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ORIGINAL ARTICLE

Computer-assisted robotic system for autonomous unicompartmental knee arthroplasty

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KEYWORDS

Arthroplasty;
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Abstract Robotic-assisted technology has proven to enhance the accuracy of bone resection and implant placement. However, robotic-assisted technology suffers from slow speed and high cost. Moreover, usually surgeries require the performance of radioactive scans. Therefore, the aim of this research is to build a low-cost autonomous system to perform rUKA (robotic Unicompartmental Knee Arthroplasty). A novel image-free registration process has been developed to eliminate the need for radioactive scans. Additionally, a CNC machine was built to perform autonomous resection. The proposed system was tested on a set of artificial tibia bones, and analysing their surfaces of the proposed system on the tibia bones was compared to Mako and BlueBelt systems. Mean error of the tibial resections was 1.9 mm compared to 2.87 mm for the Mako system, and 3.07 mm for the BlueBelt. The maximum error for the proposed system was 2.9 mm compared to 4.99 mm in the Mako and 4.5 mm in BlueBelt. To access the code, click here https://github.com/OmarShalash/TelesurgeryAutonomousControl.git

1. Introductin

Knee arthroplasty becomes necessary when the knee joint is worn or damaged reducing patients' mobility and affecting their daily activities [7]. Advancements in surgical implants and devices were designed and introduced by medical innovators in collaboration with the industrial sectors [7]. There are three main types of knee arthroplasty: Total Knee Arthroplasty (TKA), Unicompartmental Knee Arthroplasty (UKA), and Multi-Compartmental Knee Arthroplasty (MCKA) [35]. In UKA, only the most damaged part is replaced, in contrast to TKA, in which the whole knee joint is replaced [7].

The latest generation of orthopaedic surgeries involves the use of robotics to perform specific tasks according to preoperative data to enhance surgeons' abilities to install implants more precisely and consistently [23]. Robotic systems work through smaller incisions by pre-planning the cutting path or restricting the movement of the burr. This can protect the soft tissues which help with postoperative recovery and patient satisfaction [27]. Many studies show that rUKA (robotic

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Unicompartmental Knee Arthroplasty) yields better implant adjustment, improved knee motion, faster recovery period, and less post-operational complications and discomfort compared to conventional UKA knee surgeries [3,32,10,38,16,27,2,43,18].

Robotic knee arthroplasty can be classified into three main categories: passive, semi-active, and active systems [35,25]. Passive systems provide recommendations for perioperative guidance, but the surgeon directly performs the resection without assistance, for example, OMNIBotics [20]. A semi-active system is a tactile feedback system that augments the surgeon's ability to control the burr, by restricting the cut motion; however, it still requires the surgeon to manipulate the burr, for example, the MAKO system [37]. Finally, an active system performs resection without the direct intervention of the surgeon, as proposed in this research.

Many systems have been developed and prototyped [29,42,28,14,21,12,44,39,8,22,15], only a handful have been used successfully in clinical settings, these include:

- ROBODOC System [24]
- CASPAR System [41]
- MAKO [40]
- BlueBelt Navio[34]
- Acrobot [17]

Many studies have proven the superiority of the mentioned systems compared to conventional surgeries regarding multiple metrics, such as the generation of reliable pre-operative plans, improved restitution of joint-line height in resurfacing, and improve the accuracy of bone preparation [16,9,3,26], yet many studies have demonstrated that patient satisfaction is still not optimal [5,6,36].

Robotic knee arthroplasty begins by registering patients' anatomical structures using mapped points on the bone to acknowledge the system with the cutting space; therefore, a poor registration step degrades accuracy [25]. The registration process can be categorized into image-based and image-free systems. Image-based systems depend on performing Computerized Tomography (CT) scans, which imposes extra cost and radiation exposure. On the other hand, image-free systems perform registration after surgical exposure, and the surgical plan is updated throughout the registration procedure.

The aim of the proposed research is to develop a robotic system that can perform autonomous resection procedure for the UKA, while maintaining the accuracy levels comparable to commercial systems, namely, Mako and BlueBelt Navio. In order to achieve this aim, a motion capture system was used while deploying a novel open source clustering algorithm written with LUA code available with the provided REPO available in the manuscript. In addition, a CNC machine was built to perform autonomous resection. Finally, the resection surfaced of the proposed system, Mako, and BlueBelt Navio systems were laser scanned and compared.

The main contribution to this research is to propose a more affordable autonomous robotics system to perform knee joint resection precisely or more accurately than other expensive alternatives (that are only semi-autonomous) in the market.

This paper is organized as follows: in Section 2 the design and development methodology of a navigation system and a CNC machine are described, and Section 3 summarizes the experimental results and analysis of the proposed system along with comparisons with the other systems, finally, the paper is concluded in Section 5 along with suggestions for future research.

2. Methodology

The main components of the proposed system are a navigation system and CNC cutting machine, along with a set of developed applications responsible for the calibration of the navigation system, communication, path planning, wireless communication, and CNC control.

In this section design and implementation of the proposed robotic UKA system is elaborated. The basic steps involved in rUKA are:

1. Planning implant position and orientation on the knee, then performing an incision.
2. Performing knee registration process and localizing main parts included in the surgery.
3. A guided CNC machine performs the resection
4. Surgeon handles fixation of the implant and cementing phase, post-resection.
5. Surgeon closes the wound.

In this section, the two steps of knee registration and autonomous resection are elaborated.

2.1. Registration processes

During this pre-operative step, important parts involved in the resection procedure are registered and localized using a motion Capture system (MoCap). Registration is performed in order to create a path for the burr to work on the bone. In this proposed system, twelve OptiTrack Flex V100:R2 cameras are used and integrated using OptiTrack's software platform: Motive [33]. Optitrack company provides 8, 12, and 16-camera systems, the main target for the choice of number of cameras was to have a field of view covering the whole theater, as the proposed system performs the resection step in a fully autonomous manner, hence, the cameras' coverage should guarantee full tracking of the resection procedure. we choose the 12-camera system as it was the most suitable system for the available theater of operation. As the proposed system is autonomous, it could be monitored with less number of medical personnel compared to traditional surgeries, in addition to using the multi-camera OptiTrack system which is mounted in a U-shaped pattern (as shown in Fig. 2a), capturing the required markers is unlikely to be interrupted. Moreover, the system can work in different theaters as both the CNC machine and the camera system are portable and can be moved to different theaters.

Motive is a software developed by OptiTrack which controls the cameras, calculates markers locations, and streams this information to another software like DFlow which is an integrated development environment that uses LUA programming language which was used to develop the software for this procedure.

The setup has been made in a lab at Strathclyde University. The OptiTrack system was set to operate under different conditions as each camera can be configured to be adjusted to the theater of operations conditions, as shown in Fig. 3the cameras following settings could be adjusted: Frames Per Second (FPS), Exposure (EXP), Threshold (THR), LED power (LED). Therefore, the system could be set in an operating room and accommodate its different lighting conditions [11].

The MoCap tracks clusters of markers, a marker is a ball-shaped object with reflective tape which reflects Infrared beams to be visible to the cameras (Fig. 1). Each cluster was designed to have a unique positioning of its markers. Each cluster is responsible for defining the location of a specific part of the system and then tracking it during the procedure of updating the system with the moving part's new coordinates.

Cameras were mounted on the walls and configured in a "u" shape surrounding the operating table head end (Fig. 2a). Therefore, if one or two cameras were blocked by obstacles found in the operating theater, the view of the system would not be limited. Also, the "u" shaped arrangement provides a bigger capture volume with better avoidance of marker occlusion when a person is in the field of view.

In addition to Motive software, D-Flow was also used in order to make use of the markers' positions and generate a resection guide file. D-flow consists of a top layer responsible for the communication between hardware components, a multi-display rendering system, and a modular application development framework based on visual programming [13,31].

After Motive transfers markers' positions to the D-flow main application, D-flow uses them to generate the resection guide file by processing markers' positions and mapping them regarding their clusters which were used to create a coordinate frame for the system, in which the stored resection shape points are also processed and transferred to fit the operating area precisely then stored in that file.

The registration process includes two sub-processes:

1. Knee registration process
2. Clustering process.

2.1.1. Knee registration process

The registration process was performed by registering three points on the knee to match three points on the implant, the surgeon should decide where these points should be matched on the knee before the operation based on the x-rays. So, they are not considered landmarks. The process was achieved by using an old implant that has the three points pre-marked on it and then when placed on the artificial bone, the sharp pointer is used to scan these three points by the surgeon who selects and matches the area to place the implant on the knee joint. These three points match the upper hemisphere of the implant. Afterward, they are used to calculate the burring path. Knee registration process is shown in Fig. 4.

2.1.2. Clustering process

In order to identify clusters, an array of markers is retrieved from the MoCap, each marker has an associated ID and *xyz* coordinates. The Euclidean distance is calculated between all markers as shown in Eq. (1) where ed_{xy} is the calculated Euclidean distance of markers x and y, tf is the tolerance factor which is set to 50µm, x, y are the markers ID's, and detected () is the function that matches the new value to the stored Euclidean distances of each cluster. Distances are then matched with the saved data. For example in Fig. 3, if the distance between marker A and B was x, between A and C was y, and between C and B was z. When x is calculated, the system saves both IDs for markers A and B and retrieves all the distances calculated by the same markers, now the retrieved distances have the AC and BC distance (because both calculations have markers A and B IDs stored along with marker C ID), after confirming that these distances match AC and BC values then it is concluded that markers A, B, and C are found and located, with the same tactic, marker D can be located. Now that ABCD markers have been found then the tibia cluster has been located. The MoCap system updates the values of the markers with their movement. The clustering algorithm is shown in Fig. 4.

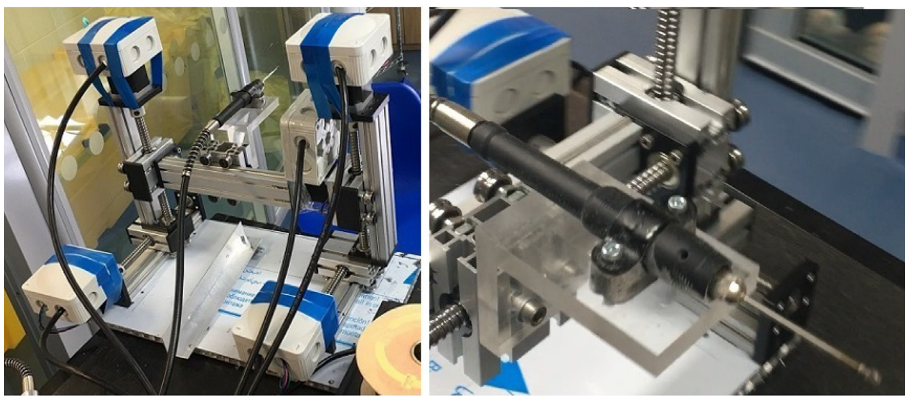
$$f(id) = \sum_{i=0}^{49} \begin{cases} ed_{xy} + tf - (i+1) * 1\mu\text{m}, & \text{if(detected(f(id))} > 1 \\ x, y, & \text{if(detected(f(id))} = 1 \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

There were two main challenges facing the clustering process during operation:

1. A marker goes missing after cluster recognition. This is solved by constantly calling a script that checks markers count before recognition, if one is missing then the system states that the cluster is off-line.

Fig. 1 Motive control panel for cameras.

(a) 12 Camera OptiTrack System Hanged on the Walls in Theater



(b) A close-up on the front side showing the flex-tube holding the cutting burr

(c) Sawbones fixed and ready for registration

Fig. 2 The proposed system.

2. Even if the markers were stationary, MoCap keeps updating their coordinates. For example, the values of the Euclidean distance between two of markers changed from 0.113192 to 0.113220, which corresponds to a 28µm change. Even though it is a small value, it causes all saved values of each cluster's Euclidean distances to mismatch. In order to overcome this challenge, the identification algorithm was made to be dynamic, in which a number is added to saved Euclidean distances associated with each cluster. Since the Euclidean distance can not be exact, the checking mechanism had to be in range. Based on the conducted tests and created clusters, the added value was found best to be 50µm. If the Euclidean distance created between two markers matches more than one stored distance, then the added value is reduced to 1µm, and then the process is repeated until only one distance gets a match.

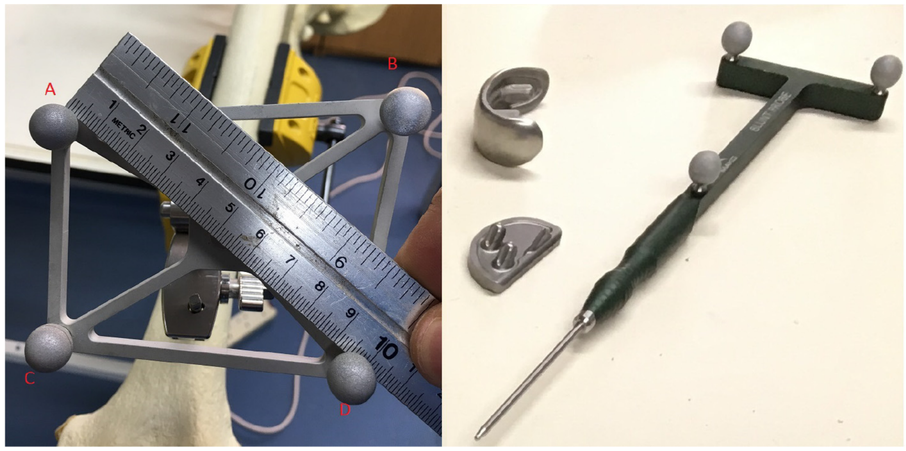


Fig. 3 Tibia cluster and blunt pointer.

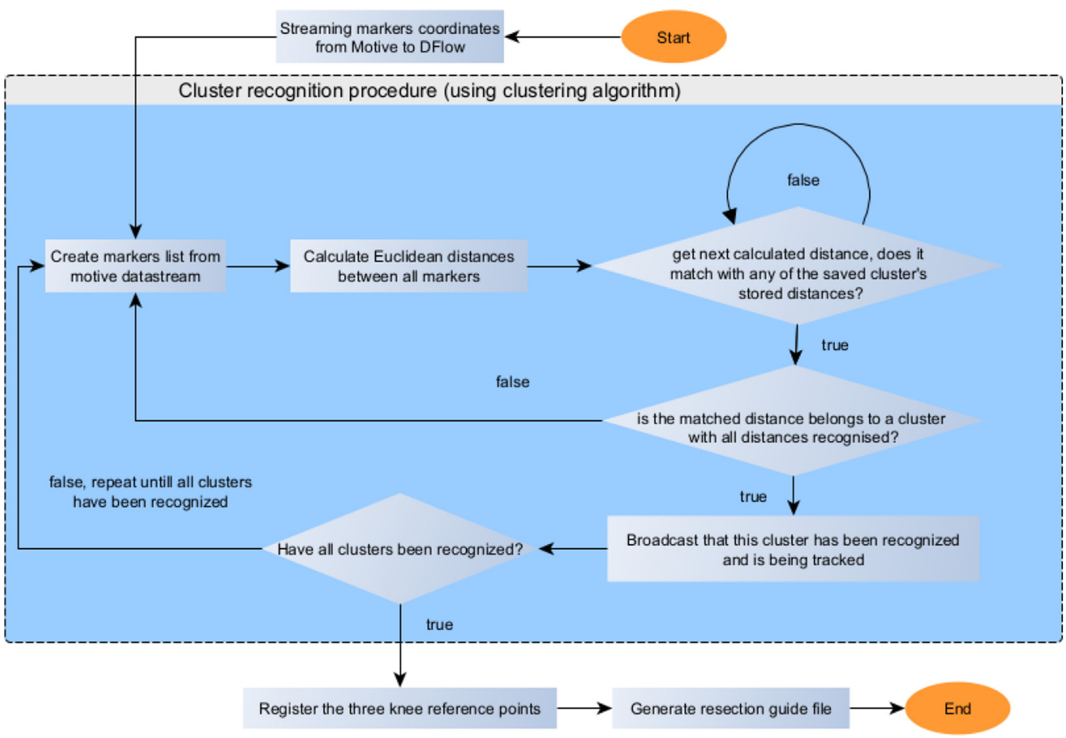


Fig. 4 Knee registration procedure.

2.2. Development of CNC Machine

A CNC machine with three degrees of freedom was built to control the movement of the burr used for resection guided by the outcome of the MoCap/navigation system: the resection guide file. High accuracy and precision had to be maintained in order to make the best use of the navigation system.

The designed CNC machine is shown in Fig. 2b. Each carriage had a 100 mm movable distance, by combining five of these rail-carriage systems, 3D motion is provided. .

Nema 23 motors [Schneider Electric motion, USA] provided 200 steps/revolution and a 64 *N.cm* holding torque. The cutting burr was fixed inside a flexible tube connected to a Maplin mini grinder 170 W variable-speed rotary tool, these parts were fixed to the Z-axis rail. Fixing this motor on a rail provided the machine with a resolution of 200 step/mm, so that the burr is driven by 1/200 mm accuracy. The total weight of the CNC machine is 25 kg and costs $852. It is controlled using Arduino controller via a wireless module communicating with the computer running the navigation system.

3. Results

The first phase -knee registration and clustering - was tested and resulted in 100% cluster detection performance and precise localization of all clusters moving in the theater. The algorithm was used in all burred artificial bones used in the next testing steps.

The entire cutting system was validated by performing flat cuts on nine tibial plateaus, followed by nine curved cuts on femoral surfaces. The sawbones and the CNC machine were placed as shown in Fig. 2b. The proposed system procedure takes average of 30 min for the trials made (the time for the procedure is relative to the area of resection), also it is recommended to recalibrate the MoCap system before each operation, the recalipration process takes about 15 min. The total time for preparing the system and resection to complete requires about 45 min. After the burring procedure, the cuts were captured using a 3D scanner. Results of the tibia bones were compared to the original sawbones shape, a flat surface (2D plane which matches the flat surface of the tibial implant shown in Fig. 5), and previously cut sawbones by the Mako and BlueBelt Navio robotic systems.

The Mako and BlueBelt Navio cutes were performed by experienced surgeons at the Royal Infirmary in Glasgow, to ensure a fair comparison. All resection artificial bones (including resection bones by the proposed system) were then 3D scanned using Matter and Form Laser Scanner to create a digital 3D file for each bone [30]. The comparisons were made using Geomagic software.

3.1. Tibial resection analysis

Tibial cuts were compared to a 2D flat surface, as the resection procedure for the tibia aims to create a flat surface. Also, additional comparisons were made between the maximum and minimum errors made by the three systems (proposed, MAKO, BlueBelt Navio).

3.1.1. Proposed system tibial resection analysis

In this subsection, tibial cuts by the proposed system are analyzed. Two 3D comparisons were performed:

1. A comparison between the cut sawbones post-resection and pre-resection. This comparison shows how much bone volume was removed off the bone surface (anterior and posterior).
2. A comparison between the cut sawbones (post-resection), and a 2D plan. This comparison shows the flatness of the bone surface after the resection, optimal cuts would show zero displacement between the bone surface and the 2D plan.

Results of the 3D comparisons between the cut sawbones and the 2D plan are color coded, such that:

1. Blue range: Lower than the 2D plan (over-cutting).
2. Green range: Optimal-cutting (matching the 2D plan).
3. Yellow - Red range: Higher than the 2D plan surface.

The more the results deviate from the 2D plan, the darker the color gets. In this section, two bones were analyses and discussed (Tibia A, and Tibia B). It can be seen in Figs. 6b that the most dominant color is green (with an error of $\pm 0.4mm$), while other blue and darker blue areas represent displacements less than 0.7 mm and 1.6 mm below the flat 2D plan respectively. Other areas were represented by yellow and darker yellow with a displacement less than 0.7 mm and 1.3 mm, respectively, above the 2D flat plan.

The images of the scanned areas are of different shapes as the resection bones received from procedure made by Mako and BlueBelt Navio were just the resection part but for our system, the full joint was scanned.

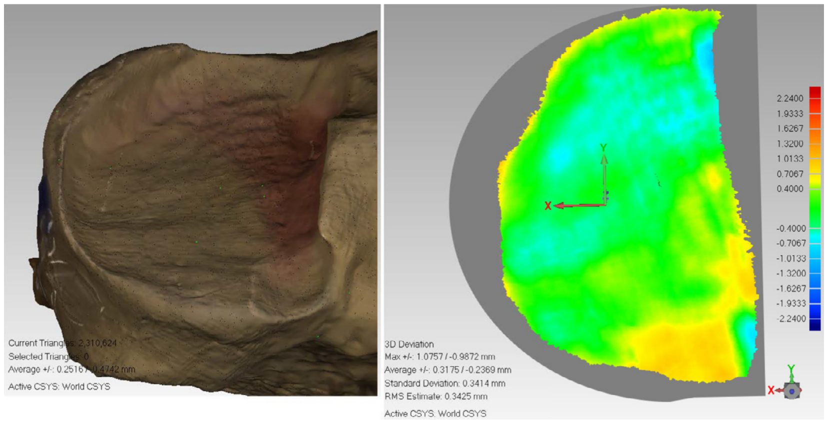
3.1.2. Mako tibial resection analysis

Figs. 6c and 6d show holes that were drilled for the Mako implant fixation; these holes were left out of the comparison. In Fig. 6d the green color is less dominant compared to the proposed system's output. The more dominant colors are within the blue range, representing displacement values of −1.04 mm, −3.4 mm and −4.99 mm. Some parts on the border showed larger displacements, but these were ignored as they represent the bone lip remaining on edge.

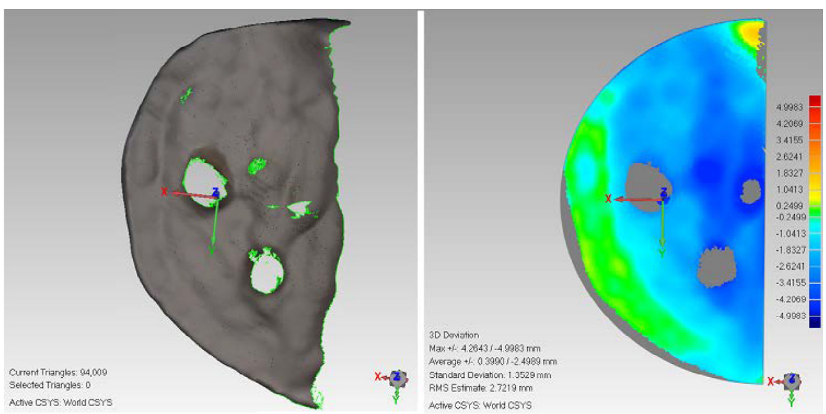
3.1.3. BlueBelt Navio tibial resection analysis

In this subsection, one of the cuts made by the BlueBelt Navio was analyses. Fig. 6f shows a variety of colors representing different displacements from the 2D plan, the image shows errors of $\pm 2.2mm$. Further gray areas are due to excessive bone cutting which can be visualized at the lateral part in the resection view in Fig. 6f.

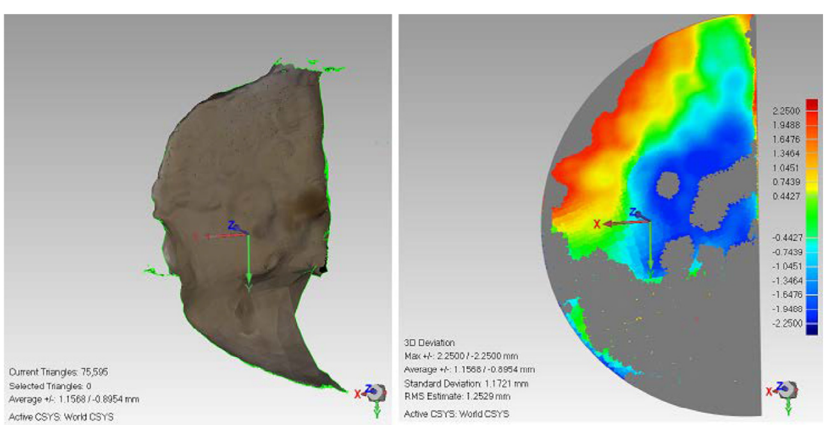
Fig. 5 Tibial implant.



(a) Tibia bone - 3D scanned (Proposed System) (b) 3D comparison with 2D plan(Proposed System)



(c) Mako - 3D-scanned (d) Mako, 3D comparison with 2D plan



(e) BlueBelt Navio, 3D scanned (f) BlueBelt Navio, 3D comparison with 2D plan

Fig. 6 Tibia bones resection by the proposed system (a, b), Mako (c, d) and BlueBelt Navio (e, f).

3.1.4. Tibial sawbones resection result summary

The results of the tibial cuts performed by the proposed system, Mako system, and BlueBelt Navio system are presented in Table 1. The table presents measured results for performing the resection process on the nine bones using the three systems in the first section, the first two columns display the minimum error and the maximum error which are the distance max distance below and above the inserted flat plan and the range

Table 1 Error range of tibial cuts performed by the systems.

	Proposed System			Mako			Blue Belt			
Bone	**Min. Error**	**Max. Error**	**Range**	**Min. Error**	**Max. Error**	**Range**	**Min. Error**	**Max. Error**	**Range**	**Unit**
1	−0.76	0.76	1.52	−4.99	0	4.99	−2.25	2.25	4.5	mm
2	−0.70	0.40	1.1	−0.82	1.18	2.00	−2.24	1.18	3.42	mm
3	−0.70	1.00	1.7	−1.89	1.18	3.07	−1.89	0.82	2.71	mm
4	−1.30	0.70	2.0	−1.30	1.60	2.90	−2.24	2.24	4.48	mm
5	−1.30	1.00	2.3	−1.53	1.53	3.06	−2.24	0.46	2.7	mm
6	−0.70	1.00	1.7	−2.24	0.46	2.70	−1.21	1.90	3.11	mm
7	−1.30	1.30	2.6	−1.89	0.46	2.35	−0.82	0.46	1.28	mm
8	−1.60	1.30	2.9	−1.20	1.61	2.81	−0.99	1.93	2.92	mm
9	−0.70	0.70	1.4	−1.18	0.82	2.00	−1.89	0.62	2.51	mm
Mean			1.9			2.87			3.07	mm
SD			0.55			0.84			0.94	mm
Max of ranges			2.9			4.99			4.5	mm

which is the sum of the absolute value of the previous columns. In the second section, the table shows the mean of the resection ranges followed by the standard deviation (SD) of the ranges followed by the maximum range (error) for each system.

The average range of errors resulted from the proposed system is approximately half of the errors of the commercial systems. The proposed system showed better standard deviation, mean error, and stable repeatability in the cutting process. Besides, the proposed system provided the smoothest and least spiky surface.

A.1

4. Discussion and limitations

4.1. Discussion

Both systems (Mako and BlueBelt) showed surface roughness in the resection procedure. The maximum error range in the developed system tibia cuts is 2.9 mm, while the average error was 1.9 mm and the standard deviation was 0.55 mm when performing the procedure on 9 tibia's. For the Mako system, the maximum error was 4.99 mm with a 2.87 mm average error and 0.84 mm standard deviation, also on a 9 tibia's set. The BlueBelt system had maximum error range of 4.5 mm while the mean error was 3.07 mm and standard deviation of 0.94 mm, the set was also 9 tibia's. Almost all of the Mako and BlueBelt bones showed a spiked, bubbly, and non-smooth surface. This is caused by the controlling mechanism both systems used for cutting. The BlueBelt is a simple robotic hand-held tool with a burr that is retrieved once its tip exits the marked cutting area. The resection bones showed excessive cuts on the border of the tibial surface which indicates that the burr retrieval safety mechanism isn't optimal. the maximum range between the tibial cuts performed by the BlueBelt system was 4.5 mm. The Mako system shows better performance than the BlueBelt but all Mako bones showed spiked surfaces, still, the maximum error range in the tibial cuts performed by the Mako system was 4.99 mm which is more than the BlueBelt system.

Almost all the Mako and BlueBelt Navio bones showed a spiked surface. Surface smoothness produced by the proposed system has some significant benefits. First, it aids in closing the gap between the bone surface and the implant, and hence reduces healing time. Second, it was reported that the cement mantle thickness in the cement TKA prosthesis should be 1.4*mm* for the femur and 0.8*mm* for the tibia [19], therefore if the same thickness is used in UKA then it will be very challenging to maintain this thickness while the Mako and BlueBelt Navio systems tibial cuts have an uneven surface with peaks of 4.99*mm* and 4.5*mm* respectively. Third, having a smoother surface can help improve cement-less prosthesis as the ideal gap between the bone and the implant in TKA was reported to be less than 1*mm* [4]. Again, if the same numbers are applied for the UKA, then the proposed system is the closest to achieving this surface finish.

The proposed CNC machine can is incomparable to the standard CNC milling machine in terms of size, weight, and portability; the proposed CNC machine weighs 25 kilograms, and can be easily moved. Also, the proposed system is haptic, so it uses the navigation system, to track the movement of the bone and redirect the burr to resume the resection procedure. Moreover, in the procedure (Knee Arthroplasty), medical personnel insert screws in the femoral/tibial bone to fix the bone they are working on so that the bone movement is reduced to a minimum. However, in the proposed prototype, the tests are not made on a human, so fixing the bone to a table was the proposed means of stabilizing the bones during the procedure. Also, in the Mako and BlueBelt Navio systems, a burr is mounted onto a moving arm so the main difference between our system and the other systems is how to move the burr, but yet they have not been described as milling machines.

For femoral resection analysis please refer to Appendix A.1.

4.2. Limitations

Some of the limitations that face our proposed system are listed below:

- If it is needed to operate in a different theater of operation, the system will need to be taken down, re-installed, and re-calibrated.
- The surgeon is responsible for matching three points on the patient's knee that would be used in the registration process and the resection afterward.
- The accuracy of resection performed by MAKO and Blue-Belt Navio depends on the experience level of the surgeon or the person performing the resection. Therefore, comparing our results to these systems depends on the learning curve associated with these systems.
- The problem of availability of bones resection by other systems to perform comparisons.

5. Conclusion and future work

5.1. Conclusion

In this proposed research, an affordable robotic knee unicompartmental knee arthroplasty system was developed and its performance was compared with the two most commonly used commercial systems: Mako and BlueBelt Navio. The operation is guided by an OptiTrack navigation system which outputs a file that guides a wireless CNC machine to perform the resection.

As shown by the 3D comparisons performed on the cut bones, the proposed system shows a significant enhancement in the quality of the cut, compared to two of the world's leading commercial systems. Performance of the proposed system on the tibia bones showed superiority over the MAKO and BlueBelt Navio systems.

In conclusion, the proposed system is affordable and provides a better resection quality.

5.2. Future work

Three approaches are suggested to improve the registration process for the proposed system; however, they need further research and analysis:

1. Using the existing MoCap system to scan more than three points.
2. Using a laser scanner to scan thousands of points on the bone surface.
3. Using a specially designed tool for registration, along with MYKNEE surgical tailored instruments [1].

The femoral cuts performed by the proposed system showed a problem with the cut shape. The designed CNC machine had only 3 degrees of freedom, producing a constant attack angle relative to the bone surface. Each femoral condyle surface has about a 90-degree curve from one end to the other. Therefore, adding one more degree of freedom (pitch) would enable the attack angle to change continuously so that the burr tip remains perpendicular to the femoral surface all the time.

Another limitation to the proposed system is the long burr length (50*mm*); this caused the burr to bend due to cutting forces after around 14 cutting trials. Therefore, a support system can be designed and attached to the burr so that it rotates without any resistance from the support.

6. List of Abbreviations

CNC	Computer Numerical Control
CT	Computerized Tomography
EXP	Exposure
FPS	Frames Per Second
LED	Light-Emitting Diode
MCKA	Multi-Compartmental Knee Arthroplasty
MoCap	Motion Capture
rUKA	robotic Unicompartmental Knee Arthroplasty
THR	Threshold
TKA	Total Knee Arthroplasty
UKA	Unicompartmental Knee Arthroplasty

6.1. Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

6.2. Code availability

Click here to reach the repository.

6.3. Availability of data and materials

Not applicable.

6.4. Compliance with Ethical Standards

Not applicable.

6.5. Consent to participate

The authors affirm that neither human participants nor animals were involved in this research.

6.6. Consent for publication

The authors affirm that no human research participants were included in this research.

6.7. Authors Contributions

The whole idea was Philip's, and Omar developed the system with the guidance of Philip Rowe.

6.8. Availability of data and materials

All data and materials as well as software applications and custom code support the published claims and comply with field standards.

Appendix A. Femoral surface resection analysis

A.1. Femoral surface resection analysis

Resection was performed on ten femoral sawbones. The femoral implant is not flat compared to the tibial implant, however, it has a 3D shape. The MAKO and BlueBelt Navio systems used different implant shapes,therefore, direct comparison of cut surfaces was inapplicable. Hence, the shape and quality of the cuts were eye compared.

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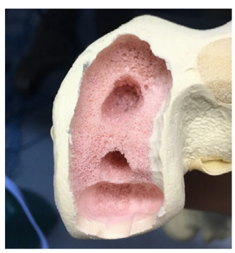
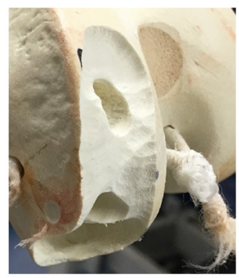
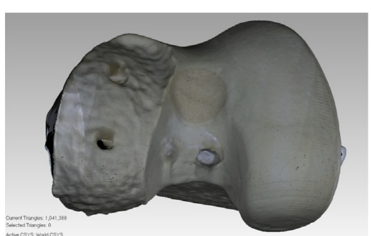
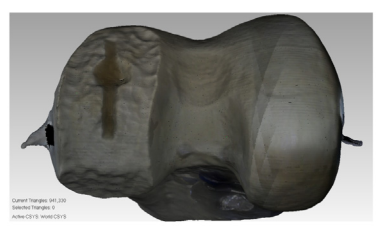

(a) Femur resection of Bone A by the proposed system


(b) Femur resection of Bone B by the proposed system


(c) After fixing the implant without cementing


(d) Femur bone resection by the MAKO


(e) Femur bone resection by the BlueBelt Navio

The shape of femur implant is more complex compared to the tibial implant (Fig. 5). As shown in the figure above, the burred surfaces are very smooth, the curved shape was close to optimal, except for the bottom part, was excessively burred.

Figures d, e, shows sawbones resected by the Mako and BlueBelt Navio, respectively. They both show uneven and rough surfaces.

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