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A Portable Pressure and Force Line Trajectory Measuring System for Unicondylar Knee Arthroplasty*

Xinyu Dai, Zhecheng Yang, Zhihua Wang, Baojun Mai, Binjie Zhu, Hong Chen

Abstract— **The pressure and force line trajectory of the distal femoral prosthesis relative to the prosthesis gasket are key factors in judging the appropriate position of implants in unicondylar knee arthroplasty (UKA) surgeries, which is critical to the success of UKA surgeries. In this paper, we propose a portable pressure and force line trajectory measurement system, which includes a pressure sensors array, an analog-to-digital converter (ADC), and a microcontroller unit (MCU). Data from twenty sensors is obtained through time-sharing scanning and transmitted to the host computer through the USB interface. We put forward an algorithm to calculate pressure value and fit the force line trajectory for better accuracy. Both the pressure value and force line trajectory are calculated and displayed on the screen of the host computer by developed software in real-time. The experiments results show that the root mean square error of fitting force line trajectory in the experiments is ±0.342mm, which has 63% reduction compared with that in the previous work, and the average pressure value measurement error is 10.03%. Besides, the pressure sensors array, the ADC and the MCU in the system are integrated in a portable handle, which is easier for clinic trial.**

Clinical Relevance—**This system can assist doctors to improve the success rate of unicondylar knee arthroplasty and reduce patient's pain.**

I. INTRODUCTION

Since the knee is the weight-bearing joint of the human body, high pressure for a long time may cause an injury to the knee joint, which can ultimately develop into an osteoarthritis (OA). The knee arthroplasty is one of the most common options, which is an artificial joint replacement surgery widely performed recent years and can relieve the joint pain thoroughly in theory [1]. A successfully implanted prosthesis can work well for several decades. Generally, there are two types of the knee replacement surgery: total knee replacement (TKA) and unicondylar knee arthroplasty (UKA) [2]. Compared with TKA surgery, UKA surgery has some advantages such as faster recovery after surgery, less postoperative complications and less bone injury [3]. According to the statistics, 85.4% of the cases returned to a higher or similar level after the UKA surgery [4].

The schematic of prothesis for UKA is shown in Fig.1 (a). A single ankle knee prothesis consists of the femoral prosthesis, the prosthetic gasket and the tibial prosthesis. The location of the unicondylar knee prosthesis is shown in Fig. 1(b) [5]. We can see that UKA can retain more bone tissue as a minimally invasive surgery, but it also makes it more difficult to calibrate the prosthesis during surgery [6]. This happens to be the key to the success of the entire UKA surgery. Proper implantation location will minimize wearing and loosening, and shorten the patient's pain period after surgery, which requires appropriate force line trajectory and matching pressure in UKA. Therefore, auxiliary devices are necessary to calibrate the position of the prosthesis in UKA.

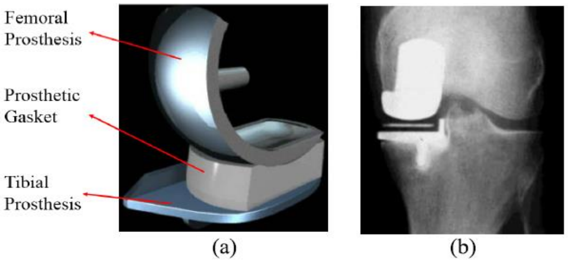

Fig1. (a) The schematic of prothesis for UKA. (b) Placement of the prothesis after UKA.

In UKA surgery, with auxiliary devices surgeons could obtain the force line trajectory of the distal femoral prosthesis relative to the prosthesis gasket by changing the patient's knee flexion and extension angle. Bad force line trajectory indicates that the implantation position of the prosthesis is inappropriate, which increased the risk of more pain after the surgery and wearing of the prosthesis [7]. In addition, mismatched pressure inside and outside the knee joint will also increase the patient's pain, accelerate the wearing of the prosthesis, and even lead to the failure of the operation. Therefore, UKA still has a rate of surgical failure now, and many efforts have been taken to improve the success ratio of the surgery. Current robotic surgical aid systems of measuring the force line trajectory are accurate enough to guarantee the success rate of UKA, but high cost and cumbersome operation limit their clinical application [8]. Besides, finite element analysis is used to establish pressure model based on the shape and material of the prosthesis gasket to fit the force line trajectory as described in [9] [10] [11]. This traditional algorithm meets the accuracy requirements, but the complex and computationally intensive mathematical model is not suitable for the real-time requirements of the system. Our previous work in [12] proposes a force line trajectory measurement system and an iterative algorithm to find the maximum pressure point and fit

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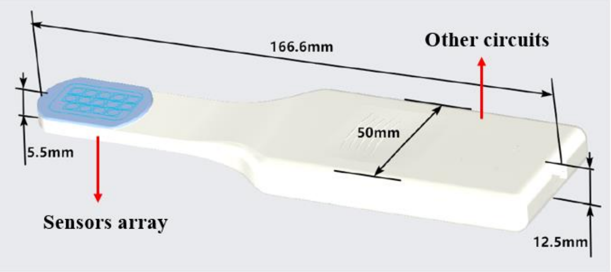
force line trajectory, which is easier to be implemented and used. However, the pressure value between the femoral and gasket prosthesis cannot be measured and displayed in real-time by the system in previous work.

In this paper, we put forward a pressure and force line trajectory measuring system integrated in a portable handle for UKA surgery. Algorithms for calculating the pressure value, solving the coordinates of maximum pressure point and fitting the force line trajectory are proposed. Compared with previous work in [12], this system not only calculate the pressure value and its coordinate of each maximum pressure point, but also fit the force line trajectory in real time. Moreover, the algorithms in this paper are simpler for hardware implementation and both the pressure value and force line trajectory can be displayed in real-time. Besides, all the circuits are integrated in a protable handle, which makes it possible for clinic trail.

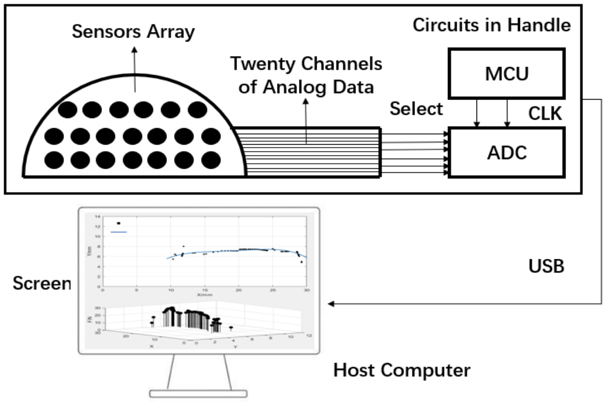
The rest of the paper is organized as follows: Section II introduces the pressure and force line trajectory measurement system for UKA. The algorithms for calculating pressure value and solving coordinates of maximum pressure point are described in section III. The experimental results will be discussed in section IV. Finally, the conclusion is drawn in section V.

II. THE PORTABLE PRESSURE AND FORCE LINE TRAJECTORY MEASUREMENT SYSTEM FOR UKA

A. *System architecture*



(a) Schematic diagram of the handle



(b) Block diagram of the system included microcontroller unit (MCU), Analog-to-Digital Converter (ADC) and clock signal (CLK)

Fig.2 System architecture and schematic diagram of the portable handle

The schematic diagram of the handle and the block diagram of the system is shown in Fig.2. From Fig.2 (a) we can see that the system is integrated inside a handle, which is convenient for doctors to use for auxiliary measurement during the surgery. The sensors array is placed in the head of the handle, which will be placed between the femoral and the prosthesis gasket in surgeries. The circuits inside the handle is shown in Fig.2 (b), which is comprised of the custom pressure sensor array with twenty resistive sensors, an analog-to-digital converter, a microcontroller unit (MCU)and USB interface.

Compared with previous work in [13], we have simplified the system and integrated the system into a portable handle for clinic experiments. The custom pressure sensor array is integrated in the head part (that is, sensors area) in Fig.2 (a), and other circuits are fixed in the body part of the handle. The system is controlled by (MCU, which replaces the FPGA used in [13]). In order to simplify the hardware circuits, data processing is implemented by our algorithms with developed software in the host computer. Besides, to reduces the power consumption of the system, we adopt wired transmission by USB interface instead of the RF circuits in [13].

B. *Pressure sensors array*

The pressure sensor array we use is customized designed and the same as that in [13]. This sensor works as follows: when a sensor unit is selected, the voltage of the unit is compared with that of the determined resistance and then the resistance of the unit is calculated.

C. *Controlling circuits*

The data from sensors is first converted into digital data by ADC, and MCU is responsible of selecting which sensor data is used and transmitted to host computer by USB interface. We use an ADC chip (AD7705) from ADI (Analog Devices, Inc.). Wired transmission is free from external signal interference by other instruments in operation room.

D. *System work flow*

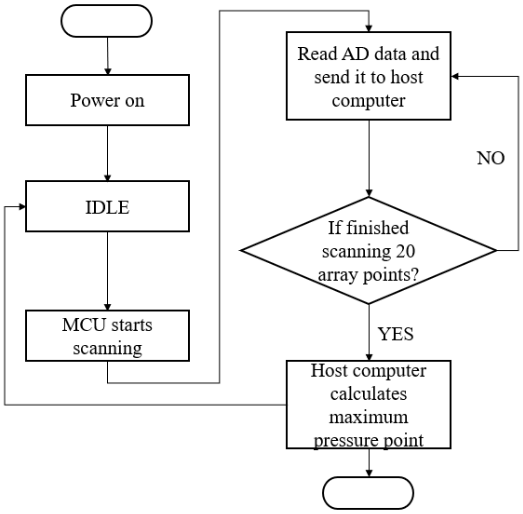


Fig.3 System workflow

The system workflow is shown in Fig.3. First, the system is powered on and starts to work by the control of the developed software in the host computer. The data from the sensors array is polled and sampled by ADC (controlled by

MCU). When the system finishes scanning 20 array points, host computer starts to calculate the maximum pressure point. The resultant force point and pressure value are displayed on the screen in real time and a force line trajectory is fitted. The time when the system is suspended or stopped is also controlled by developed software in the host computer.

III. ALGORITHM FOR MAXIMUM PRESSURE POINT AND PRESSURE VALUE

We adopt piecewise linear fittings in the algorithm for pressure value measurement, and the coordinates of maximum pressure point are calculated with a locally weighted fitting algorithm.

A. Algorithm for Maximum Pressure Value Measurement

Since the linearity of a single sensor unit cannot meet the requirement of the measurement, we take the measured values of all sensor units into consideration when we calculate the resultant force at one point, which is different from the method in our previous work [11]. In our systems, the linearity of the custom sensor depends on the applied pressure. When the pressure is more than 10N and less than 90N, we calculate the resultant force as:

$$kx + b = F \tag{1}$$

where *x* represents the reciprocal sum of the measured values of all sensor units, and *F* refers to the resultant force. When the applied pressure is less than 10N and more than 90N, we add the quadratic term for correction. That is:

$$ax^2 + bx + c = F \tag{2}$$

The coefficients in the formula (1) and (2) (such as *k, a, b*, and *c*) are obtained by fitting the existing data set.

B. Algorithm for the Coordinates of each Maximum Pressure Point

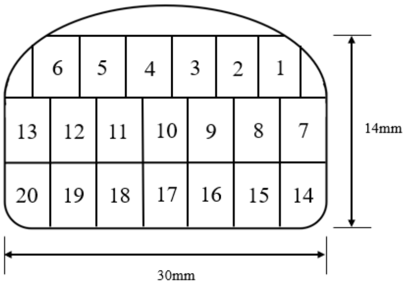


Fig. 4. The distribution of twenty sensor units

The distribution of twenty sensors is shown in Fig. 4, from which we can see that the sensors array consists twenty sensors. When pressure is applied on the sensors array, each sensor unit outputs corresponding resistance value. The smallest resistance value, the largest pressure applied on the sensor. The coordinates of maximum pressure point are obtained by locally weighted fitting considering the measured values and coordinates of nearby sensor units, where the weighting coefficient ω^i is given by (3).

$$\omega^i = exp\left(-\frac{(x^i - x)^2 + (y^i - y)^2}{2\tau^2}\right) \tag{3}$$

where the weighting coefficient ω^i for the ith sensor unit depends on the distance from the ith sensor unit to the sensor unit with the smallest resistance value output; (x^i, y^i) and (x, y) are the coordinates of the ith sensor unit and the sensor unit with the smallest resistance value output; parameter τ is used to adjust the magnitude of the weight change. Then we fit the pressure surface by (4):

$$ax' + by' + cx'y' + dx'^2 + ey'^2 = z \tag{4}$$

where x', y' are the coordinates and z is the processed pressure value from every sensor unit. Every pressure value is processed as follows:

$$z^i = F^i \times \omega^i \tag{5}$$

where i stands for the ith sensor unit. We can obtain the coordinates of the maximum pressure point after fitting the pressure distribution surface.

Finally, we use a polynomial to fit the trajectory of the force line based on the obtained points. In our experiments, fourth-order polynomial fitting can meet the requirements of the accuracy, which is given by (6).

$$ax^4 + bx^3 + cx^2 + dx + e = y \tag{6}$$

IV. EXPERIMENT RESULTS AND DISCUSSIONS

A. The Designed Experiment Platform

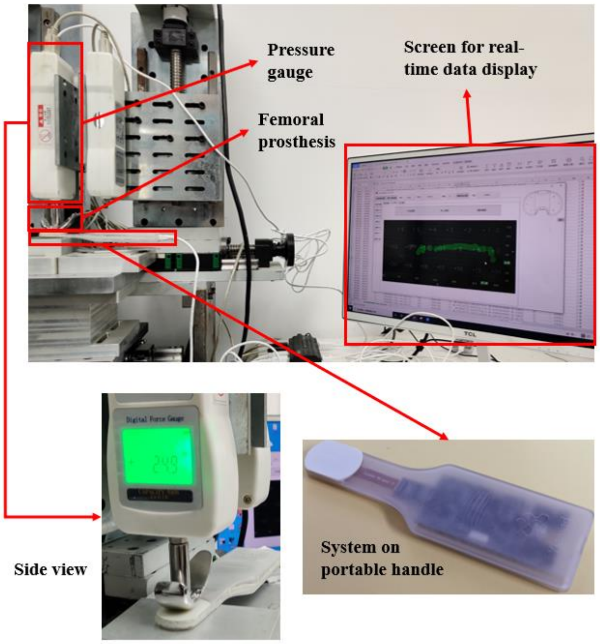
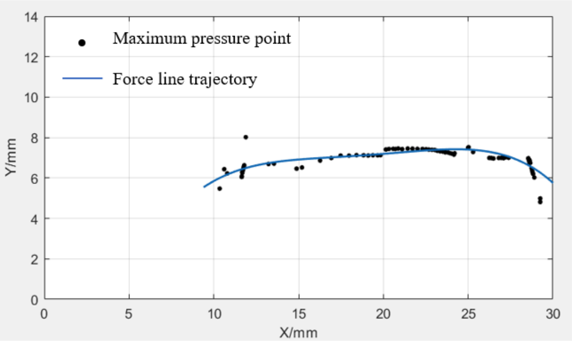


Fig5. The experimental platform

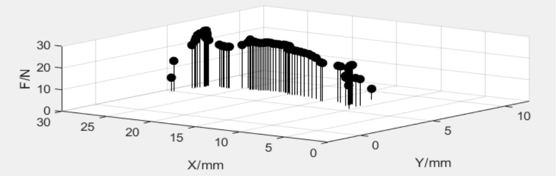
The experimental platform of the pressure and force line trajectory measurement system is shown in Fig.5, from which we can see that the pressure gauge with a designed femoral prosthesis is used to apply pressure on the head (sensors area) of the handle. The system is integrated inside the portable handle and the screen of the host computer is for real-time display. The sensor area of the handle is tough enough to bear a pressure of up to 150 N. The pressure gauge applies pressure to the sensors array through the femoral prosthesis installed on it. The handle is connected to the host computer through a USB cable.

The data from the sensors array will be first conversed to digital data, then collected and processed by the developed software on the host computer, and both the calculated pressure value and force line trajectory is displayed in real time.

B. *Experiment Results*



(a) Fitted force line trajectory



(b) Maximum pressure points and their coordinates
Fig.6 Experimental results

We have carried on 150 sets of experiments and the pressure applied on the handle ranges from 0N to 150N. The experimental results are illustrated in Fig.6 when the applied pressure is about 24.9N. In Fig.6 (a), the x-axis and y-axis stands for the position coordinates of the measured point on the sensors array. The black points are the maximum pressure points and the blue curve is the fitted force line trajectory. The pressure value at maximum pressure point is shown in Fig.6 (b), from which we can see that the measured pressure values are distributed around 25N.

In the experiments, this system completes full-sensors-array data sampling twenty times per second, which meets the requirements of real-time measurement. The effective pressure measurement value ranges from 10 N to 150 N. With 150 sets of measurement data of various pressure values, the average pressure value measurement error is 10.03% from 20N to 90N, and the error when the applied pressure is less than 20N or more than 90N is 16.02%. The root mean square error (RMSE) of the coordinates of the maximum pressure points and fitted force line trajectory in the experiments is ±0.342mm. Compared with ±0.92mm in the previous work, the measurement accuracy has 67% improvement. The average current consumption under working condition is 20 mA.

V. CONCLUSION

In this paper, a pressure and force line trajectory measurement system for UKA surgery is presented, which is comprised of the custom array pressure sensor of twenty resistive sensors, ADC, MCU and USB interface. The pressure value and force line trajectory are both calculated and displayed in real time on the screen. Experiments results show that the root mean square error of fitting force line trajectory in the experiments is ±0.342mm, which has 63% reduction compared with that in previous work, and the average pressure value measurement error is 10.03%. Besides, we have simplified the data acquisition and transmission circuits, which reduces the hardware cost. The wired data transmission of this system replaces the previous radio frequency circuit, which save power of the system. In the future, clinic experiments will be carried on.

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