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An Evaluation of Sensing Technologies to Measure Intraoperative Leg Length for Total Hip Arthroplasty

Akash Chaurasia[1], Jerry Yan[1], Robert Li[1], Kate McCarren[1], Claire State[1], Hannah Takasuka[1], Evan Bender[1], Aditi Jithendra[1], Julius K. Oni, M.D.[2], Amir Manbachi, PhD.[1]

[1]Department of Biomedical Engineering, Johns Hopkins Univeristy, Baltimore, MD USA
[2]Department of Orthopaedic Surgery, Johns Hopkins Bayview Medical Center, Baltimore, MD USA

ABSTRACT

Total hip arthroplasty (THA) procedures have been identified as high-volume procedures with growing prevalence. During the procedure, orthopedic surgeons largely rely solely on qualitative assessment to ensure an excessive limb length discrepancy (LLD) is not introduced from the implant selection. LLD can result in back pain and gait complications, with some cases of LLD requiring a revision procedure to mitigate. To address this issue, we evaluated several methods of sensing distance intraoperatively to determine the best approach to measure leg length during the THA procedure. A testing setup using a sawbones model of hip anatomy in the decubitus position was used as a simulation of the THA procedure to test the accuracy of each of the sensing modalities.

Keywords: Orthopaedic surgery, total hip arthroplasty, surgical tool

1. INTRODUCTION

During the total hip arthroplasty (THA) procedure, diseased cartilage and bone on the pelvis and femur are removed and replaced with implants in order to reinstate function, stability, and range of motion in the hip joint (Fig. 1) [1]. In up to 27% of THA procedures, patients experience a limb length discrepancy (LLD), a condition in which the operative leg is shorter or longer than that of the contralateral side [2]. This difference in leg lengths causes an uneven loading of joints (Fig. 2) [3]. An LLD is considered significant when greater than 5 mm, and results in back pain and gait complications [4, 5]. Patients that are unable to mitigate these side effects account for 0.3% of THA revision surgeries [6].

Currently available solutions that provide intraoperative leg length measurements each have shortcomings. After consulting orthopedic surgeons, we found that out of the 20 orthopedic surgeons we spoke to, 17 rely solely on visual feel and/or physical gauges alone to assess LLD during THAs.

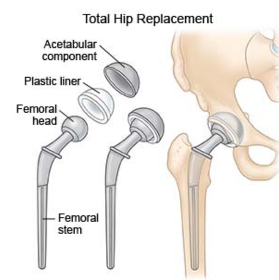

FIGURE 1: HIP PROSTHETIC COMPONENTS AND THEIR POSITIONING IN HIP ANATOMY

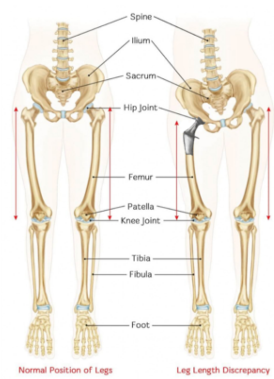

FIGURE 2: A DIAGRAM INDICATING IMPROPER HIP PROSTHESIS, WHICH CAUSES UNEVEN JOINT LOADING, RESULTING IN BACK AND JOINT PAIN

[1] Co-contact authors: akashc@jhu.edu, amir.manbachi@jhu.edu

While gauges and preoperative radiograph templating are significantly less expensive, they are often inaccurate because they use two-dimensional methods to assess this three-dimensional problem. Surgeons often do not utilize preoperative radiographs in their final assessment of leg length because inconsistent patient positioning during THAs can provide misleading measurements. Manual measurement gauges also require the use of invasive pins.

Surgical navigation systems, including Intellijoint HIP and OrthoPilot, provide real-time feedback of LLD by tracking patients' anatomical landmarks via instrument add-ons such as sensors, cameras, or tracker pins. However, incorporation of these devices often requires drilling of pins into patient anatomy, which is invasive and increases the risk of infection. Additional deterrents to adoption include the additional OR time required, which significantly increases the cost per procedure [6], and the steep learning curve associated with many surgical navigation systems [7, 8]. No current solution that addresses LLD is accurate, minimally invasive, and integrable into the current surgical workflow. These factors have proven to be significant deterrents to clinical adoption for surgical navigation, manual measurement gauges, and radiograph templating.

Overall, up to 27% of patients report symptoms of LLD after the THA procedure [3, 9]. 500,000 THA procedures are expected to occur annually in the US by 2020, so there is significant opportunity for a solution for quantifying limb length discrepancy [6]. To address this need, we propose the use of device capable of calculating distances to provide surgeons with a quick and accurate intraoperative method for determining the distance between bony landmarks in the surgical field. The main requirements for such a device are: (1) providing measurements an accuracy of under 3 mm; (2) requiring fewer than 5-10 minutes to use during the procedure. Due to the lack of effective solutions, we have identified potential technologies for such devices in the area of infrared (IR) distance sensors, ultrasonic distance sensors, and IR motion controllers. In this paper, we will quantify the accuracy of these devices, and assess how they would be integrated into the current surgical workflow. The ideal sensor will not only accurately track LLD but also minimally impede other necessary steps of the THA procedure.

2. MATERIALS AND METHODS

We used an IR range sensor (SparkFun Electronics, Boulder, CO), ultrasonic range distance sensor (Matbotix Inc., Brainerd, MN), and an IR motion controller (Leap Motion, San Francisco, CA).

We created a setup using a sawbones model of the hip joint (Sawbones, Seattle, WA) secured with a polymer mold and cardboard to simulate the lateral decubitus position used during THA procedures (Fig. 3). We placed markings at 1 cm increments and placed the sensors on the superior side of the acetabulum aimed at sensing the greater trochanter. We measured the true distances using the markings and recorded the sensor readings of the measured distance at each of the increments.

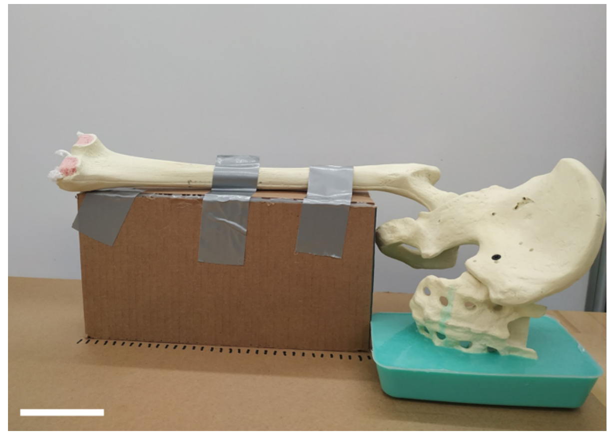

FIGURE 3: TESTING SETUP WITH SAWBONES MODEL REPLICATING THE LATERAL DECUBITUS POSITION DURING THA SURGERY. SCALE = 10 CM

3. RESULTS AND DISCUSSION

The results from our tests have demonstrated that for the purposes of distance measurement, infrared sensor provides the most consistent and accurate measurement as compared to the ultrasonic modality. Though both datasets required post-processing in order to fit the data, the ultrasonic data dropped in measurement quality at a much earlier threshold. According to Figure 4, while the IR sensor maintained a linear relationship across 30 mm, the ultrasonic sensor's accuracy drops steeply after 20 mm. We infer that past this distance, ultrasonic waves are unreliable and suffer from environmental interference, resulting in an unpredictable signal read by the receiver.

Sensor Type	% deviation from true distance	Workflow Integration
IR Distance	4.72	- Reflects a beam of infrared light off the femur and calculates distance - Requires fixation on patient and constant view of femur - Requires at least two distinct sensors to obtain LLD in 3-dimensions
Ultrasonic Distance	0.15	- Transmits ultrasonic signal to reflect against femur and calculate distance based on travel time - Requires fixation on patient and constant view of femur - Requires at least two distinct sensors to obtain LLD in 3-dimensions

IR Motion Controller	1.08	- Reflects multiple beams of infrared light to visualize a reconstruction of the surgical site - Does not require fixation on patient or constant view of the femur - Requires view of the surgical site before hip resection and during implant placement

TABLE 1: A SUMMARY OF TESTING RESULTS, INCLUDING ACCURACY AND QUALITATIVE ASSESSMENT OF HOW TECHNOLOGIES WOULD BE IMPLEMENTED INTO THE SURGICAL WORKFLOW

However, as seen by each sensor's mechanism of action, the least invasive alternative is the IR motion controller. While the other two sensors require fixation to the hip to maintain detection range for LLD, the IR motion controller can be placed at least two feet away and calculate LLD to a relative level of accuracy. Due to the negligible discrepancy in accuracy between the three sensors, the seamless integration into the surgical workflow provides the IR motion controller with advantage over the other modalities.

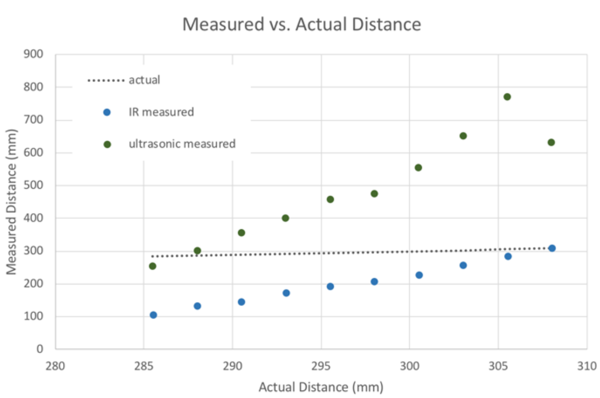

FIGURE 4: A PLOT SHOWING THE TRUE VS. MEASURED DISTANCES FOR IR AND ULTRASONIC SENSORS ACROSS THE INTERVAL OF DISTANCES USED

4. CONCLUSION

In this paper, we evaluated several methods to measure leg length intraoperatively, including IR and ultrasonic distance sensors and an IR motion controller. None of the evaluated technologies were able to deliver the desired accuracy, namely 3 mm. To deliver accurate measurements during the THA procedure, a better approach may be to use a tool registered to an IR tracking system with algorithms to track the position of the tool tip, enabling a surgeon to choose anatomical landmarks used to calculate leg length. Due to the minimally invasive approach, a tool that is either similar to the tested IR motion controller or could be used in conjunction with similar technology would be ideal.

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