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Toward a More Efficient and Effective Method for Tracking 3D Bone Position and Orientation in Fluoroscopic Images

Harrison M. Davis
The University of Vermont

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Toward a More Efficient and Effective Method for Tracking 3D Bone Position and Orientation in Fluoroscopic Images

Davis, Harrison M.
Advisor: Dr. Niccolo Fiorentino
Thesis Committee: Dr. Niccolo Fiorentino and Professor Michael Rosen
The University of Vermont

April 26, 2021

Abstract

Osteoarthritis (OA) is the primary cause of mobility-based disability in the United States. Approximately 12% of osteoarthritis cases occur following traumatic injury, through a process termed post-traumatic osteoarthritis (PTOA). PTOA accelerates the degeneration of articular cartilage, thus having profound effects, particularly on the young athletic population. It has been found that, following injury, there are both biological changes to the articulating cartilage as well as dynamic changes to the knee joint kinematics. However, it remains unclear how these changes in kinematics correlate with cartilage degradation. Understanding this relationship of the mechanisms that lead to PTOA assists in the development of effective treatments for patients who have suffered previous knee injuries. In order for researchers to be best equipped to observe and understand how altered kinematics following surgery result in cartilage degradation, new methods must be developed to quantify these changes to the kinematics. Two of the leading methods for measuring bone movement and studying knee joint mechanics are motion capture and dual fluoroscopy with model-based tracking (DF-MBT). The primary problems with these methods are that motion capture, while providing near immediate results, is relatively inaccurate since it suffers from soft tissue artifact. DF-MBT, on the other hand, is considered accurate to within a millimeter, but proper post-processing of the data requires a significant amount of time. Ideally, there would be a method that provided results as accurately as the DF-MBT method in the time interval of the motion capture method. Therefore, the purpose of this study was to develop a tracking method that is faster than DF-MBT and accurate on the order of a millimeter or less. The initial methodology behind achieving this goal was to write a code that would produce a transformation matrix between the DF-MBT and motion capture pose maps. A pose map is a representation of the position (pose) of an object in reference to a particular coordinate system at each frame. Therefore, a static frame could be used in order to define a transformation from motion capture clusters to the bone's location. This transformation matrix can then be applied to the dynamic frames to produce results on the same level of accuracy in a much shorter time frame. This study analyzed and compared the results of three different methods of measuring bone movement; traditional DF-MBT tracking (Model Based Tracking), the previously described pose map method (Skin Marker Tracking), and an additional method which combined the process of the other two methods (Combined Tracking). Despite the Skin Marker Method providing unsatisfactory results, the goal of producing a more efficient and effective method for measuring bone movement was still achieved. The Combined Tracking method, which involved using the transformation code as a starting point for traditional DF-MBT alignment, resulted in more accurate results than DF-MBT in a shorter time frame. Therefore, a more efficient and effective method for tracking 3D bone position and orientation in fluoroscopic imaging was successfully developed.

Acknowledgments

I would like to thank and acknowledge the members of my thesis committee, Dr. Michael Rosen and Dr. Niccolo Fiorentino, for their continued guidance throughout the process of developing my honors thesis. In particular, I would like to thank Dr. Fiorentino for his support over the past number of years in developing my ability to conduct research. I also would like to acknowledge my lab coworkers, who helped operate equipment needed for the physical experiment, with specific thanks to John Ramsdell for his consistent guidance on ways to improve the study. I would also like to acknowledge my close friends and classmates who have motivated me to push myself to learn more and accomplish work at the best of my ability. Finally, I thank my parents for their continued support and encouragement to pursue a better education for myself.

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1 Introduction & Background

1.1 Introduction

Osteoarthritis is the primary cause of mobility-based disability in the United States.[8] Approximately 12% of osteoarthritis cases occur following traumatic injury, through a process termed post-traumatic osteoarthritis (PTOA). PTOA accelerates the degeneration of articular cartilage, thus having profound effects on the ever increasing young athletic population. It has been stated that an ACL reconstruction of a young athlete leads to a knee that resembles that of one decades older.[5] Published reports suggest that more than half of people who have ACL and meniscus injuries eventually develop PTOA. Following injury, it has been shown that there are biological changes to the articulating cartilage and dynamic changes to the kinematics. What is unclear is how changes in kinematics correlate with cartilage degradation.[3] A better understanding of the mechanisms that lead to PTOA development would aid in the development of novel treatments for those who suffer sports related injuries.

A crucial aspect of understanding knee joint biomechanics is finding a way to measure bone movement with sufficient accuracy for understanding articular damage on the order of a millimeter or less. Having an accurate method for measuring bone and joint movement better equips researchers to study and understand the kinematics and their correlation to cartilage degradation. Currently there are two primary methods to study knee joint mechanics; motion capture and fluoroscopy imaging. Motion capture is a method that yields quick results, however these results are less accurate since it suffers from soft tissue artifact. Fluoroscopy imaging, on the other hand, uses the dual fluoroscopy machine and virtually reconstruct the positions of the x-ray emitters and image intensifiers on a pre-defined laboratory coordinate system. This method for analyzing data is referred to as dual fluoroscopy with model-based tracking (DF-MBT) and is far more accurate given that it utilizes x-rays and therefore does not suffer from soft tissue artifact. However, this method takes much longer due since it requires the use of DSX, a program which allows the user to shape match the virtual bone to the fluoroscopic images for each frame. Since this process is so labor intensive, given the need to align each individual frame, it requires a significant amount of time to complete. An optimized method for studying joint biomechanics would be both accurate and time efficient. Therefore, the purpose of this study is to develop a tracking method faster than DF-MBT and more accurate than motion capture.

1.2 Background

It is well documented that post-traumatic osteoarthritis (PTOA) in the knee is commonly found following joint trauma and reconstructive surgery. However, it is also evident that the lack of understanding related to the mechanisms leading to PTOA has hindered developments in its treatment. Having the ability to accurately quantify knee joint biomechanics is an essential step toward understanding and providing evidence that supports the mechanics that encourage PTOA. There are multiple hypotheses as to why PTOA commonly occurs following knee joint trauma, such as irregular loading experiences caused by abnormal joint kinematics post-surgery and isolated cartilage defects.[2] However, an accurate method to quantify knee joint biomechanics is needed to research and test these hypotheses. Although there are methods such as dual fluoroscopy, which can accurately measure and quantify knee joint biomechanics, these methods take a significant amount of time given how much processing is required and therefore there is a need for a more efficient and effective method.

This study aims to assist the exploration of knee joint biomechanics and PTOA development through the analysis and improvement of current methods for knee joint measurement. This was accomplished by measuring the movement of the knee joint of a cadaver with both reflective skin markers (SM) and dual fluoroscopy (DF-MBT) simultaneously. The cadaver was used as a model for the living knee joint throughout the movement of walking and internal-external rotation. Skin marker data and DF-MBT images were used to generate pose maps. Additionally, joint angles were calculated using implanted beads in the bone to serve as the gold standard for accuracy, using the Implanted Bead method (RSA). Naturally, this method cannot be used on patients because it would require implanting the beads in the patient's bone, however it serves as an excellent standard for accuracy given that the beads make it easier to precisely track the bone. The processing time was determined by recording the time it took for alignment of the Model Based Tracking and Combined Tracking methods. The accuracy of these methods were compared against the gold standard approach. These tasks resulted in the quantification of error for the soft tissue artifact, as well as evidence that the new method for bone and joint measurement, which utilized the pose maps, was faster but less accurate than the DF-MBT approach.

2 Methodology

The primary goal of this research was to develop a more efficient method for producing accurate knee joint measurements for future analysis. With this in mind, it was important to anticipate how to develop such a method. The current primary methods of motion capture and dual-fluoroscopy are excellent within their given fields of fast analysis and accurate results, respectively. However, both suffer from an inability to successfully meet both needs. The intent of this research was to create a pose map that can translate the motion capture clusters into accurate bone models in order to acquire dual fluoroscopy level accuracy in a motion capture time frame.

2.1 Setup and Calibration

Before the study could be conducted it was important to calibrate the dual-fluoroscopy and motion capture systems and make sure all components used for the study were properly setup. All motion capture cameras must be turned on and properly configured, as well as establishing the origin for the motion capture reference. The dual-fluoroscopy emitters also had to be lined up with the intensifiers and set to the appropriate voltage and current. In this case, the voltage and current were set to 125 kVp and 5 mA, respectively. Additionally, the RSA beads needed to be implanted into the bones of the cadaver leg. Since the specific leg used in this study had been used previously in the lab to measure joint movement and RSA, the beads had already been implanted. The cadaver leg was removed from the freezer 15 hours before the experiment began and was fit with sockets that allowed the cadaver leg to be situated withing the dual fluoroscopy system on the morning of the experiment. Before the leg was placed in the system a marker block, seen in Figure 1, was measured in both DF-MBT and motion capture to create a common coordinate system. Once the cadaver leg was properly situated it was outfitted with multiple motion capture markers; four on the femur, four on the tibia, one on each of the PVC pipes connected to the bones, and one on each of the emitters and intensifiers. An image from the morning of the experiment can be seen in Figure 2, showing the cadaver leg being setup for static calibration in the system. Once the motion capture markers were in place, the lab doors were closed, the emitters and cameras were turned on, and the motion capture lab was calibrated. When everything was turned on, calibrated and set up, the actual knee measurements were taken.

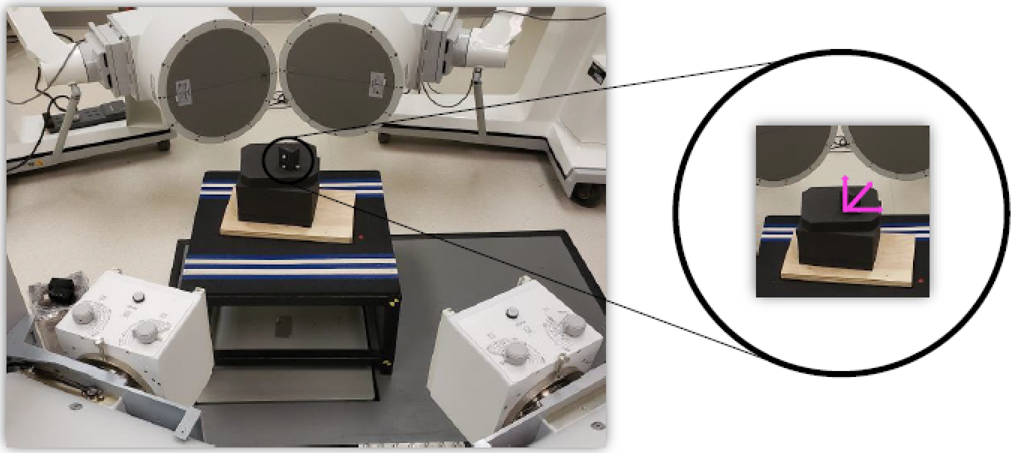


Figure 1: Marker Block inside of the DF-MBT system.

Figure 2: Image from the morning of the experiment showing the cadaver leg, outfitted with reflective skin markers, inside the DF-MBT system.

2.2 Data Collection

Once all calibrations and setup procedures were in place the static and dynamic trials could finally be conducted in the lab. During this process multiple trials were conducted measuring various types of simulated motions such as a static calibration, walking, and internal-external rotation. These trials were analysed immediately after being conducted in order to visually judge parameters such as the leg being properly in frame, an appropriate number of frames collected, no additional markers appearing or markers being dropped on the motion capture system, and expected quality of the results. All tests that appeared to be of a high enough quality were saved until a suitable trial had been conducted for each type of motion. As soon as all trials had been conducted and the data was saved the motion capture markers were each named to identify their specific location and intention. Finally, all of the data was exported from the lab computers to the computer that would be used to analyze the results.

It is worth noting that the cadaver leg was given just over 15 hours to thaw and therefore was still slightly frozen when the experiment was conducted. Given COVID-19 restraints this was the maximum amount of time that could be allotted for the cadaver leg to thaw. This is notable because it not only affected the range of motion for the leg but likely impacted the muscle density and other components of the leg's soft tissue that would result in less range of motion.

2.3 Transformation Matrix Development

In order to determine the transformation matrix for the Skin Marker Tracking method it is important to start with a static calibration. A static calibration allows for one single frame to be analyzed using DSX and applies the transformation matrix to the dynamic trials. Essentially eliminating the need for manual alignment of each frame. The basic thought process for the transformation is seen in Figure 3 in which the transformation from one coordinate system to the next is shown.

$$\begin{pmatrix}A'\\B'\\C'\\1\end{pmatrix} = \begin{pmatrix}\begin{array}{ccc|c} & \text{Rotation} & & \text{Translation} \\ -0.92514 & 0.179636 & -0.33444 & 114.4902 \\ -0.25573 & -0.94599 & 0.199287 & 81.19482 \\ -0.28057 & 0.269892 & 0.921106 & 61.85612 \\ 0 & 0 & 0 & 1\end{array}\end{pmatrix}\begin{pmatrix}A\\B\\C\\1\end{pmatrix}$$

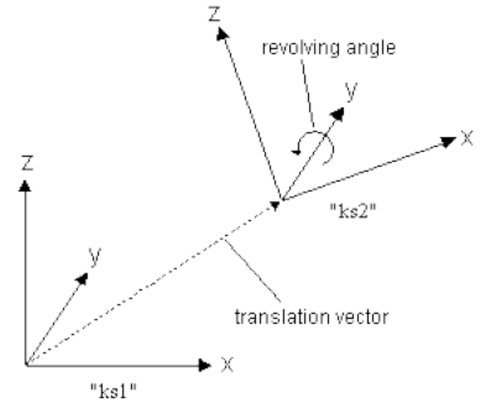


Figure 3: Simple transformation from one coordinate system to the next, shown mathematically and visually.

Using the equation seen in Figure 4 the transformation matrix is calculated using the single frame calculated by DSX. The result from this calculation can be implemented into the equation seen in Figure 5 in order to find the overall transformation matrix. In the image the green variable of MOCAP-Bone Cluster is the transformation calculated by the motion capture system for each frame of the dynamic trial and is therefore the only variable that is not constant.

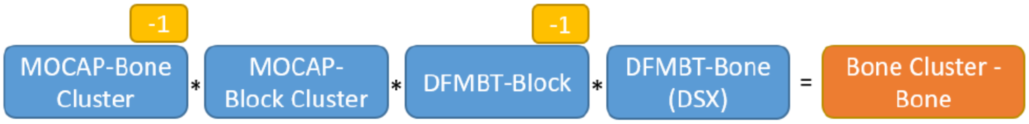


Figure 4: Static calibration calculation for transformation between Bone Cluster and Bone.

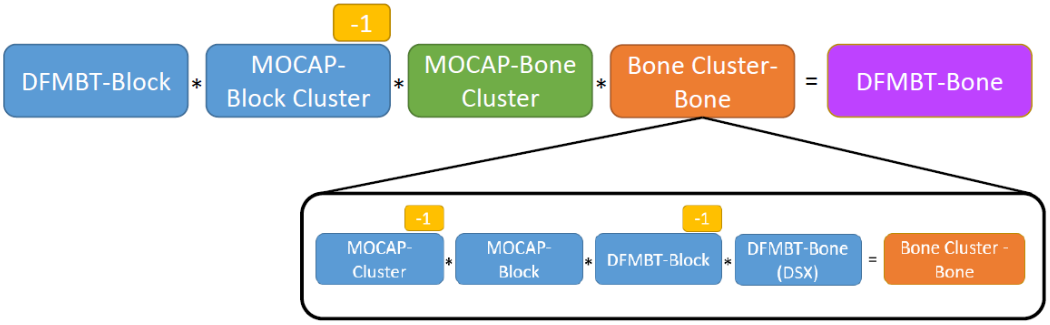


Figure 5: Calculation for transformation matrix between DF-MBT and Bone.

This process results in a direct transformation from the dual fluoroscopy images to the final bone positioning in the virtual reconstruction, while only using a single frame of DSX. Since DSX is the most labor intensive and time dependant aspect of the DF-MBT process and this method only requires one frame being analyzed in DSX this method, Skin Marker Tracking, should result in similarly accurate results in a far more efficient time frame.

2.4 Post-Processing

Given that the Skin Marker Tracking is now completed it is time to focus on producing results for the Model Based Tracking and Combined Tracking methods. First, Model Based Tracking was conducted as a representation of the dual-fluoroscopy method. This method produced a virtual reconstruction of the lab by aligning a 3D model of the bone with the fluoroscopic images, see Figure 6. Then the Combined Tracking method was conducted using the same process for manual alignment as Model Based Tracking, but while utilizing the result of the Skin Marker Tracking as a starting point. The expectation being that the Combined Tracking method would be more accurate than the Skin Marker Tracking method and take less time than the Model Based Tracking method. These methods were conducted for both the Walk and Internal-External Rotation trial in order to see how accurately the translational and rotational movement could be tracked, respectively. For both the Walk and Internal-External Rotation trials the methods were tracked every 5 frames. Using frames 20-95 for the Walk Trial and frames 75-215 for the Internal-External Rotation Trial.

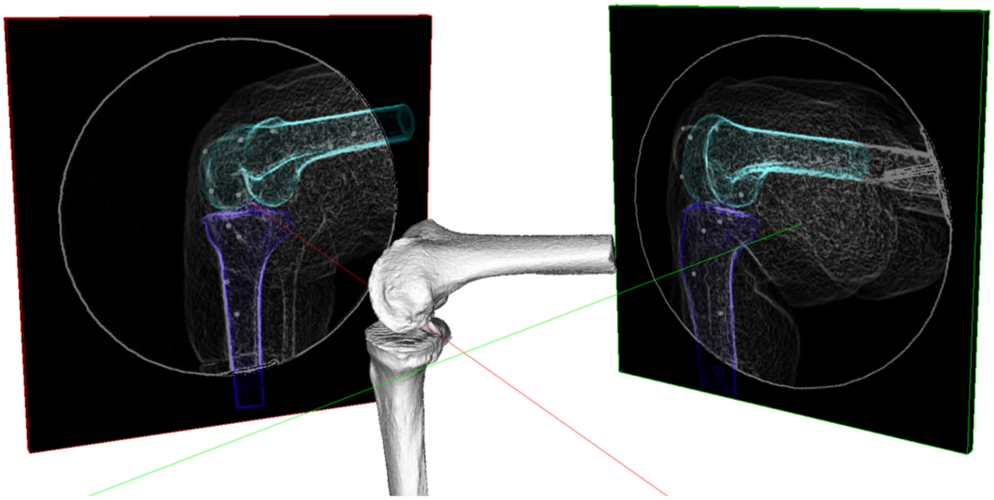


Figure 6: Visual representation of the virtually reconstructed bone using the DF-MBT images.

Once both data sets were completed the results of each method were then compared to the RSA results to measure the accuracy of each method. The accuracy was measured in three categories; bias, precision, and root mean squared (RMS) error. The RMS error quantifies the overall error in the accuracy and is therefore the primary method for measuring the accuracy of the results moving forward in the study.

3 Results & Discussion

The results for the Walk and Internal-External Rotation trials can be broken down into six categories; one for each of the three methods for both of the trials. The Walk Trial was first analyzed with the intent of primarily focusing on the code's ability to track translational movement. While the Internal-External Rotation trial was selected to focus on the rotational movement, with specific focus on internal-external rotation. For both of these trials the intent is to observe and compare the differences in time and accuracy for the Model Based Tracking, Combined Tracking, and Skin Marker Tracking methods.

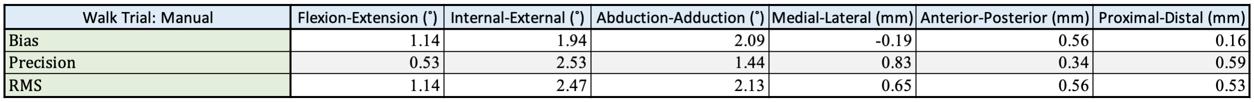
In order to quantify the accuracy found between each method and the RSA, the positions for each frame were plotted for each of the six degrees of freedom. In addition, the bias, precision, and RMS errors were calculated for each degree of freedom and are seen below with their respective methods. The bias represents the error above minus the error beneath the desired positioning for the bone. The precision depicts the range within which the positions fall relative to the RSA. Finally, the RMS quantifies the magnitude of the error in reference to the RSA. The bias, precision and RMS errors are listed for all of the methods, however, it is worth noting that the RMS error is the best way to quantify the error and is therefore the most important way of comparing the methods.

In addition to the tabular and graphical representation of the results, the imperfections in alignment can be visually seen in Figures 8, 10, 12, 14, 16, and 18. These visualizations contain two models of the knee joint, with the red representing the RSA alignment and the off-white representing that methods positioning. In all of these visuals the bones are plotted in the tibial reference frame.

3.1 Walk Trial

3.1.1 Model Based Tracking

The first method conducted was Model Based Tracking for the Walk Trial. This method served as a representation of the dual-fluoroscopy process for knee joint measurement. Therefore the expectation is that the results will be the most accurate but will also take the longest time to acquire. For both the Model Based Tracking and Combined Tracking methods it was expected that the individual conducting the adjustments put in relatively the same effort per frame to limit bias within the results. The resultant accuracy of the Model Based Tracking Walk method are found in Table 1 below.



Walk Trial: Manual	Flexion-Extension (˚)	Internal-External (˚)	Abduction-Adduction (˚)	Medial-Lateral (mm)	Anterior-Posterior (mm)	Proximal-Distal (mm)
Bias	1.14	1.94	2.09	-0.19	0.56	0.16
Precision	0.53	2.53	1.44	0.83	0.34	0.59
RMS	1.14	2.47	2.13	0.65	0.56	0.53

Table 1: Tabular representation of results for the Model Based Tracking method of the Walk Trial in all six degrees of freedom.

It was found that this method was quite accurate, yielding results for translational movement within a millimeter of the RSA results. The bias was found to be within two millimeters for all degrees of freedom. The precision yielding similar results except for in the internal-external field, where the precision had an error of roughly 2.52 millimeters. It is evident when analyzing the root mean squared error that the translational measurements were more accurate than the rotational, with the Abduction-Adduction and Internal-External fields showing the highest error of approximately two millimeters.

In Figure 7 below, the red line represents the RSA while the dotted blue line represents the Model Based Tracking results. It is again evident that the result were generally accurate and relatively precise, with the largest error being found in the Abduction-Adduction and Internal-External fields. The primary takeaway from these graphs being that Model Based Tracking alignment provides a pretty accurate representation of the bone model, but not without its imperfections which are primarily found in the rotational fields.

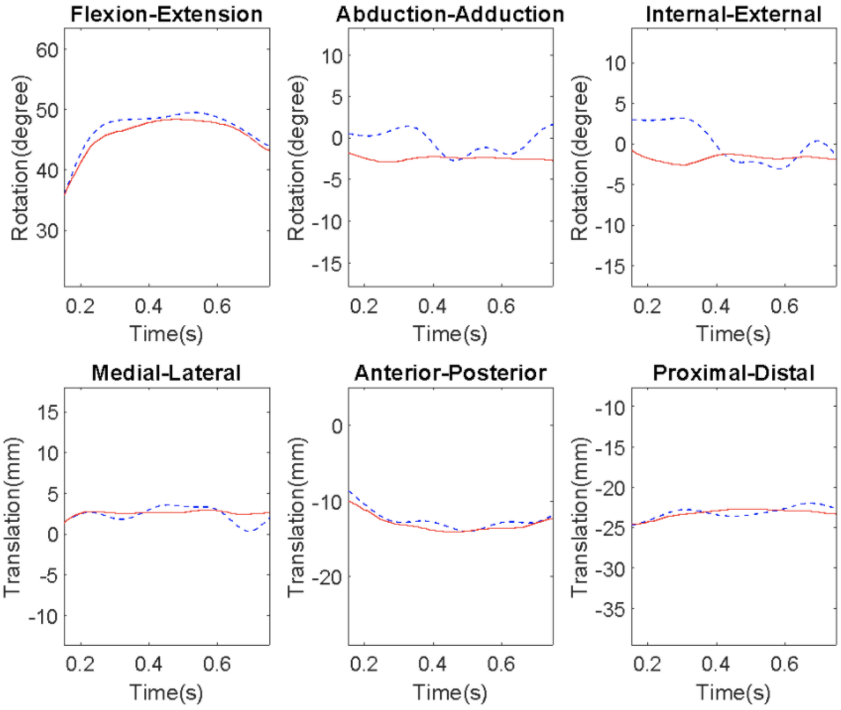


Figure 7: Graphical representation of results for the Model Based Tracking method of the Walk Trial in all six degrees of freedom.

These results are again visualized in Figure 8 where the imperfections in the bones alignment are apparent at the points where the white Model Based Tracking results are seen. This model shows that the results are quite accurate, with minimal noticeable locations of misalignment. However, given that the intent is to to produce an even more accurate model of the knee joint, these imperfections are still significant.

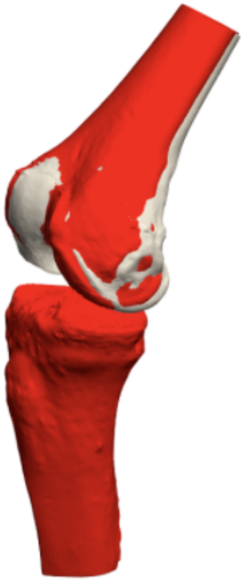


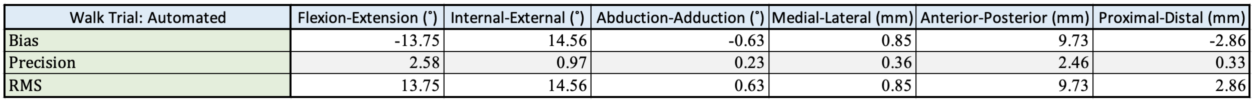
Figure 8: Walk Trial: Model Based Tracking positioning (white) presented on top of RSA positioning (red).

These results are used moving forward as a standard for what the results would have been previously given that they follow the method currently used to gain accurate measurements. It is notable to mention that this method took a total of 1 hour, 23 minutes, and 28 seconds to conduct, with 51 minutes and 57 second attributes the the femur and 31 minutes and

42 seconds attributed to the tibia. Given this time frame these results are considered to be quite accurate and precise and are therefore a good template for the current dual-fluoroscopy method moving forward.

3.1.2 Skin Marker Tracking

Counter to the Model Based Tracking method, the Skin Marker Tracking method was intended to test how accurate of results could be acquired in the shortest amount of time. These results were found entirely using the pose map created from the code and were taken as is once the code was run. The most important reason for testing both Walk and Internal-External Rotation was to analyze the pose maps' ability to track translational and rotational movement. The results of Skin Marker Tracking for the Walk Trial are depicted below and are expected to measure how well the translational movement was captured.



Walk Trial: Automated	Flexion-Extension (˚)	Internal-External (˚)	Abduction-Adduction (˚)	Medial-Lateral (mm)	Anterior-Posterior (mm)	Proximal-Distal (mm)
Bias	-13.75	14.56	-0.63	0.85	9.73	-2.86
Precision	2.58	0.97	0.23	0.36	2.46	0.33
RMS	13.75	14.56	0.63	0.85	9.73	2.86

Table 2: Tabular representation of results for Skin Marker Tracking for the Walk Trial in all six degrees of freedom.

From the table it is evident that the pose map yielded far less accurate results than the Model Based Tracking method. Although the results appear to be precise throughout with most fields being within a millimeter of error and the highest error only reaching roughly 2.6 millimeters. This precision is starkly contrasted by the high error and bias, primarily found in the Flexion-Extension, Anterior-Posterior, and Internal-External fields. The biggest observation found is that the bias and RMS errors are found to be nearly identical in magnitude throughout all degrees of freedom, which suggests that the movement was able to be tracked relatively accurately, however the positioning misaligned. This is corroborated by Figure 9 below, where it is evident that the data sets follow a similar slope although are shifted in position.

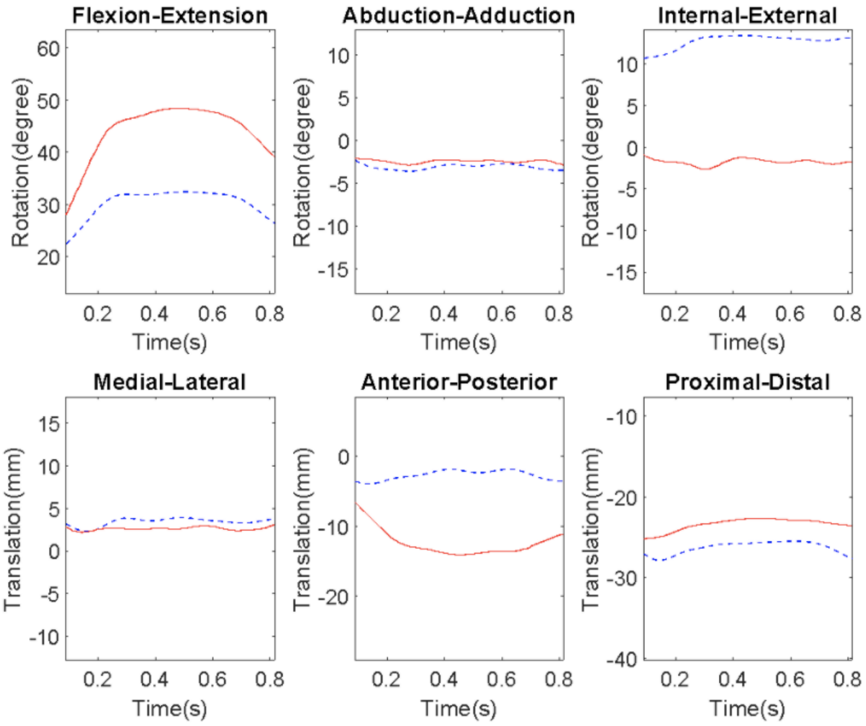


Figure 9: Graphical representation of results for Skin Marker Tracking for the Walk Trial in all six degrees of freedom.

It is very clear in Figure 10 that the bones placement is quite misaligned. The hope had been that the pose map would be able to eliminate the soft tissue element that resulted in error for the motion capture method. However, this model proves that the pose map on its own would not have been able to produce an accurate enough model of the knee joint to work with.

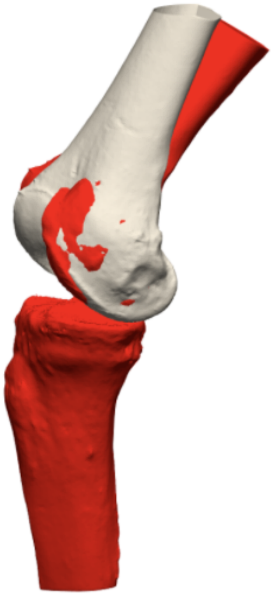


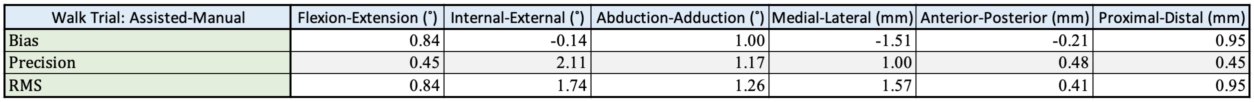
Figure 10: Walk Trail: Skin Marker Tracking positioning (white) presented on top of RSA positioning (red).

The results for Skin Marker Tracking proved to be too inaccurate to use when modeling the knee joint. Despite the fact that this method was a nearly instantaneous result and therefore took far less time than the Model Based Tracking method to acquire, the Model Based Tracking method would still be a better method for tracking knee joint mechanics.

For the Walk Trial in particular it was found that the Anterior-Posterior translation had the most inaccurate tracking, which the Medial-Lateral and Proximal-Distal translations were both quite accurate and precise.

3.1.3 Combined Tracking

The goal when starting the Combined Tracking method was that it would serve as a middle ground between the Model Based Tracking and Skin Marker Tracking methods. A method that would be as accurate as Model Based Tracking while taking less of the time. Given that this method began where Skin Marker Tracking left off it is worthy to note that the Walk and Internal-External Rotation trials were focusing more on the translational and rotational movement, respectively. The manual aspects, on the other hand, of this method and the Model Based Tracking method were conducted at similar speed and with equal distribution of effort to the best extent of the individual conducting the alignment.



Walk Trial: Assisted-Manual	Flexion-Extension (˚)	Internal-External (˚)	Abduction-Adduction (˚)	Medial-Lateral (mm)	Anterior-Posterior (mm)	Proximal-Distal (mm)
Bias	0.84	-0.14	1.00	-1.51	-0.21	0.95
Precision	0.45	2.11	1.17	1.00	0.48	0.45
RMS	0.84	1.74	1.26	1.57	0.41	0.95

Table 3: Tabular representation of results for the Combined Tracking attempt of the Walk Trial in all six degrees of freedom.

It is evident in Table 3 that this method was the most accurate of the three methods for the Walk simulation. Although the precision reached 2.11 mm for internal-external rotation, all other components of bias, precision, and RMS error were found to be within 2 mm of error. The majority of which were within 1 mm or degree of error. This is again seen in Figure 11 that the results are quite accurate, with most error being found in the precision of the results. It is clear in the figure that Abduction-Adduction and Internal-External rotation saw the highest error, which makes sense given the similar trend found for the Model Based Tracking method.

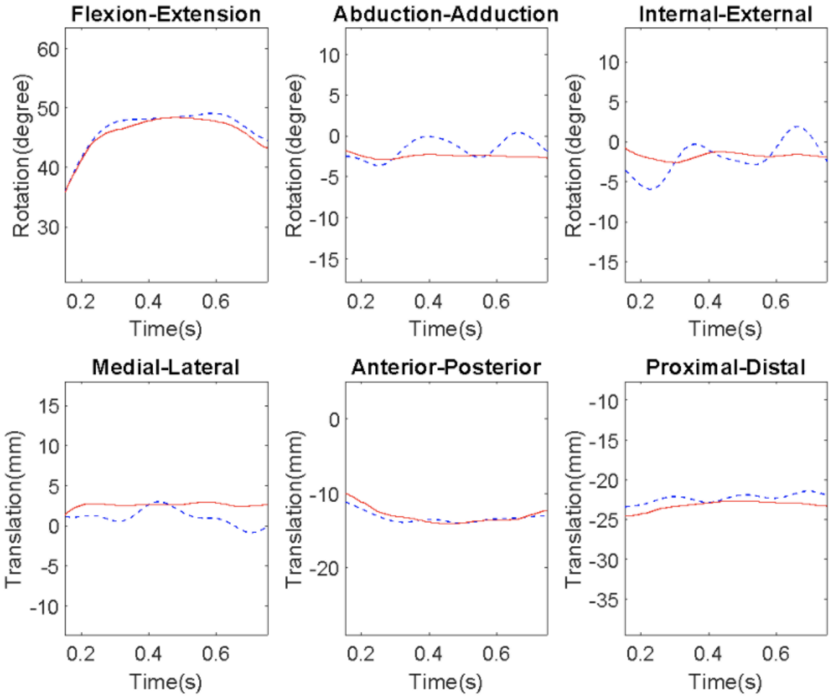


Figure 11: Graphical representation of results for the Combined Tracking attempt of the Walk Trial in all six degrees of freedom.

In Figure 12 it is clear how accurate the results are given the limited amount of white bone able to be seen. The figure also shows the error in Abduction-Adduction as the higher points on the femur come out of the page more than the RSA bone. When comparing this figure to figures 8 and 10 it is evident that the Combined Tracking method yields the most accurate results.

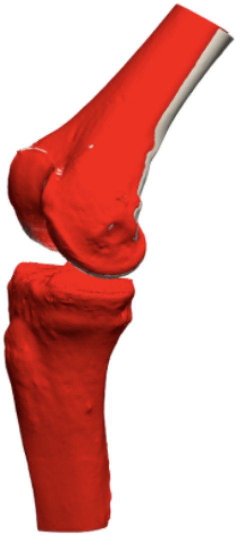


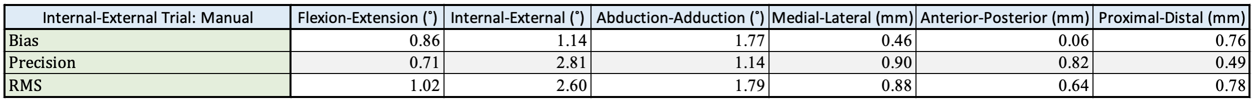
Figure 12: Walk Trial: Combined Tracking positioning (white) presented on top of RSA positioning (red).

Not only did the Combined Tracking method yield the most accurate results of the three methods in the walk simulation but it also took less time than Model Based Tracking. Having taken only 1 hour, 12 minutes, and 11 seconds; with 49 minutes and 56 seconds attributed to the femur and 22 minutes and 15 seconds attributed to the tibia. Therefore the conclusion of the Walk Trial is that the most effective means for measuring knee joint mechanics in the most efficient time frame is to use the Combined Tracking approach.

3.2 Internal External Rotation Trial

3.2.1 Manual

After completing the Walk Trial it was evident that the translational movement was able to be easily observed however the rotation was harder to analyze. Therefore a second trial of Internal-External Rotation was conducted in order to focus more on the tracking ability for the rotation. Again the first method tested was to measure alignment using Model Based Tracking in order to gain a standard for the dual fluoroscopy method. This method is expected to represent the level of accuracy and time frame the lab is currently producing.



Internal-External Trial: Manual	Flexion-Extension (˚)	Internal-External (˚)	Abduction-Adduction (˚)	Medial-Lateral (mm)	Anterior-Posterior (mm)	Proximal-Distal (mm)
Bias	0.86	1.14	1.77	0.46	0.06	0.76
Precision	0.71	2.81	1.14	0.90	0.82	0.49
RMS	1.02	2.60	1.79	0.88	0.64	0.78

Table 4: Tabular representation of results for the Model Based Tracking attempt of the Internal-External Rotation Trial in all six degrees of freedom.

From Table 4 it is found that the error was very similar to Model Based Tracking for the Walk trial, with the highest error found in the Abduction-Adduction and the Internal-External Rotation. The majority of the error was found to be within one mm of the RSA with only the internal-external rotation passing 2 degrees of error. Figure 13 shows that the results tend to fluctuate back and force along the RSA slope, which suggest that smoothing the results could have lead to more accurate results. However given that this method is entirely manual, no smoothing took place.

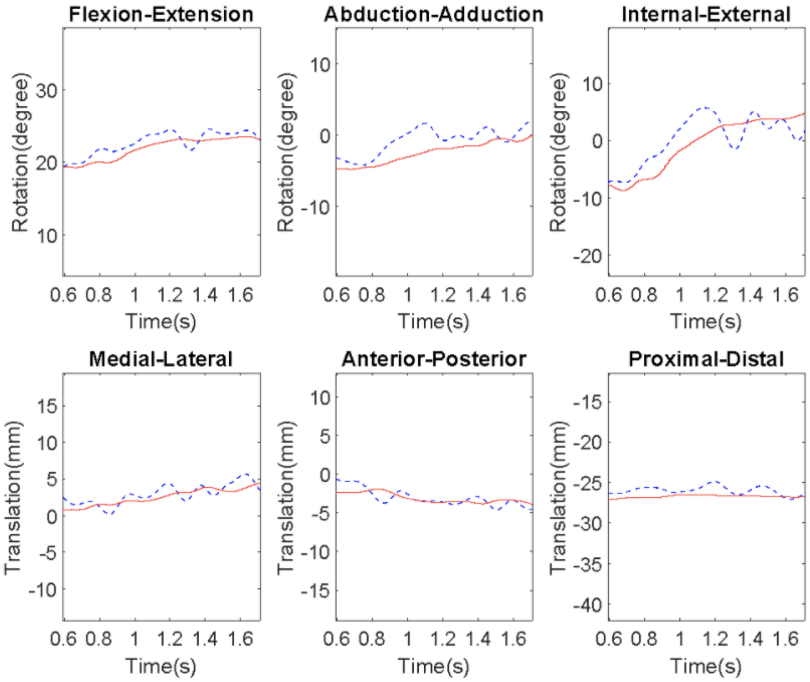


Figure 13: Graphical representation of results for the Model Based Tracking attempt of the Internal-External Rotation Trial in all six degrees of freedom.

In Figure 14 it is seen that the primary source of error is rotational, which corroborates the previously noted data. Given the limited amount of white seen these results are considered to be relatively accurate. Therefore this method is adequate to be used as the standard for the dual-fluoroscopy method comparison.

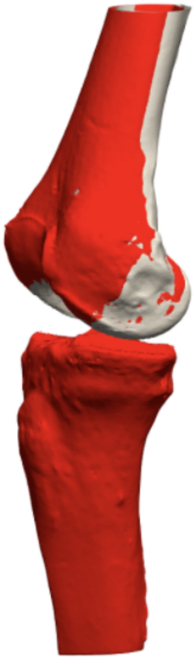
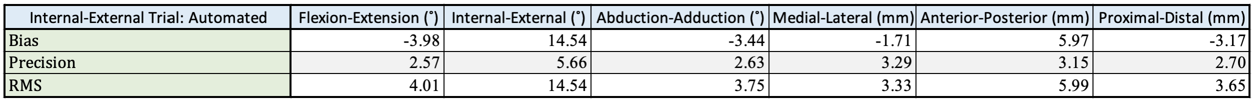


Figure 14: Internal-External Rotation Trial: Model Based Tracking positioning (white) presented on top of RSA positioning (red).

These results proved to be very similar in relative accuracy to the RSA as the Model Based Tracking for the Walk Trial and are therefore a good fit moving forward to represent the dual-fluoroscopy method for knee joint measurement. This method took a total of 1 hour, 28 minutes, and 2 seconds; with 50 minutes and 44 seconds attributed to the femur and 37 minutes and 18 seconds attributed to the tibia. This time frame suggests that the individual aligning the trials was able to keep a relatively constant pace and attention to detail between Model Based Tracking for both the Walk and Internal-External Rotation trials.

3.2.2 Skin Marker Tracking

Counter to the Model Based Tracking method, Skin Marker Tracking was again intended to see how accurate of results could be obtained given the shortest time frame. The results were again an exact result of running the same code and applying the pose map, therefore the time can be considered immediate. This method was found to be similar in error to Skin Marker Tracking for the Walk Trial with the shifted focus on the rotational accuracy of the alignment.



Internal-External Trial: Automated	Flexion-Extension (˚)	Internal-External (˚)	Abduction-Adduction (˚)	Medial-Lateral (mm)	Anterior-Posterior (mm)	Proximal-Distal (mm)
Bias	-3.98	14.54	-3.44	-1.71	5.97	-3.17
Precision	2.57	5.66	2.63	3.29	3.15	2.70
RMS	4.01	14.54	3.75	3.33	5.99	3.65

Table 5: Tabular representation of results for Skin Marker Tracking for the Internal-External Rotation Trial in all six degrees of freedom.

Table 5 depicts a relatively high error for all degrees of freedom for bias, precision, and RMS error. When comparing these results to Skin Marker Tracking for the Walk Trial, it is found that the error in abduction-adduction, medial-lateral, and proximal-distal increases, while the error in flexion-extension and anterior-posterior decreases in the Internal-External Rotation trial. It is notable that the internal-external rotation retained nearly the same bias and RMS error between the Walk and Internal-External Rotation trials, however the precision was found to be much less in Skin Marker Tracking for the Walk Trial. When looking at Figure 15 it is clear that the code had a more difficult time matching with the Internal-External Rotation Trial than the Walk Trial. Given that the slopes are evidently different between data sets for this method and the data sets shared a relatively similar slope for the Walk Trial it can be assumed that the Walk Trial is more accurate.

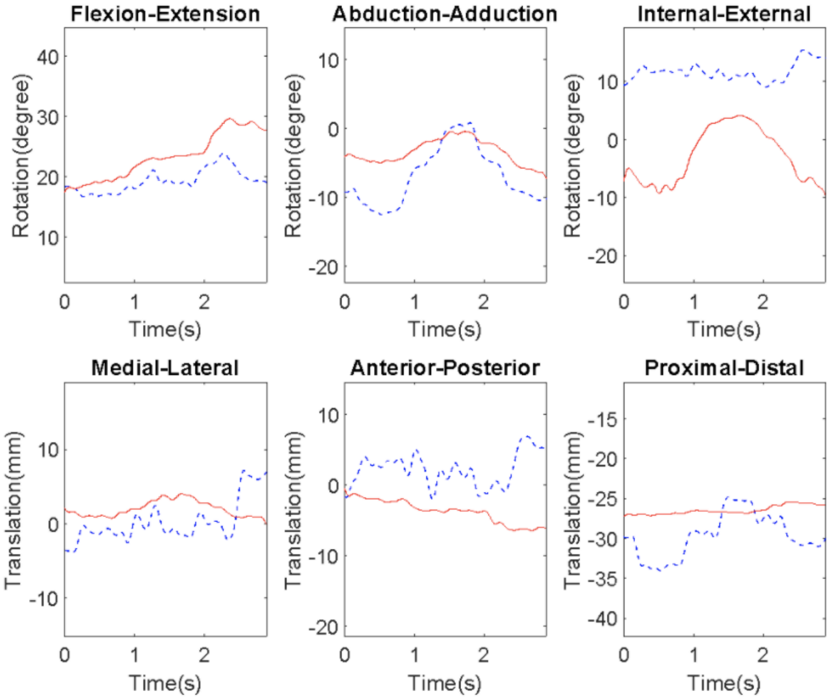


Figure 15: Graphical representation of results for Skin Marker Tracking for the Internal-External Rotation Trial in all six degrees of freedom.

Figure 16 corroborates the assumption that the results are not accurate enough to use as an appropriate model of the knee joint. However, it visually appears to be more aligned than Skin Marker Tracking for the Walk Trial. This is likely due to the lack in translational movement for this simulation, which makes it more difficult to see misalignment in the Internal-External Rotation Trial than the Walk Trial. Nevertheless, the error is evident and too large for the model to be considered accurate.

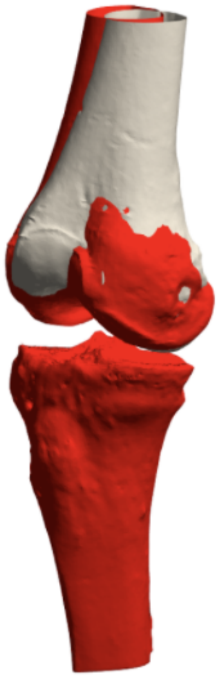
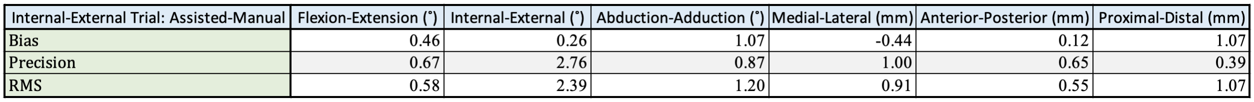


Figure 16: Internal-External Rotation Trial: Skin Marker Tracking positioning (white) presented on top of RSA positioning (red).

The results of Skin Marker Tracking for the Internal-External Rotation Trial are evidently inaccurate and easily comparable to Skin Marker Tracking for the Walk Trial. Despite being the fastest method for acquiring data, this method is not an appropriate method for measuring knee joint mechanics given its high level of inaccuracy. When analyzing the rotational information it was found that, as was the case for Skin Marker Tracking for the Walk Trial, the pose map could not properly capture the rotational movement of the knee joint.

3.2.3 Combined Tracking

Again, the Combined Tracking method is intended to serve as a middle ground for the Model Based Tracking and Skin Marker Tracking methods, with a comparable accuracy and decreased time than the manual method. The Combined Tracking Walk Trial found that although there was some fluctuation in Abduction-Adduction and Internal-External rotation, the overall results were the most accurate. The hope is to find similar results in the Internal-External Rotation Trial where the rotational components are the primary focus.



Internal-External Trial: Assisted-Manual	Flexion-Extension (˚)	Internal-External (˚)	Abduction-Adduction (˚)	Medial-Lateral (mm)	Anterior-Posterior (mm)	Proximal-Distal (mm)
Bias	0.46	0.26	1.07	-0.44	0.12	1.07
Precision	0.67	2.76	0.87	1.00	0.65	0.39
RMS	0.58	2.39	1.20	0.91	0.55	1.07

Table 6: Tabular representation of results for the Combined Tracking attempt of the Internal-External Rotation Trial in all six degrees of freedom.

It is evident from Table 6 that the results are extremely similar to the Combined Tracking Walk Trial with only a slightly larger margin of error in certain degrees of freedom. It was again found that the largest error was found to be the RMS for internal-external rotation with an error of approximately 2.3 degrees. Aside from this error almost all other variables were 1 mm/degree or less. The results are also found to be more accurate than Model

Based Tracking for the Internal-External Rotation Trial, which was expected given the Walk Simulation results. The only point found to have a larger error than its Model Based Tracking counterpart was the precision in the medial-lateral plane. This accuracy is corroborated in Figure 17 where it is clear that although there are some fluctuations around the slope of the RSA data set, they are all on a scale small enough to be considered accurate.

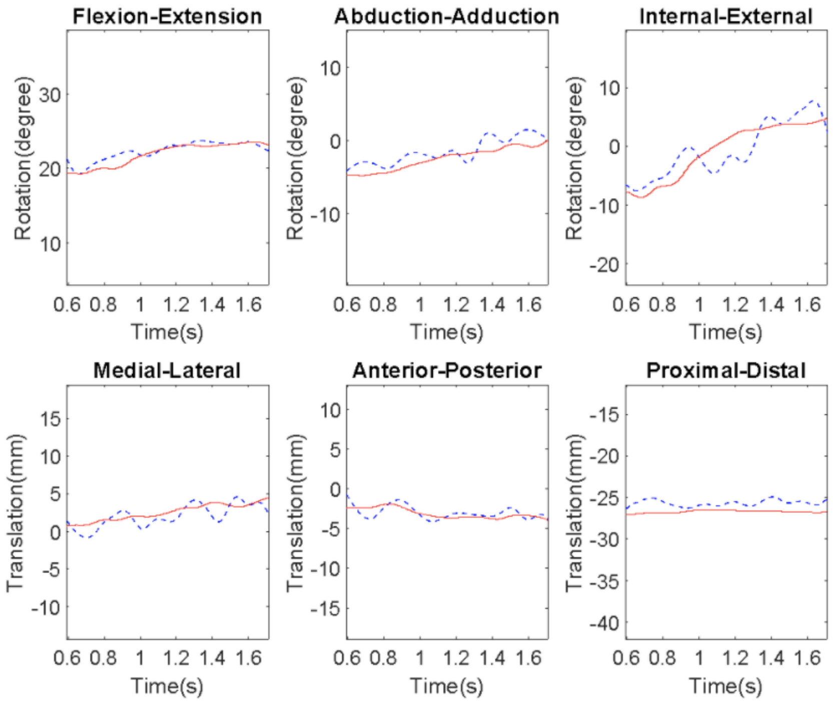


Figure 17: Graphical representation of results for the Combined Tracking of the Internal-External Rotation Trial in all six degrees of freedom.

Figure 18 supports the results and assumptions above as it is a primarily overlapping model with only a few points of misalignment. It is found and expected that there is slightly more error seen for Combined Tracking of the Walk Trial but better alignment than all other methods. This figure supports the claim that the Combined Tracking method was again the most accurate method for measurement.

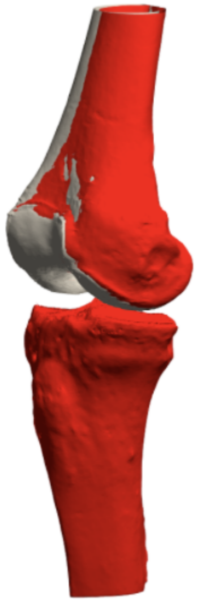
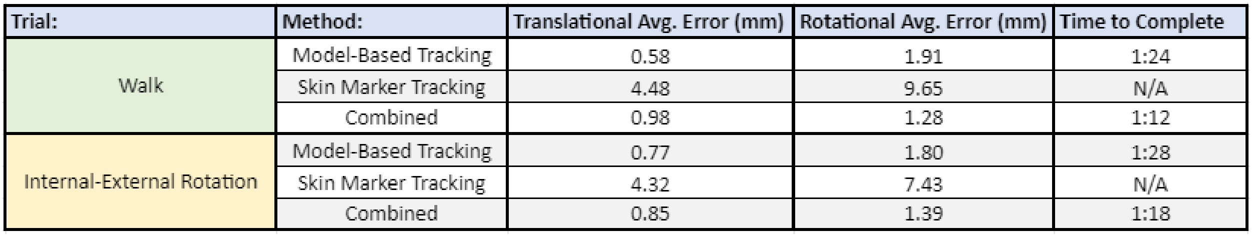


Figure 18: Internal-External Rotation Trial: Combined Tracking positioning (white) presented on top of RSA positioning (red).

The Combined Tracking method again was able to yield the most accurate results of the three methods while being conducted in a smaller time frame than the Model Based Tracking method. This method took a total of 1 hour, 17 minutes, and 31 seconds; with 36 minutes and 33 seconds attributed to the femur and 40 minutes and 58 seconds attributed to the tibia. Therefore the conclusion of the Internal-External Rotation Trial was the same as the Walk Trial; That the most effective means for measuring knee joint mechanics in the most efficient time frame is to use Combined Tracking.



Trial:	Method:	Translational Avg. Error (mm)	Rotational Avg. Error (mm)	Time to Complete
Walk	Model-Based Tracking	0.58	1.91	1:24
	Skin Marker Tracking	4.48	9.65	N/A
	Combined	0.98	1.28	1:12
Internal-External Rotation	Model-Based Tracking	0.77	1.80	1:28
	Skin Marker Tracking	4.32	7.43	N/A
	Combined	0.85	1.39	1:18

Table 7: Average translational and rotational results for accuracy for all methods in both trials compared to the time it took to complete.

These results are again seen in Figure 7 which highlights the average translational and rotational error for both trials and all three methods. This table not only puts the accuracy of all methods in respect to one another but also lists the time it took to complete each method. This table highlights the fact that Model Based Tracking was more effective for the average translational movement, while Combined Tracking was more effective for rotational movement. However, Combined Tracking still had the best overall accuracy and was more time efficient than Model Based Tracking and is therefore the most suitable method to use in the lab moving forward.

3.3 Discussion

This study found that, although the Skin Marker Tracking method for measuring knee joint angles was less accurate than hoped, the Combined Tracking method is a more efficient method for achieving similar, if not better, levels of accuracy. Unfortunately, the accuracy of the Skin Marker Tracking method for both the Walk and Internal-External trials were found to be too inaccurate to use when trying to model the knee joint at an appropriate scale, with errors reaching as high as 14.55 mm. Despite the failure of Skin Marker Tracking the study was still successful in developing a new method for tracking that is more accurate and time efficient due to the success of the Combined Tracking method.

When looking at the Model Based Tracking results for both simulations it is evident that the results are nearly accurate on the order of a millimeter or less but are not without their imperfections. What's more, this analysis excluded the use of computer optimization and smoothing of the results which would have resulted the results being more accurate. Given that this method served as a representation of DF-MBT, the previous method for gaining accurate results in the lab, it is a good indication of the overall need for an improved method. Obviously, the RSA is the most accurate way to track the knee joint positioning, however given the need to place beads throughout the bones it is not possible for living patient application. Therefore, the hope is to find a way to make Model Based Tracking as accurate as possible or use a better method such as Combined Tracking. A potential reason for the error found for Model Based Tracking is the fact that the Model Based Tracking was conducted before the Combined Tracking for both trials and therefore the individual conducting the alignments had practiced tracking before the Combined Tracking but not before the Model Based Tracking. Another probably cause of error is the speed at which the tracking was conducted. Had more time been attributed to the Model Based Tracking perhaps the results would have been more accurate. That said, the tracking was conducted at as similar of a rate and attention to detail as possible given human error.

As far as the Skin Marker Tracking method, the most likely reasoning for its evident misalignment is due to soft-tissue artifact. Although the attempt was to use the pose map in order to eliminate soft-tissue artifact as a compromising variable, it appears the code was unsuccessful in creating an appropriate pose map to meet its objective. Another potential error could have been that the cadaver leg was not only still frozen, affecting the range of motion and density of the soft tissue on the bones, but is also a very old cadaver leg who may have reached the end of its realistic resemblance to a living leg. The soft tissue is evidently sagging in the fluoroscopy images and therefore may have resulted in the impact of soft tissue artifact being higher than anticipated or would be seen in a living patient.

Finally, there is the Combined Tracking, which proved to be the most successful of the methods. The only notable difficulty found for Combined Tracking is that since the points are already set before any manual tracking is conducted, the tracking software does not adjust based on adjustments being made. Therefore if there is an error in any of the six degrees of freedom it must be manually changed throughout, when it may have been adjusted after only a few frames in Model Based Tracking. Model Based Tracking did prove to have more accurate results for average translational movement, however the increased accuracy for rotational movement for Combined Tracking outweighed these results meaning the Combined Tracking method was still more accurate. Additionally, the use of computer optimization would have resulted in even more accurate results, which allows for the assumption that this method produces accuracy on the order of a millimeter or less. Given that Combined Tracking took less time and proved to be more accurate than Model Based Tracking and Skin Marker Tracking, it was determined that this was the best method for tracking joint angle and measuring bone movement.

The simulations of a Walk Trial and an Internal-External Rotation Trial were intended to serve as a basis to establish if the translation and rotation were specifically being captured in the trials. In the results however, it appears that most of the methods showed similar results between the two trials with only minor exceptions. That said, the intent was, in a way, still achieved as the simulations proved that the results from a primarily translational and a primarily rotational simulation would yield similar levels of accuracy.

4 Conclusions & Future Work

4.1 Conclusions

The results of this study were not what was anticipated going in, however the goal of moving towards a more efficient and effective method for tracking 3D bone position and orientation in fluoroscopic imaging was still successful. The resultant method was not by any means a large improvement over the previous methods, however it served as an example of ways the process can be improved. A primary takeaway from this experiment is that even without implanting beads into a patient's bones, the lab is able to acquire data that is accurate on a scale of one millimeter or less. This ability to track 3D bone positioning and orientation so accurately allows for deeper research into the ways the knee joint mechanics operate, which could lead to a better understanding of mobility based disabilities such as the early development of PTOA. The hope moving forward being that these methods will improve and continually become more accurate to gain an even deeper understanding of the way the knee works.

4.2 Future Work

Moving forward it is important to continue to refine the measurement methods for knee joint mechanics in order to better understand the inner workings of the knee joint. If given the opportunity to continue this work, the next steps would likely include having another individual do the tracking to eliminate an individuals bias on the timing and accuracy of the tracking. Additionally, the code could potentially be adjusted to improve the pose maps and their alignment. The use of a newer cadaver leg could also serve as an effective way to test these results again. However, the most important measure that would be tested moving forward would be to implant the beads used for RSA into the motion capture markers and place them specifically so that they could properly fit the motion capture frame and the dual-fluoroscopy frame in the hopes that the same RSA method could be applied to those beads and the motion capture to dual-fluoroscopy transformation could be direct.

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