A Multi-modality Tracking, Navigation and Calibration for a Flexible Robotic Drill System for Total Hip Arthroplasty

Authors: Ahmad Nazmi Bin Ahmad Fuad [1], Kamal Deep[2], Wei Yao[1].

1. The Department of Biomedical Engineering

   University of Strathclyde

   106 Rottenrow

   Glasgow, G4 0NW

   Scotland, UK

2. Golden Jubilee National Hospital

   Agamemnon Street

   Clydebank, G81 4DY

   Scotland, UK

Abstract

Background: This paper presents a novel multi-modality tracking and navigation system that provides a unique capability to guild a flexible drill tip inside the bone with an accurate curved tunnelling.

Methods: As the flexible drill tip is not trackable via optical tracking system inside the bone, this research focus on developing hybrid tracking and navigation system for tracking a flexible drill tip by using both optical and kinematic tracking system. The tracking information is used to guide the THA (Total Hip Arthroplasty) procedure providing a real-time virtual model of the flexible drill.

Results: The flexible and steerable drill tip system is then experimented on total hip arthroplasty followed by evaluation of the positioning and orientation of femoral stem placement by femoral milling.

Conclusions: Based on this study, we conclude that the tracking and navigation system is able to guide the flexible drill to mill inside femoral canal.

Keywords

Robotics; Flexible; Steerable; Tracking; Navigation; Orthopaedics

1. INTRODUCTION

In orthopaedics surgery, implantation requires accurate operating and positioning in order to have a better outcome and better functional results. In joint replacement surgery, well-aligned and accurate positioning of hip or knee prosthesis is less likely to have a complication of dislocation or abnormal gait pattern.[1] In THA (Total Hip Arthroplasty), accurate positioning results in a better bone union and prevents limb malformation; and restoration of physiology of the limb. Currently, there are vast amount of tools and aids in orthopaedic surgery ranging from simple broaching reamer, drills, hammers, and retractors to more advanced tools such as endoscopic instruments, intraoperative fluoroscopy, and mechanical alignment jigs and cutting blocks. Now, orthopaedic surgery has been introduced with CAOS (computer-assisted orthopaedic surgery) to improve the accuracy of the surgery. It has potential to give positive impact in surgery with precise intraoperative navigation to ensure high standards of accuracy in surgery.

Navigation system can improve accuracy in surgery, allow simulation of surgery and optimize planning via pre-planning feature of CAOS, and has potential to reduce invasiveness. [2][3] One of the advantages for using navigation system is it may improve visualization and accuracy, and control in minimally invasive surgery that is known to have limited exposure and direct visualization. [4]

CT-based navigation technique has the ability to allow surgeons to precisely plan the alignment of the acetabular cup and femoral stem before the procedure and execute it according to the plan. Moreover, exact real-time measurements and tracking enable surgeons to make better judgement in final positioning of the cup relative to the pelvis and femoral stem. [5] Moreover, navigation enables development of minimally invasive surgical technique in Total Hip Arthroplasty as it permits accurate implant orientation and fixation while looking only at the monitor. [6][7] Study has been performed by Jolles et. al. concluded that a navigation system in Total Hip Arthroplasty is very accurate and reproducible, and more precise than conventional technique. [8]

In total hip arthroplasty, CAOS is currently practiced only with acetabular cup positioning and orientation while femoral stem positioning still using hand-rasping method instead of femoral milling. Hamlin *et. al* shows that several studies only focused on acetabular cup positioning due to inability of optical tracking system to track inside bone during femoral milling for femoral stem implantation. Hence, the positioning of both acetabular cup and femoral stem is based on combined ante-version technique within the acetabular cup safe zone placement. [9] On the other hands, the femoral milling has many advantages compared to hand-rasping method, such as the prevention of intraoperative fractures; and radiographic evaluation post operatively shows that femoral milling has better fit, fill and alignment. [10] Femoral stem malposition due to various placements has been associated with poor outcomes such as cement mantle fracture, component loosening and subsidence and is one of the factors in failure of femoral component. [11] Furthermore, various placements are also associated with instability. This error in technique can be minimized by the advent of CAOS, accurate and precise positioning of femoral stem is possible. [12]

Currently, there are not yet available tracking systems that can track surgical tools inside bone; hence it is not yet possible to apply CAOS in femoral milling for total hip arthroplasty. However, hybrid navigation systems are currently developing to allow surgeons to fully utilize CAOS advantages in total hip arthroplasty. [13] Hybrid navigation system combines optical tracking system with other tracking system such as electromagnetic tracking system, ultrasound tracking system, and rotary encoder tracking system. This paper presents a hybrid navigation system that combines optical tracking system and rotary encoder tracking system. The navigation software integrates the tracking systems and guides a flexible drill virtually. In a tight and obscured line of sight of optical tracking cameras, rotary tracking system further navigate and show the exact location of the tip of the flexible drill. These two inputs is then integrated in the software's kinematic algorithm resulting in the visualization of a virtual flexible drill even when the steerable sheath and the tip are within enclosed space out of the optical tracking camera's line of sight.

2. MATERIAL AND METHODS

Concept Design of the Kinematic Tracking

This tracking system has the ability to track a flexible manipulator inside the bone. This is approached by combining optical tracking system and position tracking. Optical tracking systems are used to track the surgical objects and tools outside the drill hole, while rotary encoders placed at each joint of the sheath are used to track the bending angle of a flexible drill. Combined with kinematics of the flexible drill, the tip position of the steerable drill can be tracked in this system shown in Figure 1.

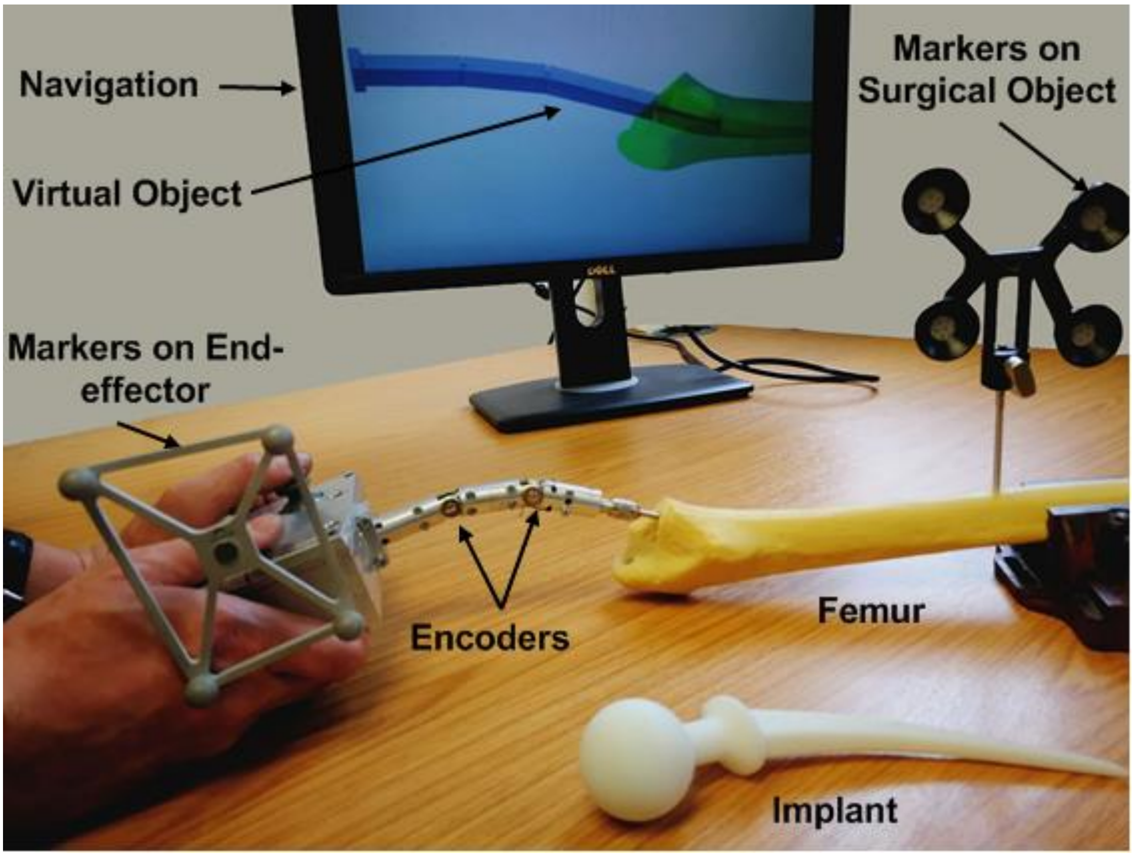
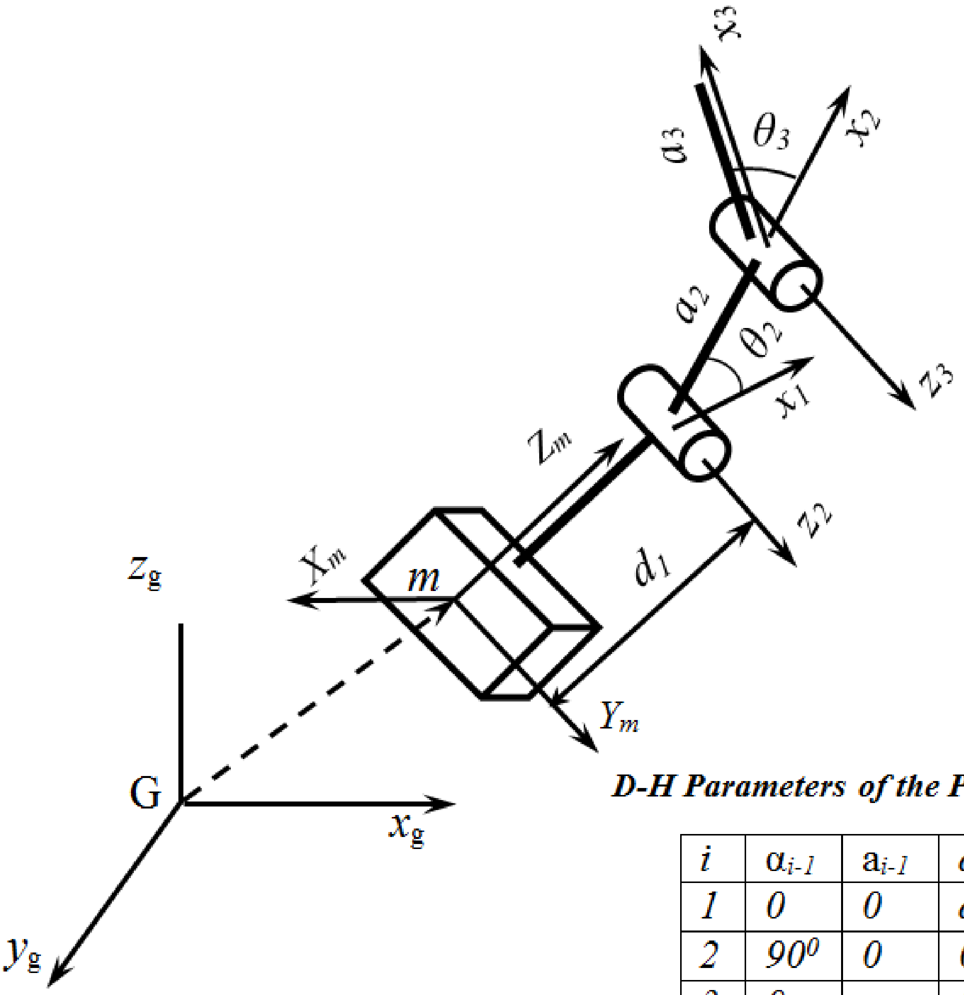


Figure 1

The tracking and navigation system.

The encoder is made up from 20kΩ button potentiometer. When potentiometer shaft rotates, the resulting voltage varies following Ohm's Law. The bending angle of each of the flexible drill sheath joints is equal to rotational angle of potentiometer shaft. Hence, the voltage output of the potentiometer at each degree of rotation is taken and mapped as bending angle of the joints. Analog data from the potentiometer is connected to a microcontroller board that converts it to digital data. The data is then read by the navigation system as rotation angle for joint 1 and joint 2. The angle data, combined with the length of each segment is then used to map the position of flexible sheath location and synchronize it with its virtual object. This tracking system tracks and updates the virtual object when the surgery has being done. As the milling process has being done, the tracking system creates a virtual



D-H Parameters of the PRR manipulator

i	α_{i-1}	a_{i-1}	d_i	θi
1	0	0	d_1	0
2	90^0	0	0	θ_1
3	0	a_2	0	θ_3

milling pattern on the CAD image.

Figure 2.

Kinematics of a PRR Manipulator for the flexible drill and transformation of its local coordinate system into global coordinate system

The kinematics of the PRR manipulator is calculated using D-H (Denawit-Hartenberg) parameters. [14] In the kinematics of the flexible drill manipulator, each T_i is defined by two parameters, a_{i-1} and θ_i. Based on Figure 2, a_2 is the distance between the two revolution joints. The angle between two joints is denoted by θ_i. The other two parameters are d_i, the distance between the y_m and z_2 axes, and α_{i-1}, which is the angle between the z_i and z_{i-1} axes. It is the structure of the manipulator, the parameters α_{i-1} are zero. A transformation of the links is established by rotating counter-clockwise by θ_i and then translating along the x-axis by a_{i-1}.

$$ {}^{m}_{3}T = {}^{m}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T \qquad (1)$$

In the kinematic analysis, T_m will be defined as a rigid-body homogenous transformation matrix and this represents the six degrees of freedom of the free handle that is tracked by the optical tracking device. The position of the end-effector in the body frame of the last link appears in the coordination of G as,

$$ {}^{g}_{3}T = {}^{g}_{m}T\,{}^{m}_{3}T \qquad (2)$$

where, G denotes the global coordinate system of the navigation software in the steerable drill navigation system.

The Graphical User Interface

The concept of this graphical guide interface is illustrated in the flowchart in Figure3. The EE (end effector) consists of the flexible drill and its joints, both of which are tracked via the hybrid tracking system. The NAV (navigator) consists of a tracking camera (optical tracking) and rotary encoders at flexible drill joints (position tracking) shown in Figure 1. The NAV also tracks the subject object, a femur bone, via the optical tracking system. Streaming data from the NAV is then registered to the VOs (Virtual Objects) through the Flexible Drill Navigation Software. The VO from two sources is obtained, which are femur bone CT scan images that have been reconstructed into a 3D model, and a 3D CAD model of a femoral stem and the flexible drill. These VOs have their own local coordinates, which they are then registered with the SO (Surgical Object) and EE (End-Effector) local coordinate systems. Should these two objects' coordinates intersect with each other, it will trigger a warning message to stop milling, as a result of the safety measure set to not allow milling beyond the surgical boundary. The3D model is the virtual objects in the guide system as shown in Figure 3. The VO has its coordinates and orientation mapped in the navigation system. The coordinates and orientation data is used to registered VO to SO. The VO is registered to the SO intra-operatively by the tracking system. It is realized by transforming the coordinates and orientation of VO to follow the coordinates and orientation of SO. The SO is referenced by attaching dynamic referencing bases (DRB) trackers to the base of steerable drill and middle shaft of the femur bone. The optical tracking system consists of optical cameras with markers. It can capture and track the reflection of the DRB trackers. Tracking the steerable drill sheath inside the bone is realized by rotary encoders attached at each joint of the sheath. The rotary encoders give each joint's bending angles. The data is then read by the navigation system as rotation angle for joint 1 and joint 2. The angles' data, combined with the length of each segment is then used to map the position of steerable sheath location and register it with its virtual object.

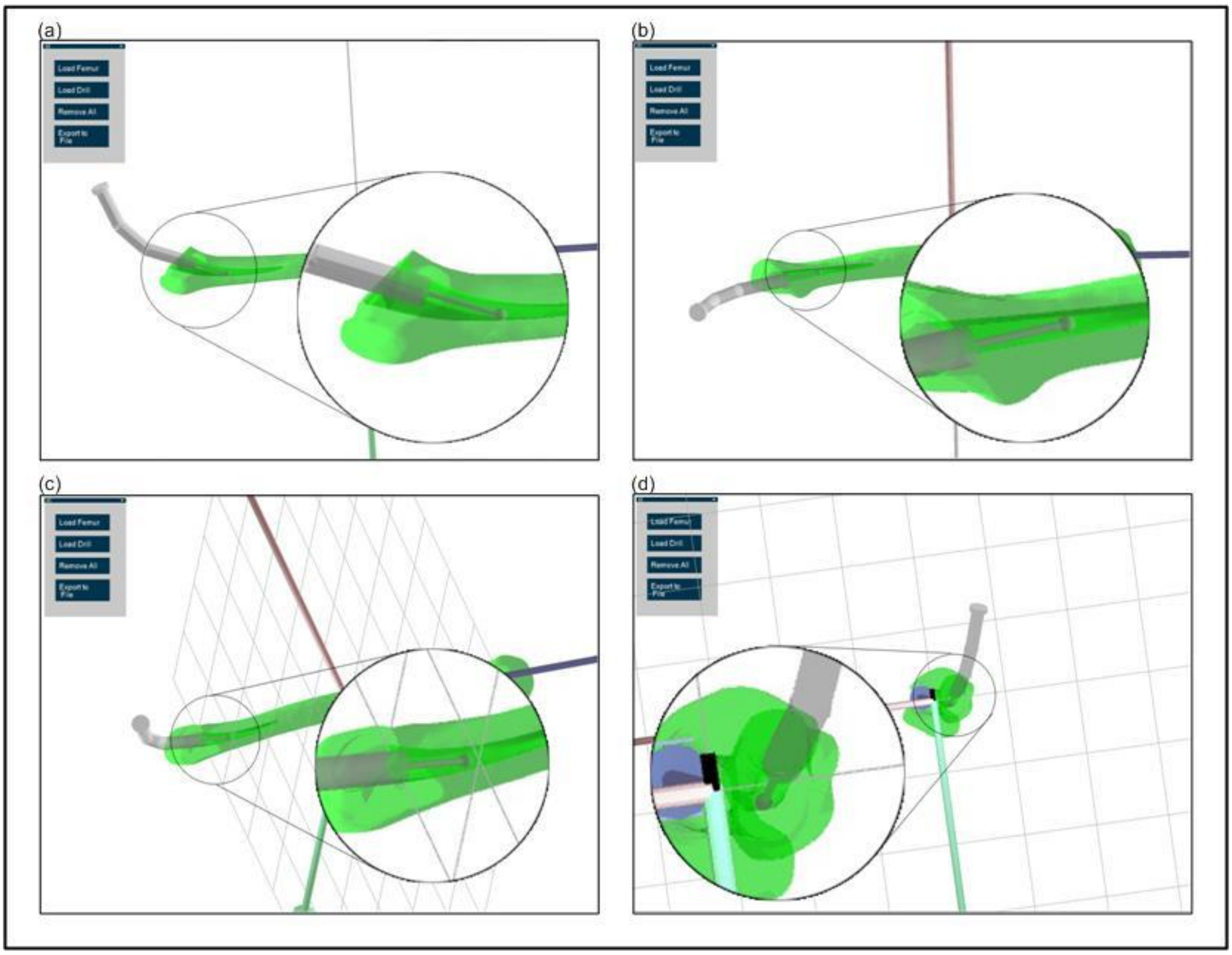


Figure 3

A GUI (graphical user interface) of the navigation system.

Once the coordinates have been paired, the real-time position tracking of the surgical object is virtually appeared at the monitor. As shown in Figure 3, the flexible drill can be guided through a small space inside the bone. The precise positioning of the drill tip is calculated through the kinematics of the flexible drill. The navigation system alerts surgeon on when the milling tip touches the surgical boundary as shown in Figure 3. The green surgical boundary covers all the bone because the area pre-planned to cut for implantation of femoral stem. Warning message to stop milling is prompted so that the surgeon will stop milling and take a step back to prevent over milling beyond the surgical boundary. It occurs when coordinates of milling tip overlap with the coordinates of surgical boundary. If the extension of the cut triggers the warning message then over milling has occurred and vice versa. However, to achieve accurate milling, we can zoom in the area in the navigation software and properly estimate the extension by virtual visualization of the milling tip next to the surgical boundary. Once the surgeon satisfies with the milling, the femoral stem can be inserted to check for fitting.

Calibration

A. Rotary Encoder-based Tracking Calibration

The encoders are calibrated by using a digital goniometer as a reference. The goniometer can be accurate up to 0.1 degree. The calibration is done by mapping the output voltage of the potentiometer to each degree of rotation. It is zero degrees when the flexible drill sheath is in a straight configuration. Calibration is done for every degree in clockwise and counter-clockwise directions from the zero degree position. Before and after calibration, the angle measurements of the potentiometer are collected and plotted onto a graph. Angle measurements are taken from the navigation system and the average of the streamed data is taken as the measurement for each degree of rotation. The absolute error percentage of the calibrated potentiometer is calculated by comparing the calibrated angle values with the goniometer angle values.

Figure 4 A and B show the comparison between the calibrated angle values of the potentiometer and the angles obtained from the digital goniometer. It shows that the potentiometer is calibrated almost perfectly when compared to the digital goniometer values. In Figure 4, there are clear deviations between degree 5 and degree 11 because there is a mixture of both positive and negative deviation of the calibrated potentiometer values to the digital goniometer values. At that range of degree, the potentiometer shaft is not sensitive enough to differentiate sub-degree precision up to 0.1 degree hence the voltage output varies from small change per sub-degree to bigger change per sub-degree. This is due to the usage of the analog potentiometer that has some variation of outputs when it returns repeatedly to the same position. This also affects the readings in Figure 4, resulting in deviation from the digital goniometer value. Besides that, in the analog potentiometer, a change of direction by a small degree sometimes might not result in a change of voltage output hence it is not sensitive enough to detect small changes in the opposite direction.

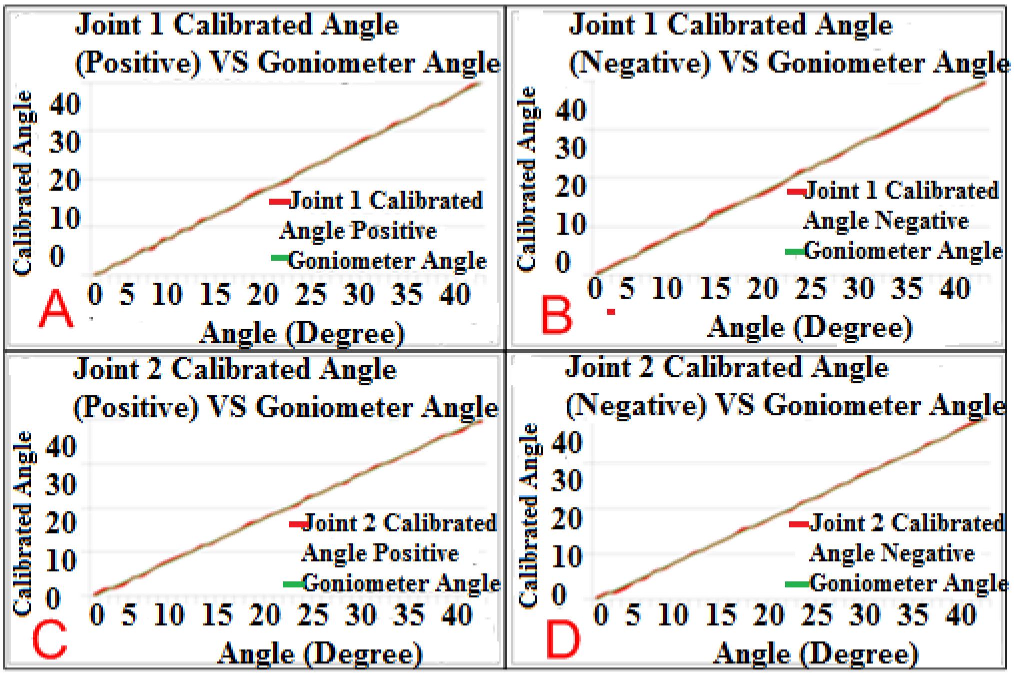


Figure 4.

(A)Joint 1 Calibrated Angle (Positive) Absolute Error vs Goniometer Angle (B) Joint 1 Calibrated Angle (Negative) vs Goniometer Angle Absolute Error (C) Joint 2 Calibrated Angle (Positive) vs Goniometer Angle (D) Joint 2 Calibrated Angle (Negative) vs Goniometer Angle

Comparison between the calibrated angle values of joint 2 (Figure 4 C and D) to the digital goniometer shows that the calibrated values have little deviation compared to joint 1. However, in joint 2, deviation occurs at the first 10 degrees of measurement. This represents the fact that joint 2 is not sensitive enough up to sub-degree precision (0.1 degree) in measuring the angle from the starting zero degree position. This is due to the sensitivity of the analog potentiometer in producing changes in voltage output in the few degrees of rotation angles from the stationary position.

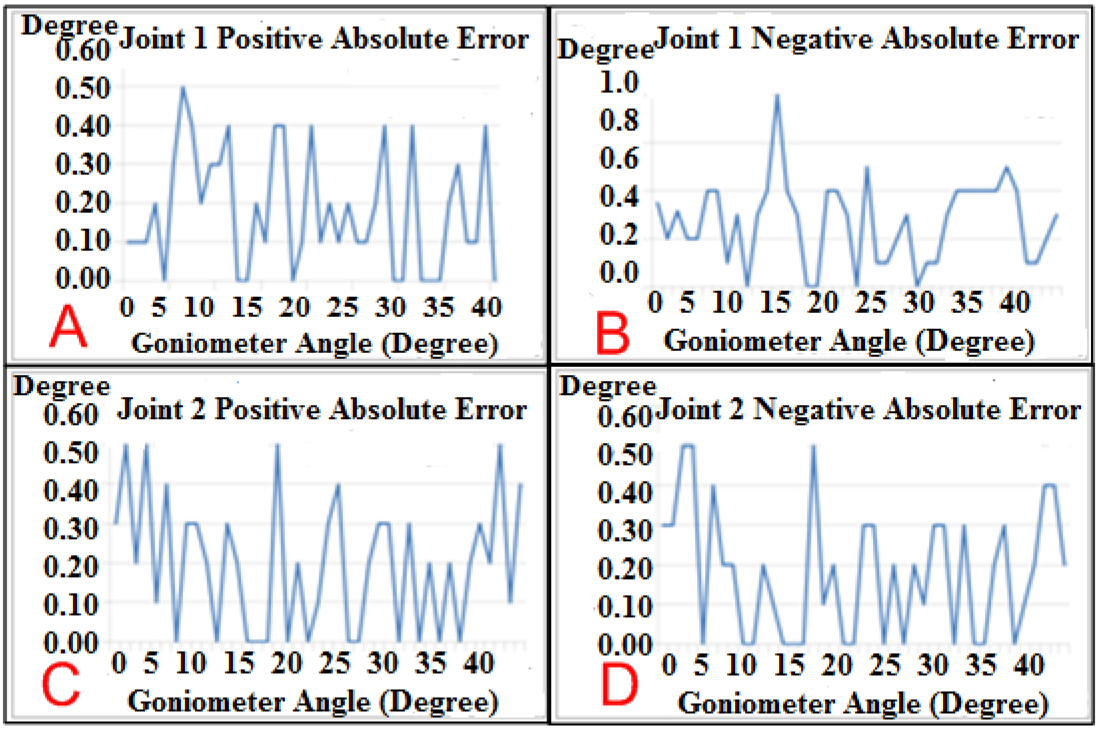


Figure 5.

(A) Joint 1 Positive Absolute Error (B) Joint 1 Negative Absolute Error (A and C) Joint 2 Positive Absolute Error (B and D) Joint 2 Negative Absolute Error

Figures 5a and 5b show the absolute error calculated for Joint 1 in positive and negative angle values relative to the digital goniometer angle value. In figure 5a, it shows that for positive angle measurements, the absolute error value is less than 0.5 degrees, which is good since the aim of the encoder is to have less than 1 degree error in measurement for each joint. In figure 9, there is one peak where the error value is greater than 0.5 degrees. This occurs when comparing the calibrated value at 12 degrees of measurement. This value is considered an outlier since it is outside the cluster of values and there is no repeated value that is similar to it when comparing it with other degrees of measurement. The mean absolute error for joint 1 positive is 0.2 degree and the mean absolute error for joint 1 negative is 0.3. Joint 1 negative has a higher mean error compared to joint 1 positive, due to the outlier with an error value of 0.8 degrees. Despite that, the error of joint 1 measurement is less than 0.5 degrees, meaning that it has sub-degree precision in measuring the angle.

5.RESULTS

The tracking and navigation system of the flexible drill system have been tested in sawbones. 3D geometric analysis of the shape of the cut area in comparison to femoral stem outline in pre-plan of navigation software is prepared to determine accuracy and repeatability of the flexible drill system. This experiment is to investigate the deviation of cut area in comparison with femoral stem outline in pre-plan of navigation software. Sawbones were used to investigate the ability of the tracking and navigation of the robotic drill system to navigate and drill inside femoral canal to produce a cut area within the outline of femoral stem. Upon completion of milling shown in Figure 6, the sawbones was sent for CT scan imaging. The 3D digitized geometry of CT image of the sawbones was analysed and the milled area boundary was isolated from the whole geometry. Pre-planned cut area was set as

reference template; while the milled area boundary was set as test object.

Figure 6

Sawbones experiment

The geometric shape variations of cut area in comparison with outline of femoral stem from pre-plan of navigation software were measured and presented using a deviation analysis. The maximum positive and negative deviation, mean positive and negative deviation, and RMSD (root mean square of deviation) shows in Table 1. The deviation distribution between cut area and outline of femoral stem from pre-plan of navigation software is shown in Table 2. The percentage of deviation distribution data is categorized in step of 1 mm.

Table 1. The maximum positive and negative deviation, mean positive and negative deviation, and root mean square of deviation.

Cut Area	dmax(+) (mm)	dmax(-) (mm)	davg(+) (mm)	davg(-) (mm)	RMSD (mm)
Femur 1	3.653	-2.950	1.151	-0.762	1.065
Femur 2	4.393	-4.387	0.888	-0.925	1.085
Femur 3	4.848	-3.565	1.127	-0.759	0.864

dmax = max deviation, davg = average deviation, RMSD = root mean square of deviation

Table 2. The deviation distribution between cut area and outline of femoral stem from pre-plan of navigation software

Cut Area	% below 1 mm	% between 1 mm and 2 mm	% between 2 mm and 3 mm	% between 3 mm and 4 mm	% above 4 mm
Femur 1	54.636	33.489	10.473	1.401	0.00
Femur 2	64.097	29.907	4.782	0.785	0.429
Femur 3	48.462	43.36	7.177	0.963	0.038
Mean	55.732	35.585	7.477	1.050	0.156
SD	7.875	6.967	2.857	0.317	0.237

The Analysis of deviation confirmed that the tracking system is able to guide the flexible drill inside femoral with deviation between cut area and outline of femoral stem from navigation software was in range of -0.759 mm to 1.151 mm in Table 1 and is slightly off from the acceptable range of 1mm. Detailed deviation analysis quantified the deviation of the cut area to outline of femoral stem from the navigation software, and it was found that a small portion of the deviation is more than 2 mm (7.477 ± 2.857% deviation between 2 mm and 3 mm, 1.050 ± 0.317 % deviation between 3 mm and 4 mm, and 0.156 ± 0.237% deviation above 4 mm). This means that the cut area was slightly deviated by up to 2 mm from the outline of femoral stem from navigation software. This is because the femoral stem outline had a tapered end and the mill bit used in this experiment was 6 mm mill bit, which unable to follow the tapered curvature less than 6 mm. The large discrepancies at the proximal brim of cut area was because of chipping of the sawbones due to difference in hardness between the sawbone's outer layer's resin and inner resin compound and structure. The outer layer's resin is harder and had a minimal hollowed structure, while the inner resin is softer with more hollowed structure. The RMSD obtained showed indirect correlation with the magnitude of deviations and it signifies the accuracy of the system in milling the cut area. However, since it has indirect correlation with magnitude of deviations, high deviation regions at the distal end of cut area contributed to the larger value of RMSD, hence reducing the accuracy of the system. Moreover, any noise or artefacts in the CT images, or manual segmentation of bones can also contribute to the higher deviation values. We also take note that even though CT slice thickness is 1.25 mm, the resolution within each slice was 0.918mm. Using the standard algorithm to reconstruct 3D CT model, by which it assumed the cross section to be in the middle of the slices, and create stereo lithography (STL) 3D model by connecting geometry between cross sections. Thus, the precision was somewhere between 0.918mm and 1.25mm. Despite these factors contributed to the errors, the results indicate that the steerable drill system was able to mill a cut area inside femoral canal guided by navigation software of the system with accuracy less than 2.0mm. The DCMs (Deviation Colour Map) gave us visualisation of 3D deviation and highlighted regions of higher deviation which shown in Figure 7. All three cut area had a higher deviation region towards the distal end and at proximal brim of the cut area.

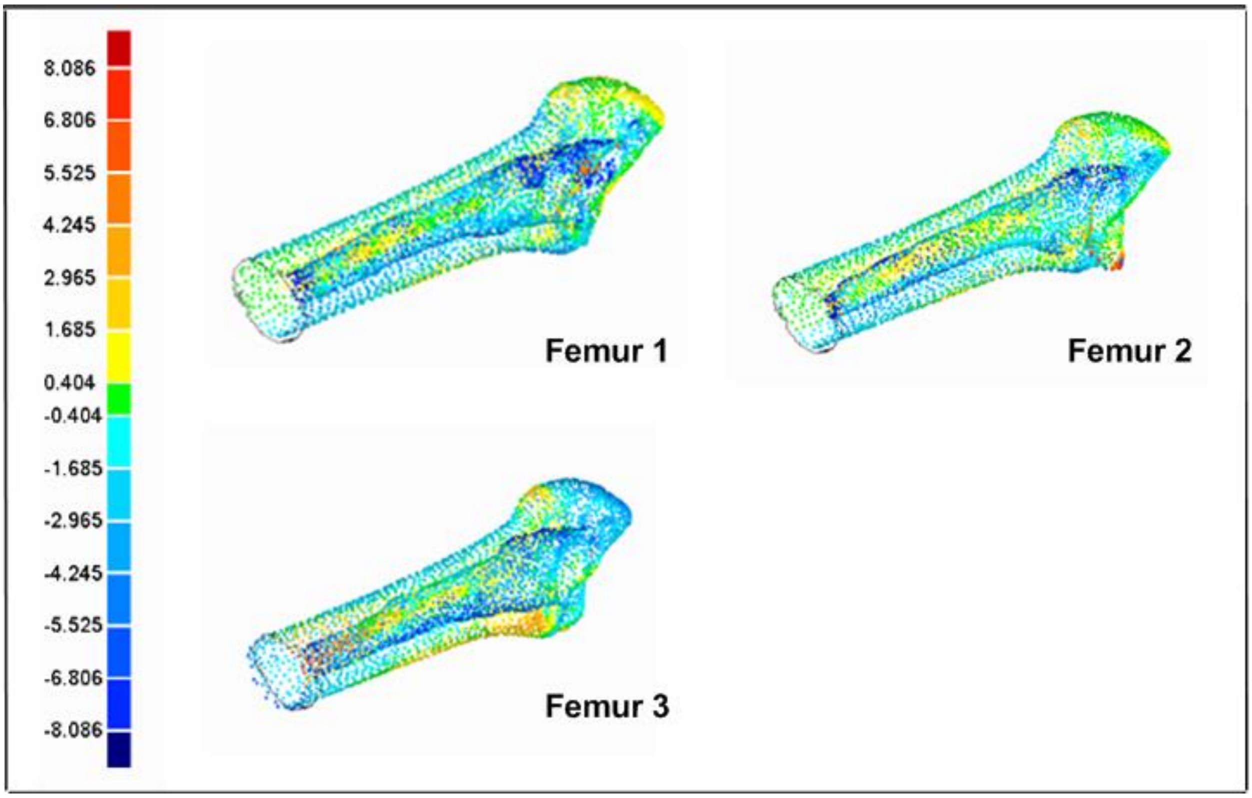


Figure 7

Isometric view of all three cut area of femur sawbones and DCM (deviation colour map)

Figure 7 shows the isometric view of chromatogram of all three cut area of femur sawbones. The colour ranges from green that indicates less than 1 mm of deviation to dark red or dark blue in colour, which indicates more than 5 mm of deviation overcut, or undercut respectively. This figure showed that there are similarities in area of overcut and undercut. Represented by blue colour gradient, the undercut area is clearly seen on the superior surface at the entrance of the cut area and the tip. These undercut areas contribute to the negative deviation value and negative deviation distribution stated in table 1 and table 2. Represented by red colour gradient, the overcut areas are clearly seen on the inferior surface at the entrance of cut area and the tip, and on the superior surface at the middle section of the cut area. These overcut areas contribute to the positive deviation value and positive deviation distribution stated in table 1 and table 2. However, there is widespread of green colour throughout the cut area surface that indicates overcut, or undercut of less than 1 mm from the pre-planned 3D model. From the Figure 7, most of the deviation between 2 mm and 3 mm and more appears in the colour of yellow at the lesser trochanter area.

The accuracy of milled area boundary was evaluated using Geomagic Qualify software that has ability to compare two 3D objects and establish a 3D deviation profile for the test object from reference template. We found out that 75.232% of the point cloud data were within ±1 SD and 93.924% of point cloud data were within ±2 SD. This indicates that majority of cloud data from the geometric shape of milled area boundary is within 1.728mm (2 SD) to the pre-planned cut area. Hence, the accuracy of the navigation system is within 1.728mm.

6. DISCUSSION

Based on this study, we conclude that flexible drill system was able to mill inside femoral canal guided by the tracking and navigation system. The accuracy of this concept is less than 2mm. Majority of the deviation is less than 2mm with only small portion of deviation to be more than 2. The result obtained from this study may have significant value in research pertaining femoral canal milling in computer assisted orthopaedic surgery total hip arthroplasty under MIS (minimal invasive surgery) approach. CAOS application in MIS total hip arthroplasty, at the moment, limited only to acetabular cup placement and biomechanical alignment. Application of CAOS in femoral stem placement is not yet available due to lack of extensive research to track milling tools inside femoral canal in CAOS total hip arthroplasty under MIS approach.

7. ACKNOWLEDGMENTS

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