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A Robot System for Biomechanical Testing of Knee Joint

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Abstract. In view of the high failure rate of knee joint surgery and the difficulty of quantitative evaluation of knee joint stability, a robot system for knee joint stability evaluation is proposed. The system achieves the purpose of evaluating the stability of the knee by testing the biomechanical characteristics of the knee joint during the surgery. The system using electromechanical control technology and servo technology implement precise force / torque loading on the knee joint, relatively accurate measurement of micro displacement of knee joint of femur and tibia using vision measurement technology, this data as biomechanical characteristics of knee joint in order to assess the stability of the knee to. The model of bone experiment shows that this system can measure the biomechanical properties of knee joint accurately, the accuracy of measurement is high, at the same time, the system movement is stable, safe and reliable, has high value in clinical research.

1. Introduction

Knee joint is the joint with most complicated structure, largest size and strongest lever effect but also the most vulnerable joint in human body [1]. Clinically, minimally invasive surgical treatment under arthroscope is generally adopted when the knee joint is badly damaged [2]; however, surgical failure rate reaches up to 8% to 25% due to narrow operation space, visual operation field and operation difficulty[3,4]. Surgical failure will bring extra complications and sustained pains to patients [5, 6]. Hence, there is an urgent clinical need for a method for quantitative evaluation on the stability of knee joint in surgery to assess the surgical effect in time, identify the problem and immediately correct it so as to improve the surgical success rate and reduce the occurrence of sequela.

At present, means for quantitative evaluation on knee joint stability mainly depend on biomechanical characteristics. Huang *et al* [7] utilized Kneelax3 to quantify tibia forward so as to make a quantitative analysis on the stability of knee joint after anterior cruciate ligament reconstruction. Minoda*et al* [8] utilized KT2000 to make a comparative evaluation on changes in the stability before and after total knee prosthesis. Song *et a*l [9] designed a knee buckling motion loading system utilizing electromechanical control technology to realize automatic loading of knee buckling motion and used to study the dynamic biomechanical characteristics of knee joint and assist the rehabilitation training after knee surgery. Han *et a*l [10] developed a system for multivariant dynamic stress test of knee joint to make multivariant stress loading experiments and study the changes in biomechanical property of knee joint after anterior cruciate ligament reconstruction and multi-bundle reconstruction. Araujo *et a*l [11] utilized 6-dof robotic manipulator equipped with force sensor at the tail end to load quantitative external force on knee joint, made the quantitative analysis on tiny displacement, and studied the influence of anterior cruciate ligament reconstruction on the stability of knee joint. Other testing devices for biomechanical characteristics of knee joint are only applicable to specimen experiment but can not be applied to the biomechanics test of knee joint in human body during the surgery due to huge size, complicated operational process and poor measurement accuracy.

In respect of the issue above, this paper proposed a robot system for evaluation on the stability of knee joint. Based on the clinical demand, this robot system is able to make more accurate measurement of biomechanical characteristics of knee joint by utilizing electromechanical control technology, vision measuring technology and force servo technology.

2. System architecture and working principle

Biomechanics test of knee joint requires to implement 134N pull/pressure and 5Nm internal and external turning/rotating torque on the tibia of knee joint when buckling angles of knee joint are 0°, 30°, 60°, 90° and 120° and tiny relative displacement of femur and tibia before and after force/torque loading shall be accurately measured [11]. In order to realize the function above, this system adopts the architecture shown in figure 1 and includes motor function test platform, vision measuring equipment and a series of visual markers and control software, among which motor function test platform is used to adjust the buckling angle of knee joint and also able to accurately implement force/torque loading on knee joint; vision measuring equipment is used to accurately measure tiny relative displacement of femur and tibia of knee joint; visual marker is supplied to vision measuring equipment for location tracking; control software is for controlling robotic motion. Working principle of the system is shown in figure 2. Human thigh and calf are fixed on femur adjusting mechanical arm and tibia adjusting mechanical arm respectively. Computer sends control instruction to the driver through CAN bus communication and DC servo motor drives the motion of femur adjusting mechanical arm and tibia adjusting mechanical arm to realize accurate adjustment of buckling angle of knee joint. Visual marker and binocular visual sensor are implanted at femur end and tibia end of knee joint respectively to realize real-time collection of Marker dual image and transmit it to computer for image processing and spatial alternation to realize real-time acquisition of position states of femur end and tibia end. Pull pressure sensor is installed at the tail end of pull pressure loading mechanism and six-dimension force sensor is installed at the tail end of internal and external turning/internal and external rotating torque loading mechanism to feed force information back to the computer in time through serial port communication and computer realizes accurate loading of pull pressure and internal and external turning/internal and external rotating torque on knee joint by virtue of force servo control technology, drive pull pressure loading mechanism, internal and external turning/internal and external rotating torque loading mechanism.

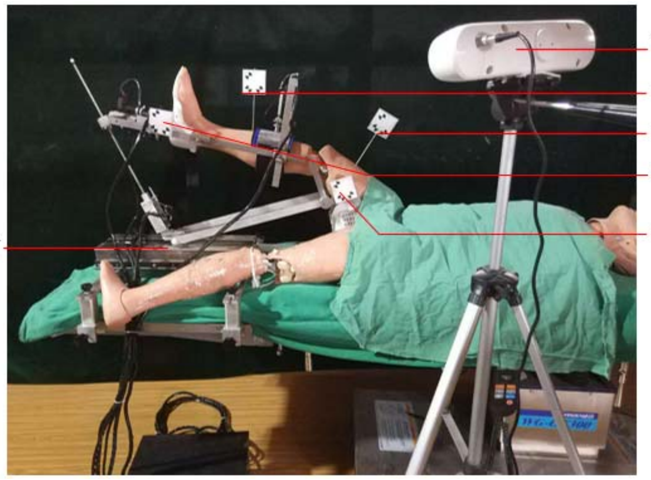

Figure 1. Knee joint stability evaluation robot system

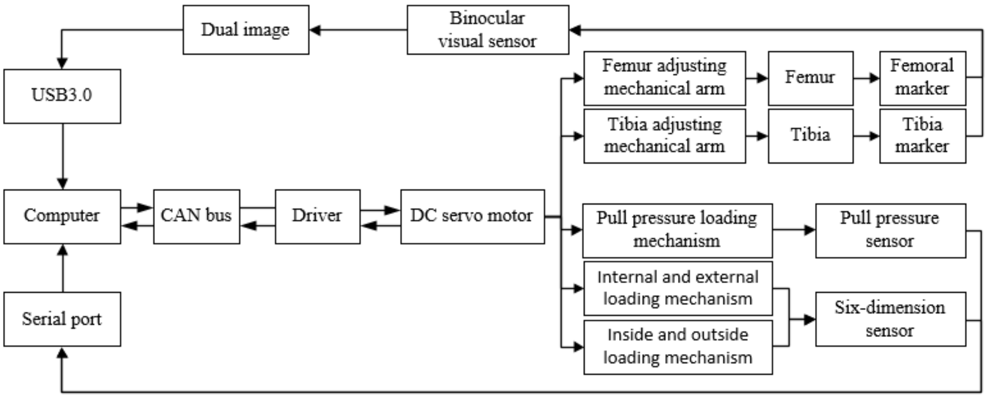

Figure 2. Block diagram of system working principle

3. System Hardware Design

3.1. Design of movement test platform

As shown in figure 3, movement test platform mainly includes femur adjusting mechanical arm, tibia adjusting mechanical arm, pull pressure loading mechanism, internal and external turning torque loading mechanism and internal and external rotating torque loading mechanism. DC servo motor drives the motion of ball screw nut mechanism through gear drive so as to make tail gripper implement pull/pressure on knee joint. Pull pressure sensor (ZNLBM-20, ZNCG) is installed on the tail gripper for real-time monitoring of pull/pressure status. Internal and external rotating torque loading mechanism is located at the tail end of tibia adjusting mechanical arm and DC servo motor drives ball screw nut mechanism through gear drive to realize reciprocating motion and internal and external rotating torque loading. Internal and external turning torque loading mechanism is installed on the feed screw nut of internal and external rotating torque loading mechanism and DC servo motor drives foot fixator through gear drive to realize loading of internal and external turning torque. Six-dimension sensor (SRI-M3705B, Sunrise) is installed on foot fixator for real-time monitoring of force loading status.

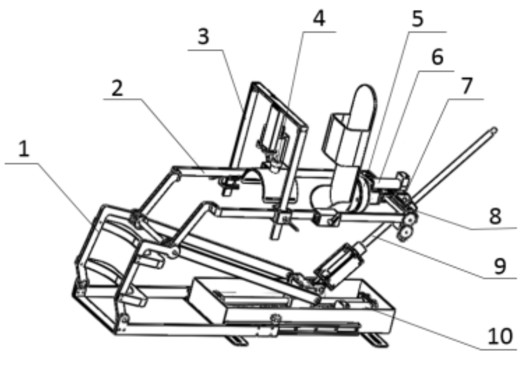

Figure 3. Sketch map of movement test platform structure
1-femur adjusting mechanical arm; 2-tibia adjusting mechanical arm; 3-pull pressure loading mechanism; 4-pull pressure sensor; 5-six-dimension sensor; 6-internal and external turning torque loading mechanism; 7-internal and external rotating torque loading mechanism; 8- internal and external rotating ball screw nut mechanism; 9-tibia adjusting ball screw nut mechanism; 10- femur adjusting ball screw nut mechanism.

3.2. Vision measuring equipment

This paper adopts Micron Tracker H40 binocular camera as visual information acquisition tool. Micron Tracker (shown on the left of figure 4) is a set of optical tracking positioning system produced by Claron Technology in Canada [12]. The positioning accuracy reaches up to 0.2mm so Micron Tracker is able to track the moving target and identify multiple groups of optical mark points simultaneously. Hence, it is widely used in various occasions including biomedical engineering experiment and robot visual system in need of accurate positioning. Vision marks sticked on visual markers adopted in this paper is shown on the right of figure 4. In the coordinate system, X axis is the straight line where short side is, Y axis is the straight line where long side is, and Z axis is determined according to right hand rule.

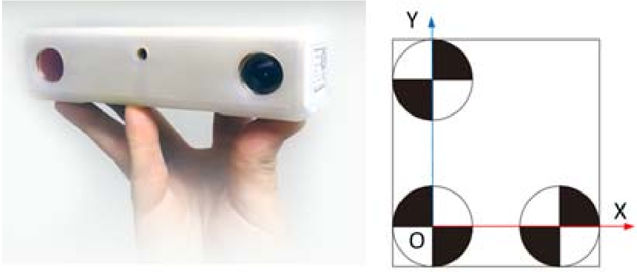

Figure 4. Micron Tracker binocular camera and visual markers

4. Research on System Algorithm

4.1. Method for adjusting and controlling buckling angle

This paper adopts the form of vision measurement for solving buckling angle. As shown in figure 1, two Markers are fixed on femur adjusting mechanical arm and tibia adjusting mechanical arm and denoted by Marker_femoralArm and Marker_tibiaArm. Vision measuring equipment bundled software is able to realize real-time acquisition of spatial homogeneous coordinates denoted by T_{fa}, T_{ta} of two Markers under camera coordinate system. Formula (1) can be used to get position description T_{ta}^{fa} of Marker_tibiaArm under Marker_femoralArm coordinate system. T_{ta}^{fa} is 4×4 homogeneous and decomposed according to formula (2). $R_{3\times3}$ represents the rotation amount of Marker_tibiaArm relative to Marker_femoralArm and $t_{3\times1}$ represents the translation amount of Marker_tibiaArm relative to Marker_femoralArm. RPY angle is adopted to describe the rotational motion of Marker_tibiaArm relative to Marker_femoralArm. $R(\mathrm{Z},\alpha),\mathrm{R}(\mathrm{Y},\beta),\mathrm{R}(\mathrm{X},\gamma)$ are set up and α,β,γ can be gained through formula (3). α is the rotation amount of Marker_tibiaArm relative to Marker_femoralArm and is the buckling angle desired by this paper.

$$T_{ta}^{fa} = T_{fa}^{-1} T_{ta} \tag{1}$$

$$T_{ta}^{fa} = \begin{bmatrix} R_{3\times3} & t_{3\times1} \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$\beta = A\tan 2(-r_{31}, \sqrt{r_{11}^{2} + r_{21}^{2}})$$
$$\alpha = A\tan 2(r_{21}, r_{11}) \qquad (3)$$
$$\gamma = A\tan 2(r_{32}, r_{33})$$

This paper adopts visual PID control to realize accurate adjustment of buckling angle. PID control is the most classic control method [13]. It compounds error proportion (P), integral (I) and differential (D) to controlled quantity to control closed-loop system. Formula (4) is digital PID formula. T is sampling cycle and k is sampling sequence number. Maximum sampling frequency and cycle of visual sensor Micron Tracker are 15HZ and 0.06s so minimum sampling cycle of PID controller $T_{\min} \geq 0.06s$. For this system, sampling cycle T can not be too large or small. Too small T adds the computational burden of host computer procedure, deviation between two times of sampling is too small and output variation of controller is not big; too large T makes it fail to realize fast visual servo[14]. In view of these factors, sampling cycle $T = 0.1s$ is selected. This paper takes movement velocity of mechanical arm as controlled object and utilizes visual PID controller to make closed-loop control.

$$\mu(k) = K_p \left(e(k) + \frac{T}{T_I} \sum_{i=0}^{k} e(i) + T_D \frac{e(k) - e(k-1)}{T} \right) \qquad (4)$$

4.2. Force control method
Knee joint tissue is nonlinear material so accurate mathematical model can not be built [15]. In order to get favorable force control effect, this paper adopts fuzzy adaptive PID control method to realize automatic optimum adjustment of PID parameter [16]. Constructed fuzzy adaptive PID controller is shown in figure 5. The Difference between expected value and current value of force loading acts as $error$. Error variation is $\frac{de}{dt}$, $error$ and $\frac{de}{dt}$ act as inputs of PID controller, and $\frac{de}{dt}$ acts as input of fuzzy inferer. Fuzzy mathematics method is utilized inside fuzzy inferer to store the experience of manual control as the rule of fuzzy control and apply fuzzy inference to realize rational adjustment of PID parameter. This paper realizes fuzzy adaptive PID control method on host computer and the realization process is shown in figure 6.

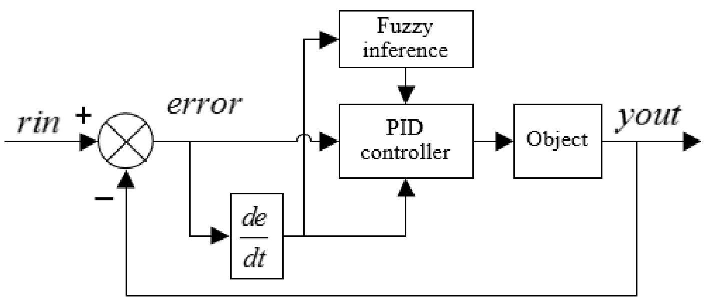

Figure 5. Fuzzy adaptive PID controller structure diagram

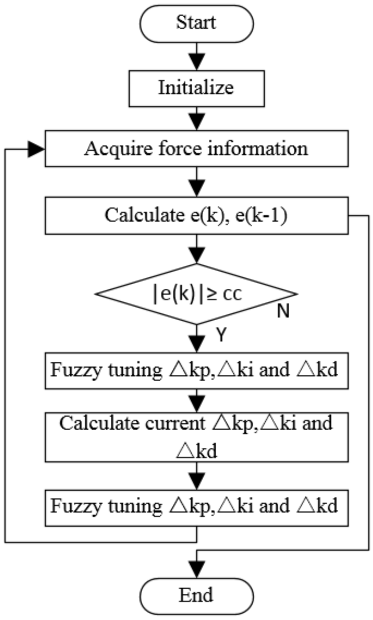

Figure 6. Force control flow chart

4.3. Calculation of femur and tibia micro displacement

In order to make accurate measurement of tiny relative displacement of femur and tibia of knee joint, this paper transforms posture changes of Marker_femoral and Marker_tibia implanted into femur end and tibia end for measurement. Marker_tibiaArm fixed in tibia adjusting mechanical arm acts as reference coordinate system, among which X direction is approximately overlapped with the direction of tibia axis. Marker pinpoint is implanted into femur and tibia so is displacement can represent those of femur and tibia. Spatial homogeneous coordinates of Marker_femoral, Marker_tibia and Marker_tibiaArm under camera coordinate system before force/torque loading are set as T_f, T_t, T_{ta} and those after loading are T_f', T_t', T_{ta}' respectively. Homogeneous coordinates of pinpoints of Marker_femoral and Marker_tibia under Marker coordinate system are known (gained by calibrating) and denoted by P_f, P_t . P_f^{ta}, P_t^{ta} , coordinates of pinpoints before force loading under reference coordinate system can be gained through formula (5) and formula (6) while those after force loading reference coordinate system under reference coordinate system can be gained through formula (7) and formula (8). Relative displacement $\vec{S}$ before or after force loading be gained through formula (9) and it can represent the tiny displacement of tibia relative to femur.

$$P_f^{ta} = T_{ta}^{-1} T_f P_f \tag{5}$$

$$P_t^{ta} = T_{ta}^{-1} T_t P_t \tag{6}$$

$$P_f^{ta}{}' = T_{ta}'^{-1} T_f' P_f \tag{7}$$

$$P_t^{ta}{}' = T_{ta}'^{-1} T_t' P_t \tag{8}$$

$$\vec{S} = (P_t^{ta}{}' - P_f^{ta}{}') - (P_t^{ta} - P_f^{ta}) \tag{9}$$

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5. System Performance Test

This paper sets up the system prototype and makes performance test on model bone. Experimental environment is shown in figure 1. Two Markers are fixed on femur adjusting mechanical arm and tibia adjusting mechanical arm and denoted by Marker_femoralArm and Marker_tibiaArm respectively. Two Markers are implanted into the thigh and calf of human model and denoted by Marker_femoral and Marker_tibia respectively. At first, knee buckling angle adjustment accuracy is measured. 5 experiments are made when buckling angles are adjusted to 0°, 30°, 60°, 90° and 120° respectively. Experimental results in table 1 show that maximum error of buckling angle adjustment is 0.85° and average error is 0.51°. Afterwards, when buckling angle is 30°, force loading accuracy test is made. ±134N pull pressure, ±5Nm internal and external turning torque and ±5Nm internal and external rotating torque are implemented on the calf and 7 experiments are made in total. Experimental results in table 2 show that maximum error of pull pressure loading is 0.78N and average error is 0.47N; maximum error of internal and external turning torque loading is 0.048Nm and average error is 0.026Nm; maximum error of internal and external rotating torque loading is 0.069Nm and average error is 0.029Nm. At last, when buckling angle is 30°, 134N pressure is implemented on the calf, when buckling angle is 30° of tibia relative to femur is measured, and 5 experiments are made. Experimental results in table 3 show that test results are relatively stable.

Table 1. Knee buckling angle adjustment accuracy test data

Angle (°)	0	30	60	90	120
Experiment I	0.15	30.35	60.38	90.43	120.76
Experiment II	-0.08	29.86	59.94	90.37	120.53
Experiment III	-0.27	30.23	59.98	89.72	119.49
Experiment IV	0.24	30.36	60.54	90.73	120.85
Experiment V	-0.17	29.83	59.78	89.65	119.53

Table 2. Apply force accuracy test data

Loading force (N)	I	II	III	IV	V	VII	VII
134.0/pull	134.41	133.43	133.23	134.15	133.36	134.12	134.67
-134.0/pressure	-134.06	-134.52	-133.41	-133.76	-133.6	-134.79	-134.71
5.0/internal turning	5.031	4.966	5.017	5.013	4.963	4.983	4.991
-5.0/external turning	-4.953	-5.028	-4.975	-5.028	-4.952	-4.978	-5.009
5.0/internal rotating	5.047	5.034	5.03	4.974	4.996	5.069	5.045
-5.0/external rotating	-5.014	-5.012	-5.032	-4.981	-4.959	-4.995	-4.974

Table 3. Relative to the femur tibia tiny displacement test data

Experiment No.	I	II	III	IV	V
Displacement (mm)	5.832	6.124	5.467	5.662	6.411

The test results above show that the system realizes functions including accurate adjustment of knee buckling angle, accurate loading of force/torque and measurement of tiny displacement of femur and tibia, and is able to achieve the purpose of biomechanics test for knee joint.

6. Conclusion

Biomechanics test of knee joint is an effective means for quantitative evaluation on the stability of knee joint and gets more and more attention from the public; however, most of the testing devices for biomechanical characteristics of knee joint can only be used in specimen experiment but can not realize the evaluation on the stability of knee joint in human body due to large size, complicated operation and low reliability.

This paper proposes and realizes a robot system for the evaluation on the stability of knee joint in surgery. This system realizes accurate test of biomechanical characteristics of knee joint by virtue of electromechanical control technology, force servo technology and vision measurement technology. At the same time, modular design is adopted and ergonomics is considered in the designing process to make the system be harmonious with the surgical environment so as to realize online testing evaluation on the stability of knee joint during surgical process.

Due to limited conditions, this paper only makes relevant experimental research on model bone and verifies the reliability and practicability of the system in biomechanical test of knee joint. Subsequently, the research group will make further experimental research on human body specimen.

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