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Design of Intelligent Monitoring System for Knee Joint

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Abstract. Combined with physical modelling, motion capture and microprocessor technology, a human knee joint intelligent monitoring system based on nine-axis attitude angle sensor WT901 is developed. The overall design of the system and its hardware and software design are completed. The system adopts STM32 to improve the practicability of the system, use App to enhance the human-computer interaction capability. The results of the system tests indicate that the system realized accurate measurement of knee-bending angle and pressure. In addition, the system can also warn of sports posture errors and knee fatigue, and it is wearable and has low energy consumption.

1. Introduction

As people's living standards improve, more and more people begin to pay attention to their own health, and want to enhance their physical fitness through exercise. At the same time, sports injuries have been plaguing people. The incidence of gonarthritis remains high in all sports injuries, and the incidence of the disease increases with age[1]. If you have gonarthritis, it will not only reduce your athletic ability, but also affect your daily life. Among the main causes of knee arthritis, the wrong use of the knee joint is a very important reason including wrong posture[2], excessive weight for a long time. If people can understand their knee status in real time, pay attention to the protection of their knee joints, and use their joints correctly, then the incidence of knee joints can greatly reduce.

In order to help users understand their knee status, relevant scholars have done a lot of research. Traditionally, monitoring and analysis of the knee joint is perform in the laboratory using the camera to identify the status of the athlete. Such a measurement system can provide accurate measurement data. However, due to the high cost of measuring devices and the difficulty of data processing in the later stages, such systems only be used in specific environments. To address this issue, some teams are working on a knee-worn monitoring system that is easy to wear. For example, some scholars have recently proposed a knee-based monitoring system based on an angle sensor[3]. However, the system only realizes the measurement and display of the bending angle of the knee joint. There are also some research teams use flexible sensors to measure the knee joint angle[4], but the sensor has high material requirements, and it is also impossible to measure excessive angles. In summary, the existing research only stayed at the measurement and display of the knee joint angle, did not perform secondary analysis of the measurement results, and did not measure the knee joint pressure, resulting in a single monitoring result and low practicability.

In view of the shortcomings of the existing design, this paper designs and produces a human knee joint intelligent monitoring system. The system measures the tilt angle and acceleration of the femur and tibia by two sensors attached to the knee joint, and then substitutes the measurement results into the knee joint physical model to calculate the meniscus pressure. Meanwhile the mobile app will display the user's knee status, including the knee-bending angle and meniscus pressure. In addition, the design can also determine whether the user is in the wrong motion posture or subject to a large pressure for a long time through the above two parameters. When the above situation occurs, the mobile app will warn the user and guide the user to relax the knee joint to avoid further damage to the knee.

2. Theoretical model analysis

2.1. Physical model building and calculation

The physiological composition of the knee joint of the human body is very complicated. For information, the knee joint is a synovial joint consisting of the upper end of the tibia the lower end of the femur, the hipbone, and various ligaments. In knee monitoring, the most important monitoring data is the knee femur bending angle, the tibial bending angle, and the meniscus pressure. Because the knee joint has a complex physiological structure, and the knee joint pressure point is inside the human body, the pressure on the meniscus cannot directly measured[5]. In order to measure the parameters, this paper simplifies the various parts of the knee joint, establishes the knee joint force model, and carries out theoretical analysis and MATLAB modelling. The model is show in 'figure 1'.

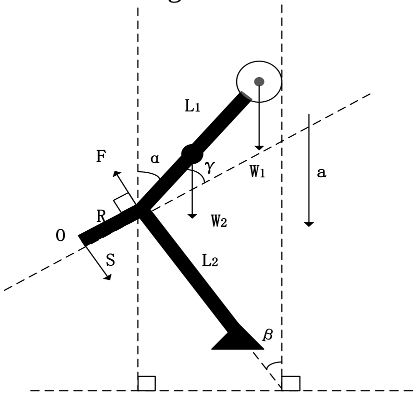

Figure 1. Human knee joint force model analysis.

The parameters in the figure represent physical quantities. The knee joint pressure is F. The upper body gravity is W_1. The thigh gravity is W_2. The ligament pull is S. the femur length is L_1. The distance from the hip ligament to the knee fulcrum is R. The femur tilt Angle is α. The inclination angle of the tibia is β. The vertical acceleration of the human body is a. The unit of gravity is Newton, the unit of length is meters, and the unit of acceleration is meters per square meter.

Point O is the force point. When the acceleration in the vertical direction of the human body is a, the analysis of Moment is performed as shown below.

$$F \times R = M_1 + M_2 \tag{1}$$

In the formula:

$$M_1 = (W_2 \cdot \cos\beta) \times (R + 0.5 \cdot L_1 \cdot \cos\gamma) + (\frac{W_2}{g} a \cdot \cos\beta) \times (R + 0.5 \cdot L_1 \cdot \cos\gamma) \tag{2}$$

$$M_2 = (W_1 \cdot \cos\beta) \times (R + L_1 \cdot \cos\gamma) + (\frac{W_1}{g} \cdot a \cdot \cos\beta) \times (R + L_1 \cdot \cos\gamma) \tag{3}$$

Meniscus pressure:

$$F = F_1 + F_2 \tag{4}$$

In the formula:

$$F_1 = (W_2 \cdot \cos\beta) \times (1 + 0.5 \cdot \frac{L_1}{R} \cdot \cos\gamma) + (\frac{W_2}{g} \cdot a \cdot \cos\beta) \times (1 + 0.5 \cdot \frac{L_1}{R} \cdot \cos\gamma) \tag{5}$$

$$F_2 = (W_1 \cdot \cos\beta) \times (1 + \frac{L_1}{R} \cdot \cos\gamma) + (\frac{W_1}{g} \cdot a \cdot \cos\beta) \times (1 + \frac{L_1}{R} \cdot \cos\gamma) \tag{6}$$

Therefore, the knee joint pressure can calculate by measuring the bending angle of the femur and the tibia and the vertical acceleration of the upper body.

2.2. Physical model parameter selection
Related studies have shown that the regression relationship between the length of the human femur and the height is as follows.

Man: $$L_1 = 0.445X - 27.91 \tag{7}$$

Woman: $$L_1 = 0.571X - 45.79 \tag{8}$$

According to the official data, the relationship between upper body weight, thigh weight and body weight is as follows.

$$W_1 = 0.816W \tag{9}$$

$$W_2 = 0.141W \tag{10}$$

The distance from the hip ligament to the knee fulcrum is as follows.

$$R = 3.3 \pm 0.5 \tag{11}$$

2.3. Knee model simulation results
By implanting the established knee joint model into MATLAB, the group obtain the following results by simulating the knee joint state at different angles. The simulation environment is 170cm in height, 60kg in weight and 0 vertical acceleration. The 3D simulation results showing in 'figure 2'.

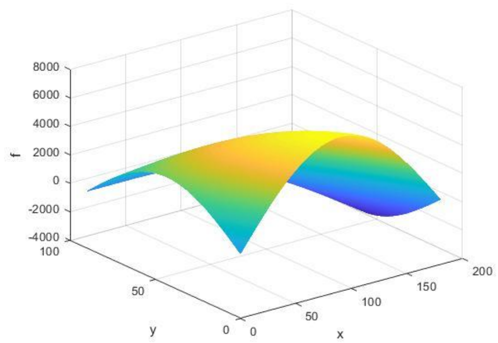

Figure 2. Three-dimensional force curve of the knee joint.

3. System Overall Design

The knee joint intelligent monitoring system consists of three parts: wearing terminal, Bluetooth data transmission and user APP. The system includes attitude detection module based on WT901, microcontroller module based on STM32F103RCT6, Bluetooth communication module based on HC-02 and the mobile app display and reminder. The system overall design diagram is shown in ‘figure 3’.

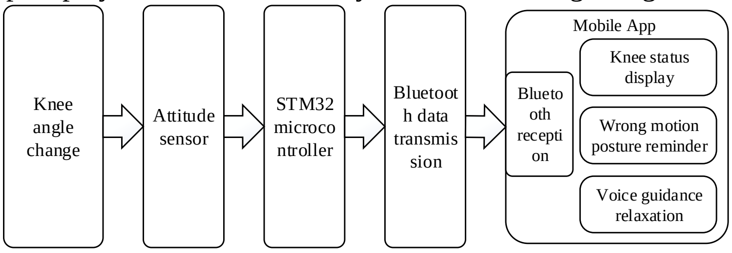

Figure 3. System overall design diagram.

Once the angle of the user's knee femur and tibia changes, the posture detection module attached to the knee joint captures the posture change, and uploads the angle, acceleration and other parameters to the STM32 microcontroller. The microcontroller processes the data obtained for the first time based on the physical model and the calculation formula, and calculates the knee joint force. After that, STM32 sent the data of force and angle to the mobile phone through Bluetooth. Then, the upper computer solve the attitude of the knee joint and display status, remind the user when a wrong posture occurs. The relax button on the App allows user to relax the knees by following the voice prompts. In addition, the system will compares the actually relax posture with the standard posture, voice helps correct wrong posture when error posture occur.

4. Hardware Circuit Design

4.1. Microcontroller circuit design

The microcontroller chip used in system is STM32F103RCT6 designed by ARM. The high-performance ARM core operating at high-speed and it has 51 enhanced I/Os. It offers many communication interfaces such as I^{2}C, SPI. With low power consumption, the standard voltage of the microcontroller chip is 3.3V. The microcontroller chip fully meets the needs of this design. The microprocessor circuit schematic is showing in ‘figure 4’.

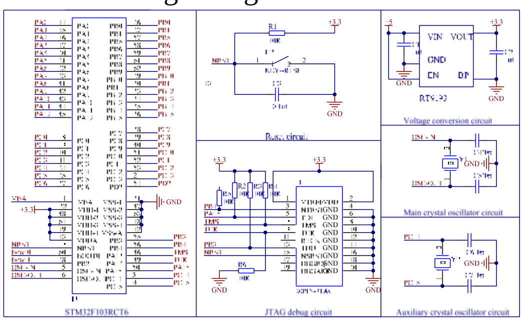

Figure 4. Microprocessor circuit schematic.

STM32 microcontroller circuit consists of five parts: a main control chip, a reset module, a JTAG debug module, a voltage conversion circuit and a crystal oscillator circuit. When the microcontroller works abnormally, the reset circuit can restore the chip to an initial state. The voltage conversion circuit steps down the 3.7V voltage provided by the rechargeable lithium battery to 3.3V for the chip. The JTAG debug circuit can help the programmer to monitor the execution of the program on the PC and reduce the error rate of the program. The crystal oscillator circuit generates a square wave of a certain frequency to provide the basic clock signal for the system.

4.2. *Attitude detection circuit design*

WT901 sensor module is used for attitude detection module integrates high-precision gyroscope, accelerometer and geomagnetic field sensor. The module use High-performance microprocessor, advanced dynamic solution and Kalmar dynamic filtering algorithm to solve the real-time attitude quickly. For communication protocol, it has the serial port and I^2C digital interfaces. I^2C interface working speed is 400k. The schematic diagram of the circuit design is showing in ‘figure 5’.

The attitude sensor communicates with the MCU through I^2C protocol. The I^2C serial bus generally has two signal lines, one is a bidirectional data line SDA and the other is a clock line SCL. Since the module's I^2C bus is open-drain, the I^2C bus is connect to VCC through 4.7k resistor in design.

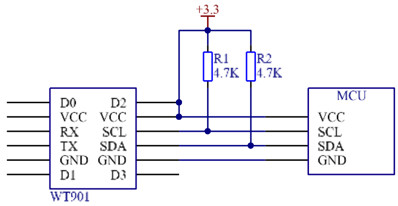

Figure 5. Schematic diagram of attitude detection circuit.

4.3. *Bluetooth transmission circuit design*

The HC-02 module based on the Bluetooth 2.0 version is compatible with BLE, dual mode, high stability and have low power consumption. The schematic diagram of the Bluetooth transmission circuit design is showing in ‘figure 6’. Due to complex wireless communication configuration and transmission algorithm is integrated in the module, so only the connection to device through the TTL serial port needs to be done when uses. The working principle of is shown in ‘figure 7’, it include data transmission among Bluetooth, microcontroller and host computer.

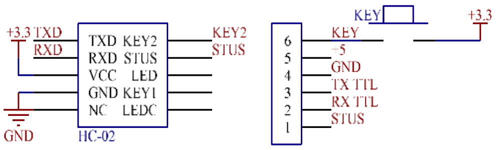

Figure 6. Bluetooth transmitter circuit schematic.

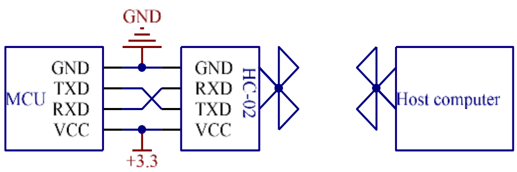

Figure 7. Schematic diagram of data transmission.

5. System Software Design

The system program consists of two parts: the microcontroller-processing program and the App. The programming flowchart shows in ‘figure 8’.

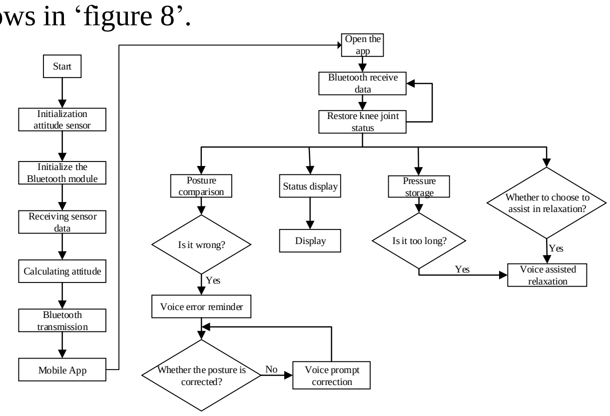

Figure 8. Program design flow chart.

First, the MCU will initialize the external attitude sensor module and the Bluetooth module. After the initialization, WT901 sent the femoral angle and the tibia angle of the knee joint to the MCU. The MCU substitute the data into the system physical model for calculation, then sent the results to the mobile app through Bluetooth. The program design flow chart is showing in 'figure 8'.

Once receiving the data, the mobile app restores the knee joint status and performs posture comparison, display status, store pressure and decide whether to select the auxiliary relaxation. In the workflow, the system notify the user of possible injury, when the knee posture detected is wrong, the system assist in correcting the wrong posture through voice guidance. The status display enables user to view the knee state on mobile phone, the pressure storage plays a role in providing history data for a long period time display.

If the user's knee joint is under high pressure for a long time, the App will sent voice and vibration warning, and then turns into voice-assisted relaxing function. Besides, the system can help the user to get knees relaxed by guiding with tutorial in voice.

6. Test result analysis

The testing scheme have the correctness test of motion posture detection and the accuracy test of pressure calculation. The test sample is healthy male height 173cm, weight 55kg. The real product photo shows in 'figure 9', the App is shows in 'figure 10'.

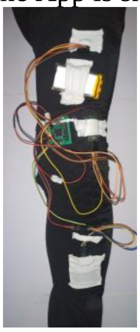

Figure 9. The real product of Human body knee monitoring system.

Figure 10. Physical picture of mobile App.

In the test of the correctness of the motion posture detection, the two movement postures of running and squatting were tested. Correct running actions, wrong running actions[6], correct squat movements and wrong squat movements[7] were respectively tested. The system judge whether the motion posture is correct. Some experimental results shows in table 1.

Table 1. Test of posture correctness.

Sports posture	Test results (number of successes / number of trials)	Success rate
Running right	26/30	86.6%
Running error	25/30	83.3%
Squat right	28/30	93.3%
Squat error	29/30	96.6%

In the pressure calculation accuracy test, pressure were respectively measured in the three kinds of actions such as standing normally[8], walking[9] and right angle bend[10]. The measured data compared with the reference pressure. The test results shows in table 2.

Table 2. Test of pressure calculation accuracy.

Test posture	Reference pressure	Calculating pressure
Standing normally	0.91-0.96W	0.93W

Walking	2.5-3.0W	2.6W
Right angle bend	5.5-6.0W	5.9W

By analysing the test results, the system can achieve high success rate of motion posture detection, and achieve accurate measurement of the pressure of the knee joint.

7. Conclusions

This paper focuses on the knee joint problem of people who often engage in sports and proposes a design method of human knee joint intelligent monitoring system. The paper includes theoretical model, hardware and software circuit design, system function introduction and test results of the system.

The experimental results show that the system can display knee joint status quickly, detect wrong knee posture accurately and do fatigue warning timely.

The human knee joint intelligent monitoring system proposed in this paper can monitor the knee joint state in practice and help people correctly use the knee joint, thereby reducing the probability of knee joint lesions.

Acknowledgments

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