Optimized Registration for Computer Assisted Total Knee Arthroplasty

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Introduction:

Total knee arthroplasty, (TKA), also known as total knee replacement, (TKR), is a surgical process that involves the removal of diseased bone and cartilage from the distal end of the femur and from the proximal end of the tibia. Once those cuts have been accomplished, a cement epoxy is then used to firmly secure the mechanical components that will operate as "new knees." Two to three hundred thousand United States residents receive knee replacements each year. The major reason for TKA is Osteoarthritis. Osteoarthritis is the stiffening of joints and bones due to a depletion of cartilage in those areas. Osteoarthritis can occur in the hands, feet, spine, knees, and hip. Severe Osteoarthritis in the knee joint involves the loss of all or almost all cartilage cushioning. Those cases can lead to bone rubbing on bone, which is extremely painful and causes rapid bone deterioration. The illness of Osteoarthritis can cause unhealthy changes in the body. People who suffer from knee joint pain are less prone to walk or exercise, which has an effect on their cardiovascular and respiratory systems. If persons experiencing pain do walk, their gait may alter as to make their walking more bearable.

This changes in their gait, which can have a crippling affect on foot angle, hip movement, and the lower back. These crippling affects can lead to obesity, alternate joint complications, and lower back pain.

The conventional procedure for total knee arthroplasty is by no means a simple or trivial process. This process is still strongly influenced by human error. There are many considerations that are necessary to perform a good TKA. Pre-operative planning is a helpful tool in TKA, but currently only has applications for choosing the proper size replacement components and choosing appropriate size jigs and guides for the patient. (Mantas & Bloebaum, 1995) Alignment issues of the femoral component are a large problem with conventional TKA. Knee alignment is based on three axes, the anteroposterior axis, the posterior axis, and the epicondylar axis. These axes represent the line or axis that the femur would rest upon if lying on a table, the line or axis that splits the femur in halves in the vertical direction, and the line or axis that goes through both epicondyles. During this procedure key anatomical landmarks for locating these axes are removed. Then it is left to the surgeon's accuracy, pre-operative planning and judgments based on X-rays, and the precision of the surgeon's tools in order to insure proper alignment. While surgeons can be extremely precise during the operation, femoral misalignment of as little as 2°-3° or 2mm - 3mm in translation will cause multiple problems for the patient post operation. If the misalignment is too severe, a revision surgery will have to take place (Amira & Whiteside, 1992).

With the incorporation of computers in the operating room, more judgments can be made based on pure math. The perception and experience of the surgeon will still be helpful but not always necessary. By using a computer to assist in TKA, the patient, the doctor, and the hospital can all be assured that the accuracy of this surgery will be near perfect each-and-every-time.

Computer assisted surgery can only be achieved through registration. Registration is a procedure where a model such as a bone is located in 3-D space, then used as a reference guide to the x, y, and z directions for the computer. Even with computers in the operating room and proper registration achieved, the precision of the cutting devices and the machining of the knee components will still limit TKA results. However, the results will still be far better than human surgeons alone can achieve.

The purpose of this study is to provide a template for future revisions of TKA that will help produce a better and more accurate TKA result. By adding the assistance of computer software and robotic arms, not only will surgeons allow less room for error in the incisions and bone removal, but also in component design specifications.

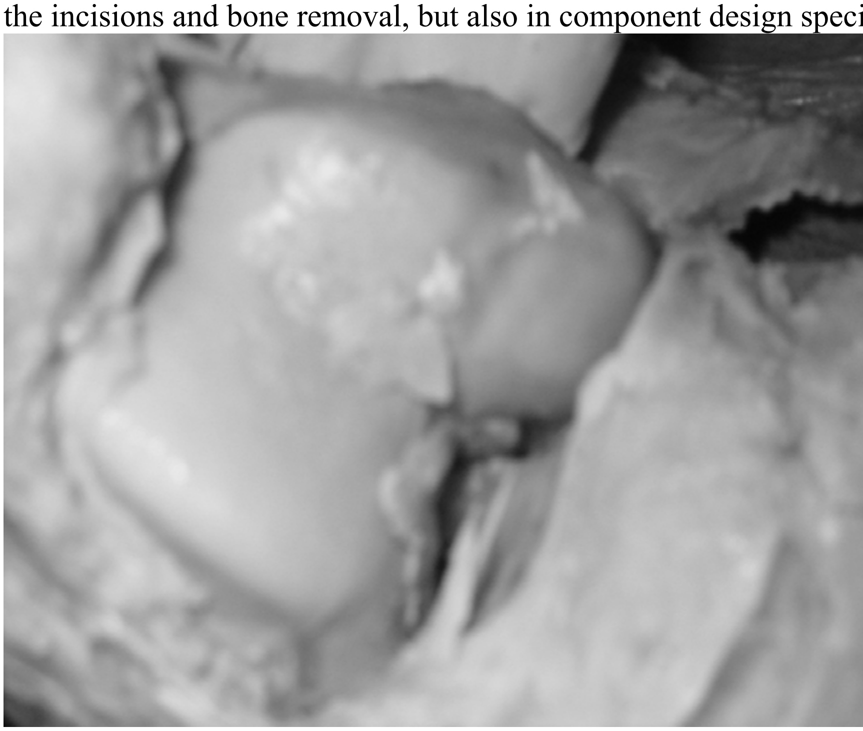


Figure 1: Frontal view of the distal end of the femur. The same view the surgeon views before bone removal takes place.

Because the actual knee components will fit on the bones more precisely, the patients will experience less pain and a greater range of motion in their knees following the operation, allowing them to enjoy a more full-filling life.

Literary Review:

Methods other than Optimized Registration for Computer Assisted TKA have been proposed and are being used. These other methods involve the use of fiduciaries and similar computer assisted set-ups. A fiduciary method involves a preliminary surgical procedure to place pins or markers on certain anatomical positions based on CT scans and/or X-ray images to help register, or locate, specific locations during the major surgery (Kienzle & Stulberg). While using the fiduciary method and computer technology, these markers/pins are located on the bones of the patient. Then, through registration and computer programming, a robot arm assists in the cutting and alignment that takes place during TKA. The fiduciary surgical procedure is not minimally invasive. It involves multiple operations on the patient while achieving only a single benefit, a new set of replacement knees (Abdel-Malek & McGowan, 1997).

Computer assisted integrated surgery became more prevalent in the world as the search for a more accurate convention for TKA continued. A program that could recognize a bone structure in virtual space and accurately register that same structure in real space was the next step in the design process. There are many algorithms used now to perform the described task, such as: segmentation, voxel, optimization, singular value decomposition, orthronormal and eigenvalue systems, unit and dual quaternion, (Eggert, 1997 and Maintz & Viergever).

The Iterative Closest Point, (ICP), proved to be the most efficient algorithm given the specific bone registration problem and operating room time constraints. The ICP algorithm is one of the most popular algorithms for image registration. Its popularity within the scientific world is accredited to its accuracy, robustness, and usability. Various papers by authors from all over the world describe and use the ICP algorithm for similar registration processes.

Besl and McKay provided the framework and the backbone for the ICP algorithm. They were the first to describe and use the ICP algorithm. The ICP algorithm that Besl and McKay produced is capable of handling different types of 3-D shapes. The algorithm uses points, lines, curves and triangles to match two sets of data to one another. The ICP algorithm always converges to the nearest local minimum. With the proper initial positioning executed, this algorithm can converge on the most complex of shapes.

The ICP algorithm registers a model set of data to an actual set of data by completing a number of very distinct steps. First the algorithm finds the closest set of data points, and then computes a registration built from quaternions. The quaternion matrix built for this registration is built from the centroids of each data set and the computation of a cross-covariance matrix. The next step involves applying the registration to the chosen data set. Lastly, the algorithm will stop transforming data points through this repetition once a certain threshold error is met or the distance between original points and the new set of points is no longer decreasing. The threshold is a value chosen by the operator, which is built from the mean error of the original points in comparison to the new set of "closest points". (Besl & McKay, 1992).

There are variations of the ICP algorithm and certain methodologies that can be performed with the ICP algorithm, which raises ICP performance exponentially. While K-d tree and Elias methods are alternate forms of registration, they suggest ideas for applications that could work conjuctively with the ICP algorithm (Greenspan, Godin, & Talbot). By building triangular neighborhoods or special reference systems, the K-d tree and Elias methods provide a guide and a network throughout the registration process.

Research similar to, and in other cases surpassing, this experiment is already being done. Yet there is room for further validity in methodology and more consistency in results. In the Laboritoio di Biomeccanica, located in Bologna, Italy, researchers have used a registration procedure similar to the "Optimized Registration for Computer Assisted TKA", but they have gone further by performing this form of computer-assisted surgery on an actual cadaver (CAOS website). CT scans produced virtual models of the bones, the ICP algorithm registered the bones, and a robotic arm performed the proper cuts and incisions for the TKA. The researchers have also performed an analogous experiment involving a unicompartmental arthroplasty. They used the ICP algorithm for registration and a similar set-up as previously described. The set-up differed only in the types of user interfaces and tools used (Marcacci & Tonet).

In Fluente and Glozman's articles, both propose and use methodologies that not only register a femur, but also provide comparative results on how a femoral registration should be achieved. These papers help to better define the discrepancy between a true fit versus an accurate registration. Meaning errors could be low, considering the threshold tolerances and initial orientation, while not necessarily attaining a near perfect registration. Through this experiment and its results, a better guide is provided that assures a near perfect femoral registration.

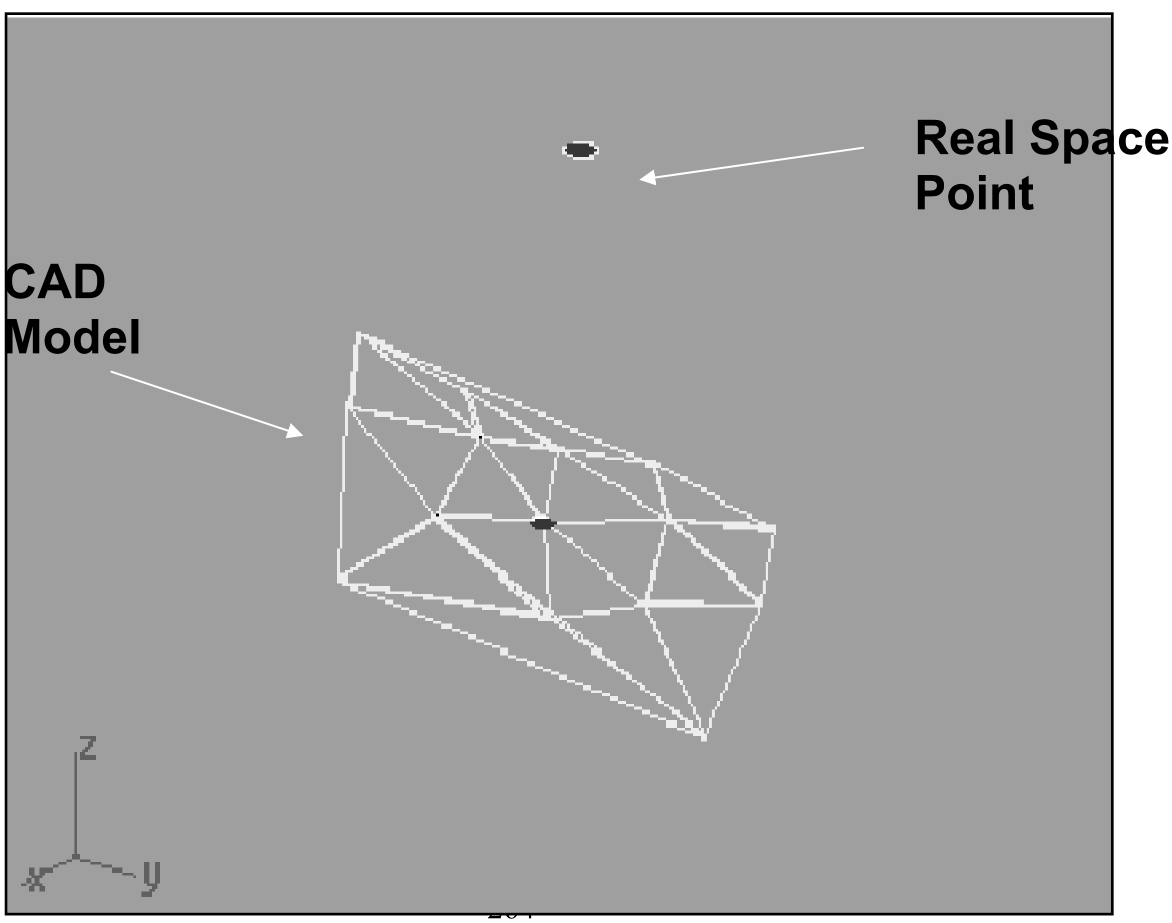
ICP Methods:

The ICP algorithm prescribed by Besl and McKay is a key tool in the analysis of a "set of best registration points." This algorithm drives two sets of points closer to each other, minimizing the mean distance of all points in one set to the corresponding "closest point" in the other set. This algorithm was applied to match two identical surfaces: 1) being the whole object or surface model, 2) being part of that object surface or the digitized sample, and then place these two surfaces in 3-D space in their proper orientation with one another.

Because this proposed solution was designed for a specific problem for a specific application, the ICP algorithm was enhanced with certain features such as a “point to line” addition, a “point to plane” addition, a “triangle neighborhood” addition and lastly, a “Good Start Position” addition.

The point to line and the point to plane addition were both added to the algorithm to help its convergence on a global minimum. Because Computer Aided Design (CAD), surfaces are defined by many triangles, being able to define lines and planes in space to represent these triangles gave the algorithm a closer look at the actual surface being investigated, instead of just a cloud of points. Using parametric equations of lines and planes and certain geometrical relationships, this algorithm was enhanced to check each aspect of the surface, from points on a surface, to lines on a surface, to triangular planes on a surface in order to find the “closest point” or “best match.”

The triangular neighborhood addition is based on vertex connectivity of triangles on the CAD, and its purpose was to make the algorithm run faster. Each point on the digitized sample has either a prescribed or a correlating “closest point” found on the CAD model. From that prescribed or correlating “closest point” on the CAD model, the vertexes of the immediate connecting triangles and those of the secondary level of connectivity were found and saved. This enabled the algorithm to check a lesser number of triangles, lines, and points for the location of the next “closest point” for every prescribed or correlating “closest point.”



Routine developed by Dr. John Challis. This smaller algorithm was applied to give the ICP a proper place to begin since it is known that the absolute convergence of the ICP algorithm is based primarily on the starting positions of the two samples in question.

This Least Squares routine was applied because there were three points of reference, which were defined on the CAD model and again on the real-space model. Those three points were the greater trocanter, the lateral epicondyle, and the medial epicondyle.

Experimental Methods:

The tools used during this experiment consisted of a CAD model from http://www.cineca.it/hosted/LTM-IOR/back2net/ISB_mesh/mesh_list.html. Sawbones.com suggested this site, and is also the company from which the 3-D foam model of the left femur was acquired. A Microscribe digitizing arm from Immersion Corporation was used to accurately register points into software packages such as MatLab, (Mathworks, Inc.; Natick, MA), and Rhino 3-D modeling software (Rhinosceros; Seattle, WA). A Dell with Pentium 4 processor was used for these computer analyses.

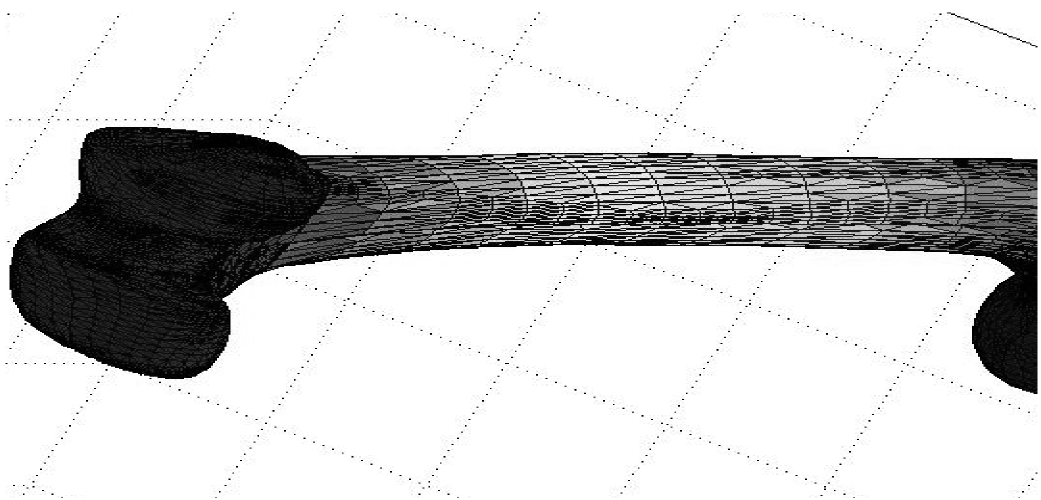


Figure 3: Computer Aided Design depiction of the left femur.

After previewing footage and diagrams of total knee arthroplasty, a defined foundational view was built in Rhino based on how much of the femur that is actually displayed during TKA, (Figures 1 & 3). The foundational view/ femoral display was divided into quadrants and an array was formed over the surface. These quadrants were built based on the prescribed view and the three axes used to align femoral components conventionally. The posterior condylar axis was used to bound the bottom of the box. The epicondylar axis was approximated to be the centerline of the box in the horizontal direction and the anterior-posterior axis was approximated as the centerline of the box in the vertical direction. The array of points consisted of 624 points on this surface.

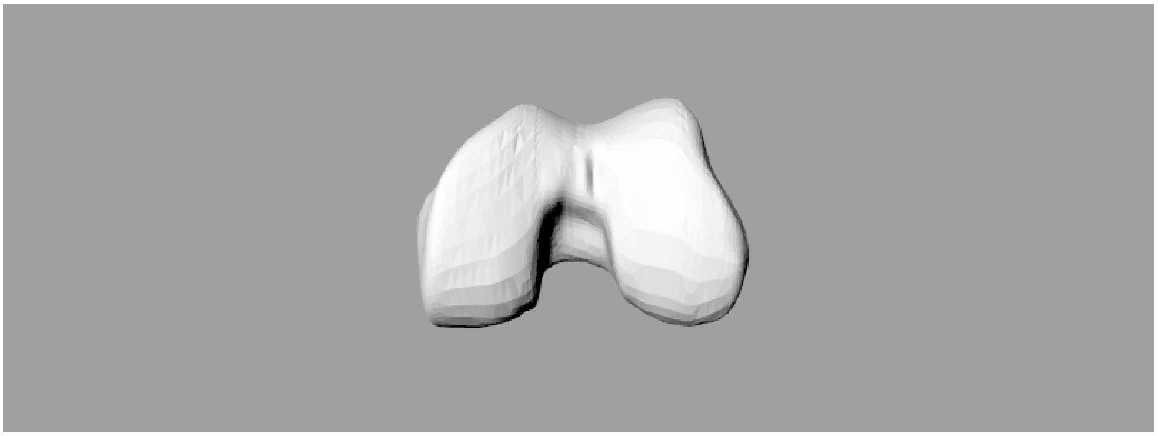


Figure 4: Distal Femur surface chosen for analysis.

The optimization portion of this analysis consisted in taking the four quadrants and running 624 tests in order to find the "best registration points". In order to find the "best registration points" in each quadrant, three of the four quadrants were held constant as a base set of points. Then, with each test, one point from the quadrant being tested was added until all the points in that quadrant were individually tested using the set of base points for that quadrant. This allowed each point to have a weighted error factor. Each quadrant tested approximately 156 points and each quadrant took over 20 hours to complete.

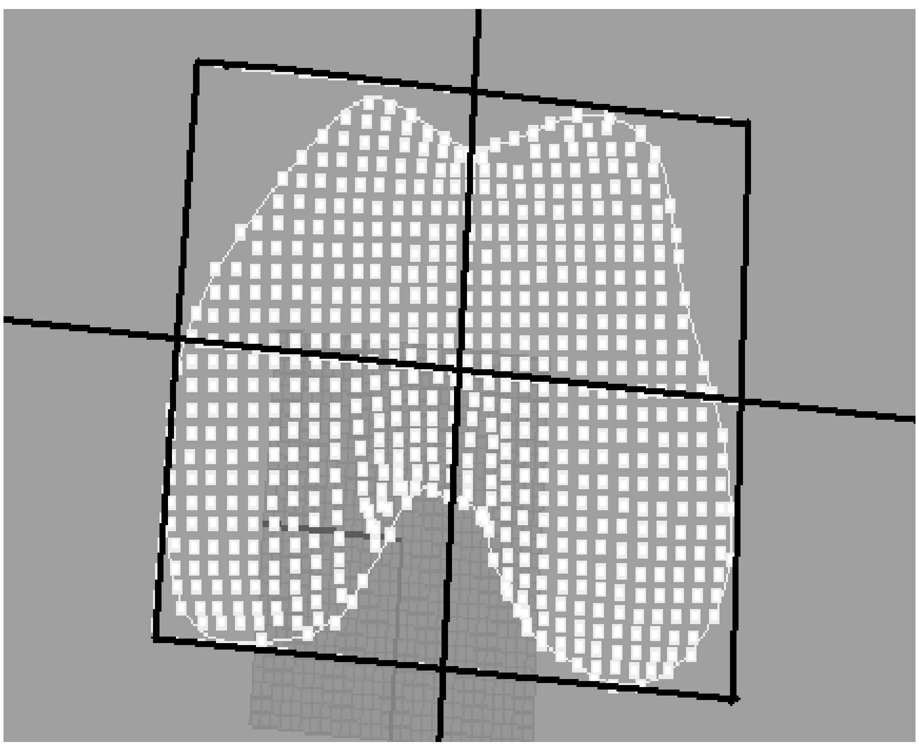


Figure 5: Top view of 3-D depiction of Four-quadrant set-up with bounding box.

The 12 points with the least weighted error were found for each femoral quadrant and saved. These 48 points were tested for accuracy and efficiency given the application. These tests involved moving the 48 points away from the CAD model and then allowing the ICP algorithm to place them back in their proper positions. From 4 different tests consisting of only translations, 7 outliers were identified and removed from the best registration point set, (Table 1 rows 1-4).

To test the “best registration points” against alternate registration points, 9 more tests were run. These tests were run with the Good Start algorithm added so starting positions became of no consequence. The first 3 tests were of the “best registration” points registered by hand using the Microscribe digitizing arm. The second 3 tests were again digitized by hand. Approximately 10 arbitrary registration points were discriminately chosen in areas other than those near the “best registration” points. The final three trials entailed approximately 10 registration points digitized by hand and representing “best registration” points as accurately as possible.

Results:

Table 1 - Data found before the implementation of the Good Start Position-

Trial	Number of Points	Point Type	Translation	Total Mean Error(mm)	Maximum Mean Error(mm)
1	624	Array Over Surface	[-.3 .2 .1]	0.2847	5.8226
2	48	Initial Best Regis	[-.3 .2 .1]	0.1922	0.8599
3	48	Initial Best Regis	[-3 2 1]	0.3836	1.3459
4	48	Initial Best Regis	[30 20 10]	0.6756	2.6006
5	41	Outlier Removal	[-.3 .2 .1]	0.1594	0.5455
6	41	Outlier Removal	[-3 2 1]	0.1921	0.9753
7	41	Outlier Removal	[30 20 10]	2.8055	7.3868
8	41	Outlier Removal	None	0.1303	0.4595

Table 1 - Continued

Trial	Number of Outliers	Time(sec)
1	51	559.69
2	7	75.69
3	9	153.17
4	8	261.69
5	9	101.39
6	5	152.21
7	3	208.16
8	8	60.168

Table 1 shows a range of tests. Trial 1 tested the 624-point array on the femoral surface. Trials 2 – 4 tested the initial set of defined "best registration" points and trials 5 – 7 tested the 41 "best registration" points. Based on the outliers found in trials 2 – 4, seven points were removed to make the 41 "best registration points". Trial 8 gives a base error and a base time that should be expected.

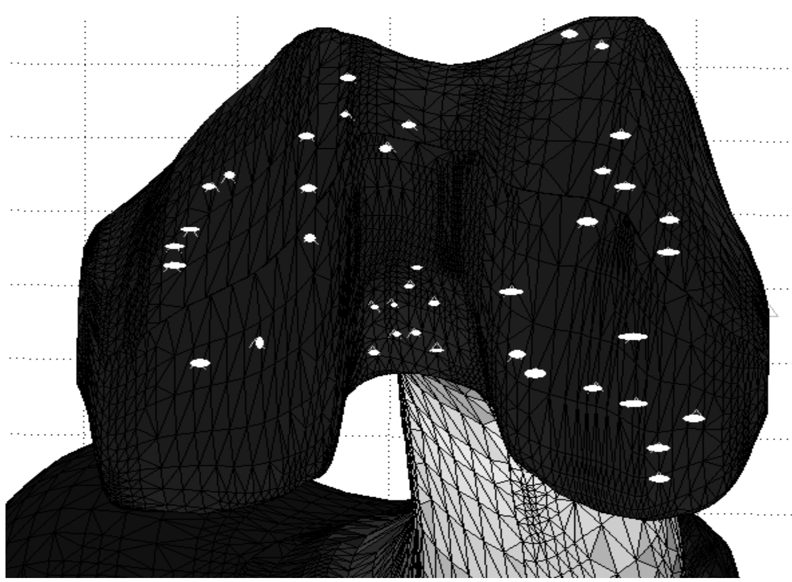


Figure 6: Showing a Matlab view of the 41 "Best registration points."

Table 2 -Data found after the implementation of Good Start Position-

Trial	Number of Points	Point Type	Total Mean Error(mm)	Maximum Mean Error(mm)	Number of Outliers	Time(sec)
1	44	Best Regis	0.245	1.3473	4	400.37
2	46	Best Regis	0.2055	1.0243	9	451
3	45	Best Regis	0.4868	2.7565	4	74.03
4	10	Arbitrary	0.1027	0.2187	3	116.89
5	10	Arbitrary	0.4562	2.0971	1	48.53
6	11	Arbitrary	0.1109	0.2547	3	210.78
7	10	Abbrev Best Regis	0.1876	0.3745	0	23.7
8	10	Abbrev Best Regis	0.0671	0.1828	2	24.02
9	11	Abbrev Best Regis	0.1143	0.2616	2	57.58

Table 3 – Averages of the Different types of trials

Trial	Number of Points	Point Type	Total Mean Error(mm)	Maximum Mean Error(mm)	Number of Outliers	Time(sec)
AVG(1-3)	45	Best Regis	0.3124	1.70930	5.667	308.47
AVG(4-6)	45.000	Arbitrary	0.22320	0.85680	2.333	125.40
AVG(7-9)	10.333	Abbrev Best Regis	0.1230	0.27290	1.333	35.10

Table 2 shows the results of tests of three different types of point sets from actual digitized samples. Trials 1 – 3 tested the accuracies and stabilities of the 41 "best registration points" with three reference points added. Because these points were digitized by hand, an extra point, or maybe a repeated point, was digitized. Trials 4 – 6 depict points designated as arbitrary because they were randomly chosen points on the femoral surface. Trials 7 – 9 tested an abbreviated set of "best registration" points. Table 3 is a color-coded chart of the corresponding averages in the previously discussed 9 trials in Table 2.

Discussion:

Some have suggested having a large array of points on a surface that, when applied to an algorithm, would better insure a proper registration. However, after examining the results of a direct comparison of the 624 points with the 41 "best registration points" and the "abbreviated best registration points", it was noted that this is not necessarily the case. The results show that there is a strong correlation between acquiring minimal errors and the choosing proper registration points. In addition to choosing proper registration points, convergence of the algorithm on a global minimum is completed more quickly than if one were to chose many registration points.

After examining the results for the "best registration" points, it appears the computer is attempting to draw the femoral view almost as an artist would make an outline sketch. This means that it looks as though the computer is trying to find "best registration" points that lay on the defining contours of the surface, in effect producing a line along the border where two surfaces meet. In addition the right condyle is relatively flat compared to the left condyle and no points were chosen in the lower right region. As in a drawing, a flat region can only be defined by shading and/or depth, but because the computer was not programmed to recognize depth nor shading, points were just not chosen in flat regions.

The intercondylar region of the femur is an extremely influential region for this type of analysis. From the 41 "best registration" points, approximately 25% of these points are in that region. When viewed by the human eye, the intercondylar region is the distinct region, which stands out from the distal portion of the femur. Indeed, without this distinction, the condyles would not be called condyles. This very distinction is what allows a proper fit or orientation to be achieved.

The acquisition of outliers is almost inevitable. Due to this phenomena, it is strongly recommended that 10 – 15 of the "best registration" points be chosen in addition to the three reference points for this application. So, if necessary, removing 2 – 3 outliers will not cause a flawed or improper registration. Outliers are a major concern in choosing a number of registration points, but with orientation also being a key component of this analysis, as more registration points are chosen, there is a greater probability that a proper orientation will be found within the specified tolerance.

Limitations:

Several limitations in this study should be noted. First, the variability of this study is low because testing was only done on one femur. Second, the registration errors could have been lower if more CAD models were available during the time of experiment. Research shows that a better registration can be found when meshes or polyhedrals of different qualities are tested in sequence from coarse to fine. The polyhedral used in this experiment differed from the foam 3-D model on a magnitude of 1.59mm to 0.79mm. This error is similar to actual procedures that take place in hospitals due to the accuracy of CT scanning, which is around 1mm at best. The final limitation of this study is that, while MatLab software carries out operations to 10 significant figures, the "best registration" points could only be approximated by the digitizing arm and operator.

Future:

This type of research will influence ACL and PCL repair procedures, and other joint replacement procedures such as hip joint replacements. Registration and computer assisted surgery has multiple applications for future procedures in spinal complications and brain surgeries. The concepts of perfect fit and improved range of motion based on proper registration are readily applicable for more efficient prosthesis.

This small study shows, that with enough research and the correct methodology, an improved TKA can be achieved. If computer assisted surgery for TKA was incorporated into the main stream of modern medicine, it would increase the success rate of TKA around the world. Not only would patients have more fulfilling lives due to their knees working as they did in the past, but research doctors, medical doctors, medical students, and others would have more time to find solutions for Osteoarthritis and other devastating illnesses that affect mankind.

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