Similarity principle; Humanoid robot.

The [1]main task of lower limb structure design is to clearly constitute elements relationship (overall design) and form the shape of these elements itself (component structure design) and draw the complete assembly sketch.For humanoid robot and rehabilitation prosthetics, the functions and external morphology aim to approach the human body, which is a sophisticated biological machine. Many scholars have done bionic design and exploration over a long period. Sullivan (Sullivan *et al*.,2003, Gailey) (Gailey *et al*.,1997)and Pandy(Pandy *et al*.,1992) have done prosthetics and humanoid design based on anatomy, and devised a muscle tendon model. By combination of the bionic theory and biological muscle electric control technology, Jin *et al*. (Jin *et al*.,1998) invented a high performance "electric current variable fluid prosthesis", Wang *et al*. (Wang *et al*.,1999)designed a new model using human lower limbs redundant muscle forces analysis. By studying he coordinated control model of the human body in specific actions, Yang *et al*.(Yang *et al*.,2004)developed a series of bionic knees with full range movement.

Many groups have developed robot-assisted rehabilitation therapy systems, such as MIT-MANUS (Krebs *et al*.,1999), MIME(Burgar *et al*.,1999), ARM Guide(Reinkensmeyer*et al*.,2000) and Bi Manu Track(Hesse*et al*.,2003). The MIT-MANUS, which allow unrestricted movements of the shoulder and elbow joints, and the MIME, which enables the bilateral practice of a 3-DoF shoulder-elbow movement, show that the recovery can be improved through additional therapy aided by robot technology.

The ARM Guide, which assists reaching in a straight-line trajectory, and the Bi-Manu-Track, which is designedto train distal arm movements by practicing bilateral elbow pronation and supination as well as wrist flexion and extension in a mirror or parallel fashion, also show how use of simple devices makes possible intensive training

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for post-stroke patients with positive results.

In addition, an online robot-assisted upper limb rehabilitation system based on motor imagery EEG has been designed(Xu *et al*.,2001), including hardware, software, feature extraction and classification algorithm, and rehabilitation robot.

Yasar *et al*.(Yasar *et al*.,2011)presented a novel approach to footstep planning in obstacle cluttered environments that employs a human-like strategy to terrain traversal. A design methodology for motion for stepping over obstacles designed for use with this algorithm was also presented. The paper puts forth simulation results of footstep planning, as well as experimental results for the stepping over trajectory designed for use with hardware execution of the footstep plan.

Although technical progress has been attained and practical results has been made, there are still many practical existing problems which need to be studied and explored step by step, especially in the experimental study of the inherent laws of human movement and motion control parameters of the model description, as well as promoting the use of prostheses(Jin *et al*.,2000).

In this article, the lower extremity gait is selected as the research object. By recording its trajectories and analysis, the structure of human motion and internal rules are revealed, and the goal of bionic structure design is proposed. With the use of bionics method and the similarity, a bionic structure of the lower limb is designed and experimented. The overall structure and kinematics and mechanics model of this design is very similar to the human body. Also combined with research on humanoid robot and rehabilitation prosthetic, brief analysis has been done on the experimental results of the prototype example.

METHODS

Gait experiments and bionics structure design

In order to simulate human gait movement so as to attain bionics effect, normal human action must be measured. Structural features and the force distribution in the lower limb shall be careful experimented and analyzed so that the design goals, specification structure and control parameters of bionic structure can be prepared.

In this experiment, special analysis system for human motion is developed as shown in Figure 1. 49 healthy volunteers are chosen as biomedical experimental samples. The system mainly consists of four parts: 1) Gait three-dimensionalforce measuring system. 2)The trajectory detecting system.Twohigh speed cameras are used toobtainkinematics information. With Direct Linear Transformation(DLT)[5-7], Parameters about three-dimensional motion are obtained by calculation. 3) Muscle electric signal measuring system.The United States manufactured Noraxon™ TELEMYO 2400Rsystem[6] is used. 4) synchronousdataacquisition andanalysis system. Inexperiment, the data issynchronous obtained throughsoftwareMyoVideo, and analyzed by softwareMyoResearch2.11 .

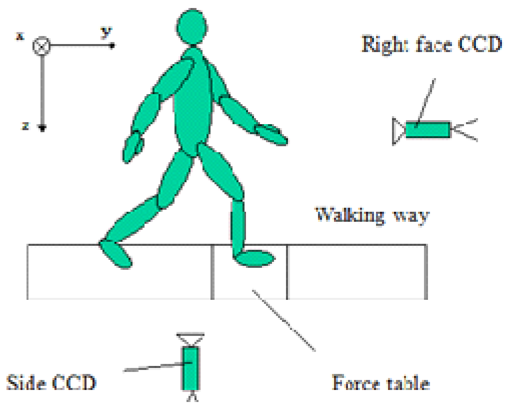

Fig. 1. Movement information of human body measuring system of figure

Lower limb structure features and simplifies

By combination analysis on the experiment results and data of muscle electric signal and muscle action sequence of lower limb, although there are many muscle groups, the human lower limb structure, for humanoid robot and rehabilitation prosthetic design, can be simplified by identifying the main features. In the sagittal plane, the muscles of the lower limb are divided into 10 groups by location and function. They are: (1) the Gluteus Maximus (GMAX); (2) slap rope muscles (HAMS); (3) Rectus Femoris (RF); (4) Group of muscles (VAS); (5) Gastrocnemius (GAS); (6) the tibial anterior muscle (TA); (7) Plantar flexor group (OPF); (8) Soleus (SOL); (9) Iliac psoas (ILIP), including skeletal muscles (iliacus) and waist major muscle (psoas major); (10) long adductor muscle (ADDL, adductor longus).

In Bionics design, according to the number of lower limb muscles across the joint and the pulley effects, the basic form of muscles across the joint can be divided into the following four kinds, (Figure 2):

(a) Cross single joints, without pulley effects; such as GMAX, TA, OPF, SOL, ILIP, ADDL.
(b) Cross single joints, with pulleys effects; such as VAS.
(c) Cross double joints, without pulleys effects; such as HAMS, GAS.
(d) Cross double joints, with pulleys role; such as: RF.

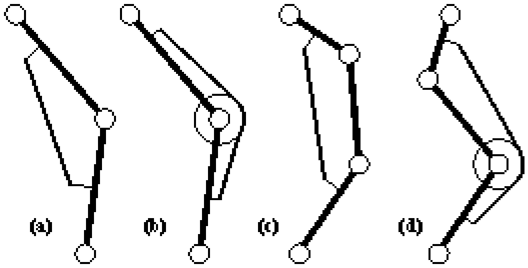

Fig. 2. Types of muscle cross joint

Layout of the 10 muscles in the sagittal plane can be drawn as similar mechanical drawings. With a similar principle (10 tension springs across joint, the rotor of joint is bionic simulated with pulley), the spatial structure of the proposed bionic layout can be set as shown in figure 3. This is also one of the goals of bionics structure design.

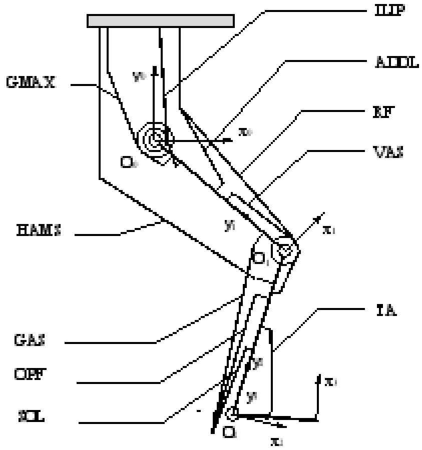

Fig. 3. Bionics structure and driving force layout

The natural gait movement

By measurement and analysis of normal gait, it is clear that lower limb movement has obvious rules such as cycling and repeatability and bilateral symmetry, which can provide parameters and experimental data comparison to that of prosthetics and humanoid robot design. Through normalization treatment, a stick diagram of natural gait cycle movement can be drawn (Fig. 4).

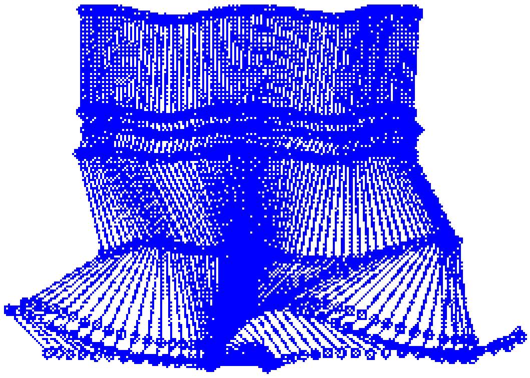

Fig. 4. Stick diagram of the natural gait cycle movement

Description parameter of lower limb movement

By comparison of gait characteristics under different walking cycles with shifting time, stepping action, walking and running, it is found that the angle fitting curve for different samples of lower limb joint have a similar topology (lower limb movement coordination element) [7]. In figure 5, the measured values and fitted curve of the knee angle of a typical sample is shown, vertical axis qk is the knee angle, and the abscissa is the normalized gait cycle.

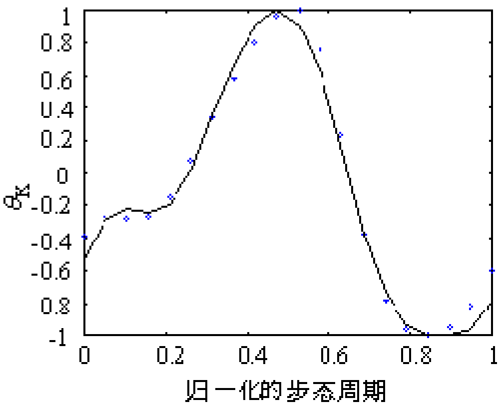

Fig. 5. knee joint angle fitting curve

Where , “o”: actual measurement angle value ; “-”: fitting curve

The three major joints (hip, knee and ankle) angle curve have roughly the shape of a unimodal or bimodal bell-shaped curve. The function is used to describe variation of lower extremity joint angles. By taking account of the different walking and running gait patterns, angle, amplitude and movement, authors’ group add shifting and scaling parameter to attain the general form of the fitting function(Yang *et al.*, 2001,2003) :

$$f(x) = a1 \cdot e^{a2 \cdot \cos(x+a3)} + a4 \cdot e^{a5 \cdot \cos(2x+a6)} + a7 \quad ...(1)$$

Where a1, a4, a7 are scaling parameter, a2, a5, a3, a6 are the shifting parameters. These coefficients can be determined according to individual gait cycle, phase, start and end point parameters. These parameters have a clear data list. Meanwhile, the list data of the double-exponential function also provides the law which must be carefully followed in the design of lower extremity movement, posture, hydraulic system, the spring characteristics and control circuit of each joint. This is also one goal of the bionics structural for motion planning and control system design.

Redundant muscle forces analysis and mechanical model

For guiding humanoid robots and rehabilitation prosthetic design with the basic structure of the human lower limb, through experimental study and the muscle simulating calculation, the synergy and control sequence of each muscle in the different gait can be obtained.

For example, in Figure 6, the muscle force normalized curve of the swing fast walking cycle on ground is shown. The vertical axis is the ratio of muscle force and the subject’s mass, the abscissa is the normalized time of the swing cycle.

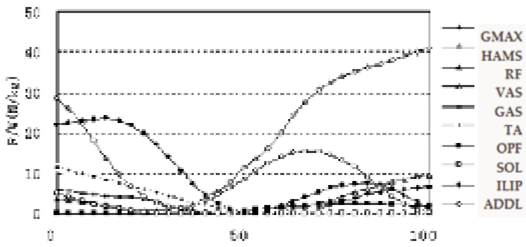

Fig. 6. The muscle force normalized curve of the swing

In Figure 6, it is also shown that the amplitude of contractile force and time of the major muscle groups in human body have certain characteristic in a specific action. The structure, control and the spring system characteristic curve of humanoid robot and rehabilitation prosthetic should also be designed according the similarity principle as the planning model of the body’s mechanics and improve the ability of functional compensation. Meanwhile, all the parameters of human lower limb linkage system (including the length, mass and inertia moment of the bone segment), the proportion of the length of each segment and the structure of the force source are one of the goals of the bionics structure design.

RESULTS AND DISCUSSIONS

Bionic structure realization

In this research, the bionics structure of the lower limb system is designed to realize the above bionics goals. A lower limb model is built and its simplified schematic diagram is shown in Figure 7.

To validate the kinematic simulation, the movement of the knee angle during swing phase is simulated in the ADAMS simulation system(Figure 8) and compared with the corresponding angle measured through the gait trial in Figure 9 (slow speed condition). We find that the two curves practically coincide, which confirms the validity of the kinematic simulation.

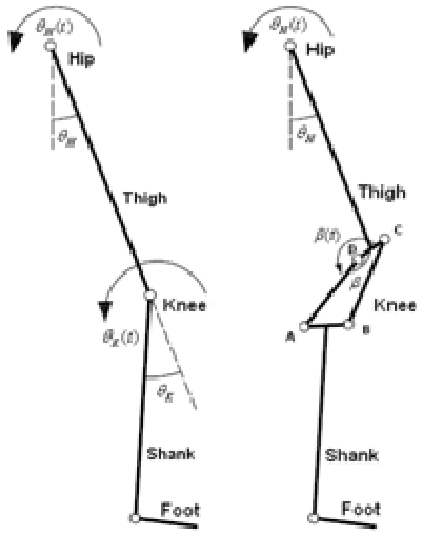

Fig. 7. Schematic diagram of the kinematicsimulation

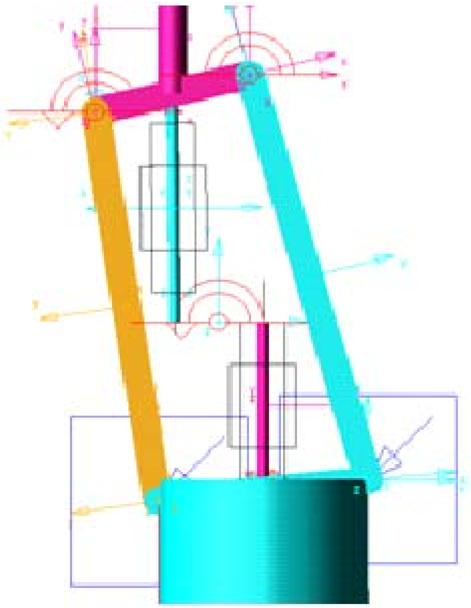

Fig. 8. driver forces and constraints to the prosthetic body

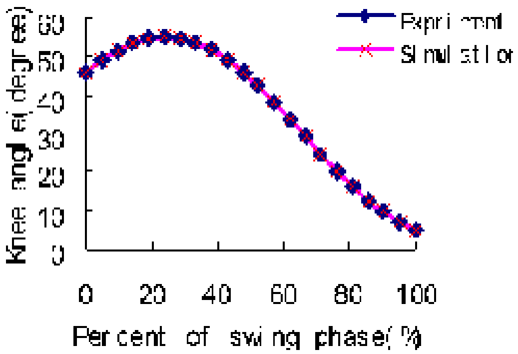

Fig. 9. Comparison of the knee angle during the swing phase between experiment and simulation

with the use of the ADAMS simulation of dynamic functions combined with the use of the VC + + powerful custom interface, we developed parametric modeling and a simulation design platform for prosthetics. There are several key aspects in the simulation design platform (a software system): the input of the established model of lower limb prosthesis, the added driver force, and the constraints to the prosthetic body. The three-dimensional assembly drawing is shown in Figure 10.

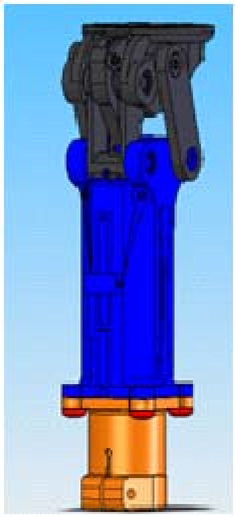

Fig. 10. Structural design in the ADAMS simulation

Experiment results

To validate the evaluation of the structures, based on the previously-mentioned analysis, a prosthesis mechanism was constructed for experimental use. In gait testing, prosthetic wearers' gaits were compared with the gaits of healthy volunteers. Some necessary kinematic data such as the hip angle and knee angle at different instants of time during the swing phase need to be collected through gait trials. Five young male subjects voluntarily participated in this study. Their average age, height and body mass were 28?2 years, 1.74?0.04 m and 62?5 kg. Ethical approval was granted for this study and all procedures were in accordance with ethical guidelines. To record the body-segmental displacements, retroreflective markers (2.54 cm and 5.08 cm in diameter) were appropriately positioned. With a 3-D, video-based, kinematic, data-acquisition system (Motion Analysis Inc., Santa Rosa), absolute displacements were recorded in three dimensions at 60 Hz. These data were then reflected onto the sagittal plane to obtain the two-dimensional coordinates of each marker relative to an inertial frame fixed on the force platform.

In the experiments, the focus was on assessing the ability of amputees wearing the new lower limb system to adapt to changing states such as walking speed, road conditions (ramps, stairs). The aim is to avoid tripping over obstacles and to guarantee security.

Four types of specific tests were conducted. Up ramp, down ramp, and slow and fast movement on level ground. Results were measured when the input of the muscle electric signal of each road condition according to different angle mode are stimulated, stepper motor measure the corresponding prosthetic trajectories of knee angle and ankle. In figure 11 and 12, the gait value of prosthetic wearing is compared with that of healthy human (simulation value) is shown.

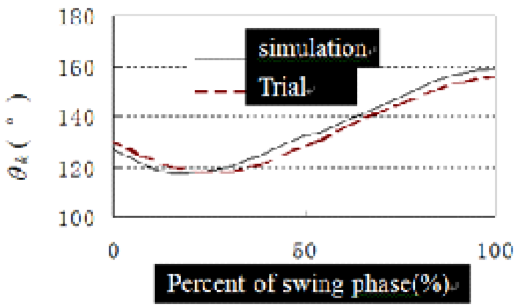

Fig. 11. Gait of the prosthetic wearer compared with the gait of healthy volunteers for the slow speed case

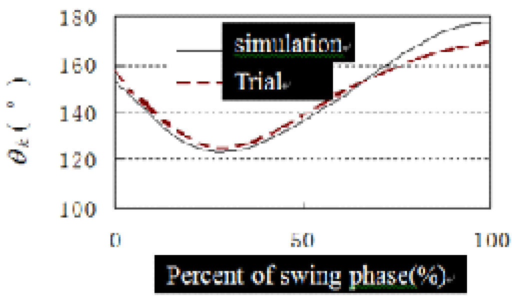

Fig. 12. Gait of the prosthetic wearer compared with the gait of healthy volunteers for the high speed case

As shown in Figures 11-12 (slow speed and high speed) . We find the two curves practically coincide, which implies the validity of the kinematic simulation.

CONCLUSION

In the bionic structure method, human body structure is imitated to create and design structure. This paper adopts the ADAMS powerful kinematics and kinetics simulation software, as the tool to carry out the kinematic analysis of the proposed prosthesis. The length of thigh, shin and foot unit of the model is determined from the measurements of the subject. Because the specific shape of the model does not affect the results of the simulation using ADAMS, a simplified model can achieve the goal so long as the length, mass and the inertial parameters of each part of the model are consistent with the results of the measurement.

No significant differences were observed between the simulation of the joint movements and trials during both stance and swing.

This study has very practical significance for the upgrade of rehabilitation engineering products and humanoid robot design. The bionics structure and control designed is a close approximation of real body mechanics. In this research, strenuous effort is also made on the control dexterity, real-time, intelligent feedback, and some progress has been obtained.

In the future, on the base of repeated actual use and trial of the prototype, the design shall be improved to get comprehensive optimization. Efforts shall also be conducted to improve the feature modeling of bionic structure design and intelligent control of prosthetics and robots.

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