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3D Visualization of Pre-operative Planning for Orthopedic Surgery

A. Steen[1] and M. Widegren[1]

[1]Linköpings Universitet, Sweden

Abstract

This paper presents ideas on 3D visualization for pre-operation planning of orthopedic surgery. The focus is on visualizing clinically relevant data for planning a Total Hip Replacement (THR) and investigating how 3D visualization can help improve the planning of procedures. The result is an application that showcases the ideas and reached conclusions. The application visualizes the fit of implants by shading them depending on distance to bone while at the same time giving the user contextual information of the bone anatomy. It also offers ways of measuring and visualizing important distances in a THR by visualizing the end points and the distance of a measurement.

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Applications—Medical Visualization

1. Introduction

Approximately one million THR are performed annually in the world [UH12]. It is a procedure commonly done because of osteoarthritis (degradation of cartilage) in the hip joint. When the surgery begins it is important that the chosen implant fits the patient well and does not lead to complications, like pain or unequal leg length. Pre-operative planning is an important step in predicting and preventing complications [S E98]. The conventional method for planning for a THR has been to use hard-copies of X-ray images and printed out templates for implants to find out which implant to use and how it should be inserted.

Today it is more common to use software for pre-operative planning that is connected to the hospital's Picture archiving and communication system (PACS). Studies have shown that using a digital planning tool is as accurate as conventional planning [Ber07, Yon09]. Most of the currently available planning tools are in 2D, using X-ray images and 2D templates of the implants.

This paper presents research done to investigate the usefulness of using 3D visualization in orthopedic planning and presents a developed prototype showcasing the results. The main contribution of this work is a way of visualizing the fit of a hip implant while still giving the user contextual information about the thigh bone's anatomy. This is done with a color coded distance visualization combined with a clipping plane, an opaque volume rendering of the bone and semi-transparent slices of the bone. With respect to previous wok, our implementation improves the visualization of the contextual information of the thigh bone giving the user a better view of the bone's internal structure.

2. Related work

The importance of planning before performing an operation is well-understood and documented [S E98]. Planning helps the surgeon anticipate the correct implant size and can also help to anticipate possible intra-operative difficulties (more than 80% of intra-operative difficulties were anticipated in the study performed in [S E98]). At the time of writing, pre-operative planning is primarily done in 2D using conventional X-ray films or digital X-ray images but there is research being done in using 3D in the planning process.

2.1. Related work in 2D

There have been studies that compare traditional X-ray films and digital X-ray images. In their study, The et al. even concluded that digital plans slightly outperform analogue plans in their accuracy regarding the implant size [Ber07]. Today, there are a number of well-established companies that offer software that allows the surgeon to perform planning in 2D before going into the operation room.

2.2. Related work in 3D

The accuracy of using 3D templates in planning has been studied.The study by Sariali et al. compared the accuracy of analogue 2D and 3D planning in THR and found that when counting both the stem and the cup in a THR, the plans would predict the implant that ended up being used in 96% of the cases when using 3D and in 16% of the cases when using 2D [E. 12]. Another study also found 3D planning to be accurate and repeatable, especially among less experienced surgeons [VLA*03].

In their article, Dick et al. discuss two methods for visualizing the 3D planning [Chr11]. The article puts its main focus on the important distances present in operation planning. It presents two different approaches and investigates the advantages and disadvantages of the two. The article also discusses some of the inherent problems with 3D visualization such as visual cluttering and occlusion and presents ways of dealing with them. These approaches were helpful as starting points during the development of this paper.

2.3. Comparison Between 2D and 3D

An advantage of using 3D data sets of the body is that it contains more information. Instead of seeing the resulting attenuation along an X-ray you have values for each voxel. The sizes are more accurate and the structures are invariant to if the patient has rotated their limbs during the scanning process. There are however some drawbacks in using 3D instead of 2D. One issue is that it is generally harder to intuitively navigate in a 3D environment since a regular monitor shows a 2D representation of the world and the mouse only has two degrees of freedom. Another disadvantage is that it is harder to present a general overview. Also specific to 3D is that the learning curve can be steep for people used to working with X-ray images. This might be more of a problem for radiologists than orthopedists.

Viceconti et al. concluded in their study that their 3D orthopedic templating tool was comparable in usage to the conventional planning with radiographs [VLA*03], indicating that the learning curve might not be so bad. They also concluded that the sizes predicted by their tool were generally more accurate than the sizes predicted with conventional planning, especially for the acetabular cup and especially for less experienced surgeons.

Otomaru et al. [Oto08] presented a method for creating pre-operative plans for THR using Computed Tomography (CT). They concluded that the plans created by their automatic software were roughly equivalent to the plan created by an experienced surgeon using the conventional method of radiographs and templates. They argue that this method will not only save time for experienced surgeons but also let less experienced surgeons create plans as good as if they were made by experienced surgeons.

3. Medical background

3.1. Anatomy

This section will discuss the parts of the body that are within the scope of this paper. These are the thigh bone (femur) and the pelvis.
The top part of the femur together with part of the pelvis can be seen in figure 1. The names of the different parts that are important for pre-operative planning are also marked in the figure. The head of the femur (caput) is connected to the pelvis via a socket in the pelvis (acetabulum) and is held in place by tendons (not pictured in the figure). The surface of the caput is covered with a layer of cartilage that together with a lubricating fluid (called “synovial fluid”) allows the caput to rotate with low friction.

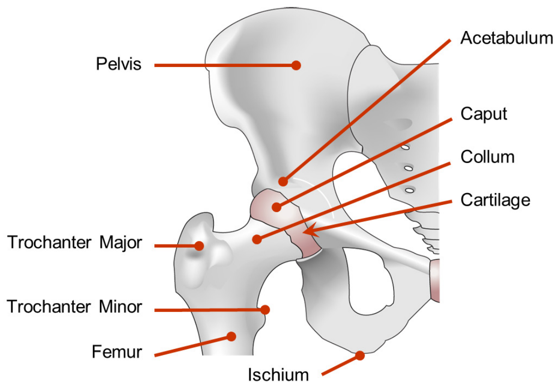

Figure 1: *Top part of the thigh bone (femur) and part of the pelvis*

3.2. Osteoarthritis

The hip joints are one of the areas in the body that are under practically constant stress daily. Because of this, most people run a risk of developing osteoarthritis with age. Osteoarthritis is the degeneration of cartilage in a joint. As the cartilage degrades, the body may try to compensate by producing more bone. Part of the smooth cartilage is then replaced by rough bone. This can eventually lead to bone rubbing against bone, causing friction and pain.

Osteoarthritis can be diagnosed using X-rays. Even though cartilage itself does not show on an X-ray due to being too soft, the lack of cartilage can be identified using X-rays. There is a certain amount of space between caput and acetabulum and in the knee where the cartilage is and if this space (called “joint space”) is smaller than it should be, that indicates a lack of cartilage. An example of this can be seen in figure 2. More information on osteoarthritis can be found in Ref [A.D].

Figure 2: *Two X-ray images, the left showing some space between caput and acetabulum in the top right part of the picture, indicating the presence of cartilage and the right showing less space indicating a lesser amount of cartilage.*

If the symptoms of osteoarthritis are not too severe, they can be treated with medication. For severe osteoarthritis in the hip, the solution is often a total hip replacement.

3.3. Total Hip Replacement

In a THR the caput is completely replaced by a metallic implant consisting of a stem and a head. While the outer shell of the femur (called cortical shell) is hard, the marrow canal inside is softer. To allow the implant stem to fit in the bone, parts of the marrow canal are removed. A so-called cup is inserted in the acetabulum which the head is then inserted into. The different parts of the implants come in many different sizes and models, a sample of the different parts can be seen in figure 3.

3.4. Pre-operative Planning

Pre-operative planning helps the surgeon prepare for the operation. It helps decide what tools will be necessary, how the procedure will be performed and also helps anticipate possible problems that may occur during the procedure.

One of the purposes of the pre-operative planning in a THR is to predict which implant model should be used as well as the sizes of the different parts of the implant. It is

Figure 3: *Photograph of a titanium stem, a ceramic head and a polyethylene acetabular cup.*

important that the implant fits well and therefore the surgical team will bring a number of implants of different sizes to be able to find a good match. A good prediction on the resulting implant will allow the surgical team to bring fewer implants into the operating room, lowering the number of tools that need to be sterilized. A good size estimate will also help decrease the time for the operation, thereby lowering the infection risk [GZP01, SMT*82, PR73].

Two other important factors regarding the acetabular cup are how much bone will need to be removed to reach “fresh” bone and at which angle the cup is to be inserted. If the angle of the cup is off, the stem might become dislocated if the patient bends their leg too much.

Due to the removing of bone and insertion of an implant there is also a risk that, after the operation, the leg will not be the same length as before the operation. This is called unequal leg length, or “leg length discrepancy”. This can be compensated for by choosing an appropriate implant.

Another important factor is the femoral offset, or the perpendicular distance from the center of rotation of the head of femur to the long axis of femur. Increasing the femoral offset after a hip replacement has been shown to have positive effects on the range of abduction and abductor strength [MMC*95].

A good plan will help the surgeon to solve the discussed issues by choosing implants accordingly.

3.5. Medical Imaging

Medical imaging is the process of obtaining images of the human body for use in medicine, such as diagnosing diseases and examining anatomy.

3.5.1. Projectional Radiography

In projectional radiography, images are obtained by having electromagnetic radiation such as X-rays hit a film after passing through an object (e.g. a human body). The varying densities of the object will absorb different amounts of radiation, resulting in an image where dense parts of the objects appear opaque and less dense parts appear transparent. This is the traditional method commonly referred to simply as “X-rays”.

3.5.2. X-ray Computed Tomography

X-ray CT is an imaging technique where X-rays are used to create tomographic images, or slices, of specific parts of the human body. These slices can be combined into a 3D volume of the scanned body part.

4. Result

4.1. Prototype

This section will describe the resulting prototype that was developed. The prototype was developed in collaboration with Sectra Medical Systems AB in Linköping, Sweden. The prototype was implemented as a module in Sectra’s already existing framework for 3D visualization.

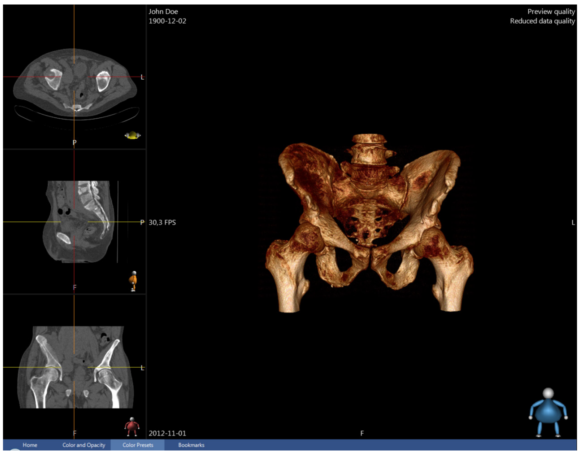

Figure 4: *Screenshot of Sectra’s visualization software showing an frontal view of a pelvis*

Figure 4 shows a screenshot of Sectra’s visualization software without any of our implementations. The three windows to the left are Multi-Planar Reformatting (MPR) views that show cross-sections of the volume. The volume is rendered in 3D in the large window to the right.

4.1.1. Basic Visualization and Control

The different implant parts are rendered as shaded polygon models. The models are semi-transparent to keep them from occluding bone. The distance shading of the implant, which is discussed later, can also be seen through the implant if it is semi-transparent. The user can switch to an implant with a different size by holding the mouse pointer over the implant and scrolling the mouse wheel. When an implant is selected, it becomes somewhat less transparent and a bounding-box is rendered around it to distinguish it from the other implant parts. Figure 5 shows a stem and an acetabular cup inserted in femur and acetabulum. The cup is selected as can be seen from the difference in transparency and the bounding box.

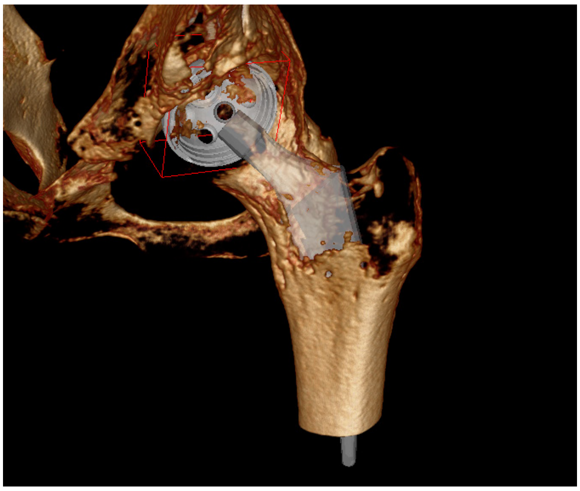

Figure 5: *Basic rendering of the implant parts with the acetabular cup selected*

4.1.2. Visualization of Relevant Data

One important aspect when deciding what implant to use is that it fits well. A good visualization of the fit is therefore essential. This section will describe the features that were implemented to help visualize the fit.

Bone Contours When positioning the implant model in the CT volume, it sometimes became difficult to see how close the implant was to the cortical shell without having to keep rotating the view. The implant was also often occluded by the bone. By allowing the contours of the bone to be visualized as well as the close proximity of the bone in the form of slices, the user can get a better understanding of how well the implant fits. The contours also help show the structure of the bone with less occlusion of the implant. The user can change the orientation and spacing as well as the number of slices. An implementation of the bone contour visualization can be seen in figure 6.

Implant Shading The shading of the implants was changed to visualize distance to the cortical shell of femur. An implant that is far away from any bone will be shaded using regular Phong shading but when being close to bone, it will interpolate between green and blue depending on the

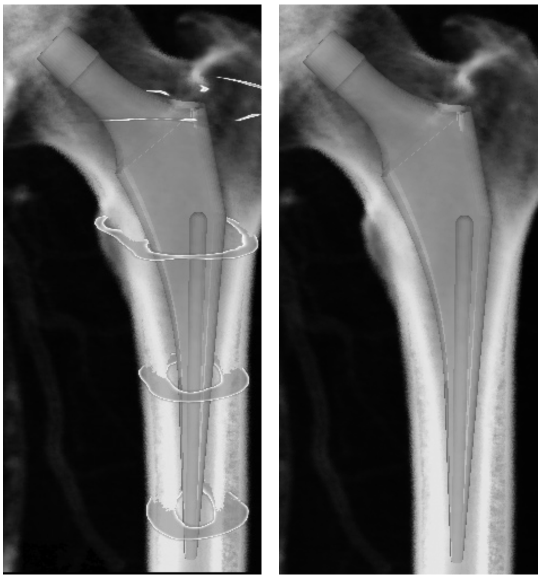

Figure 6: *Two close-up views of femur in an X-ray rendering of a CT volume. In the left image the hard outer shell is highlighted to show the contours of the bone, in the right image it is not.*

distance to bone. Parts of the implant that are close to bone will be blue. The implant should be close to but not intersect with bone and therefore if some part of the implant intersects with bone, that part will be rendered bright red as a warning. Yellow lines that are aligned with the bone contour highlights are also drawn on the implant to make it easier to see how the outlines relate to the implant.

Implant Contour in MPR View Contours of the implants are visualized in the MPR views. For each triangle of the mesh, each edge is checked for an intersection with the plane that the MPR view defines. This gives a good outline of the mesh for a thin slice. For thicker slices, we also need to take into account edges that are inside the slice. So in addition to checking intersections with the edges, we also check if each edge of the triangle is inside the slice. If they are then we fill that triangle. So if the slice contains the whole model, a filled projection of it is rendered. An example of this can be seen in figure 8.

4.1.3. Acetabular Cup

To be able to visualize the cup's position relative to the volume, the cup had to be clipped by the clipping plane as having the whole cup visible made it occlude the volume. The parts of the cup that are close to the clipping plane are rendered yellow without any diffuse or other lighting. This is done to highlight the edges more clearly. The cup is not shaded differently with regards to intersections with bone, it

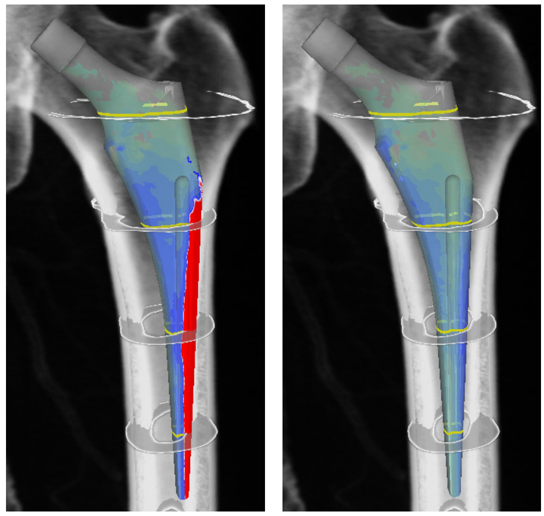

Figure 7: *Two renderings showing how the shading indicates when the implant intersects bone. In the left image the implant intersects the hard shell of femur, and in the right image it does not.*

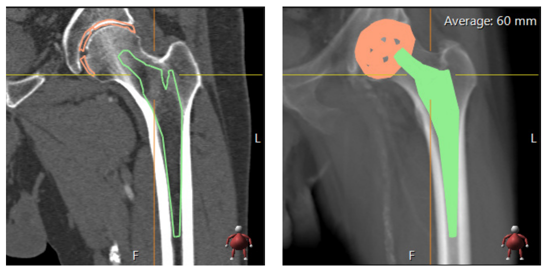

Figure 8: *The rendering of the implants in an MPR view for a thin slice (left) and a thick slice (right).*

only takes into consideration the distance from the clipping plane. The resulting visualization can be seen in figure 9.

4.1.4. Improved Control

Planning Guide A simple planning guide was implemented to help the user find implant parts with a good fit and put these in approximately the right place. When the guide is started, the user is asked to click on a number of landmarks in the MPR views. After the landmarks' positions are collected the program goes through a list of different implants to find the implant parts with the best fit and puts these into place. The camera is then moved to put focus on femur, a clipping plane is activated to give a cross-section of the bone and a number of bone contour slices are rendered. These operations make it easier to see how well the implant fits. Figure 10 shows the result of using the guide, with an implant automatically inserted into femur.

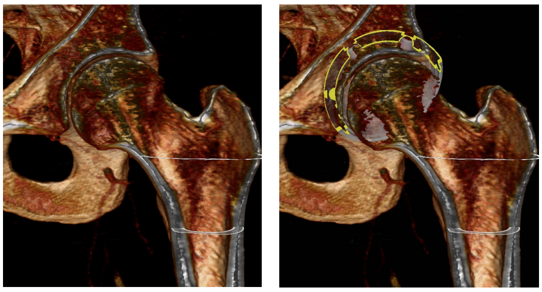

Figure 9: *Cross section of acetabulum before (left) and after positioning the acetabular cup (right).*

The goal with the guide is that with good accuracy when selecting the landmarks, the guide will create an operation plan that will give the user a good starting point and will only need some tweaking instead of having to manually move the implant parts into place and going through all possible implant sizes to find one with a good fit.

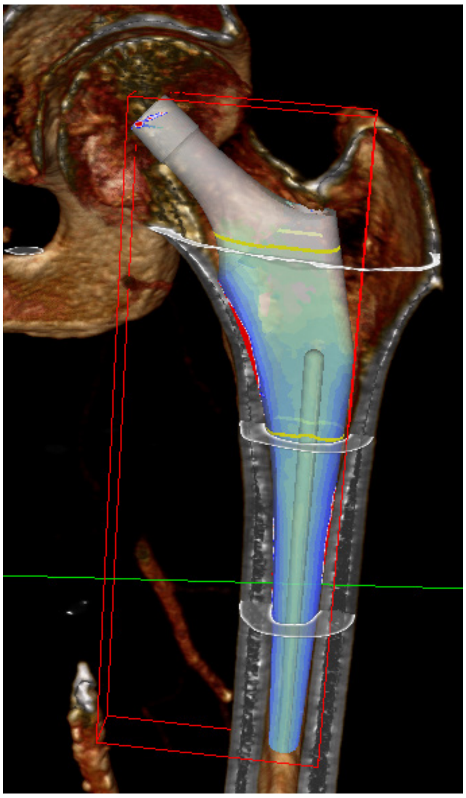

Figure 10: *Standard frontal view for visualizing how the stem fits in femur. Part of the clipping plane representation can be seen as a green out-line*

Widgets Widgets for translation and rotation in the 3D view were implemented. The coordinate system for the rotation and translation is defined by the femur coordinate system (which is set up with the planning guide), and the widgets translate and rotate in the coordinate system of the currently selected view.

4.1.5. Measurements

A tool for performing different measurements was implemented so that it could be used both manually by the user and automatically by the software itself. A simple measurement of length is visualized as a line between the two end-points and small shaded sphere at each end-point. The measured length is also displayed on the screen. The planning guide makes use of this measurement tool by providing measurements of the femoral offset by using the points provided by the user when using the guide. The distances between the points are calculated and visualized when the user completes the planning guide. The result can be seen in figure 11.

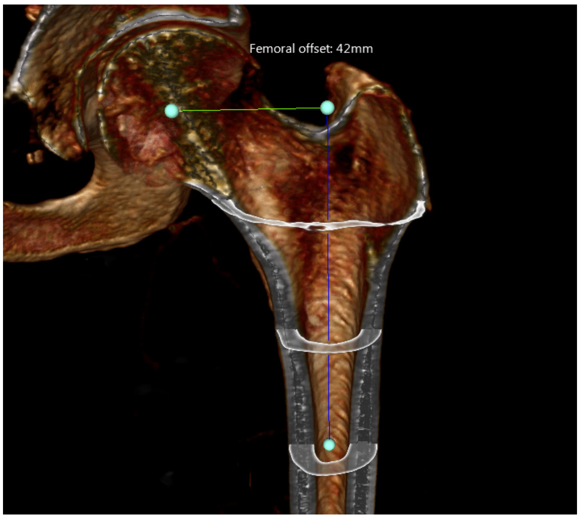

Figure 11: *Cross-section of femur with the visualization of the femoral offset*

5. Dicussion

We feel that the developed prototype helps give a good visualization of the plan by adding the 3D elements while still keeping the familiarity of 2D. Comparing our visualization methods to the ones presented in the related work we feel that our methods also improve the visualization of the contextual information of the thigh bone by rendering the bone opaque and utilizing a clipping plane to help fix the occlusion problem. The linear color map also gives a better understanding of the distance compared to a rainbow color map.

5.1. Current limitations

Some limitations existed in the 3D engine we used to implement our prototype. The volume and the polygon models are rendered separately, which lead to transparency not always working as intended. In the case of visualizing the stem in the femur, in the rendering pipeline the implant is always completely behind the volume or completely in front of the volume. This led to the implementation of an opaque bone rendering with clip planes. After some discussion with a medical expert at Sectra we feel that this is a good solution, since it is easy to see contextual information about the anatomy with this method.

Repositioning of different parts of the volume is not possible in the current engine. This means you currently can not visualize how the patient would look after the surgery is complete.

5.2. Radiation dose

The radiation dose from a CT scan increases the risk of cancer by approximately 1 in 2000. This is a noticeable increase from the 1 in 16000 increase by a pelvic X-ray. However the numbers are small compared to the 2 in 5 average risk we all have of developing cancer [NAM*12]. The additional risk of cancer introduced by a CT scan would also have to be weighted against the improved results obtained by using 3D planning reported from the discussed studies and the potential benefits from improving the 3D tools further. As concluded in the studies, a good plan will reduce the risk for intraoperative complications [S E98] as well as the risk for the need for revisional surgery (which in turn would require additional X-rays to be performed). Lowering these risks may be enough to warrant the higher dose of radiation obtained from a CT scan.

5.3. Acetabular Cup

Unlike when positioning the stem in the femur, it became hard to define a “good” or “bad” position for the acetabular cup. The hard cortical shell in femur should not be removed but when inserting the cup it is necessary to remove some hard bone from the pelvis in order to insert the cup. Different orthopedic surgeons also prefer to insert the cup at different depths. These factors led to the visualization of the cup to focus on position and visibility instead of trying to visualize the fit.

5.4. Bone cement

The current implementation assumes that the implant chosen is uncemented. A cemented implant needs a bit more space from the cortical shell for the cement coating to fit. Since most hip replacements in Sweden use cemented implants it is important that a production implementation of the application includes support for cemented implants.

5.5. Future work

This section will present some features and possible next steps for improvement that would help the prototype move closer towards a commercial product.

5.5.1. Usability testing

Usability testing would be a good method to assess how well the current interaction methods work in practice. The testing should ideally be performed with orthopedic surgeons familiar with using Sectra’s current planning tools so that the feel and work flow of the program is consistent with Sectra’s 2D planning tools.

5.5.2. Image analysis

Image analysis should be used together with the planning guide to calculate which implant fits best and how it should be placed. It could also assess the current fit, as well as find anatomical landmarks to calculate leg length discrepancy.

5.5.3. Repositioning

The ability to be able to visualize in 3D how the leg will look after the surgery would be a useful aid. It could help to visualize leg length discrepancy and femoral offset and show how different implants would affect these issues.

6. Conclusion

3D visualization and planning seems to have potential for improving the performance of pre-operative planning, as indicated by both our implemented prototype and the presented studies. The prototype was able to show relevant data and also visualize elements that are not as easily visualized in 2D. However, one of the biggest challenges for future work would be to make the interactions as intuitive as they are in 2D, as people working in the medical field have a long history of working in 2D and may not be as familiar with 3D. Furthermore, if the potential improvement of using 3D is large enough it might outweigh the extra risks from CT scans.

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