

Measurement of Femoral neck and Leg Length in Total Hip Arthroplasty Based on Optical Positioning

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Abstract: In traditional total hip arthroplasty (THA), it is difficult to accurately measure the length of femoral neck when the replacement area is limited and deep. It may eventually lead to excessive difference in the length of two legs. This paper presents a method for measuring the length of femoral neck in THA based on optical positioning. During the operation, the end of the probe with a positioning ball was used to measure the length of the femoral neck in real time to assist surgeons in surgical decision-making. According to the comparison between the ideal length and the actual length, the femoral head prosthesis was reasonably selected for adjustment. As it is difficult to accurately and quickly measure the difference of two legs after the placement of prosthesis in traditional surgery, a spatial measurement method of medical anatomical points of two legs based on optical positioning is proposed. By measuring the length of the affected leg with a probe and comparing it with the length of the normal leg before operation, the feedback information of synchronous measurement is further verified. Experiments verify the feasibility of this method for the detection of leg length difference. The average error of these experimental measurements is within 1 mm.

Keywords: Total Hip Arthroplasty, Femoral Neck, Two legs, Optical Positioning, Probe, Measurement

1. INTRODUCTION

Due to the declining bone quality of the elderly, the elderly are a high prevalence of hip fracture. With the development of an aging society, THA is one of the common methods to treat related hip diseases. According to the Blue Book of Health Industry: China's Health Industry Development Report, the number of elderly people aged 60 and above in China will reach

483 million in 2050. With the aging of people, the demand for THA will increase. However, traditional artificial joint replacement mainly relies on the subjective experience judgment of surgeon, which may easily lead to the following deficiencies. Unequal length of two legs after THA becomes an important cause of litigation for patients [1-3]. Selecting the appropriate length of femoral head prosthesis to reduce postoperative bilateral lower extremity inequality will make patient feel better and recovery more fast after the operation. Since there is an error in the depth of bone stem insertion into the meditation cavity in practice, the length of femoral neck is adjusted in real time by the measurement results to compensate for this error.

In traditional surgery, measuring the length of two legs depends on the preoperative plan. However, it lacks the steps to adjust the length of the femoral neck during surgery, and directly measure the length of the legs. At present, the common methods are as follows. The first one is CT measurement [4], which measures the difference in distance between the lower edge of the teardrop on both sides and the apex of the inner edge of the lesser trochanter on both sides to determine the difference between two legs. The disadvantage of this method is that it is difficult to ensure the consistency of the results before and after the operation based on preoperative measurements. The second one is the healthy-side comparison method [5], which determines whether the length of two legs is normal by touching the anatomical marker points such as the anterior superior iliac spine, patella, and medial ankle for symmetry. The third one is the Shuck test method [5]. When the implanted prosthesis is in place, stretch the affected limb. At this time, after visually checking that the lengths of the two legs are consistent, continuously adjusting the length of the femoral neck. The purpose is to ensure that the gap between the lining and the femoral head prosthesis is within the normal range and keep the length of the two legs consistent. The disadvantage of healthy side comparison method and shuck test method is that it has large error based on the experience of surgeon. The fourth one is the fluorescent image matching method [6], which uses flu-

orescent images to capture images of the prosthesis after placement and matches them with images of the preoperative normal leg size year over year, thus assessing the offset and the difference in length between two legs. The disadvantage is that there is an invasive risk caused by radiation exposure and additional skin incision, which increases the operation cost of other accidental risks.

Therefore, THA needs to reduce the length difference between the two legs by adjusting the femoral neck length of the prosthesis. At present, there are several ways to adjust femoral neck length during operation. The first is to adjust the length of femoral neck by measuring the distance between two reference points using a vertical ruler, vernier calipers, and kerf pins to determine the femoral eccentric distance. Kyoichi O et al.[7] used a measuring device similar to a vernier caliper for measurement. Tagomori h et al.[8] put a vertical ruler on the edge of the lining and mark the big rotor when it is close to the big rotor. Then he pulled out and measured the offset with a level ruler to judge the eccentricity. The kerfing needle positioning method [29-30]. Insert the Kirschner wire vertically above the acetabulum. After marking the outside of the greater trochanter, measure the distance between the two key points. The disadvantage of these mechanical structures is that the deployment of measuring equipment requires direct intervention in the diseased part of the patient's operation, which may interfere with the surgeon's operation. In addition, its generality is not strong and it is not convenient for surgeon to read it quickly. Surgical robots such as Mako [9] used computer-aided imaging system to measure the morphological parameters of femoral neck. The disadvantage is that surgeon need to register in the computer system in real time and wait for the system to complete the comparison between image coordinates and actual spatial coordinates. The whole process is complex, so doctors need to be familiar with the operation process after many operations [10]. In addition, the learning curve of the navigation system is slow to converge. Renkawitz T et al.[19] used an image-free navigation system to calculate the difference between the two legs with some feasibility.

The contribution of this study is to propose a method for real-time measurement of femoral neck length using a probe in a image-free surgical navigation system based on optical positioning. It has the characteristics of convenient, efficient and scalable high precision. This method is used to assist surgeons to select the appropriate prosthesis size during surgery. So as to meet the requirements of the length error difference between the two legs of the patient. It is helpful to reduce the possible postoperative complications. This method uses the principle of optical positioning. When the positioning ball is placed within the monitoring range of optical equipment, the positioning ball can be positioned with high

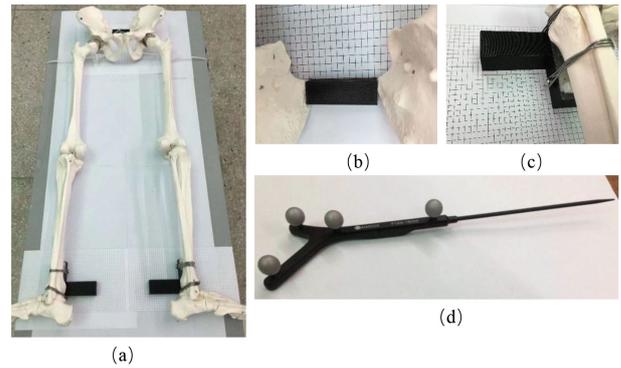


Fig. 1. Experimental materials and tools. (a)Skeletal model, (b)Hip calibration on millimeter paper, (c)The cushion block moves on mm paper, (d)Probe.

precision in real time. At the same time, because the volume of the commonly used optical positioning system is small, it does not affect the space for the surgeon to operate during the operation.

2. Materials and Methods

2.1. Simulation experiment materials

THA simulation experiments were performed using a skeletal model testbed [11], which was arranged as follows. an adjustable skeletal model (Fig.1(a) male pelvis, sacrum, PVC material) was set up, the hip was immobilized and was placed on millimeter paper calibratable for hip variation (Fig.1(b)), a calibration pad was fixedly placed under the posterior epicondyle axis(Fig.1(c)), Placing the gasket on the MM paper and drawing the outline of the cushion block, so that the two legs could be simulated to move along the MM paper with the cushion block.

2.2. Method principle

The main purpose of this experiment is to evaluate the accuracy of the measurement method proposed in this paper and to solve the intraoperative problem of fast, convenient, accurate, and real-time visualization of the stuck neck measurement of femoral neck length. The basic principle is to use optical sensors to track the optical positioning balls from different angles, and the three-dimensional coordinate position of the positioning balls in space can be determined. Placing the probe with the positioning ball under the optical positioning system. The three-dimensional coordinates of the probe tip can be determined by capturing the four positioning balls of the probe. At the same time, in order to get the relative position information of two points in space, the distance between two spatial points can be calculated by touching the two coordinate points that need to measure the distance through the end-effector. Similarly, the

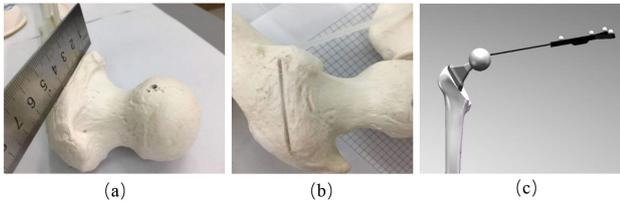


Fig. 2. Simulated femoral neck length measurement. (a) straight ruler to simulate the osteotomy surface, (b) osteotomy surface position, (c) measurement of the highest point of the prosthetic head.

distance from the point to the surface can also be calculated.

2.3. Methods and procedures of simulated surgery

In the experiment, we simulated the real-time measurement of femoral neck length. As shown in Fig.2 (a), we fixed the ruler on the osteotomy groove (Fig.2 (b)). The purpose is to simulate the osteotomy surface. The actual length of the femoral neck is obtained from the distance from the highest point to the osteotomy surface measured in real time by the optical positioning based probe (Fig.2 (c)). Then assist the surgeon to select the appropriate type of prosthetic head. After the prosthesis was installed, the length of the affected leg was measured in real time. We compared the obtained measurements with the preoperative measurements. Finally, by comparing the length of the affected leg with the length of the normal leg measured before operation, the reliability of the measured value is further verified and fed back. The experimental setup is as follows. Firstly, the length of femoral neck is measured with a probe and repeated for 20 times. secondly, the following experiments were repeated for 10 times. The difference between the two legs after operation was measured by simulation (Fig.1 (a)). The left and right legs moved 5 mm and 10 mm longitudinally along the millimeter paper. The left leg moves 5 mm and 10 mm to the left. The right leg moves 5 mm and 10 mm to the right.

Intraoperative femoral length measurement scheme based on the optical positioning principle is shown in Fig.3 (a). The distance from the rotation center of the femoral head to the osteotomy surface is called femoral neck length C . As shown in Fig.3 (b), the femoral neck length C after replacement is affected by the depth of the femoral stem that has been inserted into the medullary cavity. At the same time, the depth of femoral stem inserted into medullary cavity depends on the matching result of prosthesis template before operation and the actual inner diameter of medullary cavity after grinding during operation. Therefore, during surgery, since there is a depth error during the insertion of the femoral stalk

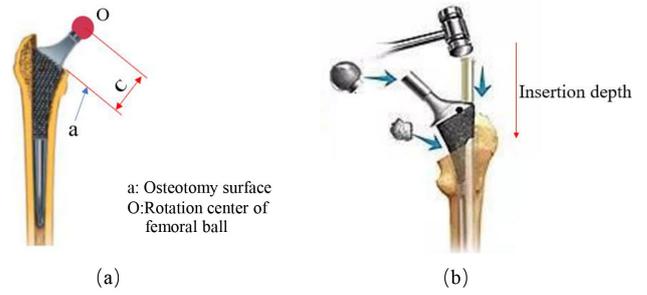


Fig. 3. Definition and influencing factors of femoral neck length. (a) Femoral neck length, (b)Factors affecting the length of the femoral neck.

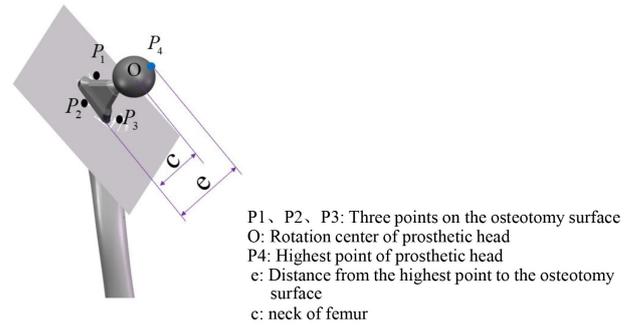


Fig. 4. Error affecting the actual femoral neck length.

into the medullary cavity, it is necessary to measure the length of femoral neck prosthesis in real time and adjust the length of femoral neck prosthesis to reduce this error.

The neck of femur length is calculated as follows. Moving the probe end at the osteotomy surface, the system can obtain the three-dimensional coordinates of three non collinear marker points on the osteotomy surface, which are $P_1(x_1, y_1, z_1)$, $P_2(x_2, y_2, z_2)$, $P_3(x_3, y_3, z_3)$. What's more, the system can construct a space plane based on those mark point positions. As shown in Fig.4, these three points determine a plane. After inserting the prosthesis femoral stem into the femur and installing the prosthesis prosthetic head, measure the highest point of the prosthetic head with a probe (Fig.2 (c)). Then get the coordinates of the point $P_4(x_4, y_4, z_4)$. According to the distance formula from the point to the surface, the distance e from the highest point of the prosthetic head to the osteotomy surface was calculated. Selecting the prosthesis femoral neck part with appropriate femoral neck length C through distance e . The intraoperative femoral neck length is $C_1(C_1 = e - r)$, and r is the rotation radius of the femoral head sphere. The femoral neck length $C_0(C_0 = e_0 - r)$, the distance from the highest point of the prosthetic head to the osteotomy surface before operation is e_0 measured by preoperative CT was compared. Therefore, the femoral head prosthesis with appropriate length

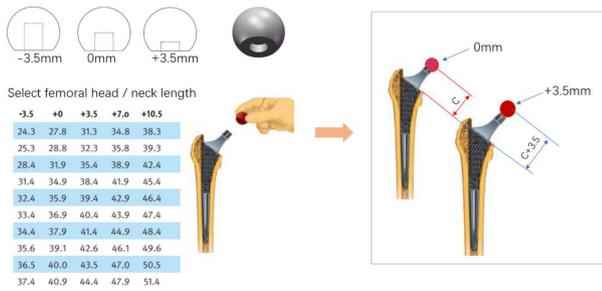


Fig. 5. Adjust the length of the femoral neck with different sizes of prosthesis

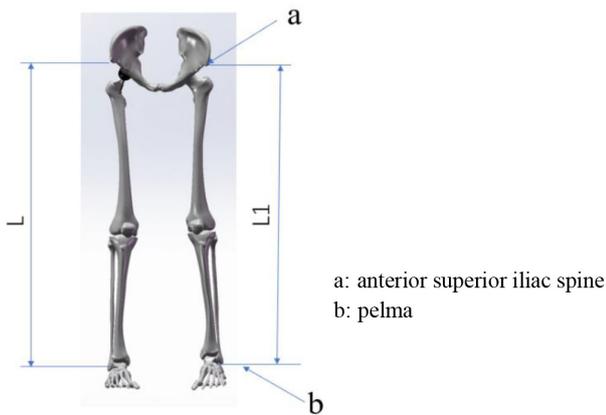


Fig. 6. Method of measuring the length of two legs

can be selected. As shown in Fig.5, after looking up the table and adjusting the length of femoral neck, selecting a femoral head prosthesis model of appropriate size.

With the help of the image-free surgical navigation system based on the principle of optical positioning, the surgeon can install the prosthesis according to the measured parameters. At the same time, after real-time feedback adjustment, the probe was used to measure the length of bilateral two legs in real time. As shown in Fig.6, the distance between the anterior superior iliac spine and the plantar of normal leg was measured before operation. It is then used as a control reference length. After prosthesis implantation, the distance between the anterior superior iliac spine and the plantar of the patient's leg was measured. The intraoperative values were compared with those before operation.

Clinical definition of unequal length of two legs [31], the length difference between two legs is less than 10 mm. As shown in Fig.6, if the length of legs $|L - L1| > 10$, the length of femoral neck prosthesis needs to be adjusted until the error is within the allowable range.

3. Experiments and Discussion

3.1. Results and Analysis

The first scheme is to measure the distance from the highest point of the prosthetic head to the osteotomy surface in real time. The measurements were repeated 20 times using a probe based on optical positioning. As shown in Fig.7 (a), the results are distributed between 68.46-69.98 mm. On the basis of Fig.2 (a), using another ruler to measure the distance between two ruler planes parallel to the groove and passing through the highest point of prosthetic head. The average value of repeated measurement for 20 times combined with caliper is 69.5 mm, which is used as the reference comparison value. The second is the scheme, without moving the cushion block under the epicondylar axis, measuring the length of the two legs (Fig.7 (b)). The third is the scheme, moving the cushion block under the epicondylar axis down different longitudinal distances along mm paper. Simulate the change when the two legs move down by 5 mm and 10 mm at the same time (Fig.7 (c)). The fourth is the scheme, comparing the length of the two legs when different transverse distances move on mm paper at the same time (Fig.7 (d)). For example, if the left leg moves 5 (or 10) mm to the left, the right leg synchronously moves 5 (or 10) mm to the right. The fifth is the scheme, when only one leg moves at different longitudinal distances, the length difference between the two legs (Fig.7 (e)). The sixth is the scheme, when only one leg moves at different transverse distances, the length difference between the two legs (Fig.7 (f)).

As can be seen from table 1, the following conclusions are obtained. The first one, the average error of measuring the distance from the highest point of the prosthetic head to the osteotomy surface is 0.15 mm. The second one, when two legs are not moved, the average difference between the two legs is 0.14 mm. The third one, when two legs move longitudinally downward for 5 mm and 10 mm at the same time, the average difference between the two legs is 0.05 mm and 0.01 mm respectively. The fourth one, when the left leg moves 5 mm to the left and the right leg moves 5 mm to the right, the average difference between the two legs is 0.1 mm. When the left leg moves 10 mm to the left and the right leg moves 10 mm to the right, the average difference between the two legs is 0.09 mm. The fifth one, the left leg remains stationary and the right leg moves longitudinally downward by 5 mm and 10 mm. The average difference between the two legs is 5.24 mm and 10.50 mm respectively. Their errors are 0.24 mm and 0.5 mm respectively. The right leg remains stationary and the left leg moves longitudinally downward by 5 mm and 10 mm. The average difference between the two legs was 5.05 mm and 10.34 mm respectively. Their errors are 0.05 mm and 0.34 mm respectively.

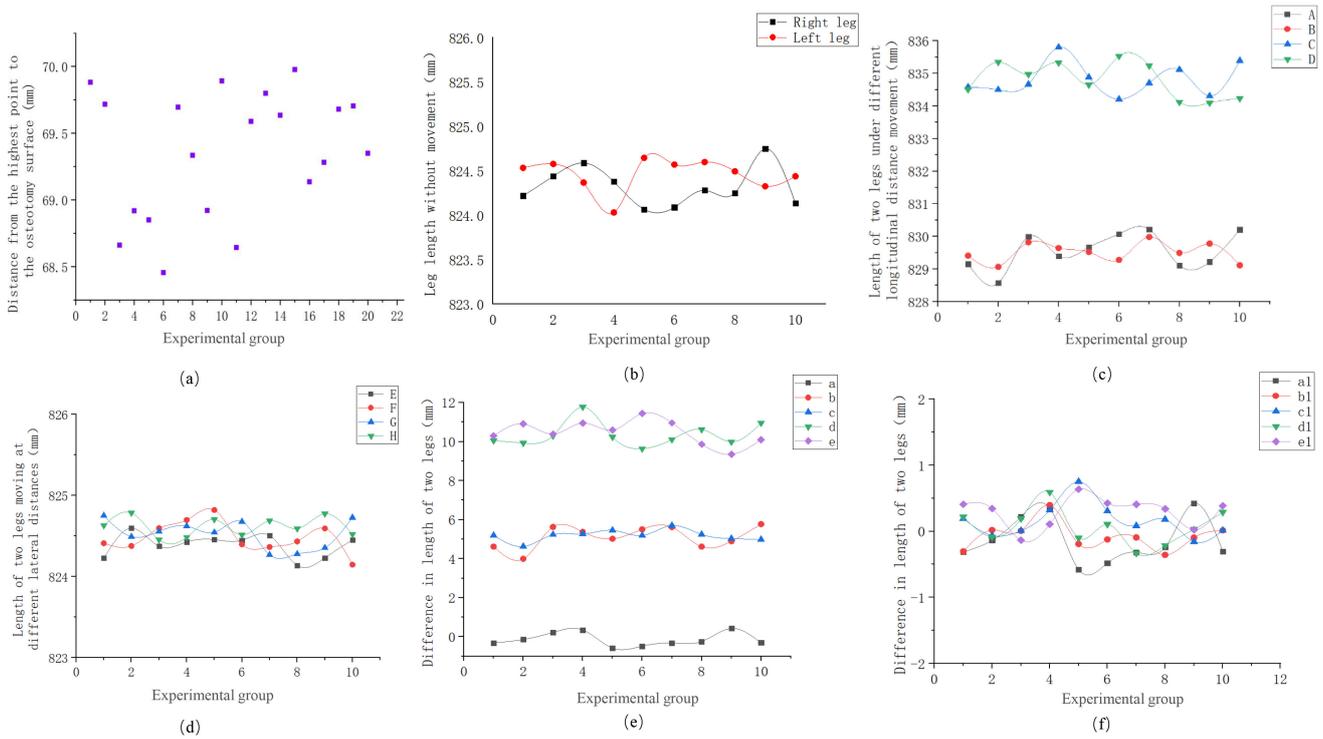


Fig. 7. Results of the experimental group. (a) Scatter plot of femoral neck length, (b) When two legs are not moved, their length curve changes, (c) when moving downward for 5 mm at the same time, A and B are the change curves of the measured right leg and left leg respectively, and when moving downward for 10 mm at the same time, C and D are the change curves of the measured left leg and right leg respectively, (d) E and F are the change curves of measuring right leg moving 5 mm to the right and left leg moving 5 mm to the left respectively, G and H are the change curves of measuring right leg moving 10 mm to the right and left leg moving 10 mm to the left respectively. (e) a is the difference curve of two leg lengths when the left leg does not move, b and d are the difference curve of two leg lengths when the right leg moves down by 5 mm and 10 mm respectively, c and e are the difference curve of two leg lengths when the right leg does not move, and when the left leg moves down by 5 mm and 10 mm respectively, (f) a1 is the difference curve of two leg lengths when the left leg does not move, b1 and d1 are the difference curve of two leg lengths when the right leg moves 5 mm and 10 mm to the right, c1 and e1 are the difference curve of two leg lengths when the right leg does not move, and the left leg moves 5 mm and 10 mm to the left.

The sixth one, when the left leg remains stationary and the right leg moves laterally to the right by 5 mm and 10 mm, the average difference between the two legs is 0.07 mm and 0.07 mm respectively. When the right leg remains stationary and the left leg moves laterally to the left by 5 mm and 10 mm, the average difference between the two legs is 0.16 mm and 0.29 mm respectively. Because the average length of the left leg is 824.32 mm, when moving laterally by 5 mm and 10 mm, the length of the moving hind leg can be calculated according to the pythagorean theorem, and then the variation values of 0.015 mm and 0.06 mm can be obtained respectively. Similarly, the changes after the movement of the right leg were 0.015 mm and 0.06 mm respectively. According to the leg difference of 0.14 mm when not moving, theoretically, the leg difference after left and right moving is 0.155 mm and 0.2 mm respectively (or 0.125 mm and 0.08 mm respectively). In the above comparison, the measurement error of the mean difference between the two legs was within 0.3 mm.

3.2. discussion

During THA, the selection of the appropriate size of the femoral head prosthesis is very important for the success of the surgery. Selecting the appropriate size by measuring the neck length of the femoral head prosthetics not only helps to avoid limb length differences after surgery, but also effectively improves the satisfaction of patients with the operation. During traditional THA, there is usually no step to measure the femoral neck length, relying on the surgeon's visual observation and subjective experience to determine the femoral head neck length and select the prosthesis, which can lead to a large discrepancy between the two legs after the prosthesis is installed. Zhang et al.[5] used intraoperative measurements to determine the difference between the two legs using the healthy side comparison method, the Shuck test method. In addition, postoperative in vitro and imaging measurements were used to determine differences between the two legs. However, the best result

Table 1. Statistical table of optical positioning system probe measurement results

Variable name	Times	Average value(/mm)	Standard deviation	Variance
Distance from the highest point of prosthetic head to osteotomy surface	20	69.3557	0.47217	0.223
Right leg not moving	10	824.3208	0.22177	0.049
Left leg not moving	10	824.4596	0.18204	0.033
The right leg moves longitudinally for 5 mm	10	829.5612	0.55809	0.311
The left leg moves longitudinally for 5 mm	10	829.5114	0.30305	0.092
The right leg moves longitudinally for 10 mm	10	834.8166	0.49645	0.246
The left leg moves longitudinally for 10 mm	10	834.8020	0.54894	0.301
The right leg moves laterally to the right for 5 mm	10	824.3857	0.14319	0.021
The right leg moves laterally to the right for 10 mm	10	824.5276	0.17732	0.031
The left leg moves laterally to the left for 5 mm	10	824.4841	0.19400	0.038
The left leg moves laterally to the left for 10 mm	10	824.6146	0.12023	0.014

was only 6.8 ± 2.5 mm. Many current methods adjust the prosthesis by intraoperatively measuring the distance between key points with a mechanical device. tagomori H et al.[8] used two rulers for simple measurement without adding new incisions in the skin or incurring additional costs, and the error of measurement of the two leg lengths was 1.86 ± 1.4 mm. Kyoichi O et al.[7] used a mechanical structure to measure the distance between the acetabulum and the greater trochanter to adjust the prosthesis femoral neck length, and the postoperative difference between the two leg lengths varied from 2.9-12.9 mm. However, these methods are not only easily limited by operation space and reading error, but also by visual inspection. Existing medical procedures use X-rays to detect the patient's leg length and offset multiple times during surgery. These methods have an additional invasive risk of radiation exposure that increases the cost of surgery. In this study, under the image-free surgical navigation system based on optical positioning, the average error of the difference between the two legs measured by the probe was within 1mm. This accuracy is significantly higher than the above accuracy. The main features of the proposed method are high accuracy, real-time data feedback. The system also allows real-time visualization to better assist the surgeon during surgery, effectively reducing the risk to the patient during total hip replacement surgery. In addition, no new skin incisions need to be added during the surgery, and the operation is simple and versatile, which can be expanded accord-

ing to the measurement needs. More effectively, the type of prosthesis can be adjusted quickly by comparing and measuring the length of the patient's two legs in real time. During the THA process, the system achieved the ultimate goal of shortening the wound exposure time and reducing the risk of surgery. This greatly improves the quality of total hip replacement surgery.

4. Conclusions

Based on the principle of optical positioning, the method can calculate the distance between the markers quickly and accurately according to the spatial transformation during the operation. When using a probe to measure femoral neck prosthesis, the prosthetic head model is selected appropriately. Measure the length of each leg after placement to assist the surgeon in verifying that the length difference between the two legs is within reasonable range. After that, the prosthetic prosthetic head model was replaced according to the difference to further verify the accuracy. The method in this study is simple and versatile. In addition, there is no need to make a new skin incision in the affected limb, which can effectively shorten the operation time and avoid the risk of prolonged exposure to the wound. The limitation of this study lies in the lack of conditions to simulate the real experimental environment, so it is necessary to further test this image-free surgical nav-

igation system in actual surgery. In the future, we will use other methods for comparative experiments. In order to more fully prove the advantages of the research. On the other hand, because the sample size of the simulation experiment needs to be as large as possible, the actual situation of the acetabular grinding file is not considered when using the probe to measure the key anatomical points. These are issues that need to be further studied.

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