I, Jacob J. Stegman, hereby submit this original work as part of the requirements for the degree of Doctor of Philosophy in Biomedical Engineering.

It is entitled:
Patient-Specific Instruments for Total Hip Arthroplasty

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Abstract

Total hip arthroplasty (THA) is a common surgery, exceeding 330,000 cases per year in the United States alone. The positioning of the implant components is critical to the success of the surgery. Excess or insufficient cup anteversion results in higher risk of anterior or posterior dislocation respectively. Excessive cup inclination correlates to osteolysis from implant edge loading. The stem anteversion must be aligned relative to the cup, to prevent implant impingement and permit a normal range of motion. Both components must be positioned to maintain the center of rotation in order to preserve tissue biomechanics. Discrepancies in leg length and hip offset results in muscle slackness or tightness, distorting normal gait.

Targets for implant orientation have traditionally been defined by ‘safe zones’ of angular position. However it is well known that these zones do not provide safety from dislocation, but only a decreased risk. Recent research has investigated patient-specific targets for implant orientation, based on bone anatomy, hip kinematics, or both. Due to the prevalence of THA, it is expected that research will continue to progress, providing improved patient-specific implant targets. Therefore, it is critical for the surgeon to be effectively equipped to achieve specific targets.

Advanced surgical techniques such as computer navigation and robotic-guided THA have shown high accuracy and precision. However, this equipment is expensive, and may not be economical for low-volume surgeons, despite that low-volume surgeons operate with a lower precision than high-volume surgeons of similar experience. Patient-specific instruments (PSIs) have been introduced in other joints as an alternative solution, but have trailed in progress for THA.

This dissertation investigated the design and testing of PSIs for THA through three specific aims: 1) to establish the design and feasibility of acetabular and femoral PSIs in THA, 2) to
investigate if an acetabular PSI can accurately place a surgical pin superior to the acetabular rim and if this pin can accurately guide cup implantation, and 3) to investigate if a femoral resection PSI can accurately control osteotomy and if a secondary femoral PSI can accurately control stem anteversion.

The feasibility of acetabular and femoral PSIs was first established in a pilot cadaver THA procedure. Upon further development of the devices and creation parameters, their accuracy and precision were assessed in a series of 20 cadaveric THA procedures. The acetabular PSI proved to be imprecise in placing the guide pin, with a mean difference (±SD) from the target of 7.1°±10.9° in inclination, and 1.6°±10.6° in anteversion. However, the pin proved effective in guiding cup implantation, with a mean difference (±SD) from the target of 0.9°±5.3° and 1.7°±3.3° in inclination and anteversion respectively. The femoral resection PSI controlled the resection plane within an average error of 3mm and 7°, while the secondary femoral PSI controlled stem version within an average error of 7°. The overall results highlighted several flaws in the design and process, however also gave promise to future improvement of the devices to enhance THA surgery.
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List of Abbreviations

2D- 2-Dimensional
3D- 3-Dimensional
A to P- Anterior to Posterior
APP- Anterior Pelvic Plane
ASIS- Anterior Superior Iliac Spine
COR- Center of Rotation
CT- Computerized Tomography
DAA- Direct Anterior Approach
MAA- Mini-incision Anterior Approach
MPA- Mini-incision Posterior Approach
MRI- Magnetic Resonance Imaging
NURBS- Non-uniform rational basis spline
OR- Operating Room
Post-op- Postoperative
Pre-op- Preoperative
PSI- Patient Specific Instrument
SD- Standard Deviation
SST- Stainless Steel
TAL- Transverse Acetabular Ligament
THA- Total Hip Arthroplasty
Chapter I: Introduction

I.A Implants

Total hip arthroplasty (THA) is a common surgical procedure involving the replacement of the native hip joint to alleviate joint pain or to correct irregular/fractured bone structure. The implants for a THA include an acetabular shell, an acetabular liner, a femoral stem, a femoral head, and sometimes an acetabular screw. In most cases, the acetabular liner snaps into the acetabular cup, however in other cases, the liner is mobile, as seen in the Stryker® Mobile Bearing Hip™ System [1]. In another variation, the femoral stem is modular, where the stem and neck are separate pieces to more easily adjust neck length and angle [2]. The implants come in a variety of materials, however, the most common are metal, ceramic, and plastic (acetabular liner only) [3]. The system can either be implanted as a press-fit, where the bone grows into a porous surface on the implant, or the system can be cemented in place with a polymethyl methacrylate bone cement [3,4]. An example of a press-fit THA implant system is shown in Figure 1.

Upon implantation, the orientation of the acetabular shell is measured by its vertical inclination (sometimes referred to as abduction) and anteversion. There are multiple variations of these two measurements, however, the most common are termed ‘radiographic inclination’ and ‘radiographic anteverision’ by Murray et al., and these definitions will be used in this text [5]. The radiographic vertical inclination is the angle formed by the face of the cup to the transverse plane, projected onto the coronal plane. Figure 2 illustrates the angle of radiographic vertical
Radiographic anteversion is the angle formed by the axis of the cup to the coronal plane. Figure 3 illustrates the angle of radiographic anteversion. The third degree of angular freedom is the roll of the acetabular shell or the rotation about the cup axis. Figure 4 illustrates the roll of the acetabular cup, measured from the anterior inferior iliac spine. The position of the cup ideally reflects the original center of joint rotation, but must also sit deep enough into the bone to achieve bone ingrowth by maximizing contact to bleeding bone (if press-fit is being used).

The femoral stem orientation is measured primarily by its femoral version. The femoral version is the angle formed by the neck of the femoral stem to the coronal plane, projected on the transverse plane. Figure 5 illustrates this angle of femoral version. The angle of the stem in the coronal and sagittal plane are primarily governed by the bow of the femoral axis but can show increased variation depending on
the type of stem used. The position of the femoral stem is primarily dependent on the location of the femoral neck resection and the initial point of broaching. Ideally, the depth of stem implantation is when the stem coating aligns with the resection level, or when the stem collar fully seats on the resected face. The neck of the femoral stem can vary in length, as well as the height of the femoral head. The combination of the stem location, orientation, the neck length, and the head height, should ideally allow the prosthesis center of rotation to match the native femoral head center of rotation.

I.B Indications and Complications

An estimation in 2010 predicted that 959,000 primary and revision THA procedures were performed annually worldwide, with over 330,000 performed in the US alone [6,7]. Some of the most common indications for THA are osteoarthritis, rheumatoid arthritis, post-traumatic arthritis, avascular necrosis, and childhood hip disease [3]. While the incidence of complications for THA is generally low, the more frequent revision causing complications include dislocation of the joint, wound infection, aseptic loosening, periprosthetic fracture, and component failure [8,9]. Implant survivorship rates vary based on the primary diagnosis, surgeon, implant design, and many other factors. Older et al. has reported an 83% 20-year survivorship rate in 5,089 cases for Charnley low-friction hip implants [10]. Furnes et al. analyzed 53,698 cases stratified by indication and reported an 80-89% 10-year survivorship rate [11]. However, the American Association of Hip and Knee Surgeons claim a 90-95% 10-year survivorship rate and an 80-85% 20-year survivorship rate [12]. Among the common complications, dislocation is the most frequent, accounting for 22.5% of revision surgeries [13]. There are many factors that can
predispose one to dislocation, including the primary diagnosis, femoral head size, surgical approach, and even sex [14]. An analysis of over 78,000 Swedish operations found that femoral neck fracture and osteonecrosis patients show significantly higher rates of dislocation than patients with other primary diagnoses such as osteoarthritis [14]. Conroy et al. would also add rheumatoid arthritis to this list based on their analysis of over 65,000 cases in Australia [15].

A reduction in femoral head size limits the mechanical range of motion, which results in earlier component impingement. Historically, acetabular liners primarily failed from excessive wear, leading one to desire thicker liners (and hence a smaller femoral head size). However, these smaller head sizes led to component impingement, which also correlates to excessive wear rates [16]. Figure 6 Figure 7 illustrate this tradeoff of a maximum range of motion with liner thickness. The radius of the acetabular shell is fixed while the size of the femoral head is varied. In this example, a 22mm femoral head would allow for 105° of motion, with 10mm of liner thickness, while a 28mm femoral head would allow 122° of motion, with 7mm of liner thickness. The erosion of the acetabular liner, whether caused by component impingement, cup orientation, or long-term use, not only distorts the hemispherical shape but the eroded particles cause osteolysis and/or metallosis, triggering an immune response, damaging the surrounding tissue and bone [17,18]. Luckily, advances in the material properties of the liner have decreased wear rates, allowing a thinner liner. Increased dislocation rates due to surgical approach remains a point of debate,
however, Hailer et al. found that posterior and lateral minimally invasive approaches lead to higher dislocation rates as compared to non-minimally invasive [14]. Kwon et al. found that failure to repair the capsule in posterior approach also lead to higher dislocation rates [19].

I.C Implant Position

A very important factor that influences dislocation is component positioning and orientation [16,20,21,26–36]. Proper component orientation restores the appropriate range of motion without impingement, and proper component positioning restores the center of rotation, maintaining leg length, hip offset, soft tissue balance. It has been shown that the orientation of the acetabular cup is more significant than femoral orientation when predicting the risk of dislocation [37]. Several authors have retrospectively analyzed the cup orientation and compared it with the incidence of dislocation to determine high-risk cup orientations [20,21,28]. Kenney et al. found that high inclination results in significantly higher rates of dislocation, osteolysis, and cup migration, while low inclination coupled with excess anteversion correlates with dislocation [28]. Lewinnek et al. analyzed 122 THAs and found that anterior dislocation is associated with excess anteversion, and proposed a ‘safe zone’ in which the risk of dislocation is reduced [20]. Lewinnek et al.’s safe zone was $15^\circ \pm 10^\circ$ of acetabular anteversion and $40^\circ \pm 10^\circ$ of acetabular inclination and is listed in Table 1 [20]. Biedermann et al. compared 127 dislocated hips to a control of 342 non-dislocated hips and found that anterior dislocation is associated with high inclination and with high anteversion [21]. Biedermann et al. also found that posterior dislocation is associated with low anteversion and proposed an updated safe zone with slightly higher acetabular inclination zone (Table 1) [21]. In contrast, Danoff et al. studied 1289 cases that were operated

<table>
<thead>
<tr>
<th>Author</th>
<th>Inclination Safe Zone</th>
<th>Anteversion Safe Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lewinnek et al. [20]</td>
<td>$40^\circ \pm 10^\circ$</td>
<td>$15^\circ \pm 10^\circ$</td>
</tr>
<tr>
<td>Biedermann et al. [21]</td>
<td>$45^\circ \pm 10^\circ$</td>
<td>$15^\circ \pm 10^\circ$</td>
</tr>
<tr>
<td>Widmer et al. [22]</td>
<td>$40^\circ - 45^\circ$</td>
<td>$20^\circ - 28^\circ$</td>
</tr>
<tr>
<td>Danoff et al. [23]</td>
<td>$40^\circ \pm 10^\circ$</td>
<td>$10^\circ - 25^\circ$</td>
</tr>
<tr>
<td>Callanan et al. [24]</td>
<td>$30^\circ - 45^\circ$</td>
<td>$15^\circ \pm 10^\circ$</td>
</tr>
<tr>
<td>McCollum et al. [25]</td>
<td>$40^\circ \pm 10^\circ$</td>
<td>$30^\circ \pm 10^\circ$</td>
</tr>
</tbody>
</table>

Table 1: Sample of publications listing a target zone of acetabular orientation to reduce the risk of dislocation.
from a posterior approach and concluded that a narrower safe zone of acetabular anteversion would optimize a risk reduction in dislocation (Table 1) [23].

Although femoral orientation hasn’t been shown to be nearly as significant as acetabular orientation, a few researchers have recommended a zone of combined anteversion [38–40]. This combined anteversion is the sum of the acetabular and femoral anteversion, which according to Amuwa et al. should lie within 25° to 50° (the cup anteversion should always be less than 30°). Amuwa et al. found that anterior dislocations are more common when the combined anteversion exceeds 50° and that men typically have a lower combined anteversion than women [38]. It has been shown that the acetabula of men naturally have statistically significantly less anteversion than females, however, native geometry in itself is statistically unrelated to the published safe zones [41,42]. Due to such variability in acetabular orientation, researchers are quick to point out that these safe zones are not an absolute solution [21,43,44]. Dislocation is a multifaceted problem and for some patients, the correct implant orientation may lie outside the published safe zones [45].

I.D Patient-Specific Implant Positioning

As an alternative to standardized safe zones, researchers have sought to identify patient-specific optimized implant orientations. One such proposed technique is aligning the acetabular cup with the transverse acetabular ligament (TAL), which bridges the acetabular notch in the inferior portion of the rim. Archbold et al. used the TAL to guide acetabular anteversion and cup depth in 1000 patients and used the remaining labrum on the superior portion of the rim to guide acetabular inclination [46]. Archbold et al. had a dislocation rate of 0.6% in their 8-41 month follow-up and identified the TAL in 99.7% of cases [46]. This dislocation rate compares favorably to most literature, as seen in Table 2, and even improves upon Lewinnek et al.’s safe zone dislocation rate (1.5%) [20]. Several other authors have agreed with Archbold et al., with Inoue et al. having 0 dislocations in 31 cases, and Miyoshi et al. having 3 dislocations in 113 cases.
One of the largest downfalls of the TAL alignment technique is the reliability of finding the TAL. While Archbold et al. identified the TAL in 99.7% of cases, other authors have reported rates between 47% - 81.6% [46,48,50,51]. It has also been noted that reproducing the same anteversion between two surgeons has been less than optimal when using the TAL for alignment, with a mean difference +/- the standard deviation (SD) of 6.4° ± 5.0° [52]. This variability is exaggerated further by comparing two similar studies, where pelves are dissected and the anteversion of the TAL is measured [53,54]. The mean anteversions of these two studies were of 1.9° and 15.4° [53,54]. There is also controversy among its usefulness for certain primary diagnoses. Abe et al. rejected the use of TAL to orient the acetabular cup for patients with osteoarthritis secondary to hip dysplasia, noting an increased anteversion and inclination as compared to patients with osteonecrosis [55]. However, Miyoshi et al. found no difference in anteversion for hips with dysplasia when aligning the cup.

<table>
<thead>
<tr>
<th>Author</th>
<th>Sample</th>
<th>Dislocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAHKS [12]</td>
<td>N/A</td>
<td>1%</td>
</tr>
<tr>
<td>Abbas et al. [8]</td>
<td>199</td>
<td>6.5%</td>
</tr>
<tr>
<td>Abdel et al. [45]</td>
<td>9784</td>
<td>2.1%</td>
</tr>
<tr>
<td>Danoff et al. [23]</td>
<td>1289</td>
<td>3.3%</td>
</tr>
<tr>
<td>Esposito et al. [44]</td>
<td>7040</td>
<td>2.1%</td>
</tr>
<tr>
<td>Jolles et al. [29]</td>
<td>2023</td>
<td>1.5%</td>
</tr>
<tr>
<td>Khan et al. [35]</td>
<td>6774</td>
<td>2.1%</td>
</tr>
<tr>
<td>Lewinnek et al. [20]</td>
<td>300</td>
<td>3.0%</td>
</tr>
<tr>
<td>Sotereanos et al. [49]</td>
<td>617</td>
<td>0.8%</td>
</tr>
<tr>
<td>Timperley et al. [43]</td>
<td>1578</td>
<td>3.2%</td>
</tr>
<tr>
<td>Yuan et al. [34]</td>
<td>2728</td>
<td>3.6%</td>
</tr>
</tbody>
</table>

Table 2: Sample of publications that list a dislocation rate
using the TAL [48]. Lastly, Epstein et al. found no significant difference in anteversion alignment when using the TAL as compared to traditional techniques [50]. Between the inconsistency of identifying the TAL, and the variability in aligning the cup to the TAL, it is clear that this technique is highly skill driven.

Another patient-specific optimized implant alignment is the concept of functional implant alignment. In the sagittal plane, the rotation of the pelvis with respect to the spine is referred to pelvic tilt. Figure 8-10 show three examples of pelvic tilt, measured from the anterior pelvic plane (APP). The pelvic tilt can change as patient moves between positions, and in particular, the pelvic tilt can vary appreciably between standing, sitting, and the supine position [56,57]. Therefore the anteversion from an anterior view changes when the patient moves from a supine to sitting or standing [58–60]. If a patient is templated for THA using a supine anterior to posterior (A to P) radiography alone, and their pelvic tilt differs significantly from supine to standing or sitting, their anteversion from an anterior view will also differ significantly [61]. In such a case, a patient templated from an A to P supine radiograph may have correct acetabular cup anteversion when laying down, but an improper anteversion when standing or sitting, increasing the risk of dislocation [61]. Figure 11-13 depict the change in apparent cup position when there is a change in pelvic tilt. The acetabular cup is in the same
position relative to the pelvis for all three figures. As the pelvis tilts from an anterior angle to a posterior angle, the cup increases in both inclination and anteversion from the front/coronal view of reference. When the pelvis is tilted posteriorly, the superior rim becomes more endangered to edge-loading, and the increased anterior opening presents a greater risk of anterior dislocation. In contrast, an anterior pelvic tilt orients the cup in a more horizontal position and presenting an increased risk to posterior dislocation. A functional anteversion accounts for changes in pelvic tilt, optimizing a cup position that ensures the reaction forces in the cup never reach the rim. Specific movements in THA patients have been found to increase the risk of dislocation, namely rising from a chair, which is used to drive this patient-specifically optimized cup position [62,63]. However, no matter how optimized the surgical planning becomes, it is not useful unless the implant position can be achieved in surgery.
Chapter II: Implantation Accuracy

When analyzing the accuracy of implantation, it is important to stratify the data by the technique used. The term conventional or traditional is often used to describe the most common technique used in THA. However, this term is rather vague because it can refer to either freehand cup placement or with the use of a mechanical guide (whether provided by the implant manufacturer or is a third-party device). For the purpose of clarity in this dissertation, conventional and traditional techniques will refer to freehand implantation without the use of fluoroscopy. Both fluoroscopy and the use of mechanical guides will be reviewed separately to understand their individual contributions. Accuracy can vary substantially between surgeons and surgical approach, so it is important to review many reports to understand the overall precision of each technique[64–66]. In the following sections, several surgical methods will be analyzed by collecting accuracy and precision data from multiple reports. This will aid in understanding the generalized effectiveness of each technique, irrespective of surgeon experience or nuances of their surgical approach.

II.A Conventional Freehand

In the conventional freehand technique, a 2-dimensional (2D) surgical plan is created on a preoperative radiograph. The acetabular cup and stem are sized appropriate to the patient’s anatomy, positioned to minimize a leg length discrepancy or change in hip offset, and oriented according to their preferred safe zone (approximately 40° of acetabular inclination, 15° of acetabular anteversion, and 30° of combined anteversion). An example of a traditional THA surgical plan is shown in Figure 14. Depending on the surgeon’s confidence, intraoperative x-rays may or may not be taken to visually confirm the orientation and position of the implants. Intraoperative changes in implant size may be necessary for a more optimal fit. When orienting
the acetabular cup, the surgical table or floor is often used a reference plane, where the patient’s APP is assumed to be parallel or perpendicular (depending on the patient position for the surgical approach being used). Mechanical guides, which are discussed in the following section, often rely on this assumption.

Researchers have found that freehand techniques do not consistently implant within a desired safe zone [64,67]. Barrack et al. found that regardless of surgeon experience, volume, or approach, freehand techniques lacked the precision to implant the acetabular cup within 30°–55° of inclination and 5°–35° of anteversion (a zone larger than what was proposed by Lewinnek) [64]. They also found that patient obesity and surgeons with a low-volume of cases increased the risk of acetabular cup malposition, while surgeon experience (apart from volume) did not [64]. A sample of reported freehand accuracies is shown in Table 3. The inclusion criteria for Table 3 were 1) clinical data, 2) postoperative imaging used for data collection (i.e. not measured via navigation), 3) included both the mean and SD for acetabular cup inclination and anteversion and 4) specifically listed freehand as the surgical technique. This table is not stratified by the surgical approach, surgeon experience, or surgeon volume, which could impact accuracy. Instead, a weighted summary was calculated using Equation 1-3 to capture an overall assessment of freehand accuracy. The grand mean was calculated using Equation 1, in which an overall mean is obtained by factoring in each study’s sample size. Equation 2 calculates the overall unbiased SD, using the grand mean, and each study’s sample size, mean, and SD. This equation is derived from the total corrected sum of squares used in the common analysis-of-variance [68]. Lastly,
Equation 3 calculates an overall percentage of cases that fell within Lewinnek et al.’s proposed ranges for acetabular inclination and anteversion.

<table>
<thead>
<tr>
<th>Author</th>
<th>Sample Size</th>
<th>Inclination (mean ± SD)</th>
<th>Anteversion (mean ± SD)</th>
<th>Within Safe Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrett et al. [69]</td>
<td>44</td>
<td>42.4˚ ± 7.6˚</td>
<td>25.8˚ ± 8.1˚</td>
<td>57%</td>
</tr>
<tr>
<td>Bosker et al. [67]</td>
<td>200</td>
<td>49.7˚ ± 6.7˚</td>
<td>16.0˚ ± 8.1˚</td>
<td>70.5%</td>
</tr>
<tr>
<td>Haaker et al. [70]</td>
<td>69</td>
<td>45.7˚ ± 9.1˚</td>
<td>28.5˚ ± 10.3˚</td>
<td>N/A</td>
</tr>
<tr>
<td>Hamilton et al. [71]</td>
<td>100</td>
<td>44.3˚ ± 6.5˚</td>
<td>22.6˚ ± 6.2˚</td>
<td>56%</td>
</tr>
<tr>
<td>Holmann et al. [72]</td>
<td>30</td>
<td>47.7˚ ± 7.5˚</td>
<td>21.2˚ ± 9.8˚</td>
<td>20%</td>
</tr>
<tr>
<td>Kalteis et al. [73]</td>
<td>22</td>
<td>42.3˚ ± 7.0˚</td>
<td>24.0˚ ± 15.0˚</td>
<td>50%</td>
</tr>
<tr>
<td>Kalteis et al. [74]</td>
<td>30</td>
<td>43.7˚ ± 7.3˚</td>
<td>22.2˚ ± 14.2˚</td>
<td>46.7%</td>
</tr>
<tr>
<td>Kobayashi et al. [75]</td>
<td>77</td>
<td>44.4˚ ± 7.0˚</td>
<td>19.3˚ ± 11.0˚</td>
<td>N/A</td>
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<tr>
<td>Lass et al. [76]</td>
<td>63</td>
<td>37.7˚ ± 5.2˚</td>
<td>17.3˚ ± 10.4˚</td>
<td>57.1%</td>
</tr>
<tr>
<td>Minoda et al. [77]</td>
<td>602</td>
<td>44.4˚ ± 6.5˚</td>
<td>17.9˚ ± 6.3˚</td>
<td>72.2%</td>
</tr>
<tr>
<td>Rathod et al. [78]</td>
<td>293</td>
<td>41.2˚ ± 7.0˚</td>
<td>24.0˚ ± 8.7˚</td>
<td>N/A</td>
</tr>
<tr>
<td>Saxler et al. [79]</td>
<td>105</td>
<td>45.8˚ ± 10.1˚</td>
<td>27.3˚ ± 15.0˚</td>
<td>25.7%</td>
</tr>
<tr>
<td><strong>WEIGHTED SUMMARY</strong></td>
<td><strong>1635</strong></td>
<td><strong>44.3˚ ± 7.6˚</strong></td>
<td><strong>20.6˚ ± 9.6˚</strong></td>
<td><strong>62.8%</strong></td>
</tr>
</tbody>
</table>

*Based only on entries that included percentage within Lewinnek zone.

Table 3: Collection of published results for freehand acetabular accuracy. The safe zone is 40˚ ± 10˚ and 15˚ ± 10˚ for acetabular inclination and anteversion respectively.

Where \( \bar{x} = \text{grand mean}, \bar{x}_n = \text{mean of each entry}, N_n = \text{sample size of each entry}, S = \text{weighted standard deviation}, S_n = \text{standard deviation of each entry}, Z = \text{weighted percent within the zone}, \) and \( Z_n = \text{percent within the zone of each entry}. \)

The study with the highest precision had 27.8% cups outside of the desired range of orientation, while the worst case left 80% outside the intended range. Collectively, this sampling of published results left 37.2% outside of Lewinnek et al.’s zone, meaning more than 1 in 3 cups were outside the intended zone. It is important to note the standard deviations of cup orientations because this value gives an indication of the spread of data (precision of the technique). A sampling of cup implants may average at the center of Lewinnek et al.’s zone (40˚ and 20˚ of inclination and anteversion), but with a large standard deviation, few will actually lie within the
desired zone. By observing the standard deviations, it is apparent that acetabular inclination is generally more precise than anteversion. Research by Bosker et al. confirmed this by finding that orthopaedic surgeons can estimate cup inclination with a mean and SD inaccuracy of $4.1^\circ \pm 3.9^\circ$ but estimates cup anteversion with an inaccuracy of $5.2^\circ \pm 4.5^\circ$ [67].

A contributing factor to the error associated with freehand techniques is the assumption of pelvic position. The APP is often assumed to be parallel to the floor when using an anterior or posterior approach and is assumed to be perpendicular when using a lateral approach. However this assumption is not always true, as pelvic tilt varies (as previously discussed in section I.D), and the pelvis has been shown to shift significantly throughout the surgery [80,81]. Excess adipose tissue can conceal anatomical landmarks, adding to the uncertainty of pelvic orientation, which is presumably why obesity is linked to acetabular cup malposition [24,82].

II.B Mechanical Guides

Mechanical alignment guides typically utilize an alignment rod connected to the acetabular impactor handle. When the alignment rod is oriented parallel to the surgical table/floor and along the patient’s longitudinal axis, the acetabular cup is oriented to a specified vertical inclination and anteversion (Note: some designs only guide inclination [83]). Alternative designs may use levels for added precision in orienting a device with respect to gravity [84]. In some cases, a goniometer may be used to adjust the mechanical guide to target a specific angle. In whatever specific design, the general concept is to align the cup impactor to the desired angles with respect to the surgical table or floor. Mechanical guides are frequently used because they are often provided in the surgical trays, and their usage is described in many surgical techniques [85–88]. Table 4 contains a sample of published results for acetabular cup orientation when using a mechanical guide. The inclusion criteria for Table 4 was 1) clinical results, 2) postoperative imaging used for data collection (i.e. not measured via navigation), 3) included both the mean and SD for acetabular cup inclination and anteversion and 4) specifically listed the use of a mechanical
guide or alignment rod. A smaller sample was found compared to freehand because fewer studies explicitly stated the use of a mechanical guide, presumably because it is included in the surgical technique and considered conventional. The weighted summary was calculated in the same fashion it was in the previous table using Equation 1-3.

<table>
<thead>
<tr>
<th>Author</th>
<th>Sample Size</th>
<th>Inclination (mean ± SD)</th>
<th>Anteversion (mean ± SD)</th>
<th>Within Safe Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domb et al. [89]</td>
<td>50</td>
<td>42.6° ± 5.4°</td>
<td>13.3° ± 7.0°</td>
<td>80%</td>
</tr>
<tr>
<td>Domb et al. [90]</td>
<td>708</td>
<td>41.7° ± 5.3°</td>
<td>21.8° ± 6.1°</td>
<td>69.5%</td>
</tr>
<tr>
<td>Gurgel et al. [91]</td>
<td>20</td>
<td>42.2° ± 3.3°</td>
<td>14.5° ± 8.3°</td>
<td>80%</td>
</tr>
<tr>
<td>Kanoh et al. [92]</td>
<td>48</td>
<td>43.8° ± 3.5°</td>
<td>14.6 ± 5.7°</td>
<td>95.8%</td>
</tr>
<tr>
<td>Najarian et al. [93]</td>
<td>53</td>
<td>47.5° ± 6.7°</td>
<td>20.9° ± 9.1°</td>
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</tr>
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<td>Parratte et al. [94]</td>
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<td>34.0° ± 7.6°</td>
<td>16.2° ± 9.6°</td>
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<td><strong>WEIGHTED SUMMARY</strong></td>
<td>909</td>
<td><strong>42.0° ± 5.7°</strong></td>
<td><strong>20.6° ± 7.1°</strong></td>
<td><strong>70.9%</strong></td>
</tr>
</tbody>
</table>

*Based only on entries that included percentage within Lewinnek zone.

Table 4: Collection of published results for acetabular accuracy when using a mechanical guide. The safe zone is 40° ± 10° and 15° ± 10° for acetabular inclination and anteversion respectively.

The use of mechanical guides showed an increase in precision as compared to freehand techniques, with an overall fraction of 29.1% of cups outside Lewinnek et al.’s safe zone. There was, however, a large range of results between studies indicating a variety of individual experience. The results from Parratte et al. for example, was less accurate than many of the freehand results and had standard deviations equal to the weighted summary from the freehand group.

In a study by Hassan et al., a mechanical guide was used to implant 50 cups split across 4 surgeons using a lateral modified Hardinge approach, and found that only 58% of the cups fell within the desired range (Lewinnek zone), despite that the operating surgeons believed them to be correct [95]. They found that cup inclination was correct for 84% of cups, while anteversion trailed with 68% of cups within the safe zone [95]. When checking with navigation rather than a postoperative radiograph, Digioia et al. found that 78% of cups were within Lewinnek et al.’s zone when using an alignment guide [96].
Maeda et al. published an interesting study that compared 3 different approaches when using an alignment guide: direct anterior approach (DAA) from a supine position, DAA from a lateral position, and posterior approach (PA) [65]. They found no significant difference in inclination, but did find a difference for anteversion: the anterior approaches exceeded the target (too much anteversion) and the posterior approach fell short of the target (too little anteversion) [65].

Echeverri et al. investigated a unique gravity-assisted device which used a system of levels, both on the device and anchored into the iliac crest [84]. They compared this device to traditional alignment rods while implanting an acetabular cup in a plastic pelvis [84]. They found a much greater precision with the gravity-assisted device than the traditional alignment rods, with an SD of 0.5° and 0.7° for abduction and anteversion, compared to 2.3° and 5.0° when using the alignment rods [84]. However, the significance is limited since the plastic pelves were fixed in the lateral decubitus position, masking any error from pelvic tilt and pelvic motion in surgery.

The error associated with mechanical alignment guides goes back to the uncertainty of pelvic position relative to the surgical table and/or floor. As discussed in section I.D, pelvic tilt varies greatly from patient to patient, and between sitting and standing. It has also been shown that the pelvic tilt can vary by up to 57° during surgery [97]. Since mechanical guides are based on being level with the floor and aligned with the longitudinal axis, any intraoperative pelvic shift results in error to cup placement. In addition, many of the popular mechanical guides were found to have a built-in mean error of 2° for inclination and 6° for anteversion [98]. In summary, mechanical alignment guides generally show an improvement in cup implantation accuracy as compared to freehand techniques. However, there is much room for improvement since approximately 29% of the cups are outside the safe zone.

II.B Fluoroscopy

Fluoroscopy is an imaging technique where x-rays are taken continuously and displayed on a monitor to give a real-time x-ray motion picture of the patient. This is advantageous because
the orientation of the acetabular reamer and/or impactor can be visualized on the monitor and observed during reaming/impaction to maintain the desired direction. A clear disadvantage is the increased dose of radiation, but also the need for a radiolucent table, and the C-arm also takes up space in the operating room (OR) [99]. However, it is a simple intraoperative check to confirm cup placement by comparing with the preoperative plan.

Table 5 contains a sample of published results for acetabular cup orientation when using fluoroscopy. The inclusion criteria for Table 5 was 1) clinical results, 2) postoperative imaging used for data collection, 3) included both the mean and SD for acetabular cup inclination and anteversion and 4) specifically listed the use of fluoroscopy.

<table>
<thead>
<tr>
<th>Author</th>
<th>Sample Size</th>
<th>Inclination (mean ± SD)</th>
<th>Anteversion (mean ± SD)</th>
<th>Within Safe Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alexandrov et al.</td>
<td>43</td>
<td>48.4° ± 7.0°</td>
<td>19.6° ± 6.6°</td>
<td>≤62.8%</td>
</tr>
<tr>
<td>Barrett et al. [69]</td>
<td>43</td>
<td>47.1° ± 6.1°</td>
<td>20.1° ± 5.9°</td>
<td>73%</td>
</tr>
<tr>
<td>Domb et al. [90]</td>
<td>942</td>
<td>42.0° ± 5.1°</td>
<td>20.4° ± 7.2°</td>
<td>73.1%</td>
</tr>
<tr>
<td>Hamilton et al. [71]</td>
<td>100</td>
<td>44.2° ± 5.0°</td>
<td>17.6° ± 4.5°</td>
<td>82%</td>
</tr>
<tr>
<td>Kobayashi et al. [75]</td>
<td>75</td>
<td>42.2° ± 6.9°</td>
<td>27.6° ± 6.3°</td>
<td>N/A</td>
</tr>
<tr>
<td>Matta et al. [101]</td>
<td>458</td>
<td>42.0° ± 4.0°</td>
<td>19.4° ± 5.2°</td>
<td>N/A</td>
</tr>
<tr>
<td>Rathod et al. (1) [78]</td>
<td>96</td>
<td>39.3° ± 5.1°</td>
<td>20.2° ± 6.3°</td>
<td>N/A</td>
</tr>
<tr>
<td>Rathod et al. (2) [78]</td>
<td>286</td>
<td>40.4° ± 4.4°</td>
<td>13.3° ± 4.0°</td>
<td>N/A</td>
</tr>
<tr>
<td>Slotkin et al. [102]</td>
<td>780</td>
<td>37.6° ± 5.5°</td>
<td>18.8° ± 5.3°</td>
<td>88%</td>
</tr>
<tr>
<td><strong>WEIGHTED SUMMARY</strong></td>
<td><strong>2823</strong></td>
<td><strong>40.8° ± 5.6°</strong></td>
<td><strong>19.1° ± 6.4°</strong></td>
<td><strong>79.8%</strong></td>
</tr>
</tbody>
</table>

Table 5: Collection of published results for acetabular accuracy when using fluoroscopy. The safe zone is 40° ± 10° and 15° ± 10° for acetabular inclination and anteversion respectively.
*Based only on entries that included percentage within Lewinnek zone.
(1) Learning curve subset
(2) Subset immediately following learning curve group

When comparing the SDs from the fluoroscopy table vs the mechanical guide table, it can be seen that fluoroscopy shows improvement in precision for the angle of anteversion. This translates into a higher percentage of cups within Lewinnek’s zone, as shown by the weighted summary in the table. However, the technique of fluoroscopy imaging still left 20.2% of cups outside of the desired acetabular zone. In contrast, a direct comparison of fluoroscopy and freehand by Beamer et al. found that in primary cases there was no statistical improvement for
cup placement [103]. However, they did show improvement in cup placement when including revisions and conversion to THA from previous hip surgery as compared to freehand [103].

In a study by Rathod et al., the learning curve of fluoroscopy was evaluated by isolating the operating surgeon’s first 100 cases [78]. They found a statistically lower precision in anteversion for the learning curve group, while the inclination statistically did not differ between the learning curve and experienced groups [78]. Alternatively, Slotkin et al. analyzed a 4-year learning curve for two surgeons with a greater volume of procedures and showed stark improvements in both inclination and anteversion [102]. They showed a single surgeon improving from 68.1% of cups (n=72) within Lewinnek’s zone to 97.4% of cups (n=189) within the desired range after 3 years of experience [102]. In an attempt to further advance fluoroscopy, one research team created a novel fluoroscopic grid that improved cup inclination, leg length and hip offset equalization [104]. However this study is difficult to compare to existing literature because they did not study anteversion and did not report their means and SDs, but only the percent within their target [104].

Fluoroscopic imaging can be summarized in that it generally shows improvement upon freehand and mechanically guided techniques, however only in cup anteversion, and possibly in hip offset and leg length. Improvements can still be made in improving these measures, particularly with cup inclination, since its precision is similar when using alignment rods. In addition, fluoroscopy has been shown to hold a long learning curve, requiring high experience for precisions above 90% within Lewinnek’s safe zone, and could arguably vary significantly between surgeons [102].

II.C CT-based Navigation

In a more advanced mode of improving cup position, CT-based navigation may be employed. With this technology, a patient undergoes a CT scan prior to surgery, so that the 3D bone geometry may be used in surgical planning. In surgery, the bone structures of interest (pelvis
and sometimes femur) need to be spatially registered to the computer model. This technique is often achieved by inserting bone pins with an array sensors into the iliac crest and using a probe with an array of sensors to identify bone surface points [105]. If the system includes femoral guidance, a femoral tracker with an array of sensors is fastened into the greater trochanter [106]. This femoral tracker monitors the femur movement while a series of femoral bone surface points are collected to spatially register the femur. The array of sensors is then often removed to continue surgery but can be replaced at any time to determine the femur’s position in space. The surgical equipment also contains an array of sensors so that the computer can calculate the relative position of the pelvis and/or femur in real-time. Therefore, the computer can display the pelvis model and the surgical tool in real-time with current angles of anteversion and inclination. If femoral guidance is being used, a probe with an array of sensors can be used to identify the ideal location for femoral osteotomy. In addition, the femoral version can be measured using a sensor device that fits over the broach neck, and global offset and leg lengthening are measured by comparing the resulting change between the femoral and pelvic trackers once the joint has been reduced. CT-based computer navigation was first studied for acetabular orientation in a clinical trial by Digioia et al. in 1998, where it was discovered that pelvic motion during surgery is significant [97].

A disadvantage of CT-based navigation is the requirement of a preoperative CT scan, which increases the wait time until surgery, has an associated dose of radiation, and the additional cost of imaging [107,108]. Disadvantages also include increased surgical time for registration (~5 min), the need for expensive equipment, and tracking pins placed outside the surgical site [99,105]. In an economic analysis of computer navigation, Beringer et al. reported that the technology increased the cost of each surgery by $600-$2000, which is a ~20% increase from the cost of conventional [109].
Table 6 contains a sample of published results for acetabular cup orientation when using CT-based computer navigation. The inclusion criteria for Table 6 was 1) clinical results, 2) postoperative imaging used for data collection, 3) included both the mean and SD for acetabular cup inclination and anteversion and 4) specifically listed the use of CT-based navigation.

<table>
<thead>
<tr>
<th>Author</th>
<th>Sample Size</th>
<th>Inclination (mean ± SD)</th>
<th>Anteversion (mean ± SD)</th>
<th>Within Safe Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domb et al. [90]</td>
<td>43</td>
<td>44.7° ± 2.9°</td>
<td>14.8° ± 5.1°</td>
<td>90.7%</td>
</tr>
<tr>
<td>Haaker et al. [70]</td>
<td>98</td>
<td>43.0° ± 4.6°</td>
<td>22.2° ± 7.4°</td>
<td>N/A</td>
</tr>
<tr>
<td>Kalteis et al. [74]</td>
<td>30</td>
<td>41.6° ± 4.0°</td>
<td>10.7° ± 5.3°</td>
<td>83.3%</td>
</tr>
<tr>
<td>Kitada et al. [106]</td>
<td>30</td>
<td>40.4° ± 3.5°</td>
<td>22.3° ± 7.7°</td>
<td>N/A</td>
</tr>
<tr>
<td>Sugano et al. (MPA) [110]</td>
<td>39</td>
<td>40.0° ± 2.6°</td>
<td>13.9° ± 2.9°</td>
<td>100%</td>
</tr>
<tr>
<td>Sugano et al. (MAA) [110]</td>
<td>33</td>
<td>40.4° ± 2.4°</td>
<td>12.3° ± 2.8°</td>
<td>100%</td>
</tr>
<tr>
<td><strong>WEIGHTED SUMMARY</strong></td>
<td>273</td>
<td>42.1° ± 4.0°</td>
<td>17.4° ± 7.6°</td>
<td>93.8%*</td>
</tr>
</tbody>
</table>

Table 6: Collection of published results for acetabular accuracy when using CT-based navigation. The safe zone is 40° ± 10° and 15° ± 10° for acetabular inclination and anteversion respectively.

*Based only on entries that included percentage within Lewinnek zone.

MPA- Mini-incision Posterior Approach
MAA- Mini-incision Anterior Approach

The weighted summary for CT-based navigation shows a clear improvement in the percentage of cups within Lewinnek’s safe zone, however, the SD for anteversion is slightly higher than in fluoroscopy. The inclusion of the results from Haaker et al. and Kitada et al. certainly lowers the calculated precision in cup anteversion, but does not affect the overall percentage within the safe zone because those studies did not provide that figure. However, even Haaker et al. found that CT-based navigation showed statistically significant improvements in cup position for both cup inclination and anteversion when compared to freehand techniques [70]. A larger sample size would be desirable for this summary, however, a larger fraction of navigation studies investigate imageless navigation, which is discussed in the section succeeding this one. Regardless, it is clear from several accounts in Table 6 that the use of CT-based navigation results in an improvement over freehand, mechanical guided, and fluoroscopically guided techniques. In the study by Sugano et al., 2 different surgical approaches were analyzed: a minimally invasive posterior approach, and a minimally invasive anterior approach [110]. In their study, they had
100% of cases within Lewinnek’s safe zone, and remarkably low SDs for both cup inclination and anteversion using either surgical approach [110].

II.D Imageless Navigation

Imageless navigation seeks to maintain or improve the accuracy of CT-based navigation, but without the pre-operative CT scan. In this technique, rather than a pre-op CT scan, the bone pins with an array of sensors and a probe with a similar array are used to identify the APP plane from the left and right ASIS and pubic tubercles. Once the APP plane is established, the probe with an array is used to capture a sample of points in the acetabulum and on the acetabular rim. While the entire pelvic surface is not known, the information from these pins and probe is sufficient for the navigation system to guide cup preparation and implantation. For femoral preparation, a femoral tracker may be fixed into the greater or lesser trochanter and the probe is used to capture key femoral surface data [111]. The functionality in surgery is similar to CT-based navigation, in that a computer screen displays the surgical tools orientation in relationship to the pelvis’ APP plane and cup. When the surgical tool is oriented according to the surgeon’s preference, reaming and/or impacting is commenced.

While the disadvantages of imageless navigation are similar to CT-based navigation, the absence of preoperative imaging is a stark difference, eliminating those associated disadvantages. However, without the preoperative CT, advanced 3D surgery templating is not available. Imageless navigation also has the disadvantages of equipment cost, the increased procedure time, and the occasional need to readjust sensors for proper registration [112]. Table 7 contains a sample of published results for acetabular cup orientation when using imageless computer navigation. The inclusion criteria for Table 7 was 1) clinical results, 2) postoperative imaging used for data collection, 3) included both the mean and SD for acetabular cup inclination and anteversion and 4) specifically listed the use of imageless navigation.
When comparing imageless computer navigation to CT-based computer navigation, it is difficult to make a finite judgment between the two. It appears that there is a slight loss in precision for acetabular inclination for imageless navigation, while precision for acetabular anteversion is greater, and yet a smaller fraction of cups lie within Lewinnek et al.’s safe zone. However, with several authors not reporting their overall percent within this safe zone for both CT-based and imageless navigation, it is difficult to discern one’s performance over the other. However it is for certain, is that imageless computer navigation shows improvement over freehand, mechanically guided, and fluoroscopic techniques. In the study by Najarian et al., the learning curve effect was investigated, and it is clear that a higher precision existed in the second set of 50 cases [93]. Although in another surgeon’s experience (Grützner et al.), they found no learning curve, which then implies that an improvement over time may be surgeon dependent [113]. In a study by Wixson et al., it was shown that imageless navigation can be performed to a high degree of accuracy even when using minimally invasive techniques [116]. In confirmation,

<table>
<thead>
<tr>
<th>Author</th>
<th>Sample Size</th>
<th>Inclination (mean ± SD)</th>
<th>Anteversion (mean ± SD)</th>
<th>Within Safe Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gurgel et al. [91]</td>
<td>20</td>
<td>41.7° ± 3.0°</td>
<td>17.4° ± 6.3°</td>
<td>90%</td>
</tr>
<tr>
<td>Grützner et al. [113]</td>
<td>236</td>
<td>42° ± 3.6°</td>
<td>21° ± 3.9°</td>
<td>N/A</td>
</tr>
<tr>
<td>Hohmann et al. [72]</td>
<td>32</td>
<td>44.7° ± 4.6°</td>
<td>19.6° ± 6.8°</td>
<td>76.7%</td>
</tr>
<tr>
<td>Jenny et al. [114]</td>
<td>48</td>
<td>44° ± 5°</td>
<td>19° ± 7°</td>
<td>79.2%</td>
</tr>
<tr>
<td>Kalteis et al. [73]</td>
<td>23</td>
<td>45.0° ± 2.8°</td>
<td>14.4° ± 5.0°</td>
<td>91.3%</td>
</tr>
<tr>
<td>Kalteis et al. [74]</td>
<td>30</td>
<td>43.2° ± 4.0°</td>
<td>15.2° ± 5.5°</td>
<td>93.3%</td>
</tr>
<tr>
<td>Lass et al. [76]</td>
<td>62</td>
<td>38.6° ± 3.6°</td>
<td>19.5° ± 4.6°</td>
<td>90.3%</td>
</tr>
<tr>
<td>Lin et al. [115]</td>
<td>22</td>
<td>40.0° ± 2.9°</td>
<td>17.7° ± 3.5°</td>
<td>88%†</td>
</tr>
<tr>
<td>Najarian et al. (1) [93]</td>
<td>49</td>
<td>44.1° ± 6.2°</td>
<td>24.1° ± 7.3°</td>
<td>N/A</td>
</tr>
<tr>
<td>Najarian et al. (2) [93]</td>
<td>47</td>
<td>45.5° ± 4.7°</td>
<td>25.1° ± 5.8°</td>
<td>N/A</td>
</tr>
<tr>
<td>Parratte et al. [94]</td>
<td>30</td>
<td>34.0° ± 5.7°</td>
<td>14.4° ± 4.5°</td>
<td>80%</td>
</tr>
</tbody>
</table>

**WEIGHTED SUMMARY**

<table>
<thead>
<tr>
<th>Author</th>
<th>Sample Size</th>
<th>Inclination (mean ± SD)</th>
<th>Anteversion (mean ± SD)</th>
<th>Within Safe Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lin et al. [115]</td>
<td>22</td>
<td>40.0° ± 2.9°</td>
<td>17.7° ± 3.5°</td>
<td>88%†</td>
</tr>
</tbody>
</table>

†Includes 3 extra cases where navigation was abandoned for clearly improper cup orientation

*Based only on entries that included percentage within Lewinnek zone.

(1) Learning curve subset
(2) Subset following (1) group

Table 7: Collection of published results for acetabular accuracy when using imageless navigation. The safe zone is $40° ± 10°$ and $15° ± 10°$ for acetabular inclination and anteversion respectively.
Murphy et al. showed a reduction in complications when using a less invasive approach with navigation, than when using a conventional technique and approach [117]. In an analysis of navigation studies reporting long-term clinical results, Moskal et al. was able to show a significant reduction in dislocation compared to conventional, confirming that higher precision reduces dislocation [118].

Due to the similarity between imageless and CT-based computer navigation, many researchers combine the data when analyzing its accuracy. Among researchers that performed meta-analyses to compare navigation to conventional techniques, they were in agreement that while the overall mean inclination and anteversion were not significantly different, navigation does significantly reduce variation and outliers [118–121]. However, in contrast with Table 6 & 7, Moskal et al. found that up to 19.25% of cups were outside the safe zone when using navigation [118]. In summary, navigation techniques (imageless and CT-based) show improvements upon conventional freehand, mechanically guided, and even fluoroscopically guided THA techniques, but results vary greatly between users.

II.E Robotic-guided

In a more technologically advanced technique, robotically guided THA is an option for precise implantation. This technology requires a preoperative CT scan for 3D hip templating. A computer model of the bone structures and desired implant positions are stored in a computer in the operating room. In surgery, a surgical pin/screw is inserted at a specified bony landmark and relays its position and orientation to the computer in real time using magnetic or optical sensors [122]. The surgeon uses a probe to touch various points of the bone surface, relaying each point to the computer, allowing a calculation to take place, reproducing the exact position of the pin/screw on the computer 3D model [122]. Once this step is completed, 3D registration is finished and the computer can display the bone positions in real time. If the robot is equipped to assist with femoral placement, a probe is used to mark the line for resection on the femoral neck
prior to osteotomy [122]. Following the broaching of the femur, a sensor can be placed on the neck of the broach to measure the stem version. For acetabular reaming, a robotic arm holds a tube for the surgeon to ream through. The tube restricts the orientation of the reamer to only the planned inclination and anteversion, as well as restricting the depth of reaming. The robotically guided tube then is enclosed over the impactor to orient the cup according to the plan and gives an indication when the cup is fully seated.

While robotic-guided surgery touts high precisions, the disadvantages include the expensive equipment, the requirement of a preoperative CT, the use of tracking pins outside the surgical site, and the valuable space it uses within the OR. Table 8 contains a sample of published results for acetabular cup orientation when using a robot to perform THA. The inclusion criteria for Table 8 was 1) clinical results, 2) postoperative imaging used for data collection, 3) included both the mean and SD for acetabular cup inclination and anteversion and 4) specifically listed the use of robotically guided cup implantation.

<table>
<thead>
<tr>
<th>Author</th>
<th>Sample Size</th>
<th>Inclination (mean ± SD)</th>
<th>Anteversion (mean ± SD)</th>
<th>Within Safe Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domb et al. [89]</td>
<td>67</td>
<td>40.0° ± 3.2°</td>
<td>16.7° ± 3.0°</td>
<td>100%</td>
</tr>
<tr>
<td>Domb et al. (PA) [90]</td>
<td>135</td>
<td>40.1° ± 3.3°</td>
<td>16.9° ± 3.9°</td>
<td>97.8%</td>
</tr>
<tr>
<td>Domb et al. (AA) [90]</td>
<td>93</td>
<td>40.8° ± 4.9°</td>
<td>19.4° ± 4.8°</td>
<td>87.1%</td>
</tr>
<tr>
<td>Elson et al. [123]</td>
<td>110</td>
<td>40.4° ± 4.1°</td>
<td>21.5° ± 6.1°</td>
<td>88%</td>
</tr>
<tr>
<td>Kanawade et al. [124]</td>
<td>43</td>
<td>39.1° ± 3.8°</td>
<td>18.9° ± 4.1°</td>
<td>100%†</td>
</tr>
<tr>
<td>Redmond et al. (1) [125]</td>
<td>35</td>
<td>40.7° ± 3.4°</td>
<td>16.5° ± 3.8°</td>
<td>97.1%</td>
</tr>
<tr>
<td>Redmond et al. (2) [125]</td>
<td>35</td>
<td>39.9° ± 2.5°</td>
<td>17.4° ± 3.4°</td>
<td>100%</td>
</tr>
<tr>
<td>Redmond et al. (3) [125]</td>
<td>35</td>
<td>39.3° ± 3.0°</td>
<td>16.7° ± 3.9°</td>
<td>97.1%</td>
</tr>
<tr>
<td>WEIGHTED SUMMARY</td>
<td>553</td>
<td>40.2° ± 3.8°</td>
<td>18.4° ± 4.8°</td>
<td>94.5%</td>
</tr>
</tbody>
</table>

Table 8: Collection of published results for acetabular accuracy when using robotic-guided implantation. The safe zone is 40° ± 10° and 15° ± 10° for acetabular inclination and anteversion respectively.
†Within ±10° of the target did not measure by Lewinnek et al.’s zone.

PA- Posterior Approach
AA- Anterior Approach
(1) Learning curve subset
(2) Subset following (1) group
(3) Subset following (2) group
The standard deviations for robotically guided hip replacement are the lowest of all the available techniques. For this reason, it is safe to differentiate the closeness in outlier percentage between CT-based navigation and robot-guided THA and conclude that using a robot will result in the least amount of outliers. Redmond et al. analyzed the learning curve effect by stratifying their dataset into 3 blocks of 35 cases and found similar precisions regardless of the amount of experience with the robot [125]. They found no statistical difference in the number of outliers when using Lewinnek et al.’s safe zone, however, a difference was observed when using a smaller target zone defined by Callanan et al. [24,125].

In an elegant study by Domb et al., 6 techniques were compared side by side: 1) Conventional posterior approach using alignment rods, 2) Conventional posterior approach with intraoperative x-ray, 3) Fluoroscopic guided anterior approach, 4) CT-based computer navigation anterior approach, 5) Robotic guided posterior approach, and 6) Robotic guided anterior approach [90]. They found that when employing Lewinnek et al.’s safe zone definition, CT-based navigation, and both robotically guided approaches were statistically equivalent in outliers [90]. They also determined that the variation between navigation and robotically guided were equivalent using Levene’s Test [90]. However when using a smaller target zone for cup implantation (inclination 30°-45°, anteversion 15°±10°), robotically guided techniques were statistically superior for minimizing outliers [90]. In summary, robotically guided techniques result in the least outliers of all techniques, but navigation techniques follow closely behind and have the capacity to reach similar precisions in the hands of highly talented surgeons.

II. F Research Question

Technology is quickly advancing for THA, with increasing precisions for implantation. These technologies are beginning to report long-term clinical results, showing reduces rates of dislocation compared to conventional, however, only in large sample sizes due to the low overall rate of dislocation [118,126]. In these cases, cups implanted using navigation resulted in both a
higher percentage within the targeted safe zone, and a higher long term survivorship rate [118,126]. While most surgeons target a generalized angular zone, advancements are being made in surgical templating to identify personalized implant positions, which have yet to prove an improved long term clinical outcome. However, regardless if a generalized angular zone or a personalized implant position is used, both will require a high precision in implantation to achieve. The technologies available for precisely implanting a THA (navigation and robotic-guided) require a capital investment for the equipment. The expenditure is justified in high-volume institutions, where the equipment is frequently used. However, the low-volume surgeons show the greatest variation in freehand implantation and could benefit most from these technologies [64]. Patient-specific instruments (PSIs) have been introduced to total knee arthroplasty, as an alternative to high precision techniques such as computer navigation [127]. Patient-specific instruments require a preoperative CT scan, in which a 3D surgical plan is created. From the plan, custom instruments are designed to uniquely fit the patient’s bony anatomy, guiding preparation and implantation. These devices are rapidly manufactured using 3D printing. The disadvantage of these instruments is that they require a preoperative CT scan, and there is an associated processing/design cost, however, there is no capital investment for equipment. At the beginning of this research, PSIs were not commercially available for THA. Therefore, I posed the question, can PSIs be designed and implemented for THA as an alternative technology for precise implantation?
Chapter III: Literature Review of PSI for THA

Prior to the commencement of this research in August 2012, only a single group had investigated PSI for THA (Hananouchi et al.). Since then, a few other groups have published results for various PSI designs in THA. This chapter is dedicated to the detailed review of each publication concerning PSIs for THA and will be explained in chronological order. The analysis will show that there was, and still is, room for novel research in this space, particularly for femoral preparation. In general, few studies have been conducted around PSIs for THA, and significant improvements can be made in the instrument design.

III.A Hananouchi et al.

The earliest publication found testing PSI in THA is from Hananouchi et al in 2008 [128]. This research team from Osaka Japan, CT scanned 8 pelvic models using 1mm slice resolution and designed a patient-specifically fitting acetabular device that directs a Kirshner wire (K-wire) just superior of the rim, as seen in Figure 15 [128]. The wire was oriented in 40° of abduction and 20° of anteversion and was used as a visual guide to orient the cup [128]. The accuracy of the device was checked using computer navigation [128]. In this preliminary foam bone model study, the cup placement was found to have a mean of 40.9° ± 1.0° and 20.1° ± 1.1° for the abduction and anteversion respectively [128].

The same group continued their research into clinical trials in 2009 [129]. With IRB approval, they enrolled 24 patients and began with a preoperative CT scan with a 2.5mm slice resolution [129]. They planned for the cup to be implanted at 40° of abduction, and 15°-20° of anteversion (which was slightly adjusted based on the femoral version) [129]. They designed an acetabular patient-specific guide to direct a K-wire just superior of the rim, as seen in Figure 16
The K-wire functioned as a visual indication of cup direction for reaming and cup impaction[129]. Cup position was determined from a CT scan 3 weeks following surgery [129]. They reported a cup position of $38.6^\circ \pm 2.7^\circ$ in the acetabular abduction and $17.4^\circ \pm 5.6^\circ$ in acetabular anteversion [129].

III.B Buller et al.

A research lab out of the Cleveland Clinic published work on a patient-specific hip system in 2013 [130]. Their study compared the use of an acetabular PSI to the traditional cup implantation technique in a foam model hemipelvis [130]. They CT imaged a foam bone model hemipelvis, at a slice resolution of 0.6mm, and templated it for $40^\circ$ of inclination and $22^\circ$ of anteversion [130]. They designed a PSI to fit uniquely in the acetabulum to guide up to 3 pins: A central pin placed near the fovea, and up to 2 peripheral guiding pins in the rim (see Figure 17) [130]. A cannulated reamer fit over the center pin, while the peripheral pins in the rim provided additional visual
guidance [130]. A secondary instrument fit into the acetabular cup and tracked on the peripheral pins to guide impaction and control cup roll (see Figure 18) [130]. The device also aided in the drilling of the screw holes [130]. Seven surgeons of varying experience each implanted two cups into foam model hemipelves using a conventional unguided technique and then two cups using the PSIs [130]. The hemipelves were CT scanned following cup impaction to measure cup position [130]. They reported a mean difference from achieved to planned of $1.4^\circ \pm 1.2^\circ$ in vertical inclination, and $5.2^\circ \pm 5.5^\circ$ in acetabular anteversion using the patient-specific guide [130]. A statistically significant difference was found when compared to the traditional techniques ($10.4^\circ \pm 9.0^\circ$ & $14.9^\circ \pm 14.2^\circ$ respectively) [130]. Using their PSI technique, $3/14$ or $21.4\%$ were positioned outside of Lewinnek et al.’s zone [130].

III.C Small et al.

From the same institution as Buller et al., a second publication was produced in 2014 investigating a similar PSI guide in a clinical study [131]. However, this updated acetabular PSI no longer used a central pin near the fovea, used a single peripheral guide pin, and did not include guidance for the screw pilot holes [131]. They tested the device in an IRB approved, randomized controlled clinical trial, using 3 orthopaedic surgeons in 36 patients [131]. A preoperative CT was taken 21 or more days prior to surgery, at a slice resolution of 0.6mm [131]. The patients were templated for surgery, and 3 acetabular patient-specific pin guides were designed for each patient (see Figure 19) [131]. The 3 guides differed by the bony anatomy they utilized for a unique fit [131]. The surgeons were asked to use whichever guide fit best [131]. The pin that was inserted using the acetabular PSI was then used as a visual guide for reaming and cup impaction [131]. 3 different surgeons performed all 36 surgeries (18 using PSIs, 18 using alignment rods), using 2
different surgical approaches (lateral and posterior) based on surgeon preference [131]. The PSI group resulted in a mean abduction of $46.4^\circ \pm 7.1^\circ$ and a mean anteversion of $18.5^\circ \pm 7.8^\circ$ [131]. This compared favorably to the control arm, which resulted in $43.5^\circ \pm 9.0^\circ$ and $28.4^\circ \pm 7.9^\circ$ of abduction and anteversion respectively [131]. A statistically significant difference was found for acetabular anteversion when compared to the standard technique, but not for abduction [131].

III.D Shandiz et al.

In 2014 at the University of Calgary, a study evaluating an adjustable PSI for acetabular reaming and cup implantation was published [132]. This patient-specific device differs from the previous studies in that it does not contain a patient-specific surface [132]. The device is designed to function with either a preoperative CT scan or even just an ordinary radiograph [132]. However, the device can only guide inclination if only a radiograph is taken [132]. The guide fits over the acetabulum and only interfaces with 3 points on the rim [132]. The device guides the insertion of surgical pins into the rim of the acetabulum, which will later be used as a visual guide for reaming and impacting [132]. The device involves dual arms that rest on specific landmarks of the acetabular rim (See Figure 20) [132]. A third arm extends perpendicular and slides freely through
a dovetail hole, directing a pin into the acetabular rim [132]. They produced a variety of these sliding arms, where each direct the pin at a slightly different angle (note the slight angle of the guiding hole in Figure 20). In this way, the pin can be inserted at a slightly different angle than what is described by the 2 points of the acetabular rim where the device rests (e.g. +2° inclination than the native, -4° anteversion than the native, etc.) [132]. In surgical planning, the planned cup orientation is compared to the acetabular rim; specifically in how the device will be angled when resting on the rim [132]. If the cup must be positioned 2° more vertical than the native rim, the +2° slider arm is used when inserting the inclination guide pin [132]. When both inclination and anteversion guidance is desired, 2 pins must be inserted [132]. The first pin describes the anteversion and is inserted when the dual arms are resting on anterior and posterior sections of the rim, with the desired slider arm directing a pin just superior to the rim of the cup [132]. This pin is only descriptive of anteversion and is not aligned correctly for inclination [132]. A second pin is inserted posterior to the rim when the dual arms are resting on superior and inferior sections of the rim [132]. The device is rocked to match the anteversion shown in the anteversion pin, and with the appropriate slider for desired inclination, the second pin is inserted [132]. This second pin describes both inclination and anteversion and is used as a visual alignment to guide reaming and impacting [132]. The initial anteversion pin can then be removed [132].

Their study included 6 fresh cadavers undergoing bilateral THA with two surgeons (one surgical trauma fellow and one expert arthroplasty surgeon) [132]. Two different approaches were used (posterior and modified Hardinge direct lateral), based on what each surgeon was most familiar with. All of the procedures were completed using the novel device, guiding both inclination and anteversion. In all cases, they targeted 40° of vertical inclination and 20° of anteversion, by the closest 2° increment (e.g. native inclination is 32.8°, the plan uses +8° slider for 40.8°). While their design included a method for depth control, it was not measured quantifiably in their study. All cadavers received a postoperative CT scan to measure final cup location. Their results showed an absolute mean accuracy of 2.5° ± 1.2° in vertical inclination and
2.5° ± 2.2° in acetabular anteversion [132]. Their mean inclination and anteversion were 41.3°±2.1° and 18.7°±3.3° respectively. Many of the cups were implanted with too much inclination and resulted in a statistically significant difference from the plan. No difference was found between the 2 surgeons.

III.E Spencer-Gardner et al.

In a 2016 publication, Spencer-Gardner et al. report a clinical study of 100 patients across 3 surgeons using a novel acetabular PSI from the posterolateral approach [133]. This patient-specific acetabular guide is unique in that it does not use a visual guiding pin [133]. The device fits into the acetabulum and shoots a laser across the room on the wall or ceiling of the OR (See Figure 21) [133]. A second laser is screwed into the pelvis and adjusted until the 2 laser points match [133]. The PSI device is then removed, leaving just the second laser point shining on the wall/ceiling [133]. Since the second laser is fixed to the pelvis, the laser point moves relative to the pelvic motion during surgery [133]. When it is time to ream/impact, a laser projects from those devices and is aligned with the existing laser point for the correct acetabular inclination and anteversion (See Figure 22) [133]. Each patient was CT scanned within 1 week from surgery to determine final cup position [133]. They found a mean error of 1.6°±4.6° and 1.0°±4.7° for acetabular inclination and anteversion respectively [133]. The absolute mean error was found to be 3.9° and 3.6° for inclination and anteversion respectively, with 91% of cases within 10° of intended inclination and anteversion [133].
Chapter IV: Specific Aims & Methodology

IV.A Specific Aim I

**Specific Aim I:** To establish the design and feasibility of patient-specific guides in THA. Many styles of guides were prototyped and tested on foam bone models to confirm a usable design. The chosen design was used in a THA cadaver surgery to establish feasibility. Successful completion of this aim provided novel technology to implement PSI for THA in a larger cadaver study. We hypothesized that a system of PSIs could be designed and implemented in a cadaver THA procedure to guide the preparation and implantation of an acetabular cup and femoral stem implant.

**Methodology of SA I:** To establish feasibility for PSI in THA surgery, functional designs needed to be created. The process of designing functional devices was critically important to the success of the research because the design directly influences the accuracy and precision, which are evaluated in subsequent aims. Therefore, considerable time and resources were used to optimize the device designs prior to testing in a cadaver study. A flowchart of the design process from this research is shown in Figure 23. The design process began with an ideation phase, brainstorming numerous possible concepts. The concepts were modeled in a CAD software and presented to orthopaedic surgeons for review. In this review, the list of concepts was narrowed down to a shortlist of favored concepts. The short list of concepts was then rapidly manufactured using 3D printing, and prepared for a bench test. In the case of this research, the prototypes were tested on a foam pelvis and femur model, replicating a
THA surgery. Following the bench test, a preferred design was chosen and design improvements were incorporated into an additional bench test. After 2 rounds of improvements (3 bench tests, top loop in Figure 23), a pilot cadaver surgery was conducted to evaluated the design. In the case of this research, additional design improvements were desired after the pilot cadaver, so a second series of bench tests were performed. As illustrated in Figure 23, following the pilot cadaver, design improvements were made, a bench test performed, and then the top loop cycled 2 additional times (3 bench tests following the first pilot cadaver). After a second pilot cadaver THA surgery, the devices were prepared for a multi-cadaver precision study: specific aims II & III. The evolution of the PSIs from this design process are described in detail in Chapters V & VI.

IV.B Specific Aim II

Specific Aim II: To determine the accuracy and precision of PSIs for acetabular cup preparation and implantation. Once the PSIs proved to be functional in THA through specific aim I, the accuracy and precision of cup placement needed to be assessed. If PSIs are to be useful in THA, they need consistently implant the acetabular cup in the preoperatively planned position. More specifically, acetabular PSIs must show an improvement over traditional techniques and consistently implant within the safe zones of implant orientation. Successful completion of this aim will provide the necessary information to compare the precision of acetabular patient-specific devices to the tolerance of Lewinnek et al.’s safe zone, and traditional techniques. We hypothesized that a PSI fitted to the acetabular fossa could accurately place a surgical pin superior to the acetabular rim and this pin could accurately guide the acetabular reamer and impactor, yielding a cup placement with greater implantation accuracy and precision than traditional free-hand techniques.

Methodology of SA II: A series of 20 acetabular cups were implanted into 10 cadavers with the assistance of acetabular patient-specific devices, which were designed in specific aim I (SA I). Each cadaver was CT scanned prior to surgery so that a CAD model of the pelvis could be
generated. A semi-automated segmentation tool was programmed in MatLab® R2014b 8.4 (The MathWorks Inc, Natick, MA USA) [134] to process the stack of CT images into point cloud surface representations of the pelvis. From the point cloud data, a detailed surface mesh was constructed and filled in to produce a solid CAD model of each bone. In cases where the semi-automated segmentation tool failed to produce a usable model, the segmentation software Amira® 5.4.5 3D Software for Life Sciences (FEI, Thermo Fisher Scientific, Hillsboro, OR USA) [135] was used. Detailed use of this software and the semi-automated MatLab® [134] program are described in Chapter VI, and the MatLab code is provided in Appendix I. Since implantation was necessary for this study, a set of acetabular cup implants were designed to accommodate a variety of cadaver sizes. The cups were designed hemispherical so that common market-released reaming tools could be used. The cup CAD models were virtually sized and positioned in each acetabulum, matching the center of rotation. From the preoperative cup positioning, a set of acetabular PSIs were created and 3D printed. The appropriately sized acetabular cups were also 3D printed for each cadaver surgery.

Dr. Todd Kelley performed all the cadaver surgeries from an anterior approach, and each cadaver was CT scanned a second time following each procedure. From the postoperative CT scan, the exact positioning of the implant system was measured and compared to the preoperative plan. The process was accomplished by first segmenting the pelvis and cup implant using Amira® [135] from the postoperative scan. The segmented postoperative pelvis model was then registered to the preoperative pelvic model, outputting a transformation matrix that describes the relative translation and rotational difference between the models. The transformation matrix was then applied to the segmented postoperative cup implant so it can be overlaid on the preoperative pelvis. Since the segmented cup implants are not always clean hemispheres, the cup implant CAD model was then registered to the segmented implant. In this method, 2 CAD models are compared in their position and orientation, rather than a CAD model to a segmented model. The holes in the pelvis created by the surgical pins of the PSIs were also segmented and overlaid on the
preoperative pelvic model. A best-fit line was calculated for each segmented hole. Since the acetabular PSI directed the surgical pin that created the hole, a comparison between planned and achieved PSI position could be made. Accuracy was defined as the average distance and angle from intended, while precision was defined as the standard deviation of the data. The study is described in detail in Chapter VII.

IV.C Specific Aim III

**Specific Aim III:** To determine the accuracy and precision of PSIs for femoral stem preparation and implantation. While much of the literature focuses on the position of the acetabular cup, the femoral stem is still an important piece of the overall joint, particularly to achieve the correct combined anteversion, leg length, and hip offset. Therefore, once the PSIs proved to be functional in specific aim I, the accuracy and precision of femoral stem placement needed to be assessed. Successful completion of this aim will provide the necessary information to understand the precision of femoral patient-specific devices. We hypothesized that a PSI fitted to the femoral neck could accurately control osteotomy to within 2.0mm and 10.0° of intended, while a secondary PSI fitting over the resected face of the femur could guide broaching to within 10.0° of intended femoral anteversion.

**Methodology of SA III:** A series of 20 femoral stems were implanted in 10 cadavers using femoral PSIs that were designed in SA I. The methodology closely followed that of SA II, except being applied to femoral stem implantation rather than acetabular cup implantation. Each cadaver was given a preoperative CT scan so that the bone geometry could be segmented into 3D surface models. The surface models were converted into solid CAD parts, where the femoral stem implants were virtually...
planned for surgery. Since CAD models of stem implants are needed for planning surgery in 3D, a set of femoral stem implants were designed for the study (See Figure 24). The stems were designed with a reduced shoulder and shortened stem length to improve the ease of implantation from the anterior approach. Since femoral stem designs/shape are not standard across the market, a set of femoral broaches were designed to match the stem implant shape and were 3D printed for surgery (See Figure 25). The stem CAD models were virtually positioned so that the center of the femoral head matched the joint’s calculated center of rotation (based on the best-fit spherical center of the acetabulum), and the stem shaft aligned in the center of the femoral shaft. The resection was planned along the porous coating edge of the femoral stem. The size of the femoral stem was planned according to stem neck length, avoiding a resection in the lesser trochanter. PSIs were created to achieve the planned femoral stem position/orientation and were 3D printed for surgery.

Dr. Todd Kelley performed all 20 surgeries from an anterior approach, and each cadaver was CT scanned following implantation. The femurs and femoral stem implants were segmented from the postoperative CT scan. Each segmented postoperative femur was registered to the corresponding preoperative femur model, and a transformation matrix describing the relative translation and rotation was determined. The transformation matrices were then applied to the segmented femoral stem implants so that they could be overlaid on the preoperative femur model. The CAD model of the femoral stem was then registered to the segmented femoral stem so that a comparison in position/orientation could be determined between the 2 CAD models: preoperative plan and postoperative achieved position. A best-fit plane was calculated for the resected face of the femur and used to compare planned to achieved resection location. Accuracy was defined as
the difference from intended, while precision was defined as the standard deviation of the data. The study is described in detail in Chapter VII.
Chapter V: Bench Testing and Pilot Cadavers

This chapter details the work for SA I, which leads into the cadaver series studies for SA II & III. The work began with an ideation phase, where several designs were built in SolidWorks® 2014 x64 (Dassault Systemes, Waltham, MA USA) [136] and presented to orthopaedic surgeons for feedback. Improvements were discussed and preferred designs were chosen for testing. 3 bench tests were conducted on foam bone models for initial testing of the PSIs, and are described in section V.B. Section V.C-V.E describe the first pilot cadaver experiment, which established the feasibility of PSIs in THA surgery, fulfilling SA I. After feasibility was established, improvements were desired in the PSI system, so 3 additional bench tests were conducted on foam bone models. The design work for these bench tests is described in Section V.F. A second pilot cadaver test was conducted after the second series of bench tests to confirm the design. This second cadaver pilot test is explained in section V.G.

V.A Ideation Phase

The work began from an initial concept and sketch provided by orthopaedic surgeon Dr. Todd Kelley. Additional concepts were brainstormed, sketched, discussed, and compared to determine the best concepts. The top concepts needed to be created in a 3D model, however, bone CAD models were needed for this. A sample CT scan was obtained from University Hospital and a basic segmentation process was learned to produce a pelvis and femoral head surface model. The specific segmentation method is outlined in Chapter VI under the discussion of Amira® [135] Segmentation. The surface model was imported into SolidWorks® [136], where PSIs could be
2 primary acetabular guides were modeled: dual-pin and tri-pin concepts. The dual pin concept guided an inferior and superior surgical pin into the acetabular rim (See Figure 26). The PSI guide is then removed from the acetabulum and depth spacers are slid over the pins. A reaming crossbar is attached to the reaming shaft in a fashion so that is cannot translate on the shaft, but the shaft can freely spin. The crossbar rides along the surgical pins to control the angle of reaming in the acetabulum (See Figure 27). A second crossbar is then attached to the impactor in a fashion that allows both translation and rotation. The crossbar also rides along the surgical pins so that the angle of cup implantation is controlled (See Figure 28).

The tri-pin concept was similar to the dual-pin concept, except that it used 3 pins for greater stability. The insertion points of the surgical pins for the tri-pin concept were inferior to the rim, the anterior inferior iliac spine, and a point on the rim near the pubic bone (See Figure 29). A third design involved the use of a central pin with a cannulated reamer. However, this concept was not modeled because the bone is thin at the base of the acetabulum, and extensive design/manufacturing work would need to take place to test such a concept (a cannulated reamer was not readily available).

Three different concepts for a patient-specific resection guide were modeled in SolidWorks® [136] for review. The first concept was a patient-specific femoral pin guide shaped as a basic...
trapezoidal block, fitting over the posterior neck of the femur (See Figure 30). 2 surgical pins would be inserted through the device into the neck once the guide is firmly seated. The guide pin holes are parallel, which allows the removal of the guide, and a stainless steel cutting guide is slid over the pins. A third pin can then be inserted at an oblique angle to keep the guide from translating on the pins (See Figure 31). Resection can then be performed along the distal edge of the guide. In this way, the holes from the surgical pins are in the portion of the femur that is cut away. These designs are such that the patient-specific pin guide is disposable while the metal resection guide is reusable.

A second concept combined the previous 2-piece arrangement, by incorporating a metal edge to a patient-specific femoral device. The device was also designed to seat on the posterior neck of the femur. Two pins would be inserted at oblique angles through the device into the femoral neck. The distal edge was slightly recessed to allow a metal edge to adhere to the surface. The concept assumed that the resection must take place over a metal edge and that the patient-specific device needed to be 3D printed in plastic. The device design can be seen in Figure 32.

A third concept for a patient-specific femoral device used the medial surface of the femoral neck. This concept was primarily created to provide a different option for the surface used to mate with the patient-specific device. This design included an arm that extends over the posterior face of the neck, which directs surgical pins into the neck, posterior to anterior (See Figure 33). The use of the medial
face and pins in the A to P orientation were thought to hold the device in place sufficiently enough to avoid the need for oblique pins.

V.B Bench Testing: Series I

Bench Test I

The first bench test was conducted on Jan. 16th, 2013. The patient-specific devices were modeled from the segmented pelvis and femur that was created from the sample CT scan initially provided to the team. Therefore, when testing the devices on the foam bone models, the devices only marginally fit. Foam bone models were purchased from SawBones® (Pacific Research Laboratories, Vashon Island, WA USA) for this first bench test. The preferred concepts from the ideation phase were improved upon and prototyped in ABS plastic for this test. The patient-specific acetabular pin guide was modified from the tri-pin concept. The design was prototyped as a circular device rather than the original triangular concept (See Figure 34). It was determined during the review that it would be ideal to allow the device to be clipped away at each pin insertion point. Breakpoints are drawn in black marker on the device to indicate locations where the device could be clipped. If the device could be clipped, then spacers could be added uniformly on each pin to control the depth of reaming, rather than using different heights of spacers on each pin.

The reaming guide is shown in Figure 35. This reaming guide is screwed together over a collar on the reamer shaft, preventing translation on the shaft. The reaming guide snaps onto the 3 surgical pins, which
guides the angle of reaming. The snap feature was too tight in this test, and the surgical pins were not all inserted parallel, so there was a degree of difficulty using the device. In this test, depth control was not implemented. It was observed that the pins were slightly too close together, causing the spacers to interfere with the reaming. A trial cup implant was successfully impacted into the prepared acetabulum using the 3 guiding pins and impactor guide.

For the femoral preparation, both an anterior and a posterior patient-specific resection guide were prototyped. Again, the device was designed from a segmented femur and not the bone foam model (the CAD model was not acquired at this point), so the device only marginally fit. The guides contained holes sized for a small K-wire. However at the time of the test, it was decided that larger pins were desired, so the holes were drilled out for a larger pin size. The guide that was prototyped was similar to the first femoral guide concept described in section V.A. A plastic version of the metal resection guide was prototyped, however, it was decided to simply resect against the initial patient-specific pin guide instead. The anterior guide was used in this test and can be seen being pinned to the femur in Figure 36. It was noted during the test that the user must be careful to make sure the saw blade is flat against the guide and not at an angle. It was also noted that the device should replicate a clinically accurate resection location, and allow an osteotome cut to spare the greater trochanter. The device contained a medial edge that matched the desired femoral implant version. A black marker was used to mark the bone by
the device’s medial edge. In surgery, this would be completed by using a bovie knife to mark the bone. Figure 37 shows the broached femur with the mark for femoral anteversion.

**Bench Test II**

The second bench test was conducted on Feb. 6th, 2013. For this test, the CAD models of a pelvis and femur foam Sawbones® model were acquired for designing the PSIs. The patient-specific acetabular pin guide was updated to use thinner connection points to each pin hole to facilitate the clipping of the guide (See Figure 38). Steel metal tube inserts were pressed into each guiding hole to aid in directing all 3 pins parallel. Each of the 3 guiding holes contained patient-specific surfaces that fit onto the rim of the acetabulum. The guide fit well onto the acetabulum, but a handle was requested to aid in positioning. The reaming guide was altered so that the triangular snaps were closer to the reaming head (See Figure 39). The reasons for this were twofold: fewer spacers would be needed, and the device would be more likely to fit into the surgical site if it is closer to the rim. During the reaming step, the feet of the patient-specific guide on the rim were found to be flawed because they interfered with reaming. The spacers were too thick and even after the spacers and plastic feet were removed, the pins interfered with reaming up to the appropriate cup size. The 3 pin locations needed to be further out from the rim, with spacers that have a smaller outer diameter to prevent interference with reaming/implanting. However, the 3 pin system was very rigid and a trial cup implant was still successfully impacted into the prepared foam acetabulum.
The patient-specific femoral resection guide was designed with larger pin holes than the first prototype and was designed for an anterior approach. The guide was also equipped with steel metal tube inserts to aid in directing the surgical pins straight and parallel. The patient-specific femoral guide is shown in Figure 40. A secondary resection guide replicating a reusable metal cut guide was not prototyped. Instead, the patient-specific device was used as the cutting surface for resection. This foam femur was smoother than the previous, having less contoured features for the guide to lock onto. However, the correct placement was still able to be felt, and the guide pinned down. The resection was made, however, the location was not in a clinically preferred location, and corrected for the following bench test. A black marker was used to mark the bone at the medial edge of the guide as an indication for femoral version. The foam femur did not model soft cancellous bone, so the femoral canal had to be drilled and aggressively rasped/broached to prepare for the stem. Figure 41 shows the final broach placement.

**Bench Test III**

The third bench test was conducted on Feb. 14th, 2013. In this assessment, a handle was incorporated into the patient-specific acetabular pin guide as previously requested (See Figure 42). A threaded hole was designed into the center of the device, and an existing surgical handle was used. However, the handle was too short because it was difficult to hold while simultaneously inserting the pins. An updated threaded hole that fits with the long impactor handle was
requested for the next iteration. It was also requested that, if possible, the acetabular guide would use more of the center of the acetabulum for patient-specific surfaces rather than the rim. In this design, the guiding holes did not have patient-specific contoured feet as before and were moved further out from the rim. The reaming and impacting did not interfere with the pins and spaces. However, it was desired that the reaming guide be positioned even closer to the reaming head to decrease the number of depth gauge spacers needed. In this test, 14mm of spacers were used, and a picture of the reaming with depth control spacers is shown in Figure 43. Since the reaming guide is screwed together over a collar near the reaming head, the reaming head cannot be disengaged unless the reaming guide is removed. This causes delays if the reaming head must be switched. Assuming templating is correct, only a single reaming head needs to be used, however, the difficulty to remove and assemble the reaming guide was noted as a flaw. The patient-specific femoral guide was designed for a posterior approach and functioned with excellence. The resection was in the proper clinical location, the guide fit well onto the neck of the femur, and was able to be pinned easily. The femoral guide was ready for use in a cadaver trial. The acetabular guides only required minimal updates, and so were also approved for a cadaver trial.
NOTE: The following 3 sections explain the first testing of these patient-specific devices on a cadaver, establishing the feasibility of PSI for THA, fulfilling specific aim I. These sections were written by Jacob Stegman and were published in the Journal of Medical Devices by the American Society of Mechanical Engineers (ASME). The reference is shown below:

V.C Methodology- Pilot Cadaver I (SA I)

A full cadaver with intact pelvis, hips, knees, and spine, was imaged from the lumbar spine through the superior tibia, using CT with 0.325mm slice resolution. The CT images were segmented using medical image processing software (Amira®, FEI Visualization Sciences Group) to isolate the rigid bodies of the femur and the pelvis, from the rest of the anatomical structures, and from each other. Anatomical reference planes were established for each rigid body using computer aided design (CAD) software (SolidWorks®, SolidWorks Corporation) [136] to create a system of coordinates in which the implants could be positioned as seen in Figure 45 - Figure 47. Mock CAD models of the implant components were created from published drawings and dimensions of a standard implant system.

The operating surgeon then created a 3D CAD template that overlaid the model of the implants over the models of the cadaver’s femur and pelvis (Figure 48), such that the center of rotation for the implant components coincided with the native center of rotation of the hip. Note that this is a departure from the traditional pre-operative two-dimensional (2D) template obtained from X-ray images of the hip joint, as seen in Figure 49. This 3D template serves the dual purpose of surgery pre-planning, and of guide design. In the pre-planning stage, the template provides critical
information to the surgeon about (1) the precise location and orientation of the femoral neck resection plane so that it can be aligned with the face of the femoral stem implant and (2) the precise orientation, reaming depth, and cup size for the acetabular implant. These decisions then inform the design of the guides (Figure 50).

The femoral guide has three salient features of the femoral guide: (1) a single patient-specific face, exactly matching the femoral neck surface, (2) a cutting edge, and (3) a medial edge.
(Figure 51). The patient-specific face allows the guide to uniquely lock onto a specific part of the femur, thus aligning the cutting edge to the femoral resection plane established in the templating step. The medial edge guides a Bovie knife that marks on the femur surface the alignment of the stem implant for the precise anteversion angle (Figure 52). Pinholes guided the threaded surgical pins that would capture the femur neck (Figure 53).

The acetabular guide system consists of two separate guides, a pin locator guide and a reaming and impacting guide. Pin-locator guide has four patient-specific faces: three of them matching specific sections on the rim of the acetabulum, and the fourth matching the fovea of the acetabulum (bottom of the cup). The pin-locators contoured to the three patient-specific faces at the edge of the acetabular cup direct three surgical pins outside the acetabular rim (Figure 54 - Figure 56), thus locking the device to a
unique position. Following pin insertion, this guide is removed and the surgical pins are clipped to a uniform length. These three surgical pins form a rail system upon which the reaming and impacting guide rides while guiding the shaft of the reaming tool and later the shaft of the impacting tool, effectively controlling both the vertical inclination and anteversion of the reamer (Figure 57 - Figure 59).

Figure 55: Acetabular pin locator guide on a foam bone model

Figure 56: Acetabular pin locator guide in use on the cadaveric acetabulum with surgical pins drilled into bone

Figure 57: Three-dimensional CAD model of reamer and impactor guide

Figure 58: Reamer / impactor guide in use on a foam bone model.

Figure 59: Reamer / impactor guide in use on the cadaver
The patient-specific devices were manufactured through the Rapid Prototype Center at the University of Cincinnati, College of Engineering & Applied Science. The parts were printed on a Dimension 1200es 3D printer using ABS plastic in sparse high density and were finished with metal inserts, screws, and sanding for an appropriate locking interface between parts.

A direct anterior surgical approach THA was performed on the cadaver using the custom guides in the University of Cincinnati’s Center for Surgical Innovation Laboratory. A post-procedural CT-scan was taken and the resulting data were processed in a manner similar to the pre-procedural method. The post-procedural CAD model was then overlaid onto the pre-procedural CAD template and the resulting differences in orientation and location were measured. Surgeon evaluation was conducted to assess the usability of the new devices.

V.D Results- Pilot Cadaver I (SA I)

The THA procedure was completed successfully with all the hip replacement components appropriately implanted. Both sets of guides worked as designed. The femoral guide locked onto the femoral neck surface as designed, and two surgical pins were successfully inserted to secure it. The oscillating saw blade followed the femoral resection cutting plane as designed, and the Bovie knife marked the femoral anteversion target. On the acetabulum side, the contoured pin locator fit securely into the acetabular rim and the surgical pins were successfully inserted. The surgical pins held firmly into the rim and effectively controlled and guided the reaming and implantation steps.

All measurements are summarized in Table 9. Preparation for implant required the resection of the femoral head and reaming of the acetabulum cup. The femoral resection was templated at 51° from vertical (in the coronal plane), with a 10° posterior tilt and the implant was templated to be anteverted 27.4°. Post-procedural measurements showed that the femoral resection plane was 1.5mm from planned, approximately the thickness of the cutting blade.
orientation of the resection plane was approximately 5° from planned in both the vertical inclination and posterior tilt. The femoral stem was implanted 11mm deeper than intended and was retroverted 11.8° from the target.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Target</th>
<th>Measured</th>
<th>Difference</th>
<th>Safe-Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of Femoral Resection</td>
<td>0.00mm</td>
<td>1.43mm</td>
<td>1.43mm</td>
<td>–</td>
</tr>
<tr>
<td>Angle of Femoral Resection- Vertical Inclination</td>
<td>51°</td>
<td>56.3°</td>
<td>5.3°</td>
<td>–</td>
</tr>
<tr>
<td>Angle of Femoral Resection- Posterior Tilt</td>
<td>10°</td>
<td>15.4°</td>
<td>5.4°</td>
<td>–</td>
</tr>
<tr>
<td>Location of Femoral Implant</td>
<td>0.00mm</td>
<td>10.96mm</td>
<td>10.96mm</td>
<td>–</td>
</tr>
<tr>
<td>Anteversion of Femoral Implant</td>
<td>27.4°</td>
<td>15.6°</td>
<td>11.8°</td>
<td>–</td>
</tr>
<tr>
<td>Direction of Acetabular Reaming</td>
<td>0.00mm</td>
<td>1.48mm</td>
<td>1.48mm</td>
<td>–</td>
</tr>
<tr>
<td>Depth of Acetabular Implant</td>
<td>0.00mm</td>
<td>4.32mm</td>
<td>4.32mm</td>
<td>–</td>
</tr>
<tr>
<td>Location of Acetabular Implant</td>
<td>0.00mm</td>
<td>4.55mm</td>
<td>4.55mm</td>
<td>–</td>
</tr>
<tr>
<td>Anteversion of Acetabular Implant</td>
<td>25°</td>
<td>24.0°</td>
<td>1.0°</td>
<td>15°±10°</td>
</tr>
<tr>
<td>Vertical Inclination of Acetabular Implant</td>
<td>45°</td>
<td>40.4°</td>
<td>4.6°</td>
<td>40°±10°</td>
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<tr>
<td>Combined Anteversion</td>
<td>52.4°</td>
<td>39.6°</td>
<td>12.8°</td>
<td>37.5°±12.5°</td>
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<td>Leg Length</td>
<td>+9.7mm</td>
<td>+1.0mm</td>
<td>8.7mm</td>
<td>–</td>
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<tr>
<td>Hip Offset</td>
<td>-19.4mm</td>
<td>-7.5mm</td>
<td>11.9mm</td>
<td>–</td>
</tr>
</tbody>
</table>

*Table 9: Measures of implant positioning on the cadaver procedure when using patient-specific guides.*

The acetabular implant was templated for a vertical inclination of 45° and an anteversion of 25°. Post-procedural measurements found both the vertical inclination and anteversion of the acetabular implant within 5° of intended. The cup position was within 1.5mm of intended in the plane of the cup face (difference in direction of acetabular reaming). However, the total displacement of cup position was 4.5mm from intended.

While we templated the combined femoral-acetabular anteversion to 52.4°, we achieved a combined anteversion was 39.6°, which lies within the published safe-zone of 25°-50°. Leg length and hip offset were calculated as +1mm and -7.5mm respectively, while we planned for a leg lengthening of +9.7mm and a hip offset decrease of -19.4mm. No statistical analysis could be performed since a single cadaver was tested, but all values fell within published safe-zones, and completion of procedure was achieved with the use of paired patient-specific guides.
V.E Discussion- Pilot Cadaver I (SA I)

Studies have shown that computer navigation systems for THA are accurate to a mean of 5.3° cup inclination and 5.6° cup anteversion [112]. Our results from this study showed that patient-specific instrumentation on a single cadaver was accurate to 4.6° of cup inclination and 1.0° of cup anteversion. Hananouchi et al., Buller et al., and Small et al. have arrived at similar conclusions with the use of patient-specific guides to control the acetabular placement, but did not measure the combined implant positioning [129–131]. To the best of our knowledge, our study is the first to show the effective use of a patient-specific femoral guide as part of a complete system of femoral and acetabular guides. Future studies will investigate the precision and accuracy of this system of patient-specific guides.

Our results reveal that measures with the greatest error were driven by visual guides such as the femoral anteversion whereas measures driven by mechanical controls (acetabular inclination, anteversion, femoral resection) show greater accuracy. The error in the femoral resection can most likely be attributed to the use of a flat edge for osteotomy rather than a slot design, as blade deflection can easily translate into an error in an antero-posterior tilt of resection. The femoral anteversion was to be controlled by marking the femur medially with a Bovie knife, as the femoral guide indicated (Figure 52). Since the knife was not available in the laboratory, an ink marker was used instead. While the femoral anteversion was only accurate to 11.8°, the measured combined anteversion (39.6°) was within the safe zone of 37.5°±12.5°.

The acetabular pin guide fit securely into the acetabulum, effectively directing the surgical pins into the acetabular rim. Once the body of the acetabular pin guide was clipped off, the remaining acetabular rail system created by surgical pins effectively constrained the direction of reaming and impacting. The surgical pins deflected minimally from their insertion point allowing a straight and controlled reaming and impacting process.
In our study, we found that use of patient-specific guides offers potential improvements in other aspects of THA procedure such as reductions in time to completion and costs, especially when it comes to the use and need of intra-operative X-ray associated with the serial reaming steps. For example, a 3D template coupled with controlled reaming negates the need to begin acetabular preparation with undersized reaming. In terms of surgical outcome, it can be presumed that greater surgical control in preparation and implantation will reduce the incidence of surgical error, mal-positioning, and thus dislocation and revision surgery.

In this study, we sought to design and test a novel system of paired patient-specific instrumentation, designed from the operating surgeon’s pre-procedural 3D template that controls both the acetabular and femoral components of a THA. Proof of concept was established through a cadaveric pilot study and showed the preliminary accuracy of such designs. We found that paired patient-specific guides have the potential to improve the accuracy of implant position and alignment. Our system was accurate to within several degrees of intended for acetabular cup implantation and fell within the safe zones of implant positioning.
V.F Volumetric Bone Loss Analysis

It was recognized that robust planning tools are needed to optimize implant position as new surgical techniques such as patient-specific instruments focus on precise implantation. Bone sparing techniques, maximizing bone ingrowth, and restoring center of rotation in 3D space are often surgical targets, however current planning techniques inadequately allow for these measures. The goal of this analysis was to define a method to determine bone loss and bone-to-implant contact area with various implant sizes at a reaming depth that restores the native hip center of rotation when performing preoperative three-dimensional templating for THA.

We CT scanned a cadaver, segmented the images, and exported the bone geometry into a CAD software. An acetabular cup was virtually positioned, vertically inclined 40°, anteverted 15°, at varying depths (0mm to 9mm, from fovea), and using various cup sizes (48mm to 72mm). The total bone loss and percent cup contact to bone was calculated for each combination, at the depth that restored the center of rotation. The cadaver was imaged using an anteroposterior x-ray and sized for a 58mm cup.

As shown in Figure 60 for volumetric bone loss, calculated bone losses increased with increasing cup size and reaming depth. Figure 61 shows the percent of acetabular cup contact to bone for various implant sizes and varying reaming depths, with an overlaid center of rotation curve. It is obvious that percent cup contact could be optimized at each reaming depth for any acetabular implant size that restores the center of rotation. For this particular patient, a 54mm cup restored center of rotation and maximized percent cup contact to bone (75%) at 3mm reaming depth, while remove 7578 mm³ of bone. However, in this example, if reaming 3mm does not reach bleeding bone and deeper reaming is required, an offset liner can correct the difference in depth to restore the center of rotation. Note that cups larger than 66mm would require intra-pelvic reaming to restore center of rotation for this cadaver.
Figure 60: Shows the volume of bone that would be reamed out of the acetabulum to receive an acetabular cup implant, analyzed for cup sizes 48mm-72mm in diameter, and for reaming depths of 0mm-9mm. The required reaming depth to maintain the center of hip rotation for each size is plotted with black dots.

Figure 61: Plots the percentage of bone coverage of an acetabular cup implant, as it relates to cup size, and depth of implantation. The percent of acetabular cup contact to bone when the anatomic center of rotation is achieved is depicted with a black dot for each size of acetabular implant.
With developments in computer navigation, robotic surgery and PSIs, improved preoperative implant positioning is desired. Plotting percent cup contact to bone, volumetric bone loss, and indicating depths to restore center of rotation is one such measure that could aid in preoperative planning. This analysis describes an example of 3D surgical planning that can aid implant sizing and positioning to accompany precise implantation techniques such as patient-specific instrumentation.

V.G Bench Testing: Series 2

**Bench Test IV**

The fourth bench test (first of series 2), was conducted on April 8th, 2015. The time between the pilot cadaver experiment and the second series of bench tests was used to develop a reliable segmentation method and acquire research funding for the second series of bench test and the cadaver series studies. A testing rig was constructed to simulate a Hana® surgical table for the anterior approach (See Figure 62). It was decided after the cadaver pilot test, that the anterior approach would be targeted for these devices because it was becoming a more popular muscle sparing technique. The rig was clamped to a table and had two swinging arms that held the femurs. The femurs could be translated along the longitudinal axis and could be hinged into external rotation. The pelvis was anchored to the base of the rig with bolts and nuts. The construction firmly held the bones, however, the femur slide in the clamps under broaching, and the clamps were difficult to secure/release (two blocks bolted together). In addition, the rig was too low in elevation to replicate a common surgical table. It was desired that the rig is raised an extra 12 inches for ease of use.
The patient-specific acetabular pin guide was significantly adjusted from the cadaver revision. The cadaver revision contained 1 bridge between each guide hole and the central portion of the guide. During the cadaver procedure, the guiding holes would catch on soft tissue and cause the bridges to snap before the guide was fitted in the acetabulum and pinned down. Therefore, in this iteration, the design returned to 2 bridges between each guide hole and the central portion (See Figure 63). The guide was also updated to use a much larger portion of the acetabulum as a patient-specific surface. In the cadaver revision, only 3 portions of the acetabulum were used for patient-specific surfaces because the entire acetabular surface was not able to be converted to a CAD surface. Since the CAD model of the foam pelvis was available, a larger patient-specific surface could be used. Chapter VI discussed the improvements in segmentation and CAD creation from CT scans in order to convert the entire bone surface, unlike the first pilot cadaver. The guiding holes were extended in length to interface with the reaming guide for depth control. Rather than the use of spacers which are more difficult to handle, an adjustable reaming handle/guide was invented (See Figure 64). The handle comprised of 2 parts that threaded together, which allowed for small adjustments in the handle’s length. The reaming guide was incorporated into the reaming handle rather than being screwed together over the reaming shaft collar. A spring-loaded nub on the reamer shaft prevents the handle from sliding into the chuck of the drill. Depth control was achievable because the handle could not translate past the spring-loaded nub and the 3 arms would eventually halt reaming once they reach the spacers (See Figure 64). This reaming handle
was novel because the threaded handle allowed precise adjustments in reaming depth intraoperatively. During reaming, it was noted that the guiding pin sleeves slid and spun on the surgical pins. Since the feet contained patient-specific surfaces, spinning caused slight changes in the mechanical stop for depth. Pins with collars were requested to hold the guiding pin sleeves firmly against the bone. With the addition of a new reaming handle/guide, a new impactor guide was also investigated (See Figure 65). The impactor guide slid over the impaction handle, rode on the 3 surgical pins, and fit into the acetabular cup implant. 3 nubs on the impactor guide fit into the screw holes of the implant, effectively controlling the rotation of the cup about the axis of the impactor. Unfortunately, the nubs were in the radial direction rather than in-line with the pins, so the impactor guide could not be removed after impaction. Rather than impacting a market-released trial acetabular cup, an acetabular cup implant was designed, 3D printed and successfully impacted into the foam pelvic acetabulum. It is common to ream the acetabulum 1mm less in diameter than the cup for a press-fit, however, the plastic cup fit best in the foam pelvis when the acetabulum was reamed to the same diameter as the cup. For this bench test, a new screw guide was developed and tested (See Figure 66). The guide fit into the acetabular cup implant and directed the drilling of the screw pilot holes. However, the guide was flawed in this first iteration because it did not constrain the flexible drill bit to a single direction, and was not able to fully seat within the acetabular cup implant.
For the femoral side, a new CAD model was purchased for a foam femur that included porous cancellous bone so that broaching would more closely reflect that in a human femur. The femoral resection guide was updated to include a resection slot and is shown in Figure 67. The previous versions provided a simple flat face to resect against, however, it was difficult to control resection tilt- that is, ensuring the resection on the opposite side of the femoral neck is not too superior or inferior. The femoral resection guide also included a flat face to guide a superior-inferior cut to spare the greater trochanter. However in the test, the oscillating saw partially cut into the greater trochanter. In addition, the saw slightly cut into the medial end of the slot.

A set of femoral stem implants were designed, so that complete femoral templating could be achieved (See Figure 68). The stems were designed with a reduced shoulder to aid in implantation from an anterior approach. The stem length was also shortened as compared to a similar market-released fit-and-fill straight stem implant. The middle portion of the stem implant contained ribbing to replicate a porous coating. As a consequence of designing femoral implants, a set of femoral broaches were also required (See Figure 69). The broaches were designed with straight teeth on the anterior-posterior faces and pointed teeth on the medial and lateral faces. The pointed teeth were designed to cut into hard cortical bone to set the femoral version, while the straight teeth were designed to scrape/push softer cancellous bone anteriorly and
posteriorly. A small, medium and large broach were 3D printed in titanium for this bench test and for future tests.

A new PSI was invented and introduced in this bench test. A patient-specific femoral anteversion guide was designed to fit over the resected face of the femur. The guide was shaped as a plate with a keyhole that guides a punch. The punch imprints the planned version, so that the initial broach has both a starting location and orientation. However, the punch was not manufactured quick enough to be tested in this bench test. Instead, the first broach was partially impacted through the keyhole to give an indication of version and the starting location (See Figure 70). It was requested that patient-specific femoral anteversion face plates be provided with larger keyholes to guide each successive broach.

Bench Test V

The fifth bench test (second of this series) was conducted on April 22nd, 2015. For this bench test, a new testing rig was constructed so that the pelvis and femurs were elevated. Figure 71 shows the new construction. Two different bars could be inserted underneath the swinging legs so that the femurs could be parallel to the floor or in extension. The patient-specific acetabular pin guide was adjusted so that the guiding pin sleeves were not as long (achieved by extending the reaming handle). Collars were added to the surgical pins, and color coded so that the appropriate length pins were used at each point (See Figure 72).
The guide maintained two bridges to each guiding pin sleeve and was successfully clipped (See Figure 73). Calibrations were incorporated into the reaming handle in 2mm increments, and the handle extended closer to the reaming head (See Figure 74). Reaming is shown in Figure 75, and was successful in constraining the direction and depth. The impactor guide was updated so the nubs were no longer directed radially, but were directed parallel with the impaction direction. With this update, the impactor guide was able to correctly slide back out of the acetabular cup implant after impaction. In addition, the arms of the impactor guide were color coded according to the 3 surgical pins so the guide would engage the surgical pin rail system in the correct orientation. The impactor guide is shown in use in Figure 76 and Figure 77. The screw guide was able to be fully seated within the acetabular cup implant and successfully constrained the direction of drilling the pilot screw hole (See Figure 78).
For the femoral devices, the patient-specific resection guide was updated with an angled slot (See Figure 79). The angle spares the greater trochanter, and a surgical pin can be inserted and removed at the angle to round the corner, preventing a stress riser. In order to use a resection guide with an angled slot, however, a reciprocating surgical saw was needed instead of the traditional oscillating bone saw. Switching to the reciprocating saw allows a clean resection, fully protecting the greater trochanter. Since an anteversion guide was desired to direct each femoral broach, a system of devices was designed to fit on the resected femur. A patient-specific base plate fit over the resected face of the femur and formed a U shape, holding to the posterior,
medial, and anterior rim of the resection. Inserts were designed to fit onto the patient-specific base plate and then direct femoral broaches. Figure 80 shows the patient-specific base plate with the insert that guides the starting broach. The starting punch idea was abandoned since each broach would be guided independently. The broaches were able to be fully seated into the femur as seen in Figure 81, however, the version guides inadvertently placed the broaches in extreme varus, causing the broaches to puncture the lateral side (See Figure 82). This serious flaw is thought to have been caused by a combination of problems: 1) The flat face plate gives the tendency to broach perpendicular, instead of 130°. 2) The broaches contained a sharp point which contributed to puncturing the lateral wall. A blunted end would be more likely to ride the lateral wall inferiorly. 3) It was thought that the broaching could be performed in an arc, however in practice with these foam bone models, the broaches could only be driven linearly.

**Bench Test VI**

The sixth bench test was conducted on July 8th, 2015. In this test, the patient-specific acetabular pin guide was grossly re-evaluated due to the unlikelihood of the device fitting into a normal incision. The 3 pin rail system would be impeded by soft tissue, and cleaning 3 portions of the acetabular rim would require excessive time. In this experiment, 2 patient-specific
acetabular pin guides were evaluated: A T-slot design, and a dual thickened pin design. The dual thickened pin design directed 2 pins just superior to acetabular rim. The pins had a metal sleeve hot-pressed over them, leaving a short portion of the pin exposed on either end. The metal sheath prevented the pins from being inserted too far and increased pin stability. The main portion of the pin guide was able to be removed after the pins were inserted, as shown in Figure 83. An adjustable reamer handle/guide contained an arm that rode along the two thickened pins, controlling the direction of reaming (See Figure 84). The arm bottomed out on the patient-specific foot during reaming as a method of controlling depth.

The T-slot acetabular pin guide design used a patient-specific foot in the same location as the dual thickened pin design (See Figure 85). The guide directed 2 oblique pins into the pelvis, and then the main portion of the pin guide could be removed from the acetabulum. The reamer handle/guide contained a T arm which fit into the T-slot, controlling direction (See Figure 86). The T arm contained a stop, which prevented the reamer from reaming too deep. However, the reamer handle could still be adjusted for depth by screwing the 2 handle pieces together. The impactor guides were updated to ride along the
thickened pins and T-slot but were otherwise unchanged. The screw guide was unchanged and functioned as expected. The acetabular cups were successfully impacted into the foam pelvis.

The patient-specific femoral resection guide was left unchanged from the previous revision. To correct the previous error in the direction of broaching, a new starting broach was designed and is shown in Figure 87. This starting broach was designed with holes in the A to P direction along the lateral side. A surgical pin could be inserted through the hole, and the pin laid flush with the vertical resection that spares the greater trochanter. Figure 88 shows the pin in the starter broach along this resected face, however, due to the wedge shape, it broke the medial edge of the femur. The device did assist in lateralization and correctly set up the subsequent broaches to follow the intramedullary canal. The foam femur was cut in order to confirm that the distal position of the femoral stem was centered, and is shown in Figure 89.

It was concluded from the bench tests that the foam bones do not provide an adequate model for real human bones, particularly in femoral implantation. The broaching step took significantly more force in the foam models than in a human femur. It was believed that the fracture of the medial rim would not have occurred...
in a real femur because the cancellous bone is much softer than the porous foam. Therefore, since the system functioned properly with the exception of the fraction on the medial femoral rim, the designs were moved to be tested in a cadaver model. For the patient-specific acetabular pin guide, the T-slot design was chosen to move forward to cadaver testing. The two designs functioned similarly, so the T-slot was chosen because of the difficulty in assembling the thickened pins.

V.H Pilot Cadaver 2

The second cadaver test was conducted on a preserved cadaver due to the free availability of the specimen. Since it was preserved, however, a normal incision was not able to be used. The preservatives cause excessive stiffness, which prevents proper retraction of the muscles away from the joint. However, the body was still able to be used as a trial for segmenting the bone structures, designing the patient-specific devices from a 3D THA template, and testing their fit on the cadaver. The cadaver was CT scanned at University Hospital from the top of the iliac crest through the knee, with a slice thickness of 0.625mm. The CT scan was segmented using a custom MatLab® [134] algorithm written for this research. The algorithm is described in detail in section VI.B, and the complete code is included in Appendix I. The resulting CAD model was then templated in 3D for a right THA surgery (See Figure 90). From the templated THA, the patient-specific system was designed. The devices were 3D printed in ABS plastic and used to replace the hip joint.
Dr. Todd Kelley performed the surgery from an anterior approach. Figure 91 shows the patient-specific femoral resection guide, with collared pins holding the device firmly to the femoral head. The device fit very well to the femoral neck, and the resection was successfully performed without any concerns. The patient-specific acetabular pin guide did not fit in the acetabulum as well as the femoral guide, but a best-fit was agreed upon and the surgery proceeded. The position of the acetabular pin guide is shown in Figure 92. The center of the guide was threaded so that the impaction handle could be used to position the device, however, the plastic threads quickly became stripped during positioning. The foot of the guide fit under the head of rectus femoris near the muscle’s origin, as intended. The medial surgical pin fit securely into the pelvis, however, the lateral pin glanced off the pelvic surface on the first 2 tries of inserting the pin. Once the pins were inserted, there was some difficulty in pulling the body of the guide from the acetabulum, but it was able to be removed. Before reaming, it was noted that the patient-specific foot was sitting proud near the lateral pin, so the pin was removed. The foot was repositioned into the correct location, and the second pin was reinserted adjacent to the patient-specific foot, wedging it in place. The foot successfully guided the reaming and is shown in Figure 93. Depth control was successful by using the adjustable reaming handle. The handle was
calibrated to 1mm increments. The acetabular cup implant was successfully impacted into the acetabulum, shown in Figure 94. This image also clearly shows how the lateral pin was inserted adjacent to the foot of the guide.

The surgery then returned to the femoral side with the use of the starter broach as seen in Figure 95. The starter broach aided in lateralization of the femoral stem did not fracture the medial cortex and prevented broaching in varus. The femoral stem was successfully implanted after femoral broaching. The final total hip replacement is shown in Figure 96. Despite the results of the previous bench test (medial femoral cortex fracturing), the femoral instruments functioned very well. The only request was an improvement on the control of femoral anteversion. The starter broach used the surgical pin for alignment to the vertical resection cut, however, this was not an ideal solution. In terms of the acetabular instruments, while they functioned very well in the bench test, many difficulties arose in the cadaver test.

**Design Adjustments**

Due to timing deadlines on funding, the cadaver series needed to begin after this second cadaver pilot. A few adjustments were made to this existing instrumentation for the cadaver series study. The first adjustment was increasing the attention to pin placement for the patient-specific
acetabular guide. Since the lateral pin glanced off the bone instead of drilling into the bone, the foot of the guide was carefully positioned so that the lateral pin would not be inserted into a slope. In addition, milling bits were acquired to flatten the bone slope, preparing it for pin insertion. The adjustments for femoral instrumentation all related to controlling femoral anteversion. A patient-specific anteversion guide was designed to fit around the resected rim of the femur in a U shape (See Figure 97). Two extension arms projected superiorly from the device, where the surgical pin could slide between when using the starter broach. A new set of broaches were manufactured (3D printed in bronze) with the same holes as the starter broach. Therefore, the anteversion guide could be used with the starter broach, and then the following broaches as well (See Figure 97). Since new broaches needed to be manufactured, adjustments were also made to the femoral stem implant design. The stem was requested to be shortened further and with a decrease in the angle on the shoulder. These designs then proceeded to the cadaver series studies in Chapter VII.
Chapter VI: CT Segmentation, CAD Conversion, & Registration

VI.A Amira® Segmentation & CAD Conversion Revision I

The procedure outlined below was developed for the first pilot cadaver test. A sample CT scan of a hip and femur were provided to create this procedure. The process was designed to allow for the creation of .STL files using the Isosurface feature in Amira® [135]. The created procedure is described below:

1. Import the DICOM data into the Amira® [135] Object Pool by selecting Open Data in the File menu. Select all the DICOM image files and press Load. A summary window will pop up showing the loaded data. Press OK. The data will now be shown in green in the Object Pool.
2. Create an Isosurface of the data by selecting the data (green) and clicking Isosurface. In the Properties Manager below the Object Pool, select a threshold value and click Apply. Increasing the threshold value eliminates voxels that are below the threshold. Ideally, the threshold value should allow for as much detail as possible while minimizing the surrounding noise caused by surrounding tissue and vasculature.
   NOTE: A threshold value of 225 was being used by the design team. An optimized threshold value may be necessary.
3. Extract a surface from the created Isosurface by selecting the Isosurface (yellow), clicking ExtractSurface, and then selecting Apply in the Properties Manager. This feature creates a new dataset with only the data that above threshold in the Isosurface.
4. Hide the Isosurface by clicking on the orange square next to the Isosurface icon in the Object Pool.
5. Generate a Surface View from the new data by selecting the Extracted Surface Data (green) and clicking SurfaceView.
6. The next step is to remove unwanted voxels from the SurfaceView. Select the SurfaceView (yellow), and in the Properties Manager, use the Buffer port to select unwanted voxels and
remove them. Click Draw and in the Viewer, draw a profile around any unwanted voxels. The selected voxels will be highlighted in Red. Click Remove and repeat until all unwanted voxels are removed. Rotate the surface and zoom in/out to facilitate visualization of unwanted voxels.

7. Extract a surface from the created SurfaceView by selecting the SurfaceView (yellow), and clicking ExtractSurface. Click Apply in the Properties Manager. A new dataset will be created.

8. Simplify the Extracted Data. Select the New Extracted Data (green), and in the Properties Manager, select Simplifier. In the Simplify port, set faces = 50,000, max dist = 0, min dist = 0 (Note: Optimized values may be necessary). In the Action port, click Simplify Now. Save the simplified data as an STL. Select the simplified New Extracted Data (Green), right click and select Save Data As. Under File Type, select STL asci (.STL), and select Save.

9. Launch MeshLab v1.3.3 64bit (Visual Computing Lab – ISTI-CNR, http://meshlab.sourceforge.net/) [137]. Under the File menu, select Import Mesh, and then select the .STL file from Amira® [135]. Select OK in the pop-up menu to unify duplicated vertices. Under the Filters menu, select Cleaning and Repairing, Remove Isolated Pieces (wrt Diameter). Use the Default setting and select Apply. Under the File menu, select Export Mesh As…, and save the file as a .STL.

10. Launch SolidWorks® [136], and before importing a model, go to the Tools menu, select Add-Ins... and check ScanTo3D. Under the File menu, select Open, update the File Type to Mesh Files. Open the .STL created from MeshLab [137] (if STL too large, import back into MeshLab [137] and apply the filter: “Remove Faces from Non-Manifold Edges” found under Cleaning and Repairing. Export again and attempt to open in SolidWorks® [136] again)

11. Prepare the mesh using Mesh Prep Wizard. RHT click on Mesh1 in the FeatureManager design tree and select Mesh Prep Wizard. Select the RHT arrow through all of the default settings. Upon mesh completion, unselect “Launch Surface Wizard” and select the check.
(Launching Surface Wizard directly from the Mesh Prep Wizard does not remove the topological errors)

12. Create the Pelvic anatomical planes:

12.1. Create the Sagittal plane using a mid-point on the pubis, the most inferior point on the sacrum, and a midpoint on a lumbar spine.

12.2. Create the Coronal plane by selecting the anterior most point on the iliac spine, the anterior most point on the pubis, and setting the plane perpendicular to the Sagittal plane.

12.3. Create the Axial plane by selecting the inferior most point on the ischium and setting the plane perpendicular to the Sagittal plane and Coronal Plane. The intersection of these three planes is now to be considered the origin.

13. Create the Femoral anatomical planes:

13.1. Create a plane 15mm±1mm inferior to the lesser trochanter as close to perpendicular with the femur as possible. Find the center of the intramedullary canal on the newly created plane by finding the intersection of two diameters (one of which is coincident on the Linea Aspera).

13.2. Create a second plane parallel to the one created in 13.2.1. 60mm±1mm superior to the epicondyles. Find the center of the intramedullary canal on this plane by drawing a sagittal line through the cross-section and finding the midpoint. The femoral axis is created by selecting the two created points within the intramedullary canal.

13.3. Generate the axial plane by setting the plane perpendicular to the femoral axis and coincident with the superior-most point on the greater trochanter.

13.4. Generate the coronal plane by first drawing a line tangent to both epicondyles. Create a second line 9.5° anterior to the epicondyle tangent line and coincident with the lateral bony peak. The coronal plane is generated by setting the plane perpendicular to the axial plane and coincident with the line just created.
13.5. Generate the sagittal plane by setting the plane perpendicular to the coronal plane and coincident with the femoral axis.

14. Create the Acetabular Cup Plane:

14.1. Set the anteversion by drawing a line on the coronal plane superiorly from the origin with the angle measured from the sagittal plane.

14.2. Set the vertical tilt by drawing a line on the axial plane posteriorly from the origin with the angle measured from the sagittal plane.

14.3. A plane is created from the two lines defined in the two previous steps. This plane specifies the angle of the cup. At this point, a design table may be created at the engineer’s discretion.

15. Isolate the section of interest by creating planes separating the section of interest from the rest of the pelvis (two or three planes). Right click on Mesh1 and select surface wizard. Select OK when the pop-up menu says that the topological errors will be removed. Proceed through Guided creation, not Automatic creation. When the split plane option is reached, select one of the last planes created. Drop the sensitivity and complete the surface wizard steps. Delete meshes that appear away from the acetabulum on the opposite side of the split plane. Right click the mesh in the design window and select surface wizard. Arrow through the options and the when split plane option opens, select one of the planes that isolates the cup. Drop the sensitivity and complete the surface wizard steps. Repeat until the section of interest is isolated. The last repetition should retain normal sensitivity. Delete sub-meshes that do not contribute to the model (possibly all but one).

16. To generate a surface, first right click on the mesh and select Mesh Prep Wizard. Arrow through the options until removal of extraneous material is reached. Delete abnormal protrusions off the model then proceed to the next option. Increase the global and boundary smoothness to the first interval. When hole patching is reached, do not fill any holes that may compromise the true geometry. Do not launch the Surface Wizard from the Mesh Prep
Wizard. Launch the Surface Wizard by RHT clicking on the newly created mesh. Use automatic creation rather than guided creation. If the program crashes, try to trim down the cup or increase the smoothness in the Mesh Prep Wizard. The program will create the surface and solid modeling can commence. If the surface is enclosed, a solid will be generated.

Conclusion

The above process allows a set of DICOM images to be changed into a SolidWorks® [136] surface, within a couple hours. This process does not allow for the entire bone surface to be created, but was satisfactory for use in the first cadaver experiment, confirming the feasibility of PSI in THA. This process can be validated and optimized by changing the values for threshold, the number of faces, max dist, and min dist. Figure 98 and Figure 99 show a surface model of an acetabulum and a solid model of a femoral head and neck, created using this process with the above-specified parameters.

VI.B MatLab® Segmentation

Goal: To develop a MatLab® [134] based program to read and process a computer tomography (CT) scan of a pelvis and femurs. It was of specific interest to separate the femur from the pelvis in the presence of arthritis, causing narrowing of the joint space. The program needs to output data describing the 3D shape of each femur and the pelvis. The data must be usable by a meshing or CAD software so that the PSIs can be designed.
Challenges

Three main challenges were present in developing an automatic or semi-automatic segmentation of CT images of joints for patients with osteoarthritis:

1. **Noise**

   In an ideal CT image of joint, CT values for tissue voxels are significantly less than bone voxels; therefore a simple thresholding technique is enough to isolate the bones from tissue voxels. In practice, CT images are noisy, meaning that some tissue voxels have CT values comparable to those of bones and a noise removal algorithm needs to be implemented. The main issue is that noise removal techniques usually leads to image smoothing and therefore results in weakening and diffusing the bone boundaries.

2. **Weak and diffused bone boundaries**

   In CT images of joints, the narrow joint space, deformed bones result in weak and diffused bone boundaries. Signal weakening in CT images is due to the presence of different types of tissues within the joint. To strengthen the weak boundaries, an image enhancement technique needs to be implemented. The main issue is that directly implementing an image enhancement technique on raw CT images amplifies the noise.

3. **Narrow joint space**

   In patients with osteoarthritis, the joint tissue is partially or fully degraded and automatically differentiating the bones at the joint is particularly difficult. Therefore a novel approach needed to be developed to split the bones at the joint.

Importing and Accessing

The first problem to overcome was importing the CT scan and storing it in a manner that the coronal slices can be easily accessed. A coronal view was desired because it is easiest to see the lengths of the femurs as well as the body of the pelvis. The CT scan was stored as 999 files on a CD. Each file describes an axial slice of data, 0.625mm apart from each other. The command
dicomread() can be used to read a single slice, so a loop was created to open all of the files and store them in a 3-dimensional matrix. The 3-dimensional data (512x512x999), was simple to access for axial slices, i.e. AxialSlices(:,:,a) where 'a' is the slice number, however, to view a coronal slice, the data needed to be rotated. The commands permute() and rot90() were discovered and implemented to achieve this. Figure 100: Image a reconstructed coronal slice through the right femur from an axial CT scan. shows the right side of a coronal slice through the femoral head.

**Thresholding and Edge Detection**

The second challenge was to determine if using only thresholding and edge detection could successfully separate the femur and pelvis. The process began by experimenting with various threshold values to determine the relative difference between soft tissue value intensity and bone value intensity. It was discovered that no single value could be used to completely and fully separate bone from soft tissue. A value too low would capture all of the bone, but not the bone canals, and included excessive scatter in the soft tissue. A value too high could exclude the soft tissue scatter, but not include all of the bone. Additionally, no value could be determined to identify the joint space, separating the femur from the pelvis.

Edge detection was initialized using 2D Laplacian edge detection. While hopeful for effective separation of the femur and acetabulum, no value threshold could be found that fully separated the femur and acetabulum on every slice. The value would have been too high, which eliminated most of the bone edges. Additionally, a very low value would have needed to be used to capture a fully encompassing bone edge (without holes). The edge detection was improved by
switching to 2D Sobel edge detection, preventing confusion between the maximum and minimum side of an edge.

**Scatter Removal and Bridging Gaps**

The next approach was to investigate methods of removing scatter and/or bridging edge gaps; the two problems that occur with too high or too low of thresholding value. 2 different methods of scatter removal were investigated. Both methods required a binary image input, which was created from an earlier thresholding step (defining the smaller values to be 0 and the larger values to be 1). The first method identified all cluster groupings and ordered them by the number of pixels in each grouping. The largest cluster groups were retained, while the vast majority of the cluster groupings removed. The second method identified all of the cluster groupings and then eliminated all groupings with x or fewer pixels. The later approach was preferred because it was difficult to know how many pixel groupings were true to the bone. It was more certain that very small pixel groupings could be considered scatter.

To bridge the edge gaps, several methods were attempted, but only one functioned properly with the data. Failed methods included the use of snakes and tracers. However, a combination of dilation, imfill, and erosion techniques proved to bridge the gaps and then fill any holes. However, since this technique involves dilating the image and then eroding by the same degree, a smoothing effect was created, possibly eliminating the truest edge. With both scatter removal and bridging the gaps, separation of the femur and pelvis was still not achieved.

**Edge Detection Improvement**

In the current method, 2D Sobel edge detection, only the edge outline was calculated. In the event that the slice is parallel to a bone surface, the edge is not represented. To correct this, a 3D edge detection method needed to be employed. In order to do this, three 3x3x3 matrices needed to be created to detect edges in the x-direction, y-direction, and z-direction. They were all
combined by way of magnitude, to yield the 3D Sobel edge detection. However, since the data contains over 26 million points, MatLab® [134] ran out of memory attempting to calculate. Therefore, the data was split into the left and right halves. MatLab® [134] had sufficient memory to calculate on only the left or the right. Figure 101 shows a coronal slice after 3D Sobel edge detection.

Circle Detection

It was thought that if the femoral head and/or the acetabular cup were approximated as a circle or arc on every slice, the joint space could be identified, allowing separation the joint. To accomplish this, the command imfindcircles() was tested with varying ranges of radii. The command was tested with various combinations of edge detection and thresholding but unfortunately, could not define a circle over the femoral head or acetabulum. However, a circle could be fit if a dataset of (x,y) points that roughly lie on the circle, is provided. To obtain the dataset, the command getpts() was used. After plotting circles approximating the femoral head and also the acetabulum, it was confirmed that the joint space/line could be estimated from the average of the 2 circles. To fully implement this strategy, it would need to operate in a ‘slice-by-slice’ fashion, which is too time-consuming for a user to select points.

Ellipsoid Approximation

To improve upon the circle approximation method, it was observed that an ellipse could be used on each slice. Additionally, to reduce the required user input of an ellipse on each slice, a 3D ellipsoid could be approximated. In this model, only a few slices need to be sampled to create the 3-dimensional approximation. The code was written to request the user to select points on
the femoral head, and then the acetabular cup, in 2 different axial slices, and 2 different coronal slices. The ellipsoid approximation code written by Petrov was found on MatLab® [134] Central, a free file exchange website [138]. Figure 102 shows a sample slice in which the user was requested to select points on the femoral head. The average of a femoral head ellipsoid and an acetabulum ellipsoid appeared to be an excellent model to split the joint. Figure 103 shows slice number 230 with the cross-section of the ellipsoid overlaid on the image. The two tails on the ellipsoid reflect real parts of complex numbered solutions, which were not used in the proceeding masking step.

**Masking and Identifying Region of Interest**

At this point, since an effective joint separation model was developed, secondary operations were needed to finish the program. The first of which was masking soft tissue. Much of this work had been accomplished earlier, but only needed to be combined correctly. The final algorithm first used a thresholding operation to identify bone. The scatter was eliminated, and then the gaps/holes were filled using dilate, imfill, and then erode. This left the ‘shadow’ of the bone structures, with all holes filled in. At this point the shadow was dilated again and multiplied by the 3D Sobel edge detected image, leaving only the bone edges. Figure 104 and Figure 105 show first the dilated bone mask, then after it is multiplied with the edge detected image. At this point, the user is asked to select the approximate center of the femoral head (on a coronal slice). Following selection, the
axial slice that passes through the point is shown and the user must select the center of the femoral head on this axial slice. This gives an approximate \((x,y,z)\) point for the center of the femoral head. The slices used to select points for the ellipsoid are driven from this point.

**Separating the Joint**

While the ellipsoid showed passage precisely through the joint space, the raw data still needed to be separated into femurs and pelvis. To do this, the pixels that resided inside the ellipsoid were identified and defined as a mask to the raw data. With the femoral heads masked, the pelvis was fully separated from the femurs and was stored. To capture the femur shape, the pelvis was used as a mask, leaving just the femurs. At this point, however, the precise bone surface is not known, but just the raw data separated by pelvis and femur. The bone surface needed to be defined as completely enclosed (without any gaps in the bone wall), despite soft edges existing throughout the model.

**Defining the Bone Boundary**

Thresholding and edge detection are very useful for identifying general shapes and ridges, however, a fully enclosed object is difficult to produce. Weak bone boundaries created gaps in the segmented bone edges and therefore, more advanced techniques were needed. At this stage, 3 large matrices existed: 1) left femur, with pelvis & right femur masked, 2) pelvis, with both femurs masked, and 3) right femur, with pelvis & left femur masked. As a preliminary step, the edge of the mask was softened so that it is not detected as a possible bone boundary. This was achieved
by introducing random noise over the mask. A sheetness filter was then applied to the bone matrices, as described by Krčah [139]. The sheetness filter is a score related to the degree of flatness, tubularity, and globularity, calculated through Hessian analysis [139]. The bone matrix is first unsharpened by a Gaussian convolution [139]. The unsharpened image was then used to produce a smoothed Hessian matrix, through convolutions with the 3 directional derivatives (∂x, ∂y, ∂z) of the Gaussian distribution [139]. The eigenvalues of the Hessian are determined (λx, λy, λz), and are used to calculate the values for flatness, tubularity, and globularity/noise, as shown in Equation 4 [139].

\[
R_{Sheet} = \frac{\lambda_y}{\lambda_z}, \quad R_{Tube} = \frac{\lambda_x}{\lambda_y|\lambda_z|}, \quad R_{Noise} = \frac{|\lambda_x| + |\lambda_y| + |\lambda_z|}{T}
\]

*Equation 4: Describes the values for flatness, tubularity and globularity/noise for calculating the sheetness value [139].*

Where T is the average trace of the Hessian at each voxel (∂xx + ∂yy + ∂zz)

The sheetness values can then be calculated from the values for flatness, tubularity, and globularity/noise, as shown in Equation 5 [139].

\[
Sheetness = -\text{sgn}(\lambda_3) \left( e^{-\frac{R^2_{Sheet}}{\alpha^2}} \right) \left( e^{-\frac{R^2_{Tube}}{\beta^2}} \right) \left( 1 - e^{-\frac{R^2_{Noise}}{\gamma^2}} \right)
\]

*Equation 5: Calculation for sheetness [139].*

Where α, β, and γ can be adjusted to amplify or suppress flatness, tubularity, or noise.

The suggested values for α, β, and γ by Krčah were used in the program [139]. Once the sheetness had been calculated, the intensity of the 3D Gaussian distribution could be varied over a range of values and the sheetness recalculated [139]. The intensity of the 3D Gaussian is adjusted by an σ value, and the ranges suggested by Krčah were used in the program [139]. With each adjustment of σ, the maximum absolute values of sheetness for each voxel were stored [139].
The result was a superior edge detected matrix, where voxels with a high sheetness indicated a bone boundary [139].

**Optimizing the Bone Surface**

To complete the segmentation of the bone structures, a max-flow/min-cut methodology was applied. The voxels with the strongest sheetness and highest threshold were defined as initialization ‘sources’, while the largest clusters of voxels with low thresholds were defined as the ‘sink’. A flow network was solved for the 3D image, where a flow capacity was defined at each voxel. A flow was calculated from the source to the sink. Points in the network where the flow was bottle-necked, where the flow equals the flow capacity, was defined as a bone boundary. Flow networks follow a conservation of flow, where the flow entering a voxel must equal the flow exiting the voxel. The flow capacity at each voxel was defined by a positive shift in the sheetness factor, such that only positive values existed. The flow network was solved using the multiplier-based maximal-flow algorithm proposed by Yuan et al. [140]. This flow algorithm ran iteratively and converged to a solution after an error threshold of less than 0.00001 was reached. The algorithm outputted a $\lambda(x) \in [0,1]$ matrix, where 1 values described bone and 0 described all other voxels. Internal bone geometries were not described (no bone canals). The bone boundary was then exported as a point cloud, where a mesh could be generated in MeshLab [137] or SolidWorks® [136]. The complete MatLab® [134] code may be found in Appendix I.

**VI.C Amira® Segmentation & CAD Conversion Revision II**

The procedure below was created as an improvement upon the initial Amira® [135] segmentation protocol. It served as a backup method if the MatLab® [134] segmentation program failed to produce usable models. This segmentation method was frequently used because the MatLab® [134] segmentation program often failed to produce one or more of the bone structures. Amira® [135] Segmentation Revision II became the primary protocol after the 7th cadaver due to the frequency of failure using the MatLab® [134] program, however, CAD
Creation Revision III was developed by the 6\textsuperscript{th} cadaver, making CAD Creation Revision II eventually obsolete. The procedure is described below:

**CT Scan**

1. Cadaver undergoes CT scan.
2. CT technician burns data to disc.
3. Disc delivered to engineering.

**Segmentation-Femur**

*Note: it is possible to segment both femurs and the pelvis in a single network defined as different materials. However, issues frequently arose when using multiple materials in close proximity. It was found to be more reliable to use a separate networks for each segmented bone.

4. Download the CT data to an engineering computer and import the files into Amira® [135]. Save the network according to the surgery number, and right or left femur.
5. Choose Volren to visualize the data, and adjust the AlphaScale to clearly see the bones.
6. Use the Crop Editor on the CT data to isolate one femur of interest.
7. Under the Segmentation Editor tab, create a new Label Data, and a new Material, named ‘Femur’.
8. Using the Threshold tool, select points that are greater than 150 Hounsfield units.
9. Add the selected points to the ‘Femur’ Material previously created.
10. Many stray voxels will be included that are not truly part of the femur (See Figure 106). Therefore, select the femur within the window (all connected voxels will be included).
selected), invert the selection in all slices, and then subtract the selection from ‘Femur’.

11. Zoom to hip joint (Shift+Z), and set the brush tool with masking enabled for voxels with less than 300 Hounsfield units.

12. Slice by slice, select voxels using the brush tool within the joint space, being careful not to select voxels that describe the femoral head (See Figure 107).

13. Subtract the selected voxels from the ‘Femur’ material.

14. Select the femur voxels (all connected voxels will be selected) and invert the selection in all slices. Subtract the selection from the ‘Femur’ material.

15. If the acetabulum is still connected to the femoral head, carefully scan through each slice looking for the connection points. Use the brush tool to select the acetabular voxels connected to the femoral head and subtract them. Repeat step 14.

16. Zoom to the knee joint, and set the brush tool with masking enabled for voxels less than 300 Hounsfield units.

17. Slice by slice, select voxels using the brush tool within the joint space between the femur and tibia, being careful not to select voxels that describe the femur.

18. Subtract the selected voxels from the ‘Femur’ material.

19. Slice by slice, select voxels using the brush tool within the joint space between the femur and patella, being careful not to select voxels that describe the femur.

20. Subtract the selected voxels from the ‘Femur’ material.

21. Select the femur voxels (all connected voxels will be selected) and invert the selection in all slices. Subtract the selection from the ‘Femur’ material.
22. If the patella and tibia are still connected to the femur, carefully scan through each slice looking for the connection points. Use the brush tool to select the tibial and patellar voxels connected to the femur and subtract them. Repeat step 21.

23. Fill holes on all slices in the coronal plane.

24. Fill holes on all slices in the sagittal plane.

25. Fill holes on all slices in the axial plane.


27. Fill remaining obvious crevices in the femur by first using the brush tool with masking enabled for less than 300 Hounsfield units, to capture the bone boundary (See Figure 108).

28. Fill the remaining holes using a brush tool without masking enabled, or use the fill holes function.

29. Smooth labels by 3, twice.

30. Export ‘Femur’ as .STL file, save the segmentation network.

31. Repeat 4-30 for the opposing femur.

**Segmentation- Pelvis**

32. Import the CT data into Amira® [135].

33. Choose Volren to visualize the data, and adjust the AlphaScale to clearly see the bones.

34. Use the Crop Editor on the CT data to isolate the pelvis.

35. Under the Segmentation Editor tab, create a new Label Data, and a new Material, named ‘Pelvis’.

36. Using the Threshold tool, select points that are greater than 150 Hounsfield units.

37. Add the selected points to the ‘Pelvis’ material previously created.
38. Many stray voxels will be included that are not truly part of the pelvis. Therefore, select the pelvis within the window, invert the selection in all slices, and then subtract the selection from ‘Pelvis’.

39. Zoom to the first hip joint, and set the brush tool with masking enabled for voxels with less than 300 Hounsfield units.

40. Slice by slice, select voxels using the brush tool within the joint space, being careful not to select voxels that describe the pelvis.

41. Subtract the selected voxels from the ‘Pelvis’ material.

42. Select the pelvis voxels and invert the selection in all slices. Subtract the selection from the ‘pelvis’ material.

43. If the femur is still connected to the pelvis, carefully scan through each slice looking for the connection points. Use the brush tool to select the femoral voxels connected to the acetabulum and subtract them. Repeat step 14.

44. Repeat steps 37-41 for the second hip joint.

45. Zoom to the sacral-lumbar joint, and slice by slice select lumbar spine voxels that connect to the sacrum using the brush tool.

46. Subtract the selected voxels from the ‘Pelvis’ material.

47. Select the pelvis voxels and invert the selection in all slices. Subtract the selection from the ‘pelvis’ material.

48. Confirm that the pelvis is fully separated from the lumbar spine, and if not, repeat steps 43-45.

49. Fill holes on all slices in the coronal plane.

50. Fill holes on all slices in the sagittal plane.

51. Fill holes on all slices in the axial plane.

52. Repeat steps 47-49.
53. Fill remaining obvious crevices in the pelvis by first using the brush tool with masking enabled for less than 300 Hounsfield units, to capture the bone boundary.
54. Fill the remaining holes using a brush tool without masking enabled, or use the fill holes function.
55. Smooth labels by 3, twice.
56. Export ‘Pelvis’ as .STL file, save the segmentation network.

**CAD Conversion-Femur**

57. Launch SolidWorks® [136].
58. Enable ScanTo3D.
60. Launch Surface Wizard Feature.
61. Use default settings and ‘Automatic’ solid generation.
62. Define ‘Point1’ as the center of the femoral shaft, 15mm below lesser trochanter.
63. Define ‘Point2’ as the center of the femoral shaft, 60mm above epicondyles.
64. Define ‘Femoral Axis’ by connecting ‘Point1’ and ‘Point2’.
65. Define ‘Axial Plane’ as perpendicular to ‘Femoral Axis’ and coincident to the superior-most point of the femur.
66. Define ‘Medial Epicondylar Peak’ as the medial-most point on the epicondyles.
67. Define ‘Lateral Epicondylar Peak’ as the lateral-most point on the epicondyles.
68. Define ‘Trans-Epicondylar Axis’ by connecting ‘Medial Epicondylar Peak’ and ‘Lateral Epicondylar Peak’.
69. Define ‘Coronal Plane’ as coincident to ‘Femoral Axis’ and parallel to ‘Trans-Epicondylar Axis’.
70. Define ‘Sagittal Plane as coincident to ‘Femoral Axis’ and perpendicular to ‘Coronal Plane’.
72. Define ‘Center of Rotation’ as the center of the femoral head.
73. Define ‘Femoral Version Plane’ as coincident to ‘Femoral Axis’ and ‘Center of Rotation’.

74. Define ‘Resection Line’ on ‘Femoral Version Plane’ as a line across the femoral neck at an angle X (default 35°) from ‘Femoral Axis’ and at a distance X (default 15mm) superior to the lesser trochanter.

75. Define ‘Osteotome Line’ on ‘Femoral Version Plane’ parallel to ‘Femoral Axis’, tangent medially to the greater trochanter, connecting to ‘Resection Line’.

76. Define ‘Resection Plane’ as coincident to ‘Resection Line’ and at an angle X (default is 90°) to ‘Coronal Plane’.

**CAD Conversion-Pelvis**

77. Import ‘Pelvis.STL’ as a new file to SolidWorks® [136], and as a ‘Mesh’ file.

78. Launch Surface Wizard Feature.

79. Use default settings and ‘Automatic’ solid generation.

80. Define ‘Point1’ as the anterior and superior-most point on the right iliac spine.

81. Define ‘Point2’ as the anterior and superior-most point on the left iliac spine.

82. Define ‘Point3’ as the anterior and superior-most point on the pubic symphysis.

83. Define ‘Coronal Plane’ by ‘Point1’ ‘Point2’ and ‘Point3’.

84. If ‘Coronal Plane is not tangent to the pelvis, readjust ‘Point1’ ‘Point2’ or ‘Point3’ accordingly.

85. Define ‘Point4’ as a medial point on the spinous process of the inferior most lumbar spine.

86. Define ‘Point5’ as a medial point on the pubic symphysis.

87. Define ‘Sagittal Plane’ as perpendicular to ‘Coronal Plane’ and coincident to ‘Point4’ and ‘Point5’.

88. Define ‘Axial Plane’ as perpendicular to ‘Coronal Plane’ and ‘Sagittal Plane’ and coincident on the inferior most point on the pelvis.

89. Define ‘New Origin’ as the intersection of ‘Coronal Plane’ ‘Sagittal Plane’ and ‘Axial Plane’.
90. Define ‘Vertical Inclination Line’ as a line from ‘New Origin’ on ‘Coronal Plane’ at an angle X (default is 40°) from ‘Axial Plane’.

91. Define ‘Cup Angle Plane’ as coincident on ‘Vertical Inclination Line’ and at an angle X (default is 15°) from perpendicular to ‘Coronal Plane’ (angling anteriorly).

92. Import ‘Femur.SLDW’ file into ‘Pelvis.SLDW’ and overlay using the original coordinate system.

93. Define ‘Center of Rotation’ from the femur file into the pelvis file.

94. Remove the femur file, leaving the point of the center of rotation.

VI.D THA Templating and PSI Creation

**Surgical Plan**

95. Import acetabular cup implant into ‘Pelvis.SLDW’ file and position the center of the implant coincident with ‘Center of Rotation’ and parallel to ‘Cup Angle Plane’.

96. Adjust the cup implant diameter to appropriate size.

97. Adjust the rotation of the cup such that the screw holes align into thick bone.

98. Import screw implant into ‘Pelvis.SLDW’ and position within cup implant screw holes.

99. Adjust the length of screw and check cup positioning.

100. Import femoral stem and head implant into ‘Femur.SDLW’ file and position the center of the femoral head implant coincident with ‘Center of Rotation’ and the plane of the stem implant coincident with ‘Femoral Version Plane’.

101. Adjust the stem implant to the appropriate size and positioning down the femoral canal.

102. Adjust ‘Resection Line’ to be in line with femoral stem implant coating line.

**Guide Creation**

103. Import ‘Base-Model-Pin-Guide.SLDW’, size X (where X is the cup size) into ‘Pelvis.SLDW’.

104. Arrange ‘Base-Model-Pin-Guide.SLDW’ so ‘Center of Rotation’ points are coincident, and is parallel to ‘Cup Angle Plane’.
105. Rotate ‘Base-Model-Pin-Guide.SLDW’ such that the pins holes align with thick bone.
106. Subtract the pelvis model from the base model pin guide, to create ‘Patient-Specific-Pin-Guide.SLDW’.
107. Open ‘Base-Model-Impactor-Guide.SLDW’ and rotate the hemisphere with respect to the arms according to the Pin Guide and Cup Implant template.
110. Subtract the femur from the base model femoral resection guide, to create ‘Patient-Specific-Resection-Guide’.
111. Load ‘Femur.SLDW’.
112. Delete femoral head using ‘Resection Plane’, leaving the greater trochanter as defined by ‘Osteotome Line’.
114. Position ‘Base-Model-Femoral-Version-Guide.SLDW’ such that ‘Resection Plane’ from each model are coincident with each other, and ‘Osteotome Line’ from each model are coincident with each other.
115. Subtract the femur from the base femoral version guide, to create ‘Patient- Specific-Femoral-Version-Guide.SLDW’.

VI.E CAD Conversion Revision III

This method was discovered after the 6th cadaver in the cadaver series experiment because previous methods did not produce surface or solid models accurate to the initial mesh model. Frequently, detailed meshes were generated from the segmentation, and imported into SolidWorks® [136]. However, SolidWorks® [136] would produce multiple surface errors when attempting to create a solid model. The method described below produced very detailed meshes and eliminated errors caused by SolidWorks® [136] ScanTo3D.
Meshing

1. Import the .STL bone model into MeshLab [137], and export as a point cloud .XYZ file.

2. Import the point cloud .XYZ file and under Filters > Point Set, compute the normals for point sets. Use the default settings for Neighbour num: 10, and Smooth Iteration: 0. Apply the filter.

3. Under Filters > Remeshing, Simplification, and Reconstruction, select Surface Reconstruction: Poisson. Set the Octree Depth and Solver Divide to 9, while keeping the Samples per Node and Surface offsetting at 1. Apply the filter.

4. Show the Layer Dialog, and delete the point cloud mesh, leaving the Poisson mesh.

5. If the mesh appears black, under Filters > Normals, Curvature, and Orientation, select Invert Faces Orientation. Use Force Flip and apply the filter. The bone should appear as shown in Figure 109.

6. At this point, the mesh is too detailed for this method of conversion into CAD. Therefore, select the mesh facets of less interest (e.g. femoral shaft and epicondyles).

7. Under Filters > Remeshing, Simplification, and Reconstruction, select Quadric Edge Collapse Decimation. Set the target number of faces to 20,000 and apply the filter.

8. The mesh model can then be exported as a .STL file.

Figure 109: Image of a left femur mesh model.
9. Import the .STL file into Rhinoceros® v5 SR13 64bit (McNeel North America, Seattle, WZ USA) and run the command MeshToNURB. This command converts each mesh facet into a non-uniform rational basis spline (NURBS), surface.

10. Export the NURBS model as a .STEP file.

11. Import the .STEP file into SolidWorks® [136], this may take several minutes. Save the SolidWorks® [136] file. Figure 110 shows an example of a CAD femoral head converted by using this protocol.

**VI.F Postoperative Measurements**

The following protocol was used to segment the post-op bone models, and then 3D registers them to the pre-op bone models. This registration allowed a direct comparison between planned and achieved implant position/orientation. Part of the challenge was that the acetabular cups used in the cadaver series were 3D printed in stainless steel (SST). This produced significant scatter in the images preventing the use of the previous segmentation methods. Figure 111 shows the image scatter in an Amira® [135] Volren representation of a post-op CT scan. The cadaver had SST acetabular cups and plastic femoral stems. It can be seen that primarily voxels within the same axial plane as the SST cups are affected by the scatter, while the rest of the geometry is relatively unaffected. Therefore, bone structures outside of the axial plane with the SST cups were primarily used for 3D registration. The protocol is outlined in detail below:
**Postoperative Segmentation**

1. Load the CT scan into Amira® [135], and in the Segmentation Editor tab, create new Label Data. Create a new material and name it ‘Acetabular Cups’.

2. Use the thresholding tool to select the voxels with the absolute greatest Hounsfield values, and add them to the material ‘Acetabular Cups’. These voxels will exclusively be metal objects within the scanned field.

3. Use the brush tool to select the voxels that are clearly not acetabular cups (e.g. acetabular screws, staples, bone plates, body bag zipper, etc.), and subtract them from the “Acetabular Cups” material.

4. Create a new material and name it ‘Acetabular Screws’. Enable threshold masking with the brush tool to paint the voxels representing the acetabular screws, slice by slice. Add the selection to the material ‘Acetabular Screws’.

5. Create a new material and name it ‘Femoral Stems’. Zoom to each femoral stem and use the brush tool to paint the voxels representing the femoral stem, slice by slice. Enable threshold masking to aid in distinguishing between objects when needed. Add the selection to the material ‘Femoral Stems’.

6. Create a new material and name it ‘Pin Holes’. Zoom to the superior rim of the acetabulum, and search for voxels with reduced intensity in alignment, representing the hole left by the guiding surgical pin. Enable threshold masking with the brush tool to paint the voxels representing the pin holes, and add them to the material ‘Pin Holes’.

7. Create a new material and name it ‘Pelvis’. Use the thresholding tool to select voxels with a Hounsfield value between 300 and 2000, and add them to the material ‘Pelvis’.

8. Select the pelvis and invert the selection. Subtract the selection from the material ‘Pelvis’. If the pelvis is not detached from the femurs, use the brush tool to paint the voxels connecting the bodies, and subtract them from the material ‘Pelvis’. Then repeat the inversion-subtraction technique.
9. Use the brush tool to select the voxels that have increased Hounsfield values due to the scatter, and are clearly not pelvis. Subtract the voxels from the material ‘Pelvis’.

10. Create a new material and name it ‘Femurs’. Use the thresholding tool to select voxels with a Hounsfield value between 300 and 2000, and add them to the material ‘Femurs’.

11. Select both femurs and invert the selection. Subtract the selection from the material ‘Femurs’. Use the brush tool to select the voxels that have increased Hounsfield values due to the scatter, and are clearly not femurs. Subtract the voxels from the material ‘Femurs’.

12. Export all six materials as independent .STL files.

13. Import the Femoral Stems .STL into MeshLab [137]. Select the mesh facets and points describing the left femoral stem, and delete the selection. Export the mesh as a .STL titled ‘Post-op Right Femoral Stem Mesh’. Repeat for the opposing stem, and then follow this approach for the Femurs file, created right and left femur mesh files.

**Registration**

14. Import a pre op femur or pelvis .STL file into MeshLab® [137], and then import the corresponding post-op bone model .STL.

15. Launch the Align Tool, select the pre op mesh, and select Glue Here Mesh. Select the post op mesh and then select Point Based Gluing. Figure 112 illustrates the point based gluing operation.

16. Select at least 4 matching paired points on the two bone meshes, using obvious bony landmarks. Spreading out the paired points yields the best results (paired points on greater trochanter and epicondyles, when registering a femur). Select ok.
17. The post-op and pre-op bone models will be given an initial alignment. Select Process for the registration to optimize. If the two bone structures do not appear to be aligned properly, select Process again. If the Process function does not properly align the bone structures, go back to step 15 and use different paired points until the bones are aligned. Figure 113 shows a post-op and pre-op femur that are properly registered.

18. Save the MeshLab [137] project as an Align Project (.aln) file type. Open the file with a text reading application. The second 4x4 matrix gives the transformation matrix that describes the translation and rotation that must be applied to the post-op bone for it to be aligned to the pre-op bone. The first 4x4 matrix should be the identity matrix. If it is not, the post-op bone mesh may have been imported before the pre-op mesh. Copy the transformation matrix.

19. Import the post-op implant .STL file for the bone that was just registered, into CloudCompare v2.7.0 64bit (CloudCompare 3D point cloud and mesh processing software, Open Source Project, http://www.cloudcompare.org) [141]. Select the mesh and under the Edit tab, ‘Apply a Transformation’. Using the Matrix 4x4 tab, paste the transformation matrix into the field and select ok. Export the mesh as a .STL, being sure to label it as ‘shifted’. This process should be executed for all implants and pin holes in accordance with their bone’s transformation matrix.

20. Repeat the registration techniques described in steps 14-19 on .STL files of the CAD acetabular cup and femoral stem implants, aligning them with the post-op implant positions.

21. Import the shifted pin holes .STL into MeshLab [137] and export each pin hole as a separate point cloud (.xyz) file without normals. Open the files using a text reading application and use the points to calculate the best fit line for each pin hole. Repeat this step for the shifted screws .STL as well.
22. In the pre-op surgical planning SolidWorks® [136] assembly file, import the corresponding shifted post-op CAD mesh. Mate the shifted post-op implant origin (0,0,0) with the pre-op bone origin. The position and orientation of the post-op implant can now be directly compared to the planned position and orientation.

23. In CloudCompare [141], apply the femoral transformation matrices to their corresponding post-op femur mesh and export them as an .STL, being sure to label it as shifted post-op femur left/right.

24. Import the shifted post-op femur into SolidWorks® [136] and take a uniformly spaced sample of points on the resection plane. Use the point coordinates to calculate a best-fit plane.

25. Create axes and planes in the pre-op surgical SolidWorks® [136] assembly file according to the calculated lines for the pin holes and screws, and calculated planes for the femoral resection. The achieved pin holes, screw angle, and femoral resection can now be directly compared to the pre-op plan. Figure 114 and Figure 115 shows an example of a completed registration ready for measurement.
Chapter VII: Cadaver Series (SA II & III)

NOTE: The following 6 sections explain the testing of the patient-specific devices on a series of cadavers, establishing the accuracy and precision of PSI for THA, fulfilling specific aims II and III. These sections were written by Jacob Stegman, and are being submitted for peer reviewed publication.

A sample surgical plan printout that was created for each cadaver may be found in Appendix II. The complete dataset for this study may be found in Appendix III. A complete collection of achieved vs planned implant overlays may be found in Appendix IV.
VII.A Methodology- Acetabular Cup (SA II)

The system of PSIs used in this study is a revision of the system used in our initial pilot study [142]. This updated system consists of 4 devices: a patient-specific acetabular pin-guide, a surgical pin, an impactor guide, and a modified reamer/impactor handle. The patient-specific acetabular pin-guide was seated in the native acetabulum and utilized the acetabular fossa for a unique fit (Figure 116). This acetabular guide was designed to direct a 3.2mm x 230mm surgical pin superior to the acetabulum (Figure 117). The modified reamer/impactor handle was equipped with guiding hooks forming a crosshair target, to align the reamer and impactor parallel to the surgical pin (Figure 118). The modified handle interfaced with an impactor guide designed to position the screw holes of the acetabular cup within the posterior-superior quadrant of the acetabulum (Figure 119 and 120). This impactor guide used two or three tabs to lock into the cup screw holes and another tab to lock into the reamer/impactor handle. Therefore, it allowed precise control in the rotation about the cup axis, by...
referencing the pin location from the acetabular pin-guide. Figure 121 shows the measurement of cup rotation for this study: the angle formed at the center of the cup, from the guide pin to the line bisecting the screw holes.

The acetabular cup was a traditional hemispherical two or three hole cup, where the number of screw holes is dependent on cup diameter. The acetabular cups were designed and 3D printed for this study in order to maintain neutrality across implant manufacturers using stainless steel, bronze, or nylon. Cup fixation used twenty-five mm length screws and a plastic liner was set into the cup following screw insertion. The liner was designed without the snap-locking feature so that the implants could be more easily retrieved following the study. The cup liners, PSI guides, reaming/impacting handle, and impactor guide were all 3D printed in plastic for this study.
A total of 10 fresh cadavers were sequentially given bilateral THA operations using the PSIs and the implant system previously described. Prior to operation the cadavers were computed tomography (CT) scanned, at a slice thickness of 0.325mm starting from the iliac crest to the proximal tibia. Image segmentation of the CT scans extracted three-dimensional (3D) surface models of the two femurs and pelvis. The surface models were then converted into 3D Computer Aided Design (CAD) models using SolidWorks® 2014 x64 (Dassault Systemes, Waltham, MA USA) and the anatomical coordinate system was established. The pelvic anatomic coordinate system was established by first defining the sagittal plane precisely between the acetabula. A theoretical center of rotation (COR) for each acetabulum was calculated by sampling 20-uniformly spaced points on each lunate surface that was subsequently used to estimate the enclosing sphere using a Matlab algorithm (Figure 122) [143]. The sagittal plane was positioned at the mid-point and perpendicular to the line connecting the acetabular centers (Figure 123). The coronal plane was established as perpendicular to the sagittal plane, along the line tangent to the pubic tubercles and the anterior superior iliac spines (ASIS) (Figure 124). The transverse plane was defined as mutually perpendicular to the sagittal and coronal plane, and tangent to the inferior-most point on the ischial ramus (Figure 124).
All of the cadavers were templated for bilateral THA in the software SolidWorks®. The planned orientations of the cup implants were anatomically based, using the native acetabular inclination and anteversion. Sampling 20 uniformly distributed points along the acetabular rim and calculating a best-fit plane determined the native acetabular inclination and anteversion. The cup rotation was set with the screw holes in the posterior-superior quadrant, and adjusted to avoid penetration through the internal wall of the pelvis when using a screw length of 25mm. The system of PSIs were resized according to the planned implant size on each cadaver, and oriented to match the planned implant position. The acetabular pin-guide was oriented such that the surgical pin would be perpendicular to the cup face. The impactor guide was designed and 3D printed for each cadaver to achieve the specific planned cup rotation for each acetabulum. The patient-specific surface of each pin-guide was 3D printed to match the acetabulum for its respective cadaver.

All cadaver operations were performed in the University of Cincinnati’s anatomical lab. A direct anterior approach was used for all procedures without the use of a specialized positioning table. A single surgeon performed all 20 procedures. The surgeon was instructed to follow the guide in all cases, regardless of their visual estimate, so that the accuracy of the guides may be assessed.

Following each bilateral THA, a CT scan was taken to determine achieved implant position. The CT scans were segmented using Amira 5.4.5 3D Software for Life Sciences (FEI, Thermo Fisher Scientific, Hillsboro, Oregon USA) to extract a post-op set of 3D bone and implant surface models. Registration of the post-op pelvis model to pre-op model was executed in MeshLab v1.3.3 (Visual Computing Lab – ISTI – CNR, http://meshlab.sourceforge.net/), using an initial rough manual paired point based registration and then followed by an iterative closest point (ICP) and global alignment algorithm. The ICP algorithm minimizes the distance between the surface models, converging to an optimized 3D registration. This method is common for 3D
registration and has been shown effective for use in orthopaedics [144,145]. The pelvis registration yielded a unique transformation matrix that described the pre-op to post-op change in the cadaver’s pelvic position on the CT bed. This transformation matrix was then applied to the segmented implants, so that the achieved cup implant position was overlaid in 3D on the pre-op pelvis bone models. Acetabular vertical inclination and anteversion were measured using Murray et al.’s definition for radiographic inclination and radiographic anteversion [5]. To examine the acetabular pin-guide accuracy, each surgical pinhole in the pelvis was segmented from the post-op CT scan images to identify its centerline and then compared directly to the planned surgical pinhole positions.

**Statistical Analysis**

A literature search was conducted to find studies that investigated freehand implantation accuracy, using post-op CT imaging to measure radiographic inclination and anteversion, as well as reporting the average absolute difference from the planned target. Since freehand accuracy and precision varies among surgeons, two differing controls sets (Saxler et al. & Lass et al.) were found to compare with this PSI approach. Saxler et al. used an anterolateral surgical approach with an n=105, and Lass et al. used a modified transgluteal approach with an n=63 [79,76].

The cup inclination and anteversion data were compared using a Games Howell post hoc test to compare the means in a pairwise fashion, giving a measurement of accuracy. Cup inclination and anteversion were also analyzed using a Fisher’s test to compare the variances of the groups, giving a measurement of precision. Both of these statistical tests assume a normal distribution, an assumption Biedermann et al. verified for both anteversion and abduction (inclination) in freehand control groups of n=114 and n=342 respectively [21]. The results were also compared to Lewinnek’s widely referenced ‘safe zones,’ which have a tolerance of ±10° in both acetabular vertical inclination and acetabular anteversion [20]. The accuracy of the system is defined as the mean difference from target, and the precision is defined as the standard
deviation (SD). An accurate and precise set of procedures would return a mean of 0° from the target, with a SD of ± 0°.

VII.B Results- Acetabular Cup (SA II)

Of the 10 cadavers, 9 were female and 1 was male. Of the 20 procedures, 5 guide-orientation data and 7 cup-orientation data were excluded due to material or component failures. In the first two hips, the material of the 3D printed cup crumbled under impaction. In addition, the PSI guide failed to fit appropriately or could not direct a guide pin into solid bone in the first 5 hips. In two later hips, the 3D printed reaming handle failed from swelling in steam sterilization. This allowed 13 cup-orientation data and 15 guide-orientation data available for analysis. The planned cup sizes ranged from 46mm to 62mm in diameter. The three columns in Table 10 describe the accuracy of overall cup position, the accuracy of positioning the guiding pin, and the accuracy of aligning the cup to the guiding pin respectively. The total error in cup inclination and anteversion is recorded in the first column of Table 10, in terms of the mean difference from the target position, ± SD, and in terms of the mean absolute difference from the target. The mean difference from the target cup inclination ± SD was 5.4° ± 9.9°, and a mean difference from the target anteversion ± SD was -1.1° ± 11.6°. Columns two and three break down this alignment error into its components. The first component is the error attributable to patient-specific acetabular guide (recorded in the second column). This error in orientation of the patient-specific acetabular guide was measured based on the pinhole location as seen in Figure 116B. The PSI guide was positioned with a mean difference from the target inclination ± SD of 7.1° ± 10.9°, and a mean difference from the target anteversion ± SD of 1.6° ± 10.6°. The error attributable to reaming/impacting handle’s ability to follow the guiding pin was recorded in the third column. It shows how closely the cup is aligned to the guiding pin, irrespective of the plan and it was measured as the difference in anteversion and inclination between the achieved cup axis to the guiding pinhole. The error between the PSI guide pin and the cup had a mean inclination error ±
SD of 0.9° ± 5.3°, and a mean anteversion error ± SD of 1.7° ± 3.3°. The table also includes the cup orientation data for the freehand controls published by Lass et al. and Saxler et al, in the fourth and fifth columns. The absolute value of the errors were averaged, resulting in the mean absolute difference from the target, and is given in the bottom two rows for an additional comparison of precision between the groups. Both the mean difference from target and the mean absolute difference from the target were used to allow direct comparison to relatable studies.

<table>
<thead>
<tr>
<th></th>
<th>Experimental</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acetabular Cup (Difference from Target) (n=13)</td>
<td>Acetabular Pin-Guide (Difference from Target) (n=15)</td>
</tr>
<tr>
<td>Mean</td>
<td>Inclination 5.4° ± 9.9°</td>
<td>7.1° ± 10.9°</td>
</tr>
<tr>
<td></td>
<td>Anteversion -1.1° ± 11.6°</td>
<td>1.6° ± 10.6°</td>
</tr>
<tr>
<td>Mean Absolute</td>
<td>Inclination 8.4° ± 7.3°</td>
<td>10.1° ± 8.0°</td>
</tr>
<tr>
<td></td>
<td>Anteversion 9.5° ± 6.2°</td>
<td>8.1° ± 6.7°</td>
</tr>
</tbody>
</table>

Table 10: Mean difference and mean absolute difference from the target for inclination and anteversion.

Figure 125, 126, and 127 show the inclination vs anteversion from the target position of each cup placement, guide placement, and difference between the guide and the cup orientation. These three plots are the graphical representation of each data point captured in columns 1-3 of Table 10. An accurately placed implant would be at (0°,0°) indicating zero error in both anteversion and inclination for all three plots. Lewinnek’s tolerance of ± 10° is plotted as a square for reference and comparison. Figure 125 shows that the cup implants were not consistently implanted within ± 10° of the intended position. Figure 126 highlights that the PSI guides were also not consistently positioned with ± 10° of the intended orientation. However,
Figure 126: PSI guide orientation, as a difference from the target.

Figure 127: Cup orientation as a difference from the pin-guide.

Figure 127 shows that the cup implants were aligned within ± 10° with the PSI guide position for all cases except one.

Table 11 captures the results for equality of means (i.e. accuracy) and equality of variance (i.e. precision) for the two controls against the cup position using PSIs, the PSI position, and then the difference between the cup and the PSI position. In the first two columns, a Games Howell pairwise post hoc test was evaluated for each row, comparing the experimental data and the 2 control datasets simultaneously. The last 2 columns of Table 11 show the p values when comparing the variances (i.e. precision) between the experimental data and the control literature. A Fisher’s test was evaluated for each control comparison.

<table>
<thead>
<tr>
<th>Experimental data</th>
<th>Pairwise post hoc test for equality of means</th>
<th>Fisher’s test for the equality of variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cup</td>
<td>Inclination</td>
<td>0.041</td>
</tr>
<tr>
<td></td>
<td>Anteversion</td>
<td>0.601</td>
</tr>
<tr>
<td>Acetabular Pin-Guide</td>
<td>Inclination</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>Anteversion</td>
<td>0.969</td>
</tr>
<tr>
<td>Cup to Pin-Guide</td>
<td>Inclination</td>
<td>0.141</td>
</tr>
<tr>
<td></td>
<td>Anteversion</td>
<td>0.935</td>
</tr>
</tbody>
</table>

Table 11: Pairwise post hoc test for equality of means and Fisher’s test for the equality of variance (p values)
The planned cup rotation averaged 64.4° ± 14.2° from the planned guide pin position, and measured as seen in Figure 121. The achieved cup rotation averaged 58.6° ± 1.5° from the achieved guide pin position. The resulting mean difference in rotation of the cup with respect to the guide pin was -5.7° ± 4.6°, where a negative angle refers to an anterior roll from the target rotation. The achieved cup rotation was measured from the achieved pin location (all other measurements reference the planned). Therefore, the mean difference in cup rotation directly evaluates the impactor guide, since the impactor guide was designed to achieve a specific cup rotation from the pin. To our knowledge, this is the first study to report data on attempts to control rotation to optimize screw placement.

VII.C Discussion- Acetabular Cup (SA II)

Acetabular cup malposition has repeatedly been correlated to increased rates of dislocation [30,28,20,21]. Conventional freehand implantation techniques have failed to implant the acetabular cup consistently within the target angular zone [79,67,96]. It is critical to improve implantation precision to reduce the risk of joint dislocation. Advancements in surgical technology introduced computer navigation and robotic-guided implantation have significantly reduced the incidence of outliers in cup orientation compared to conventional techniques [89,146]. Subsequently, a meta-analysis of long-term results in computer navigation has indicated a significant reduction in dislocation compared to conventional implantation techniques [118]. It is of interest to continue to investigate precision techniques, particularly those that differ from computer navigation and robotic-guided by not requiring investment in additional OR equipment. Such new technologies can provide more cost-effective solutions for low-volume surgeons and hospitals.

The error in positioning the cup is the summation of errors associated with all the elements of the PSI set. Our analysis identifies the primary source of positioning error to be associated with our patient-specific acetabular pin-guide and to a lesser extent, to the surgeon’s
ability to align the cross hairs on the reamer/impactor with the surgical guide pin. As shown in Table 10 and 11 positioning the acetabular guide contained similar amounts error to the cup position. We noticed a similar spatial distribution of the inclination and anteversion data points between the final cup position in Figure 125 and the acetabular pin-guide in Figure 126.

The results showed that the precision error associated with the impactor following the guide pin was significantly less than the precision error for freehand cup implantation by Saxler et al. for both inclination and anteversion. This guide-pin to cup precision error was also significantly less for anteversion when compared to freehand cup implantation by Lass et al. One outlier in inclination can be seen in Figure 127 for the ‘Cup to Pin-Guide Difference’ results. This outlier was one of the 2 instances that a solid nylon cup was used, leading to difficulty in achieving a firm press-fit implantation. The cup was screwed down while slightly loose, which may have resulted in slight cup migration from its original position. While the nylon cups were easy to 3D print compared to the stainless steel cups, the parts were too flexible and smooth to hold in the acetabulum, which may have affected the data. Excluding this outlier in the ‘guiding pin to cup’ data, the range in inclination error was only 4.53°, while the anteversion error was 11.45°; both considerably less than the range of 20° specified by the safe zones. The data suggests that if an acetabular patient-specific guide can be made to fit correctly, and accurately locate a guide pin, then that single guide pin would produce significant improvements in accuracy and precision of cup placement.

We found that the error associated with aligning the impactor to the guide pin falls within the range of precision reported for cup implantation when employing computer navigation or robotic assisted THA. Lass et al. reports a mean ± SD of 38.6° ± 3.6° and 19.5° ± 4.6° for cup inclination and anteversion (n=62) when using imageless computer navigation [76]. Kanawade et al reports a mean ± SD of 39.1° ± 3.8° and 18.9° ± 4.1° for cup inclination and anteversion (n=43) when using robotic assisted THA [124]. For comparison, our study with PSI guides found a mean ± SD of 0.9° ± 5.3° and 1.7° ± 3.3° for the error associated with aligning the impactor to
the guide pin. A Fisher’s test for equality of variance shows that our precision in aligning the impactor tool to the guide pin is equal to the precision of implanting a cup using navigation or robotic surgery for both inclination and anteversion (all p values ≥ 0.05) \[76,124\]. Overall, computer navigation and robot assisted THA show higher precision in cup inclination and anteversion than our patient-specific system. However improving how the acetabulum patient specific guide fits within the acetabulum would allow this technology to compete in precision with both computer navigation and robotic-assisted THA.

In a related study, Spencer-Gardner et al. investigated an acetabular PSI for cup reaming and implanting in 100 patients \[133\]. Their embodiment differed by their use of lasers to orient the reamer and impactor, and achieved a mean absolute deviation of 3.9° and 3.6°, in inclination and anteversion \[133\]. For comparison, our cups achieved a mean absolute deviation of 8.4° and 9.5°; however, our cup to pin-guide data resulted in mean absolute difference of 2.6° and 2.8° for inclination and anteversion respectively. Another related study by Small et al. tested an acetabular PSI in 18 patients and found a mean difference from target ± SD of -1.96° ± 7.1° and -0.22° ± 6.9° for abduction and anteversion (mean ± SD) \[131\]. For comparison, our cups achieved a mean difference from target ± SD of 5.4° ± 9.9° and -1.1° ± 11.6°; however, our cup to pin-guide data resulted in 0.9° ± 5.3° and 1.7° ± 3.3° for inclination and anteversion.

A limitation was that all surgeries were direct anterior approach. However, this made the surgical technique consistent. The surgeries were conducted in a cadaver lab without specialized retractors, lighting, and specialized anterior approach surgical table. In the absence of the anterior approach surgical table, a cross-leg technique was utilized for exposure of the joint, however, a larger than normal incision size was necessary to complete the procedure. Another limitation was that we designed the complete implant system instead of using market-released products. We designed our own implant system to have knowledge of every dimension, allowing for 3D surgical templating. The first few procedures highlighted material flaws in our 3D printed devices, which led to mechanical failure of either the cups or reamer/impactor handle, and were
corrected for the subsequent procedures. The cup orientation data for 5 procedures were omitted due to failed guide pin insertions and cup implant material failures. Two additional cup orientation data were invalid due to failure of the 3D printed modified reamer handle from autoclave sterilization swelling. Thus, the sample size of cup orientation data was reduced from 20 to 13 and the acetabular pin-guide data from 20 to 15. This allowed little room for a learning curve and is certainly a factor in the higher than expected variation.

The highest error was in the PSI guide’s ability to lock into the acetabulum. We believe that the fit of the acetabular pin-guide can be improved by optimizing the image segmentation process. Another factor influencing the fit of the acetabular pin-guide was that the cadavers used in this study were not diagnosed with severe hip arthritis. Therefore, the abundant cartilage likely negatively impacted the fit of the guide, since the cartilage is not visible in CT imaging. In addition, it could prove beneficial to update the design such that a portion of the acetabular rim is used as a patient-specific surface in tandem with the fovea, thus increasing the stability of the device. An MRI based guide could also improve the PSI fit because an MRI can visualize cartilage and soft tissue where a CT scan cannot. Most cadavers used in this study did not have hip arthritis, which likely negatively impacted the fit of the PSI acetabular guide since joint cartilage is not visible in CT imaging, yet affected the fit of the patient specific guide in the acetabulum and fossa. A similar study in patients with osteoarthritis could lead to improved PSI fit inside the acetabulum. A patient study would also allow an improved comparison to control data, as this study was limited by comparing cadaveric data to clinical data.

In conclusion, the study indicates that a properly placed guide pin would statistically improve both accuracy and precision for both acetabular inclination and anteversion as compared to freehand implantation. Our data showed that improvements in the fit of the PSI guide would likely meet that criterion such that the cup is positioned correctly within a clinically relevant tolerance. Pending improvements on the patient-specific fit, the technology may achieve comparable results to computer navigation and robotic-assisted THA. Work should continue to
develop cost-effective, accurate, and precise solutions for acetabular cup implantation, as surgical planning methods continue to improve, allowing for patient-specific optimized implantation.

VII.D Methodology- Femoral Stem (SA III)

A series of 20 THA procedures were performed on 10 cadavers to study the precision of two femoral PSIs: a resection block and a broaching anteversion guide. Each cadaver was preoperatively computed tomography (CT) scanned and segmented for the 3 dimensional (3D) bone geometry. The bone geometry was imported into a CAD software, where 3D templating took place for bilateral THA. Femoral implants and broaches were designed and manufactured so that 3D templating could take place. The two femoral PSIs were customized for each joint according to the unique bone surfaces and the desired implant positions. The PSIs were manufactured using 3D printing, and were used for the preparation and implantation of the femoral stem. All 20 procedures were performed by the same surgeon from the direct anterior approach. All cadavers received a postoperative CT scan, and the achieved implant position was compared to the planned.

Instrument Design

Two PSIs for THA femoral preparation and stem implantation were developed: a femoral resection guide and a version guide for femoral broaching. Both guides were designed for use with the direct anterior surgical approach. The femoral resection guide was designed for a unique fit over the anterior portion of the femoral neck (Figure 128) using a patient-specific surface that matches the surface of the bone. The guide contains an ‘L’ shaped resection slot, which spares the greater trochanter from resection. A surgical pin may be inserted and removed at the slot elbow.
near the greater trochanter to eliminate a sharp corner that could create a stress riser in the bone. Superior to the resection slot are two holes for fixation via surgical pins to the femoral head.

A set of femoral stem implants were designed for this study, characterized as a short press-fit stem with a reduced shoulder and were 3D printed in plastic for use in the cadaver THA procedures (Figure 129). A set of broaches were also designed for this study, and were shaped to match the set of stem implants. Design for these broaches included 2 anterior to posterior pinholes, in which a surgical pin can be inserted (Figure 129). The set of broaches were 3D printed in bronze for use in the cadaver THA procedures. The second patient-specific guide, the version guide, fits around the resected neck of the femur. A guiding channel extends superiorly from the device, along the trajectory of the planned implant orientation. The surgical pin through the broach rides in the guiding channel of the version guide during broaching (Figure 130). This mechanism assists in both lateralization of the prepared femoral cavity, and controlling the femoral version of broaching.
Experimental Design

A series of 10 fresh cadavers underwent bilateral THA to test the accuracy and precision of these femoral PSIs. Prior to surgery, the cadavers were CT scanned and the images were segmented into 3D surface mesh models. These were imported into computer-aided design (CAD) software to establish an anatomic coordinate system for each femur and a center of rotation (COR) for each femur head. The implant stems were then templated in 3D and the two PSIs designed.

Each cadaver was scanned using CT from the iliac crest through the knee at a slice thickness of 0.325mm. The image set was segmented using Amira 5.4.5 3D Software for Life Sciences (FEI, Thermo Fisher Scientific, Hillsboro, Oregon USA) to extract the bone anatomy into a 3D surface mesh model where a surgical plan could be created. The mesh model was refined in MeshLab v1.3.3 (Visual Computing Lab – ISTI – CNR) and then imported into the CAD software SolidWorks® 2014 (Dassault Systems, Waltham, MA USA) as a solid CAD model.

An anatomic coordinate system was created for each femur, analogous to the full body planes, for the purpose of precisely defining and comparing implant positions. The coordinate system was established by first estimating an anatomical axis via a proximal and distal center point of the shaft. The transverse plane was defined as perpendicular to the anatomical axis, and tangent to the superior-most point of the greater trochanter (Figure 131). The coronal plane was defined along the anatomical axis, and

![Figure 131: CAD image depicting how the anatomical planes for the coordinate system were defined.](image-url)
perpendicular to the transverse plane, and parallel to the transepicondylar axis of the distal femur (Figure 131). Finally, the sagittal plane was defined as mutually perpendicular to the transverse and coronal plane, and along the anatomical axis (Figure 131).

Templating the femoral stem implant was set to always match the native femoral anteversion and COR, and was sized according to femur size. The native femoral anteversion was recreated in 3D templating by first calculating the joint’s COR. Using a sphere algorithm in Matlab, a sample of 20 uniform points were taken on the lunate acetabular surface and used to calculate a best-fit sphere, with an example of the point selection shown in Figure 132 [143]. The origin of the best-fit sphere was used to identify the joint’s overall COR, and transcribed to the 3D SolidWorks® femur model. The femoral stem was positioned such that the center of the femoral head implant matched the COR point. The stem was aligned to follow the center of the femoral shaft as the anatomical axis defined in Figure 131. This combination of constraints on the positioning of the femoral implant is designed to replicate of the native femoral anteversion.

The implant position and orientation in relation to the anatomical coordinate system was recorded so that it could be compared to the achieved implant positions after the THA procedures. The resection guide was virtually templated such that it would prepare a resection along the porous coating of the planned implant location, and sparing the greater trochanter. Once the guide was positioned properly, its posterior surface was updated as a negative mold of that femur, giving it the patient-specific surface. The version guide was then virtually positioned over the resected femur in line with the stem implant. In a similar manner, the version guide’s inferior
surface was updated as a negative mold of the femur for a patient-specific fit. The femoral PSI guides and stem implant were then 3D printed in plastic and prepared for use in the cadaver.

All 20 THA procedures were performed by an experienced orthopaedic surgeon using the direct anterior approach in an anatomical lab. A surgical table for anterior approach was not available, so a crossed-leg technique was used with an increased incision size for the appropriate surgical exposure.

Following implantation, each cadaver received a post-op CT scan so the implant position could be measured. Both the bone anatomy and the implants were segmented into 3D surface mesh models using Amira 5.4.5. These surface mesh bone models were 3D registered to the pre-op bone model in MeshLab v1.3.3, yielding a transformation matrix that describes the relative change in cadaver position on the CT scanning table. The transformation matrix was then applied to the segmented implants, so that their position could be directly compared to the planned position in a 3D overlay using SolidWorks®. Additionally, a uniform sample of 20 points were taken on the post-op resected bone face and used to calculate a best fit plane in order to compare the achieved resection to the planned resection.

Three important measures were taken in comparing the resection plane: resection inclination, resection tilt, and resection displacement. These three measures describe the

![Figure 133: CAD images illustrating the angles of resection inclination and the angle of resection tilt. Third image provides an example of how resection displacement is measured.](image-url)
effectiveness of the patient-specific resection guide. We defined resection inclination as the angle between the anatomical axis and the neck cut, measured in the coronal plane (Figure 133). The resection tilt we defined as the anterior tilt of the resection measured in the sagittal plane (Figure 133). Lastly, the resection displacement is the offset of the resection plane, measured along the planned stem implant neck axis (Figure 133). The achieved stem position was measured in relation to the original anatomical coordinate system and compared with the planned stem position. Femoral version was determined by the angle between the coronal plane and the neck axis, measured in the transverse plane (Figure 134).

VII.E Results- Femoral Stem (SA III)

<table>
<thead>
<tr>
<th></th>
<th>Mean Error</th>
<th>Absolute Mean Error</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resection Inclination</td>
<td>-1.76° ± 5.45°</td>
<td>4.28°</td>
<td>-15.31° – 8.83°</td>
</tr>
<tr>
<td>Resection Tilt</td>
<td>2.02° ± 7.78°</td>
<td>6.14°</td>
<td>-13.26° – 22.05°</td>
</tr>
<tr>
<td>Resection Combined Angle</td>
<td>6.85° ± 4.50°</td>
<td>6.85°</td>
<td>0.25° – 17.25°</td>
</tr>
<tr>
<td>Resection Displacement</td>
<td>0.91mm ± 3.06mm</td>
<td>2.68mm</td>
<td>-4.69mm – 7.49mm</td>
</tr>
<tr>
<td>Stem Version (Angle in Transverse Plane)</td>
<td>-5.22° ± 7.80°</td>
<td>6.60°</td>
<td>-22.03° – 5.46°</td>
</tr>
<tr>
<td>Stem Angle in Coronal Plane (+ Varus, - Valgus)</td>
<td>0.43° ± 1.94°</td>
<td>1.50°</td>
<td>-3.70° – 4.13°</td>
</tr>
<tr>
<td>Stem Angle in Sagittal Plane</td>
<td>-2.39° ± 2.39°</td>
<td>2.95°</td>
<td>-6.27° – 2.46°</td>
</tr>
<tr>
<td>Leg Lengthening from Stem</td>
<td>-0.14mm ± 3.50mm</td>
<td>2.68mm</td>
<td>-8.03mm – 5.13mm</td>
</tr>
<tr>
<td>Hip Offset from Stem</td>
<td>1.95mm ± 3.73mm</td>
<td>3.50mm</td>
<td>-4.63mm – 8.14mm</td>
</tr>
</tbody>
</table>

*Equal to absolute mean error because measurement is always positive by nature

All 20 cadaveric THA procedures were successful in preparing the femur using the PSIs. In 2 instances (single cadaver, left and right hip), the final position of the broach was used to determine implant position, because the 3D printed femoral implants were not available. Nine of the cadavers were female, while a single cadaver was male. The mean error, absolute mean error,
and range of error in resection plane orientation and stem position are recorded in Table 12. The absolute mean is determined by taking the absolute value prior to calculating the mean, which gives an average error irrespective of direction.

The mean error (± standard deviation) was -1.76° ± 5.45° and 2.02° ± 7.78° for resection inclination and resection tilt respectively. This shows that on average the resection was 1.76° too vertical, and the resected face was 2.02° too anteverted. The absolute mean error was 4.28° for resection inclination, and 6.14° for the resection tilt. Figure 135 plots the inclination and tilt error as paired coordinates on a scatterplot, showing 85% within ±10° of inclination and tilt. The outlier with 22.05° of resection tilt was noted in surgery to be irregular, however the femur was not recut in order to retain the data of the resection guide.

The angular combination of inclination and tilt describes the resection plane. The combined angular error of the resection plane was found to have a mean error of 6.85° ± 4.50° (where the values are all positive by nature). The displacement of the resection plane differed from the plan with a mean and standard deviation of 0.91mm ± 3.06mm, showing that the resection was on average slightly proximal than the planned resection (measured along the axis of the planned stem neck). Using the mean error and standard deviation of the resection plane displacement and resection inclination, a resection zone was determined...
and overlaid on a sample femur in Figure 136. This resection zone gives a visual representation of 65% (13/20) of the resections when using only displacement and inclination data.

The stem implant version held a mean error of $-5.22^\circ \pm 7.80^\circ$, indicating that on average the stem was inserted with $5.22^\circ$ less anteversion than the plan specified. Figure 137 plots each angular error in stem version, where $0^\circ$ is achieving the planned version. The plot illustrates a cluster at $0^\circ$, but also several negative outliers which skewed the distribution and therefore the mean. The median value for error in stem version was $-2.67^\circ$, almost 50% less than the mean, confirming a skewed distribution. It is also of importance to note that the 4 greatest errors in stem version were not uniformly distributed in the sample set, but came from the left and right hip of 2 cadavers (first and fourth specimen). Omitting these 2 outlier cadavers would have resulted in the mean and standard deviation version error to be $-2.06^\circ \pm 4.66^\circ$. The overall absolute mean error for stem version was $6.60^\circ$, and would have been $3.79^\circ$ had the outliers been omitted.

The stem angle in the coronal plane described the varus/valgus angle. The patient-specific version guide aided in the lateralization of stem insertion, which helps to prevent a stem from being inserted with excess varus. The mean error for stem varus/valgus was $0.43^\circ \pm 1.94^\circ$, where positive values indicate a stem angled with more varus than planned. The range of error in stem varus/valgus was from $-3.70^\circ$ to $4.13^\circ$, indicating no stem angled outside of $5^\circ$ from planned. The mean absolute error was $1.50^\circ$ for stem varus/valgus. Leg lengthening and hip offset held mean

![Error in Stem Version](image)

*Figure 137: Plot of the error in stem anteversion. $0^\circ$ indicates the stem anteversion matched the plan. Sample femur and stem are overlaid for reference.*
errors of -0.14mm ± 3.50mm and 1.95mm ± 3.73mm respectively. The absolute mean error was 2.68mm and 3.50mm for leg length discrepancy and hip offset respectively.

VII.F Discussion- Femoral Stem (SA III)

The patient-specific resection guide controlled the range of resection inclination (24.14°) to a tighter range of values than in resection tilt (35.31°). The resection tilt had a slightly larger absolute mean error when compared to resection inclination (6.14° vs 4.28°), but both were well within the hypothesized target of less than 10.0°. The difference in error between inclination and tilt was somewhat expected because the reciprocating saw could be angled across a larger range in resection tilt than rotated in resection inclination. It was desirable for the resection guide to maintain a low profile for ease of use in the surgical site, however reducing its profile compromised control in resection tilt. For this reason, even if the resection guide consistently fit perfectly on the femoral neck, the resection tilt would still contain more error than the resection inclination. While calcar planing is an option to correct errors in resection tilt, the patient-specific version guide is dependent on a correct resection plane to fit properly. Therefore the error in stem position should theoretically compound with the error from neck resection when using these devices. This would lead one to expect stem position to be more erroneous when the neck resection is incorrect. However, a linear regression model showed that error in neither resection inclination, tilt, or displacement were significant predictors of error in stem version (p=0.066, 0.417, & 0.500 respectively, $R^2= 0.259$). This likely means that another factor played a more significant role in contributing to the error in achieved stem version. Femur geometry and/or the fit of the PSIs are two of the most probable factors. The hard cortical bone of the femur can easily cause a femoral broach to deflect in version if the planned stem position is not carefully positioned in soft cancellous bone. For this study, the inner femur geometry was not segmented into the 3D bone model, and therefore was not used in surgical planning. An improvement in the surgical planning would include a bone density map of the femur or simply include the femoral canal to
ensure an achievable stem placement. Such an addition would also in theory improve the precision in controlling the stem varus/valgus and angle in the sagittal plane. Without the segmentation of the canal, the stem was planned to simply follow the center of the femoral shaft. If the canal was present in the models, improved templating would better reflect what can be achieved in surgery. Another possible improvement would be a study that optimizes the segmentation to PSI process. This type of study would determine the ideal segmentation parameters and PSI creation factors, which would further reduce errors in how each PSI fit on the bone geometry.

The absolute mean error for stem version met the hypothesized target of 10.0° or less, but it was highly expected to since the pilot study, which resulted in a stem version error of 11.8°, had no method for controlling stem anteversion. On average, the stems were consistently implanted with less anteversion than planned (planned anteversion always matched the native anteversion). Figure 138 shows a top down view of a resected femur with the patient-specific version guide in use. The figure illustrates the odd angle required between the anterior face of the guide and the surgical pin which inserts through the broach. A natural tendency is to create a 90° angle, which reduces the anteversion of the broach. A simple correction that would likely improve the error in version, is to adjust the anterior face of the device to be perpendicular to the surgical pin. The four negative outliers originated from the left and right hip of two cadavers, suggesting that a factor common to the cadaver caused the increased error, such as the bone segmentation and/or the surgical planning. The first cadaver contained the most error in stem version, which could simply be attributed to the effect of a learning curve.
The absolute mean error in resection displacement (2.68mm, n=20) was 87% greater than the error found in the pilot study (1.43mm, n=1), and also exceeded our hypothesized target of 2.00mm. While the overall precision could not match the original target, it is still considered minimal since the thickness of the sawblade is approximately a third of this error (0.88mm). Authors generally allow a total leg length discrepancy of 10mm or less [147,148]. Neck resection contributes to overall leg length discrepancy when it is used as the target depth for femoral broaching (as in the case for this study). The contribution to leg length discrepancy from the femoral side would therefore be the sum of error in resection, error in full impaction of the stem, and any planned leg length discrepancy. In the case of this study, it was coincidence that the absolute mean error in resection displacement equaled that of leg lengthening caused by stem position. This average allows for 7.32mm of error in acetabular leg lengthening before the overall lengthening exceeds the threshold of 10mm.

A comparable study by Ito et al. investigated a PSI for femoral stem implantation in 10 patients, reporting the stem anteversion, varus/valgus, and tilt in the sagittal plane [149]. While their guide indicated the appropriate resection level, it was not measured postoperatively [149]. They reported similar results, with a mean absolute difference from planned, of 4.73˚, 1.04˚, and 2.14˚ for anteversion, varus/valgus, and tilt in the sagittal plane respectively [149]. For comparison, this study reported 6.60˚, 1.50˚, and 2.95˚ for the same measurements.

A limitation of the study was that the appropriate table for anterior approach was not available. A straight stem is difficult to implant from the anterior approach with the appropriate table, so in order to implant our straight stem, an increased incision size was needed. It is possible that the normal incision size is too small for the PSIs to function properly, and may need slight modification. Another limitation was that this system was designed and tested for direct anterior approach only. The PSIs would need to be redesigned to fit onto available boney landmarks for alternative surgical approaches, and could therefore vary in accuracy and precision. This study
also did not include a control arm, as it was more necessary to consolidate resources into increasing the sample size in testing the patient-specific guides. Future studies with more finalized PSI designs should include a control arm for appropriate comparisons.

In conclusion, this study presents two patient-specific guides that can aid in femoral preparation and implantation of the femoral stem in THA. Additional work can be done to improve the accuracy and precision, particularly with the control of stem anteversion. However this study supports the future development of PSI for THA as an alternative to more costly methods of accurate and precise implantation.
Chapter VIII: Future Work & Conclusions

VIII.A Design Changes

Upon completing these studies, several design improvements have become evident. When the patient-specific pin guide was being placed in the acetabulum, it was generally difficult to find the unique fit. Only using the fovea and lunate surface to create a unique fit tended to let the guide slip and spin. Prior designs utilizing the acetabular rim for patient-specific surfaces created more stability, however, those surfaces were not always easily accessible in surgery, and needed to be scrapped clean for use. A design improvement for the patient-specific pin guide would be to include crossbars that touch the acetabular rim but do not use the rim as a patient-specific surface. These crossbars would assist in the initial alignment of the guide relative to the acetabular rim, within +/- a few degrees. Then the crossbars could be removed and the guide could be minimally shifted/rotated to find the best fit. Such an improvement would help reduce outliers because even when the guide has a poor fit, the guide will always be placed within a few degrees of the intended position. In addition, the crossbars would help in finding the true position and may speed the process of finding the best fit.

Also in relation to the patient-specific pin guide, depth control was abandoned when the guided needed an emergency revision at the beginning of the cadaver series. The T-slot guide too frequently placed pins that would not catch bone but skived off the bone surface instead. Transitioning to the single guide pin eliminated the ability to control depth. Since the guiding hole on the device did not contain a patient-specific surface (to avoid the need to clear the bone surface), it was not possible to know how much tissue was between the guiding pin hole and the bone. Therefore, the top surface of the guiding pin hole could not be used as a depth reference if it was clipped away from the main body of the guide (similar to the design in previous revisions). However, it is not outside the realm of possibilities to incorporate a depth control, such as
markings on the guide pin, or a removable collar on the pin. In such cases, the pin could be inserted until a specific mark, or up until the removable collar is reached, giving the specific knowledge of how deep the pin has been inserted. The reamer and impactor could then receive depth measurements from the guide pin. No design changes are needed to the impactor guide at this time. The impactor guide fit with the handle and acetabular cup very well. Errors in the cup rotation were likely due to the ability to align the handle with the guide pin and not the performance of the impactor guide.

The screw guide, in general, worked well save for one design feature. The screw guide was designed to slide into the acetabular cup and then rotate a few degrees to lock into place. In almost all cases, the screw guide was not able to be rotated into place due to small burrs on the devices. Therefore, nearly every pilot hole was drilled at a slight deviation from intended. Since the screw guide was held securely in place without the locking rotation feature, an easy design fix would be to eliminate the rotational lock. It is also recommended that a removal loop is added to aid in extracting the device from the cup.

The patient-specific resection guide also performed well, fitting much easier than the acetabular pin guide. Design improvements for the resection guide would be to ensure part of the device fits over a larger bony landmark such as part of the femoral head or greater trochanter. When the device utilized these larger features, the patient-specific fit was easier to find. Only using the femoral neck can lead to a half-cylindrical patient-specific surface, which leads to the device slipping around the neck. In addition, an updated resection guide could use a metal slot instead of the 3D printed plastic. A metal slot would improve control in resection tilt and prevent plastic debris from entering the surgical site.

The patient-specific femoral anteversion guide could be improved in many ways. The largest flaw in this device was in its difficulty to use. The device needed to be held in place by an assistant attending the physician, while the surgeon broached. The device gives a reasonable estimation of
anteversion and lateralization, however once broaching begins, the device is slowly torqued to wherever the broach is going rather than guiding the broach. This is primarily evident when the broach is removed and the device shifts back into its original place. Therefore, the problem is twofold: first that the device has to be held in place by an assistant, and second that the broaching doesn’t truly follow the guide. A solution to the first problem is not yet known, however, there are a few possible solutions to the second. The anteversion guide was typically shifted medially during broaching, meaning that lateralization was not fully achieved. The use of a proper reaming device could be used to ensure full lateralization, which was not available during the cadaver series study. Alternatively, a device could fit into both of the A to P broach holes and extend a ‘flag’, or flat plane next to the stem of the broach. This flag would slide between the guiding arms of the anteversion guide, aiding in the initialization of broaching and ensuring lateralization. This flag device will also set the initial varus/valgus since it is a plane. When a single surgical pin is used through the broach hole, varus/valgus is not controlled. Therefore, the bottom hole could be used to initialize broaching, but if the varus/valgus is not set, then broaching will push the anteversion guide rather than follow it.

VIII.B Segmentation Improvements

An early vision for this project was to develop a fully automated segmentation algorithm in order to reduce human error and have a very repeatable method. It became apparent during the development of the segmentation algorithm, that a fully automated program that functions on every patient would require extensive work and resources that were not available for this project. Various methods claiming full automation were attempted, but could not be repeated on our CT scans of patients with osteoarthritis and thin joint spaces. Therefore the semi-automated segmentation algorithm was developed, where the separation of the joint was aided by a user selecting points in the joint space. However as the cadaver series progressed, this program frequently failed to produce usable models, leaving the manual segmentation method to be used.
The segmentation could be improved by 1) fixing the existing program to always produce usable models, 2) eliminating the need for user input, and 3) optimizing the parameters used in the program. Alternatively, if the program was abandoned, the manual method could be improved by optimizing its various parameters. More specifically, the bone surface that is created needs to be validated as an accurate enough representation for a patient-specific device to effectively fit. Even if the precise bone surface is determined, the resulting patient-specific guides may not fit due to the small presence of soft tissue and fluids.

A study should be conducted where segmentation parameters are optimized according to the best fit of patient-specific guides. A simpler form of this study could involve a few cadavers, in which each cadaver is segmented several different times using slightly different parameters. A patient-specific guide could be manufactured for each segmentation method, and the guides could be compared side by side for best fit according to the surgeon’s feel. A more precise study would require many more cadavers. A segmentation method would be used for several cadavers to place a patient-specific surgical guide, and a CT scan determines the achieved pin hole positions. The achieved pin hole positions are compared to the planned positions. After a number of data points are collected for one segmentation method, several other segmentation methods with altered parameters would need to be evaluated in the same manner. The segmentation method showing the least error would be considered to have the optimized parameters. Examples of such parameters to be evaluated would be thresholding (for several different steps in the procedure), dilating/eroding the 3D body, and smoothing.

VIII.C Future Experimental Study

For future experimental studies, the precision should be reevaluated after design improvements are implemented. The Segmentation Improvements section also listed two possible experimental studies to optimize segmentation parameters. However, the patient-specific guides will also need to be tested as patient-ready devices. The segmentation methods
used for these studies are not FDA approved. The segmentation program could be fixed, rewritten as more robust language (in C++ for instance, instead of MatLab® [134]), and could possibly obtain FDA approval. However, the Amira® [135] segmentation method could not be used in the clinical setting because the program is specifically listed for research only and is not an FDA approved device. Therefore, a segmentation method that can be submitted to the FDA will need to be finalized and used in a future cadaver series. In addition, the patient-specific devices were not 3D printed in a biocompatible material and were not sterilized for surgery. Once the patient-specific guide designs are finalized, the devices should be tested in a cadaver series where they are 3D printed using the correct material and sterilized before surgery as if they were for a real patient. The devices will also have to be tested with market-released implants, or with new implant designs that are ready to be filed with the FDA and manufactured as a production equivalent. The previous tests used 3D printed implants that are not ready to be filed with the FDA. Following the success of these tests, approval from an institutional review board could be sought after for clinical trials. In the clinical trials, measures such as time of surgery and cost of surgery could be evaluated in addition to the effectiveness of the patient-specific guides.

In addition to improving and testing the accuracy and precision of the patient-specific instruments, it will be important to establish their long-term clinical relevance. Many studies have shown the correlation between implant malposition and dislocation, however few studies prospectively show that high precision implantation techniques result in significantly less dislocations. To establish the sensitivity of implant malposition, a biomechanical study should be conducted. Such a study could involve finite element analysis and/or a dynamic range of motion study to predict the severity of implant malposition across a range of orientations, depths, and size of implant. This would further define a clinically relevant required implant precision and accuracy for techniques such as PSIs, navigation, or robotics. After PSIs have been used in patients for 2 or more years, it will also be important to report on the dislocation rate as compared
to manual techniques. Such a study would test the postulation that patient-specific instruments can reduce the rate of dislocation due to the increased accuracy and precision of implantation.

VIII.D Conclusions

Current literature on THA has correlated implant malposition to an increased rate of dislocation [16,20,21,26–36]. The ideal implant position has been debated as a range of angular implant orientations, matching the native center of rotation, restoring leg length and hip offset, and even personalized orientations via biomechanical and gait analyses. New technologies have been developed to improve implantation precision, and are beginning to show reduced rates of dislocation [118]. The technologies that deliver the highest precision require a large capital investment and increase surgical time [99,105,109]. Such an investment can be limited to hospitals with a high volume of THAs/yr. Unfortunately, regardless of years of experience, surgeons operating at a low volume of THAs/yr have the lowest precision when using conventional techniques, and could benefit most from such new technologies [64]. Patient-specific guides have been used in other large joints as an alternative technology for precise implantation, without requiring a large capital investment, but have been underdeveloped for THA [127].

For this dissertation, patient-specific guides for total hip arthroplasty, as well as accompanying implants, and instrumentation were designed and tested. The devices were tested in six foam bone model bench tests, two cadaver pilot tests, and one series of 20 cadaver THA procedures. The patient-specific guide designs were patented and evaluated for commercialization [150]. A segmentation method was created for these tests, and a method of 3D mesh registration for measuring the achieved implant positions. The results of these studies showed that patient-specific guides have a hope in improving the accuracy and precision of traditional THA surgery. The patient-specific devices for acetabular preparation and implantation did not, however, show improvement upon traditional techniques in their current
state. Although the data showed high precision in aligning an acetabular cup implant with a single guide pin. Future improvements in segmentation and guide design are expected to improve the overall precision in positioning a patient-specific acetabular guide so that the guide pin is correctly placed for aligning the cup. The patient-specific devices for femoral preparation and implantation yielded accuracies averaging less than 7° and 4mm of error for all critical measures. The prospective design and segmentation improvements are expected to increase the accuracy and precision of these devices. As the volume of THAs per year increases with the aging population, it is expected that the development of patient-specific planning tools will advance in their ability to pinpoint ideal implant positioning for each patient. Precision implantation tools are in development to match the required accuracy, and patient-specific instruments will likely rise as an alternative solution to computer navigation and robotic-guided THA, as a more cost-effective option for low-volume surgeons. This dissertation presented the initial development of these devices, proved its feasibility and showed hope for improvement over current techniques.
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Appendix I: Semi-Automated MatLab® Segmentation Code
*Functions in alphabetical order. Primary program titled 'MATLAB_Segmentation_Code' on page 172

1/24/17 2:10 PM F:\Ortho-Specific\MatLab ...\CT No Femur.m   1 of 1

% Confidential - University of Cincinnati

function [CTnoFemur, FinalRHTFemur, FinalLFTFemur, Total_Final_Time] = CT_No_Femur
(CoronalSlices, Femur_Matrix, OnesM, Total_Final_Time)

% CT No Femur
fprintf('Applying the femur mask in the CT scan \n');
tic %starting the time measurement for this section of the code

% A Mask is created and used to multiply the Coronal slices in order to
% isolate the pelvis
CTmultiplier = OnesM - Femur_Matrix;
% CTnoFemur = CTmultiplier.*double(CoronalSlices);

% The Mask is separated in the right and left side and a cleaning is made
% to get rid of any unwanted pixels
RHTFemur = Femur_Matrix(:,:,1:257,:);
LFTFemur = Femur_Matrix(:,:,256:512,:);

cc = bwconncomp(LFTFemur);
numPixels = cellfun(@(numel,cc.PixelIdxList);
[biggest, idx] = max(numPixels);
FinalLFTFemur = zeros(size(Femur_Matrix,1),257,512);
FinalLFTFemur(cc.PixelIdxList(idx)) = 1;

cc = bwconncomp(RHTFemur);
numPixels = cellfun(@(numel,cc.PixelIdxList);
[biggest, idx] = max(numPixels);
FinalRHTFemur = zeros(size(Femur_Matrix,1),257,512);
FinalRHTFemur(cc.PixelIdxList(idx)) = 1;

% After the cleaning, the right and left mask are concatenated to make a
% final version of the femur mask
Cleared_CT = [];
for Yslice = 1:size(FinalLFTFemur,3)
    Cleared_CT(:,:,Yslice) = horzcat(FinalRHTFemur(:,:,1:256,Yslice), FinalLFTFemur(:,:,2:257,Yslice));
end

% The mask is applied in the CT scan
CTmultiplier = OnesM - Cleared_CT;
CTnoFemur = CTmultiplier.*double(CoronalSlices);

clear CTMultiplier Cleared_CT OnesM Femur_Matrix %Memory Management
fprintf('Mask successfully applied');

time = toc;
Total_Final_Time = Total_Final_Time+time;
fprintf('Point Cloud Generation complete in 0.3f seconds\n','time);
function [CTnoPelvis, OnesM, Total_Final_Time] = CT_No_Pelvis(CoronalSlices, PelvisB, ✔
                          Total_time, Total_time1)

fprintf('Applying the pelvis mask in the CT scan \n');
tic % starting the time measurement for this section of the code

% A ones matrix is created to make the base for the pelvis mask and the
% mask is applied in the CT scan
OnesM = ones(size(CoronalSlices));
CTMultiplier = OnesM - PelvisB;
CTnoPelvis = CTMultiplier.*double(CoronalSlices);

clear Xc CTMultiplier % Memory Management
fprintf('Mask successfully applied \n');

time = toc;
Total_Final_Time = Total_time1 + Total_time + time;
% Calculate the eigenvalues of massive 3x3 real symmetric matrices.  
% Computation is based on matrix operation and GPU computation is  
% supported.  
% Syntax:  
% [eigenval1,eigenvalue2,eigenvalue3] = eigenvaluefield33( a11, a12, a13, a22, a23,  
% a33)  
% a11, a12, a13, a22, a23 and a33 specify the symmetric 3x3 real symmetric  
% matrices as:  
% a11 a12 a13  
% a12 a22 a13  
% a13 a23 a33  
% These six inputs must have the same size. They can be 2D, 3D or any  
% dimension. The outputs eigenval1, eigenvalue2 and eigenvalue3 will  
% follow the size and dimension of these inputs. Owing to the use of  
% trigonometric functions, the inputs must be double to maintain the  
% accuracy.  
% eigenval1, eigenvalue2 and eigenvalue3 are the unordered resultant  
% eigenvalues. They are solved using the cubic equation solver, see  
% http://en.wikipedia.org/wiki/Eigenvalue_algorithm  
% The peak memory consumption of the method is about 1.5 times of the total  
% of all inputs, in addition to the original inputs. GPU computation is  
% used automatically if all inputs are matlab GPU arrays.  
% Author: Max W.R. Law  
% Email: max.w.r.law@gmail.com  
% Page: http://www.cse.ust.hk/~maxlawwk/  

function [b,j,d] = eigenvaluefield33( a11, a12, a13, a22, a23, a33)  
% multiprocess;  
% b=a11*0;  
% j=a11*0;  
% d=a11*0;  
% parfor i=1: numel(a11)  
% [~,j]=eig([a11(i) a12(i) a13(i); a12(i) a22(i) a23(i); a13(i) a23(i) a33(i)]);  
% b(i)=1(1,1);  
% j(i)=1(2,2);  
% d(i)=1(3,3);  
% end  
% return;  
ep=1e-50;  
b=double(a11)+ep;  
d=double(a23)+ep;  
j=double(a33)+ep;  

  c = -(double(a12).^2 + double(a13).^2 + double(a23).^2 - b.*d - d.*j - j.*b);  
d = -(b.*d.*j - double(a23).*2.*b - double(a12).*2.*j - double(a13).*2.*d + 2*double(a13).*double(a12).*double(a23)));
b = -double(a11) - double(a22) - double(a33) - ep - ep -ep;

d = d + ((2*b.^3) - (9*b.*c))/27;

% c = c - (b.*c)/3;
% c = c.^3;
% c = c/27;
% c = (d.^2/4 - (d.^2/4 + c));

%%%% c = (d.^2/4 - (d.^2/4 + ((3 * c - (b.*c))/3).^3/27));

j = c.*c/1/3;

c = c+ (c == 0);

d = -d/2/./c;

d = max(d, 1);

d = max(d, -1);

d = real(acos(d)/3);

j = single(-c-d+b);

d = single(-c+d+b);

b = single(2*c+b);

end
function [ center, radii, evecs, v ] = ellipsoid_fit( X, flag, equals )
%
% Fit an ellipsoid/sphere to a set of xyz data points:
%
%  [center, radii, evecs, pars ] = ellipsoid_fit( X )
%  [center, radii, evecs, pars ] = ellipsoid_fit( [x y z] );
%  [center, radii, evecs, pars ] = ellipsoid_fit( X, 1 );
%  [center, radii, evecs, pars ] = ellipsoid_fit( X, 2, 'xz' );
%  [center, radii, evecs, pars ] = ellipsoid_fit( X, 3 );
%
% Parameters:
% * X, [x y z] - Cartesian data, n x 3 matrix or three n x 1 vectors
% * flag - 0 fits an arbitrary ellipsoid (default),
%          1 fits an ellipsoid with its axes along [x y z] axes
%          2 followed by, say, 'xy' fits as 1 but also x_rad = y_rad
%          3 fits a sphere
%
% Output:
% * center - ellipsoid center coordinates [xc; yc; zc]
% * ax - ellipsoid radii [a; b; c]
% * evecs - ellipsoid radii directions as columns of the 3x3 matrix
% * v - the 9 parameters describing the ellipsoid algebraically:
%      Ax^2 + By^2 + Cz^2 + 2Dxy + 2Exz + 2Fyz + 2Gx + 2Hy + 2Iz = 1
%
% Author:
% Yury Petrov, Northeastern University, Boston, MA
%
error( nargchk( 1, 3, nargin ) ); % check input arguments
if nargin == 1
    flag = 0; % default to a free ellipsoid
end
if flag == 2 && nargin == 2
    equals = 'xy';
end

if size( X, 2 ) ~= 3
    error( 'Input data must have three columns!' );
else
    x = X(:, 1);
    y = X(:, 2);
    z = X(:, 3);
end

% need nine or more data points
if length( x ) < 9 && flag == 0
    error( 'Must have at least 9 points to fit a unique ellipsoid' );
end
if length( x ) < 6 && flag == 1
    error( 'Must have at least 6 points to fit a unique oriented ellipsoid' );
end
if length(x) < 5 && flag == 2
    error( 'Must have at least 5 points to fit a unique oriented ellipsoid with two axes equal' );
end
if length(x) < 3 && flag == 3
    error( 'Must have at least 4 points to fit a unique sphere' );
end
if flag == 0
    % fit ellipsoid in the form Ax^2 + By^2 + Cz^2 + 2Dxy + 2Exz + 2Fyz + 2Gx + 2Hy + 2Iz = 1
    D = [ x.*x, ...
          y.*y, ...
          z.*z, ...
          2*x.*y, ...
          2*x.*z, ...
          2*y.*z, ...
          2*x, ...
          2*y, ...
          2*z ]; % ndatapoints x 9 ellipsoid parameters
elseif flag == 1
    % fit ellipsoid in the form Ax^2 + By^2 + Cz^2 + 2Gx + 2Hy + 2Iz = 1
    D = [ x.*x, ...
          y.*y, ...
          z.*z, ...
          2*x, ...
          2*y, ...
          2*z ]; % ndatapoints x 6 ellipsoid parameters
elseif flag == 2
    % fit ellipsoid in the form Ax^2 + By^2 + Cz^2 + 2Gx + 2Hy + 2Iz = 1,
    % where A = B or B = C or A = C
    if strcmp( equals, 'yz' ) || strcmp( equals, 'zy' )
        D = [ y.*y + z.*z, ...
              x.*x, ...
              2*x, ...
              2*y, ...
              2*z ];
    elseif strcmp( equals, 'xz' ) || strcmp( equals, 'zx' )
        D = [ x.*x + z.*z, ...
              y.*y, ...
              2*x, ...
              2*y, ...
              2*z ];
    else
        D = [ x.*x + y.*y, ...
              z.*z, ...
              2*x, ...
              2*y, ...
              2*z ];
    end
else
    
end
% fit sphere in the form A(x^2 + y^2 + z^2) + 2Gx + 2Hy + 2Hz = 1
D = [ x .* x + y .* y + z .* z, ... 
  2 * x, ... 
  2 * y, ... 
  2 * z ];  % n datapoints x 4 sphere parameters

% solve the normal system of equations
v = ( D' * D ) \ ( D' * ones( size( x, 1 ), 1 ) );

% find the ellipsoid parameters
if flag == 0
    % form the algebraic form of the ellipsoid
    A = [ v(1) v(4) v(7); ... 
          v(4) v(2) v(6); ... 
          v(7) v(6) v(9); ... 
          v(8) v(9) -1 ];
    % find the center of the ellipsoid
    center = -A( 1:3, 1:3 ) \ [ v(7); v(8); v(9) ];
    % form the corresponding translation matrix
    T = eye( 4 );
    T( 4, 1:3 ) = center';
    % translate to the center
    R = T * A * T';
    % solve the eigenproblem
    [ evecs evals ] = eig( R( 1:3, 1:3 ) / -R( 4, 4 ) );
    radii = sqrt( 1 ./ diag( evals ) );
else
    if flag == 1
        v = [ v(1) v(2) v(3) 0 0 0 v(4) v(5) v(6) ];
    elseif flag == 2
        if strcmp( equals, 'xz' ) || strcmp( equals, 'zx' )
            v = [ v(1) v(2) v(1) 0 0 0 v(4) v(5) ];
        elseif strcmp( equals, 'yz' ) || strcmp( equals, 'zy' )
            v = [ v(2) v(1) v(1) 0 0 0 v(4) v(5) ];
        else % xy
            v = [ v(1) v(1) v(2) 0 0 0 v(3) v(4) v(5) ];
        end
    else
        v = [ v(1) v(1) v(1) 0 0 0 v(2) v(3) v(4) ];
    end
    center = ( -v( 7:9 ) ./ v( 1:3 ) )';
    gam = 1 + ( v(7)^2 / v(1) + v(8)^2 / v(2) + v(9)^2 / v(3) );
    radii = [ sqrt( gam ./ v( 1:3 ) ) ]';
    evecs = eye( 3 );
end
function [Femur_Matrix, Lambda] = Femur_Segmentation(CTnoPelvis)

%% Find the Femurs
xx = CTnoPelvis>350;
SE = strel('disk',10);
xx = imdilate(xx,SE);
CC = bwconncomp(xx);
S = regionprops(CC, 'Area');
L = labelmatrix(CC);
Area = sort([S.Area],'Descend');
xx = ismember(L, find([S.Area] >= Area(2)));
CC = bwconncomp(xx);
S = regionprops(CC, 'BoundingBox');

Lambda = zeros(size(CTnoPelvis));
%% First Femur
%% Limit the domain to just femurs
I_temp = CTnoPelvis(ceil(S(1).BoundingBox(2)):floor(S(1).BoundingBox(2)+S(1).BoundingBox(5)),:,:),...
        ceil(S(1).BoundingBox(1)):floor(S(1).BoundingBox(1)+S(1).BoundingBox(4)),:,:),...
        ceil(S(1).BoundingBox(3)):floor(S(1).BoundingBox(3)+S(1).BoundingBox(6)),:,:);

% I_temp([1 end],:,:) = min(I_temp(:,:)); I_temp(:,[1 end],:) = min(I_temp(:,:)); I_temp(:,:,1:end) = min(I_temp(:,:,:));
% Run MaxFlow Algorithm
[Lambda_temp] = MaxFlow3D(I_temp);

Lambda(ceil(S(1).BoundingBox(2)):floor(S(1).BoundingBox(2)+S(1).BoundingBox(5)),:,:),...
        ceil(S(1).BoundingBox(1)):floor(S(1).BoundingBox(1)+S(1).BoundingBox(4)),:,:),...
        ceil(S(1).BoundingBox(3)):floor(S(1).BoundingBox(3)+S(1).BoundingBox(6)),:,:)) = Lambda_temp;
clear Lambda_temp I_temp

%% Second Femur
%% Limit the domain to just femurs
I_temp = CTnoPelvis(ceil(S(2).BoundingBox(2)):floor(S(2).BoundingBox(2)+S(2).BoundingBox(5)),:,:),...
        ceil(S(2).BoundingBox(1)):floor(S(2).BoundingBox(1)+S(2).BoundingBox(4)),:,:),...
        ceil(S(2).BoundingBox(3)):floor(S(2).BoundingBox(3)+S(2).BoundingBox(6)),:,:);

% I_temp([1 end],:,:) = min(I_temp(:,:)); I_temp(:,[1 end],:) = min(I_temp(:,:)); I_temp(:,:,1:end) = min(I_temp(:,:,:));
% Run MaxFlow Algorithm
[ Lambda_temp ] = MaxFlow3D( I_temp );

Lambda( ceil(S(2).BoundingBox(2)):floor(S(2).BoundingBox(2)+S(2).BoundingBox(5)),...
   ceil(S(2).BoundingBox(1)):floor(S(2).BoundingBox(1)+S(2).BoundingBox(4)),...
   ceil(S(2).BoundingBox(3)):floor(S(2).BoundingBox(3)+S(2).BoundingBox(6)) ) = Lambda_temp;
clear Lambda_temp I_temp

% Femur_Matrix = Lambda>0.3;
Femur_Matrix = Lambda>0.3;
CC = bwconncomp(Femur_Matrix);
S = regionprops(CC,'Area');
Area = [S(:,Area)];
Area = sort(Area,'descend');
Femur_Matrix = bwareaopen(Femur_Matrix,4000);
Femur_Matrix = imfill(Femur_Matrix,'holes');
function [Pelvis, PelvisB, Total_time1, Total_time] = Final_Pelvis(PelvisRHT, MaskLFT, ✓
LeftCoronalSlices, LeftCoronalBinaryMatrix, SobelEdges1, Total_time1, Total_time);

tic

% With the Final Mask created, the mask is dilated and multiplied by the
% ellipsoid matrix again. This is used to make sure we got every point in
% the pelvis and don’t get any point of the femur. Finally, the image is
% multiplied by the edge detected image and output the final result for the
% left side
PelvisLFT = [];
for Yslice = 1:size(LatCoronalSlices,3)
    Dilate = imdilate(MaskLFT(:,:,Yslice), strel('disk',1), 'same');
    Dilate = imdilate(Dilate, strel('disk',8), 'same');
    FemurMaskLFT(:,:,Yslice) = Dilate.*LeftCoronalBinaryMatrix(:,:,Yslice);
    PelvisLFT(:,:,Yslice) = FemurMaskLFT(:,:,Yslice).*SobelEdges1(:,:,Yslice);
end

clear Dilate FemurMaskLFT MaskLFT

% Display the time for this section for analysis purpose
Tic = toc;
Total_time1 = Total_time1 + Tic;
fprintf('Left Side Cleaning complete in %.3f seconds \n', Tic);


tic
% Now that the masks for the right and left side are created, both masks
% are concatenated together to make the final mask for the pelvis. The mask
% is finally transformed into a logical variable to be further applied in
% the CT scan
Pelvis = [];
for Yslice = 1:size(PelvisRHT,3)
    Pelvis(:,:,Yslice) = horzcat(PelvisRHT(:,:,1:256,Yslice), PelvisLFT(:,:,2:257,Yslice));
end
clear PelvisRHT PelvisLFT
PelvisB = logical(Pelvis>0);
Tic = toc;
Total_time1 = Total_time1 + Tic;
fprintf('Pelvis Left Side complete. Time elapsed %.3f seconds \n', Tic);
fprintf('Total operation time: %.3f seconds \n', Total_time1 + Total_time1);
function [g3,g3x,g3y,g3z]=Gaussian3(SD,g_radius)

% SETTING UP THE KERNEL WINDOW
range=-g_radius:g_radius;
[x,y,z]=meshgrid(range,range,range);

% CALCULATE THE GAUSSIAN DIST. AND ITS DERIVATIVES
      g3=(exp(-((x.^2+y.^2+z.^2)/(2*SD^2))))/(((2*pi)^1.5)*SD^3); g3 = g3/sum(g3(:));
g3x=-x/SD^2.*g3; g3x = g3x / (sum(abs(g3x(:))));
g3y=-y/SD^2.*g3; g3y = g3y / (sum(abs(g3y(:))));
g3z=-z/SD^2.*g3; g3z = g3z / (sum(abs(g3z(:))));
function [] = implay_AutoColorMap(image)

handle = implay(image);

% Confidential - University of Cincinnati

function [xLFTcenter,yLFTcenter,zLFTcenter,Total_time1] = Left_Center_Determination\(Yslice, AxialSlices, LeftCoronalSlices, XscaleRight, Xscale, Yscale, Zscale, Xresol, Yresol, Zresol, Total_time1)\)

% Center Determination
 tic % Starting the time measurement for this section of the code

% Set the slice for selecting points to determine the center of the left femur and set the zoom on
figure(7)
X=LeftCoronalSlices(:, :, Yslice);
imagesc(XscaleRight, Zscale, X); colormap(gray(256)); axis equal;
xlabel('x [mm]'); ylabel('z [mm]');
title(['\textbf{Select Center of Left Femoral Head}'; ['\textsize{12}Coronal Slice #', num2str(Yslice)])];
zoom on
pause()
[x1,z]=getpts(figure(7));
Zslice=round(z/Zresol);
X=AxialSlices(:, :, Zslice);
imagesc(Xscale, Yscale, X); colormap(gray(256)); axis equal; axis tight;
xlabel('x [mm]'); ylabel('y [mm]');
title(['\textbf{Select Center of Left Femoral Head (The one on the right)}'; ['\textsize{12}Axial Slice #', num2str(Zslice)])];
zoom on
pause()
[x1,y]=getpts(figure(7));

% Average both measurements
xLFTcenter=round(((x1+x1+255*Xresol)/2)/Xresol);
yLFTcenter=round(y/Yresol);
zLFTcenter=Zslice;

% Display the time for this section for analysis purpose
fprintf('Center Determination complete \n');
time = toc;
Total_time1 = Total_time1+time;
% Confidential - University of Cincinnati

function [SobelEdges1,Total_time] = Left_Edge_Detection(Yslice,LeftCoronalSlices,
  Total_time);

tic %starting the time measurement for this section of the code
fprintf('Starting Edge detection Process\n');

%Begins by analyzing Coronal Slice 281, a slice that shows the joint line

X=LeftCoronalSlices(:,:,Yslice);

%Perform Sobel Edge detection
SobelX=[-1 0 1; -2 0 2; -1 0 1];
SobelX(:,:,2)=[-2 0 2; -4 0 4; -2 0 2];
SobelX(:,:,3)=[-1 0 1; -2 0 2; -1 0 1];
SobelX=single(SobelX);
SobelY=[1 2 1;0 0 0; -1 -2 -1];
SobelY(:,:,2)=[2 4 2; 0 0 0; -2 -4 -2];
SobelY(:,:,3)=[1 2 1;0 0 0; -1 -2 -1];
SobelY=single(SobelY);
Sobel12=[1 2 1;2 4 2; 1 2 1];
Sobel12(:,:,2)=[0 0 0;0 0 0; 0 0 0];
Sobel12(:,:,3)=[-1 -2 -1; -2 -4 -2; -1 -2 -1];
Sobel12=single(Sobel12);
SobelEdges1=sqrt(convn(LeftCoronalSlices,SobelX,'same').^2 + convn(LeftCoronalSlices,SobelY,'same').^2 + convn(LeftCoronalSlices,Sobel12,'same').^2);

%Initial Thresholding to remove soft tissue
Cortical2=(X>126);
ThresholdX=Cortical2.*double(X);
P=18;
NoNoiseX=bwareaopen(ThresholdX,P);

%Fill Holes
se=strel('disk',1);
DilateX=imdilate(NoNoiseX,se,'same');
FilledX=imfill(DilateX,'holes');
BoneShadowX=imerode(FilledX,se,'same');
P=50;
BigGroupsX=imdilate(bwareaopen(BoneShadowX,P),strel('disk',7),'same');

clear Cortical2 %Memory Management

% Display the time for this section for analysis purpose

time = toc;
Total_time = Total_time+time;
fprintf('Edge detection complete in %0.3f seconds \n',time);
function [BinaryMatrix,cavgl,Total_time1] = Left_Ellipsoid_Calculations(AxialSlices,c2,r2,v2,c3,r3,v3,xresol,yresol,zresol,Total_time1);
fprintf('Starting Left Femoral Ellipsoid Calculations\n');
tic

% Starting the time measurement for this section of the code
EllipsoidX = []; EllipsoidY = []; EllipsoidZ = []; Ellipsoid = []; EllipsoidXI=[];
EllipsoidYI=[]; EllipsoidZI=[]; EllipsoidI=[];

% Averaging the femoral head ellipsoid and the acetabular ellipsoid
cavgl=(c2+c3)/2;
ravgl=(r2+r3)/2;
vavgl=(v2+v3)/2;

% Defining parameters to solve the equation
A=vavgl(1); B=vavgl(2); C=vavgl(3); D=vavgl(4); E=vavgl(5); F=vavgl(6); G=vavgl(7);
H=vavgl(8); I=vavgl(9);

% Defining x interval to solve the equations
x=(cavgl(1)-ravgl(1)-1):.5:(cavgl(1)+ravgl(1)+1);

% The slices for the for loop were chosen as the center plus the radius and
% a error margin for a better ellipsoid output. The number 10 showed
% to be a good value to set the ellipsoid in this procedure.
for Zslice = (round((c2(3)-r2(3)-10)/zresol)):(round((c2(3)+r2(3)+10)/zresol))
z=Zslice*zresol;

for K = 1:size(X,2)
    x = X(K);
    y= EQ2;
yl= EQ3;
end

% The results for x, y and z are stored in a vector
EllipsoidX=[EllipsoidX; round(x/Xresol)];
EllipsoidY=[EllipsoidY; round(y/Yresol)];
EllipsoidZ=[EllipsoidZ; round(repmat(z/Zresol,size(X,2),1))];
end

% Defining x interval to solve the equations
Y=(cavgl(2)-ravgl(2)-4):.5:(cavgl(2)+ravgl(2)+4);

% The slices for the for loop were chosen as the center plus the radius and
% a error margin for a better ellipsoid output. The number 10 showed
% to be a good value to set the ellipsoid in this procedure.
for Zslice = (round((c2(3)-r2(3)-10)/zresol)):(round((c2(3)+r2(3)+10)/zresol))
z=Zslice*zresol;

for K = 1:size(Y,2)
y = Y(K);
    x= EQ2;
xl= EQ3;
EllipsoidX1 = [EllipsoidX1; round(x/Xresol) round(x/Xresol)];
EllipsoidY1 = [EllipsoidY1; round(y/Yresol)];
end
EllipsoidZ1 = [EllipsoidZ1; round(repmat(z/Zresol, size(Y, 2), 1))];
end

% The results for the final ellipsoid is stored in two different vectors, % one for the points stored in the coronal plane and the other for the % points stored in the sagittal plane
Ellipsoid = [EllipsoidX EllipsoidY(:, 1) EllipsoidZ; EllipsoidX EllipsoidY(:, 2) EllipsoidZ];
Ellipsoid1 = [EllipsoidX(:, 1) EllipsoidY1 EllipsoidZ1; EllipsoidX(:, 2) EllipsoidY1 EllipsoidZ1];
Ellipsoid = vertcat(Ellipsoid, Ellipsoid1);
clear Ellipsoid1 % Memory management

% Get rid of the imaginary numbers on the final vector
ImagRows = [ ];
for L = 1:size(Ellipsoid, 1)
    if isreal(Ellipsoid(L, :)) == 0
        ImagRows = [ImagRows L];
    end
end
Ellipsoid(ImagRows, :) = [ ];
Ellipsoid = unique(Ellipsoid, 'rows');
clear ImagRows L % Memory management

% A zeros matrix is created and used to store the coordinates for every % point in the ellipsoid as ones
EllMatrix = zeros(size(AxialSlices));
for P = 1:size(Ellipsoid, 1)
    EllMatrix(Ellipsoid(P, 2), Ellipsoid(P, 1), Ellipsoid(P, 3)) = 1;
end
clear Ellipsoid P % Memory management

% A fill command is used to fill the remaining holes in the ellipsoid matrix % The ellipsoid matrix is used to create a matrix where everything is one % besides the ellipsoid points
for p = (round((c2(3) - r2(3) - 10) / Zresol)): (round((c2(3) + r2(3) + 10) / Zresol))
    EllMatrix(:, :, p) = imfill(EllMatrix(:, :, p), 'holes');
end
EllMatrix = imfill(EllMatrix, 'holes');
OnesMatrix = ones(size(EllMatrix));
BinaryMatrix = OnesMatrix - EllMatrix;
clear OnesMatrix EllMatrix p % Memory management

% Display the time for this section for analysis purpose
time = toc;
Total_time1 = Total_time1 + time;
fprintf('Femoral Ellipsoid Calculations complete in %0.3f seconds\n', time);
function [Total_Final_Time] = Left_Femur_Cloud(FinalLFTFemur,Xresol,Yresol,Zresol,✓
Total_Final_Time)

fprintf('Starting left femur point cloud generation \n');
tic %starting the time measurement for this section of the code

% Left Femur Cloud
A2 = [];
LEFTBF = FinalLFTFemur;

% For each slice, the .mat file is transformed into a grayscale image so the
% command bwboundaries can be used to get the pixels in the boundaries
% for each object in the image. Then, the pixels coordinates are stored
% in a vector called A2 and multiplied by de resolution.
for Yslice = 1:size(LEFTBF,3);
    Q = LEFTBF(:,:,Yslice);
    I = mat2gray(Q);
    [B,L,N] = bwboundaries(I);
    for k=1:length(B),
        boundary = B{k};
        A2 = [A2; boundary(:,2) repmat((size(LEFTBF,3)-Yslice),size(boundary,1),1)];
    end
end
A2(:,1) = A2(:,1).*Xresol + (size(FinalLFTFemur,2)-1)*Xresol; %x
A2(:,2) = A2(:,2).*Yresol; %y
A2(:,3) = A2(:,3).*Zresol; %z

% After the first set of points is sorted, the matrix is rotated and the
% same process is repeated so the pixels in boundaries that couldn't be
% reached in the previous code can be stored
TransversalLFTFemur = [];
for i=1:size(LEFTBF,3);
    TransversalLFTFemur (:,:,i)=flipud(LEFTBF(:,:,i));
end
Xc=num2cell(TransversalLFTFemur ,[1,2]);
Xc=cellfun(@(x) rot90(x,1),Xc,'uni',false);
TransversalLFTFemur =cat(3,Xc(:,i));
TransversalLFTFemur =permute(TransversalLFTFemur ,[3,1,2]);
A3 = [];
for Zslice = 1:size(TransversalLFTFemur ,3);
    Q = logical(TransversalLFTFemur (:,:,Zslice)>0);
    I = mat2gray(Q);
    [B,L,N] = bwboundaries(I);
    for k=1:length(B),
        boundary = B{k};
        A3 = [A3; boundary(:,2) boundary(:,1) repmat(Zslice,size(boundary,1),1)];
    end
end
clear TransversallLFTFemur Xc
A3(:,1) = A3(:,1).*Xresol + (size(FinalLFTFemur,2)-1)*Xresol; %x
A3(:,2) = (size(LEFTBF,3)-A3(:,2)).*Yresol; %y
A3(:,3) = A3(:,3).*Zresol; %z

% Both matrices are concatenated into one n-by-3 matrix representing the
% coordinates for all the pixels in the boundaries. After that, the
% repeated rows are eliminated for a better point cloud without double
% points.
A3 = vertcat(A2,A3);
A3 = unique(A3,'rows');

% The file is stored as a .xyz file in the current MATLAB folder
csvwrite('LFTFemurCloud.xyz',A3)
clear A2 A3 LEFTBF %Memory Management
time = toc;
Total_Final_Time = Total_Final_Time+time;
fprintf('Point Cloud Generation complete in %0.3f seconds
',time);
% Confidential - University of Cincinnati

function [MaskLFT,LeftCoronalBinaryMatrix,Total_time1] = Left_Femur_Mask_Calculations(BinaryMatrix,LeftCoronalSlices,Nx,Total_time1);

fprintf('Starting Left Femur Mask Calculations and Cleaning\n');
 tic
% Rotates AxialSlices 90 degrees and stores them as CoronalSlices, which
% can be accessed by CoronalSlices(:, :, a)
CoronalBinaryMatrix=permute(BinaryMatrix,[2,3,1]);
Xc=num2cell(CoronalBinaryMatrix,[1,2]);
Xc=cellfun(@(x) rot90(x,-1),Xc,'uni',false);
CoronalBinaryMatrix=cat(3,Xc{:});
 for i=1:size(BinaryMatrix,1);
     CoronalBinaryMatrix(:, :, i)=flipud(CoronalBinaryMatrix(:, :, i));
 end
LeftCoronalBinaryMatrix=single(CoronalBinaryMatrix(:,1:Nx/2+1,:));
clear CoronalBinaryMatrix

% Apply the threshold, fill the holes and take of the right femoral head
% using the ellipsoid
MaskLFT = zeros(size(LeftCoronalSlices));FinalMask = []; 
 for Yslice = 1:size(LeftCoronalSlices,3)-117
     W = LeftCoronalSlices(:, :, Yslice);
     Cortical2=(W>216); % Changed to 300 for Gloria
     Threshold=Cortical2.*double(W).*LeftCoronalBinaryMatrix(:, :, Yslice);
     P=18;
     NoNoise=bwareaopen(Threshold,P);
     se=strel('disk',1);
     Dilate=imdilate(NoNoise,se,'same');
     Filled=imfill(Dilate,'holes');
     BoneShadow=imerode(Filled,se,'same');
     P=10;
     % BigGroups=imdilate(bwareaopen(BoneShadow,P),strel('disk'),7),'same');
     % BigGroups=imerode(BigGroups,strel('disk'),7),'same');
     % BigGroups=imfill(BigGroups,'holes');
     BigGroups=imfill(BoneShadow,'holes');
     MaskLFT(:, :, Yslice) = BigGroups.*LeftCoronalBinaryMatrix(:, :, Yslice);
 end
 clear Cortical2 BigGroups BoneShadow Filled Dilate NoNoise Threshold W %Memory Management

% Display the time for this section for analysis purpose
 time = toc;
 Total_time1 = Total_time1+time;
 fprintf('Left Femur Mask Calculations complete in %0.3f seconds\n',time);
 tic
 % The element with the most number of pixels is choose in the
 % RightBinarymatrix and teh rest is deleted. This should get rid of
 % everything besides the pelvis
 cc = bwconncomp(MaskLFT);
numPixels = cellfun(@(numel,cc.PixelIdxList)
    [SortedPixels,I]=sort(numPixels,'descend');
idx=I(1);
MaskLFT = zeros(size(LeftCoronalSlices));
MaskLFT(cc.PixelIdxList(idx)) = 1;
imshow(MaskLFT)
disp('Scroll through to see if femur is masked')
pause
button=questdlg('Is the femur masked?','Confirm Mask','Yes','No','Yes');
switch button
    case 'Yes'
      disp('Femur successfully masked')
    case 'No'
      idx=I(2);
      MaskLFT = zeros(size(LeftCoronalSlices));
      MaskLFT(cc.PixelIdxList(idx)) = 1;
      imshow(MaskLFT)
pause
      button=questdlg('Is the femur masked?','Confirm Mask','Yes','No','Yes');
      switch button
        case 'Yes'
          disp('Femur successfully masked')
        case 'No'
          idx=I(3);
          MaskLFT = zeros(size(LeftCoronalSlices));
          MaskLFT(cc.PixelIdxList(idx)) = 1;
          imshow(MaskLFT)
          disp('Will continue as is')
          pause
      end
end

% Display the time for this section for analysis purpose
time = toc;
Total_time1 = Total_time1+time;
fprintf('Left Side Cleaning complete in %0.3f seconds \n',time);
% Confidential - University of Cincinnati

function [c2,r2,e2,v2,c3,r3,e3,v3,Total_time] = Left_Gather_Ellipsoid_Points
(AxialSlices,LeftCoronalSlices,SobelEdges1,xLFTcenter,yLFTcenter,zLFTcenter,Xresol,Yresol,Zresol,Total_time);

tic % Starting the time measurement for this section of the code
% Gather Ellipsoid Points
% Set scales and limits for the selection of ellipsoid points
x=[ ]; y=[ ]; z=[ ]; cupx=[ ]; cupy=[ ]; cupz=[ ];
Xlim=(xLFTcenter-50:255); Xlim(xLFTcenter+50:255);
Ylim=(yLFTcenter-50:255); Ylim(yLFTcenter+50);
Zlim=(zLFTcenter-50:255); Zlim(zLFTcenter+50);
XlftScale=[Xlim(1)*Xresol Xlim(101)*Xresol];
YlftScale=[Ylim(1)*Yresol Ylim(101)*Yresol];
ZlftScale=[Zlim(1)*Zresol Zlim(101)*Zresol];

% Set the Yslice (based on the center), apply threshold, fill and display
% the image to the user so he can select the points for the ellipsoids
figure(7)
Yslice=yLFTcenter+16;
X=LeftCoronalSlices(:, :, Yslice);
Cortical2=(X>126);
ThresholdX=Cortical2.*double(X);
P=18;
NoNoiseX=bwareaopen(ThresholdX,P);
se=strel('disk',1);
FilledX=imfill(DilateX,'holes');
BoneShadowX=bwareaopen(FilledX,P);
BoneEdgesX=SobelEdges1(:, :, Yslice).*BigGroupsX;
imagesc(XlftScale, ZlftScale, BoneEdgesX(Zlim,Xlim));
colormap(gray(256)); axis equal; axis tight; xlabel('x(mm)'); ylabel('z(mm)');
title(['ontsize{16}Select Points on Left \bf Femoral Head'; 'ontsize{12}Coronal Slice #',num2str(Yslice)]);
x=x(x;x1); z=[z;z1]; y=[y; remat(Yslice*Yresol,size(x1,1),1)];

figure(7);
x=[cupx;x2]; cupx=[cupz;z2]; cupz=[cupx;x2];

% Set a new Yslice (based on the center), apply threshold, fill and display
% the image to the user so he can select the points for the ellipsoids
Yslice=yLFTcenter+16;
X=LeftCoronalSlices(:, :, Yslice);
Cortical2=(X>126);
ThresholdX=Cortical2.*double(X);
P=18;
NoNoiseX=bwareaopen(ThresholdX,P);
se=strel('disk',1);
DilateX=imdilate(NoNoiseX,se,'same');
FilledX=imfill(DilateX,'holes');
BoneShadowX=imerode(FilledX,se,'same');
P=50;
BigGroupsX=imdilate(bwareaopen(BoneShadowX,P),strel('disk',7),'same');
BoneEdgesX=SobelEdges1(:,:,Yslice).*BigGroupsX;
imagesc(XlimScale, YlimScale, BoneEdgesX(Xlim,Xlim));
colorbar(gray(256)); axis equal; axis tight; xlabel('x(mm)'); ylabel('y(mm)');
title('{\footnotesize Select Points on Left \textit{bfFemoral Head}}';
   '{\footnotesize Coronal Slice #}', num2str(Yslice)));
[x1,z1]=getpts(figure(7));
x=[x1;x1]; z=[z1;z1]; y=[y;repmat(Yslice*Yresol,size(x1,1),1)];

title('{\footnotesize Select Points on Left \textit{bfAcetabular Cup}}';
   '{\footnotesize Coronal Slice #}', num2str(Yslice)));
[x2,z2]=getpts(figure(7));
cupx=[cupx;x2]; cupz=[cupz;z2]; cupy=[cupy;repmat(Yslice*Yresol,size(x2,1),1)];

% Set a Zslice(based on the center for the ellipsoid), apply threshold,
% fill and display the image to the user so he can select the points for
% the ellipsoid
Zslice=ZLEFCTcenter+16;
X=AxialSlices(:,:,Zslice);
Cortical2=(X>126);
ThresholdX=Cortical2.*double(X);
P=18;
NoNoiseX=bwareaopen(ThresholdX,P);
se=strel('disk',1);
DilateX=imdilate(NoNoiseX,se,'same');
FilledX=imfill(DilateX,'holes');
BoneShadowX=imerode(FilledX,se,'same');
P=50;
BigGroupsX=imdilate(bwareaopen(BoneShadowX,P),strel('disk',7),'same');
for i=1:256
    AxialSobelSlice(:,:,i)=SobelEdges1(Zslice,i,:);
end
BoneEdgesX=AxialSobelSlice.*BigGroupsX(:,:,257:512);
imagesc(XlimScale, YlimScale, BoneEdgesX(Ylim,Xlim));
colorbar(gray(256)); axis equal; axis tight; xlabel('x(mm)'); ylabel('y(mm)');
title('{\footnotesize Select points on Left \textit{bfFemoral Head}}';
   '{\footnotesize Axial Slice #}', num2str(Zslice)));
[x1,y1]=getpts(figure(7));
x=[x1;x1]; y=[y1;y1]; z=[z;repmat(Zslice*Zresol,size(x1,1),1)];

title('{\footnotesize Select Points on Left \textit{bfAcetabular Cup}}';
   '{\footnotesize Axial Slice #}', num2str(Yslice)));
[x2,y2]=getpts(figure(7));
cupx=[cupx;x2]; cupz=[cupz;repmat(Zslice*Zresol,size(x2,1),1)]; cupy=[cupy; y2];
% Set a new Zslice(based on the center for the ellipsoid), apply threshold, 
% fill and display the image to the user so he can select the points for 
% the ellipsoid 
Zslice=LFTcenter-16; 
X=AxialSlices(:,1,Zslice); 
Cortical2=(X>126); 
ThresholdX=Cortical2.*double(X); 
P=18; 
NoNoiseX=bwareaopen(ThresholdX,P); 
se=strel('disk',1); 
DilateX=imdilate(Noise,se,'same'); 
FilledX=imdilate(DilateX,'holes'); 
BoneShadowX=imerode(FilledX,se,'same'); 
P=50; 
BigGroupsX=imdilate(bwareaopen(BoneShadowX,P),strel('disk',7),'same'); 
for i=1:256 

AxialSobelSlice(:,i)=SobelEdges1(Zslice,i,:); 
end 
BoneEdgesX=AxialSobelSlice.*BigGroupsX(:,257:512); 
imagesc(WhiteScale, YtintScale, BoneEdgesX(Ylim,Xlim)); 
colorbar(gray(256)); axis equal; axis tight; xlabel('x(mm)'); ylabel('y(mm)'); 

title({'
Select points on Left \bf Femoral Head';['Select points on Left Axial Slice #';num2str(Zslice))]); 
[x1,y1]=ginput(figure(7)); 
X=[x1;x1]; Z=[Z1;repmat(Zslice*3resol,size(x1,1),1)]; Y=[y1;y1]; 


title({'
Select Points on Left \bf Acetabular Cup';['Select Points on Left Axial Slice #';num2str(Yslice))]); 
[x2,y2]=ginput(figure(7)); 
cupx=[cupx;x2]; cupz=[cupz;repmat(Zslice*3resol,size(x1,1),1)]; cupy=[cupy; y2]; 

% Apply the function ellipsoid_fit to fit an ellipsoid in both set of 
% points 
[c2,r2,e2,v2]=ellipsoid_fit([x,y,z]); 
%c3,r3,e3,v3=ellipsoid_fit([cupx,cupy,cupz]); 
% Output: 
% * center - ellipsoid center coordinates [xc; yc; zc] 
% * ax - ellipsoid radii [a; b; c] 
% * evcs - ellipsoid radii directions as columns of the 3x3 matrix 
% * v - the 3 parameters describing the ellipsoid algebraically: 
% A*x^2 + B*y^2 + C*z^2 + 2Dxy + 2Exz + 2Fyz + 2Gx + 2Hy + 2Iz = 1 

% Display the time for this section for analysis purpose 
close all 
Time = toc; 
Total_time = Total_time+time; 
fprintf('Gather Ellipsoid Points for the Left Femur complete \n');
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function [Total_Final_Time] = Left_Pelvis_Cloud(Left_Pelvis_No_Sacrum,Xresol,Yresol,✓
Zresol,Total_Final_Time)

fprintf('Starting pelvis left side point cloud generation \n');
tic %starting the time measurement for this section of the code

% Left Pelvis Cloud
A1 = [];
Pelvis = Left_Pelvis_No_Sacrum;

% For each slice, the .mat file is transformed into a grayscale image so the
% command bwboundaries can be used to get the pixels in the boundaries
% for each object in the image. Then, the pixels coordinates are stored
% in a vector called A1 and multiplied by de resolution.
for Yslice = 1:size(Pelvis,3);
Q = logical(Pelvis(:,:,Yslice)>0);
I = mat2gray(Q);
[B,L,N] = bwboundaries(I);
for k=1:length(B),
    boundary = B(k);
    boundary = B(k);
    A1 = [A1; boundary(:,2) repmat((size(Pelvis,3)-Yslice),size(boundary,1),1)];
end
end
A1(:,1) = A1(:,1).*Xresol; %x
A1(:,2) = A1(:,2).*Yresol; %y
A1(:,3) = A1(:,3).*Zresol; %z

% After the first set of points is sorted, the matrix is rotated and the
% same process is repeated so the pixels in boundaries that couldn't be
% reached in the previous code can be stored
TransversalPelvis = [];
for i=1:size(Pelvis,3),
    TransversalPelvis(:,:,i)=fliplr(Pelvis(:,:,i));
end
Xc=num2cell(TransversalPelvis,[1,2]);
Xc=cellfun(@(x) rot90(x,1),Xc,'uni',false);
TransversalPelvis=cat(3,Xc(:,:));
TransversalPelvis=permute(TransversalPelvis,[3,1,2]);
A4 = [];
for Zslice = 1:size(TransversalPelvis,3);
Q = logical(TransversalPelvis(:,:,Zslice)>0);
I = mat2gray(Q);
[B,L,N] = bwboundaries(I);
for k=1:length(B),
    boundary = B(k);
    A4 = [A4; boundary(:,2) boundary(:,1) repmat(Zslice,size(boundary,1),1)];
end
end
A4(:,1) = A4(:,1).*Xresol; %x
A4(:,2) = (size(Pelvis,3)-A4(:,2)).*Yresol; %y
A4(:,3) = A4(:,3).*Zresol; %z

% Both matrices are concatenated into one n-by-3 matrix representing the
% coordinates for all the pixels in the boundaries. After that, the
% repeated rows are eliminated for a better point cloud without double
% points.
A4 = vertcat(A1,A4);
A4 = unique(A4,'rows');

% The file is stored as a .xyz file in the current MATLAB folder
csvwrite('Left_Pelvis_No_Sacrum.xyz',A4)
clear A1 A4 Pelvis Xc % Memory Management
time = toc;
Total_Final_Time = Total_Final_Time+time;
fprintf('Point Cloud Generation complete in %0.3f seconds\n',time);
clear all
close all
cic

tic
% Accessing data files: Each file is an axial slice, 512x512
disp('Loading images')
params.CTdata_path = 'E:\Ortho-Specific\006 Fresh Cadaver\Dicom'; %This is the directory of the dicom files
listing=dir(fullfile(params.CTdata_path,'*.dcm'));

if length(listing) == 0
    listing=dir(fullfile(params.CTdata_path));
    listing(1:3) = [];
    listing(end) = [];
end

% Resort the filenames
filenames = {(listing(:,).name)};
filenames = sort_nat(filenames);

oldFolder=pwd;
cd(params.CTdata_path);
meta = dicominfo(listing(1).name);
for i=1:numel(filenames)
    image2D=dicomread(filenames{i});
    AxialSlices(:,:,i)=image2D;
end
AxialSlices = AxialSlices * meta.RescaleSlope + meta.RescaleIntercept;
cd(oldFolder);
clear image2D i listing oldFolder

AxialSlices = AxialSlices - 50;

% The code immediately below is set as comments to save memory
% Rotates AxialSlices 90 degrees and stores them as SagittalSlices, which
% can be accessed by SagittalSlices(:,:,a)
% SagittalSlices=permute(AxialSlices,[3,1,2]);
% Xc=num2cell(SagittalSlices,[1,2]);
% Xc=cellfun(@(x)rot90(x,-1),Xc,'uni',false);
% SagittalSlices=cat(3,Xc(:));

% Rotates AxialSlices 90 degrees and stores them as CoronalSlices, which
% can be accessed by CoronalSlices(:,:,a)
CoronalSlices=permute(AxialSlices,[2,3,1]);
Xc=num2cell(CoronalSlices,[1,2]);
Xc=cellfun(@(x) rot90(x,-1),Xc,'uni',false);
CoronalSlices=cat(3,Xc{:});
for i=1:size(AxialSlices,1);
  CoronalSlices(:,:,i)=flipr(CoronalSlices(:,:,i));
end
CoronalX = size(CoronalSlices,2);
CoronalY = size(CoronalSlices,3);
CoronalZ = size(CoronalSlices,1);

% Defines the resolution of the CT scan, sets scale and store the right half
% of the CT scan, since the whole image is too much for MATLAB to handle
Xresol=0.703125; Yresol=0.703125; % Voxel size
Zresol= 0.625; % Slice thickness
Nx=size(AxialSlices,2); Ny=size(AxialSlices,1); Nz=size(AxialSlices,3);
Xscale=[Xresol Xresol*Nx];
Yscale=[Yresol Yresol*Ny];
Zscale=[Zresol Zresol*Nz];
RightCoronalSlices=single(CoronalSlices(:,:,Nx/2+1,:));
XscaleRight=[Xscale(1) Xscale(2)/2];

implay_AutoColorMap(CoronalSlices);
Handle.Parent.Name='Find a Slice Clearly Showing the Right Joint';
fprintf('Click on the Movie Player Window \nFind a slice that clearly shows the joint\nline for the right joint (left hand side) \nPress enter \n');
pause();
close all hidden
YsliceR = input('Type the number of the slice that shows the joint line for the right\nside: ');
implay_AutoColorMap(CoronalSlices);
Handle.Parent.Name='Find a Slice Clearly Showing the Left Joint';
fprintf('Click on the Movie Player Window \nFind a slice that clearly shows the joint\nline for the left joint (right hand side) \nPress enter \n');
pause();
close all hidden
YsliceL = input('Type the number of the slice that shows the joint line for the left\nside: ');
% Display the time for this section for analysis purpose
time = toc;
Total_time = time;
fprintf('Loading complete in %.3f seconds',time);
clear i Xc CoronalSlices % Memory Management

% Note: All of the functions from this point on will input and output the
% time the operation takes. Because of that, the comments below will not
% describe the input and output related to the time.

% The function Right_Edge_Detection take as inputs the Yslice choosed by the
% user and the RightCoronalSlices. This function take the right half of
the CT scan, perform the edge detection process and output the Edge
Detected image:
[SobelEdges, Total_time] = Right_Edge_Detection(YsliceR, RightCoronalSlices, Total_time);

The function Right_Center take as inputs the Yslice selected by the user
the Axial and RightCoronal Slices, the scales and the resolutions; It has
as outputs the three coordinates for the center. A image showing the
RightCoronalSlices in the Yslice selected by the user pops up and the
user select points for the center of the right femural in the Coronal and
Transversal plane.
[xRHTcenter, yRHTcenter, zRHTcenter, Total_time] = Right_Center_Determination(YsliceR, AxialSlices,
RightCoronalSlices, xscaleRight, yscale, zscale, xresol, yresol, zresol, Total_time);

The function Right_Gather_Ellipsoid_Points take as inputs the matrices in
the Coronal and in the Axial plane for the right side, the edge detected
image, the coordinates for the center and the resolution for the image.
In this function, the user will select points for the femural head and the
acetabular cup in four images (two in the Coronal Plane and two in the
Transversal Plane). All the four images are focused in the acetabulum and
display the edge detected image. The output of this function is all the
parameters used to fit the femural head ellipsoid and the acetabular
ellipsoid.
[c,r,v,c1,r1,v1, Total_time] = Right_Gather_Ellipsoid_Points(AxialSlices, AxialSlices,
RightCoronalSlices, SobelEdges, xRHTcenter, yRHTcenter, zRHTcenter, xresol, yresol, zresol, Total_time);

The function Right_Ellipsoid_Calculations take as inputs the parameters
for both ellipsoids fitted in the previous function, the AxialSlices and
the image resolution. The function uses the parameters entered as inputs
as inputs to calculate the ellipsoid and make a binary matrix with the
same size as the image, where the zeros represents the ellipsoid and the
rest is setted as one. The function outputs the Binary Matrix for the
ellipsoid and its center.
[BinaryMatrix, cavg, Total_time] = Right_Ellipsoid_Calculations(AxialSlices, c, r, v, c1, r1, v1, xresol, yresol, zresol, Total_time);

The function Right_Femur_Mask_Calculations take as input the Binary
Matrix outputed in the previous function, the RightCoronalSlices and the
size Nx. The function uses both matrices to make a mask for the pelvis.
The function outputs the Mask for the right side of the pelvis and the
Binary Matrix that represents the ellipsoid for the right side.
[MaskRHT2, RightCoronalBinaryMatrix, Total_time] = Right_Femur_Mask_Calculations
(BinaryMatrix, RightCoronalSlices, Nx, Total_time);

The function Right_Side_pelvis take as inputs the Mask from the previous
function, the Binary Matrix that represents the ellipsoid for the right
side and the edge detected image. The function applies the Mask in the
edge detected image and outputs the final mask for the right side.
[PelvisRHT, Total_time] = Right_Side_Pelvis(MaskRHT2, RightCoronalSlices, RightCoronalBinaryMatrix, SobelEdges, Total_time);
% Starting Operations for the left side: Rotates AxialSlices 90 degrees and % stores them as CoronalSlices, which can be accessed by % CoronalSlices(:,::,a). After that, the CoronalSlices is split in half so % we can work with the left side of the CoronalSlices.
printf('Starting calculations for left side\n');
tic
CoronalSlices=permute(AxialSlices,[2,3,1]);
Xc=num2cell(CoronalSlices,[1,2]);
Xc=cellfun(@(x) rot90(x,1),Xc,'uni',false);
CoronalSlices=cat(3,Xc{:});
for i=1:size(AxialSlices,1),
    CoronalSlices(:,i,:)=fliplr(CoronalSlices(:,i,:));
end
LeftCoronalSlices=single(CoronalSlices(:,Nx/2:Nx,:));
time = toc;
Total_time1 = time;
clear Xc %Memory Management

% The function Left_Edge_Detection take as inputs the Yslice choosed by the % user and the LeftCoronalSlices. This function take the Leftt half of % the CT scan, perform the edge detection process and output the Edge % Detected image.
[SobelEdges1,Total_time1] = Left_Edge_Detection(YsliceL,LeftCoronalSlices,Total_time1);

% The function Leftt_Center take as inputs the Yslice selected by the user % the Axial and LeftCoronal Slices, the scales and the resolutions; It has % as outputs the three coordinates for the center. A image showing the % LeftCoronalSlices in the Yslice selected by the user pops up and the % user select points for the center of the left femoral in the Coronal and % Transversal plane.
[xLFTCenter,yLFTCenter,zLFTCenter,Total_time1] = Left_Center_Determination(YsliceL, %
AxialSlices,LeftCoronalSlices,XsclaeRight,Xscale,Yscale,Zscale,Xresol,Yresol,Zresol, %
Total_time1);

% The function Left_Gather_Ellipsoid_Points take as inputs the matrices in % the Coronal and in the Axial plane for the left side, the edge detected % image, the coordinates for the center and the resolution for the image. % In this function, the user will select points for the femoral head and the % acetabular cup in four images (two in the Coronal Plane and two in the % Transversal Plane). All the four images are focused in the acetabulum and % display the edge detected image. The output of this function is all the % parameters used to fit the femoral head ellipsoid and the acetabular % ellipsoid.
[c2,r2,e2,v2,c3,r3,e3,v3,Total_time1] = Left_Gather_Ellipsoid_Points(AxialSlices, %
LeftCoronalSlices,SobelEdges1,xLFTCenter,yLFTCenter,zLFTCenter,Xresol,Yresol,Zresol, %
Total_time1);

% The function Left_Ellipsoid_Calculations take as inputs the parameters % for both ellipsoids fitted in the previous function, the AxialSlices and
the image resolution. The function uses the parameters entered as inputs
as inputs to calculate the ellipsoid and make a binary matrix with the
same size as the image, where the zeros represents the ellipsoid and the
rest is set as one. The function outputs the Binary Matrix for the
ellipsoid.

[BinaryMatrix, cavgl, Total_time] = Left_Ellipsoid_Calculations(AxialSlices, c2, r2, v2, c3, r3, v3, xresol, yresol, zresol, Total_time);

% The function Left_Femur_Mask_Calculations take as input the Binary
% Matrix outputed in the previous function, the LeftCoronalSlices and the
% size Nx. The function uses both matrices to make a mask for the pelvis.
The function outputs the Mask for the left side of the pelvis and the
% Binary Matrix that represents the ellipsoid for the left side.
[MaskLFT, LeftCoronalBinaryMatrix, Total_time] = Left_Femur_Mask_Calculations;
(BinaryMatrix, LeftCoronalSlices, Nx, Total_time);
clear BinaryMatrix

% The function Final_Pelvis take as inputs the Mask from the previous
% function, the final mask for the right side, the Binary Matrix that
% represents the ellipsoid for the left side and the edge detected image.
The function applies the Mask in the edge detected image for the left
% side and the concatenate both masks togther to output the Final Mask for
% the whole Pelvis in double and logical values.
[Pelvis, PelvisB, Total_time, Total_time] = Final_Pelvis(PelvisRHT, MaskLFT, LeftCoronalSlices, LeftCoronalBinaryMatrix, SobelEdges1, Total_time, Total_time);
clear Pelvis MaskLFT2 MaskRHT2 PelvisRHT LeftCoronalSlices RightCoronalSlices

% The function CT_No_Pelvis take as inputs the Coronalslices and the Binary
% Pelvis Mask. This function applies the mask in the whole CT scan and
% outputs the CT scan with no pelvis.
[CTnoPelvis, OnesM, Total_Final_Time] = CT_No_Pelvis(CoronalSlices, PelvisB, Total_time, Total_time);

% HERE GOES THE SADEGH CODE FOR THE FEMUR (INPUT: CT SCAN WITH NO PELVIS,
% OUTPUT: FEMUR_MATRIX -> SEE THE FOLLOWING FUNCTION).

% Sadegh Rias
fprintf('Femur Segmentation ...')
tic
[Femur_Matrix, lambda_Femur] = Femur_Segmentation(CTnoPelvis);
fprintf(' DONE! (%d seconds)
', round(toc))

% clear CTnoPelvis
% The function CT_No_Femur take as inputs the Coronalslices and the
% Femur_Matrix (A binary matrix that represents both femurs as ones and the
% rest as zeros. The function separates both femurs and clean the noise
% inside both matrices. The function outputs the CTnoFemur (The CT scan
% with a mask in both femurs) and two binary matrix, one for each femur.
[CTnoFemur, FinalRHTFemur, FinalLFTFemur, Total_Final_Time] = CT_No_Femur(CoronalSlices, Femur_Matrix, OnesM, Total_Final_Time);
clear OnesM

%% Sadegh Riasi
fprintf('Pelvis Segmentation ...

tic;
[Pelvis_Matrix, Lambda_Pelvis] = Pelvis_Segmentation(CTnoFemur);
fprintf('DONE! (%f seconds)

HERE GOES THE SADEGH CODE FOR THE PELVIS (INPUT: CT SCAN WITH NO FEMUR,

clear CTnoFemur

%% Sacrum Plane Fit
The function Sacrum_Plane_Fit takes as input the coordinates for the
right and the left center for the joint ellipsoid, the Binary Matrix that
represents the Pelvis and the CoronalSlices. The function finds the
middle point between the two ellipsoid centers, fits a sagittal plane that pass
through the middle point and add a thickness to this plane in order to
cover the whole sacrum and spinal chord. The function output the product
of the Binary Matrix that represents the plane, the Binary Matrix that
represents the Pelvis without the sacrum and a Binary Matrix that
represents the Sacrum.

[Pelvis_No_Sacrum, Sacrum_Matrix, Total_Final_Time] = Sacrum_Plane_Fit(Pelvis_Matrix, CoronalSlices, round(cavg(1)/Xresol), round(cavg(2)/Yresol), round(cavg(3)/Zresol), 225+round(cavg(1)/Xresol), round(cavg(2)/Yresol), round(cavg(3)/Zresol), Total_Final_Time);

%% Pelvis Split
The function Pelvis_Split takes as input the coordinates for the
right and the left center for the joint ellipsoid, the Binary Matrix that
represents the Pelvis and the CoronalSlices. The function finds the
middle point between the two ellipsoid centers, fits a sagittal plane that pass
through the middle point and uses this plane to split the pelvis in two
halves. The function output the product of the Binary Matrix that
represents the right side and the Binary Matrix that represents the Pelvis
as well as the product of the Binary Matrix that represents the left side
and the Binary Matrix that represents the Pelvis.

[Right_Pelvis_No_Sacrum, Left_Pelvis_No_Sacrum, Total_Final_Time] = Pelvis_Split(Pelvis_No_Sacrum, Sacrum_Matrix, round(cavg(1)/Xresol), round(cavg(2)/Yresol), round(cavg(3)/Zresol), 225+round(cavg(1)/Xresol), round(cavg(2)/Yresol), round(cavg(3)/Zresol), Total_Final_Time);
clear Pelvis_No_Sacrum

%% Pelvis Cloud
The function Right_Pelvis_Cloud takes as inputs the Pelvis_No_Sacrum (A binary
matrix representing the Right Pelvis without the sacrum) and the CT scan
resolution. The function find the coordinates for the boundaries and
store them as an .xyz file in the current MATLAB folder.

[Total_Final_Time] = Right_Pelvis_Cloud(Right_Pelvis_No_Sacrum, Xresol, Yresol, Zresol, Total_Final_Time);

%% Pelvis Cloud
The function Left_Pelvis_Cloud takes as inputs the Pelvis_No_Sacrum (A binary
% matrix representing the Left Pelvis without the sacrum and the CT scan
% resolution. The function find the coordinates for the boundaries and
% store them as an .xyz file in the current MATLAB folder
[Total_Final_Time] = Left_Pelvis_Cloud(Left_Pelvis_No_Sacrum,Xresol,Yresol,Zresol,
Total_Final_Time);

% The function Left_Femur_Cloud takes as inputs the FinalLFTFemur (A binary
% matrix representing the left femur) and the CT scan resolution. The function
% find the coordinates for the boundaries and store them as an .xyz file in
% the current MATLAB folder
[Total_Final_Time] = Left_Femur_Cloud(FinalLFTFemur,Xresol,Yresol,Zresol,
Total_Final_Time);

% The function Right_Femur_Cloud takes as inputs the FinalRHFemur (A binary
% matrix representing the right femur) and the CT scan resolution. The function
% find the coordinates for the boundaries and store them as an .xyz file in
% the current MATLAB folder
[Total_Final_Time] = Right_Femur_Cloud(FinalRHTFemur,Xresol,Yresol,Zresol,
Total_Final_Time);

% The function Sacrum_Cloud takes as inputs the Sacrum_Matrix (A binary
% matrix representing the Sacrum) and the CT scan resolution. The function
% find the coordinates for the boundaries and store them as an .xyz file in
% the current MATLAB folder
[Total_Final_Time] = Sacrum_Cloud(Sacrum_Matrix,Xresol,Yresol,Zresol,Total_Final_Time);

fprintf('Total segmentation time: %.3f seconds \n',Total_Final_Time);
fprintf('The coordinates for the Right ellipsoid center are: %.3fmm x, %.3fmm y, %.3fmm z\n', cavg(1), (size(AxialSlices,2)*Yresol)-cavg(2),cavg(3))
fprintf('The coordinates for the Left ellipsoid center are: %.3fmm x, %.3fmm y, %.3fmm z\n', (255*Xresol)+cavg(1), (size(AxialSlices,2)*Yresol)-cavg(2),cavg(3))
function [Lambda] = MaxFlow3D(I)

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% MaxFlow3D
% Sadegh Riazi (ms.riasi@gmail.com)
% MODIFIED from Yuan's method for continuous Max Flow Algorithm.
% References below:

% The original algorithm was proposed in the following papers:

% [1] Yuan, J.; Bae, E.; Tai, X.-C.
% A Study on Continuous Max-Flow and Min-Cut Approaches
% CVPR, 2010

% [2] Yuan, J.; Bae, E.; Tai, X.-C.; Boycov, Y.
% A study on continuous max-flow and min-cut approaches. Part I: Binary labeling
% UCLA CAM, Technical Report 10-61, 2010

% The mimetic finite-difference discretization method was proposed for
% the total-variation function in the paper:

% [1] Yuan, J.; Schn"{a}rr, C.; Steidl, G.
% Simultaneous Optical Flow Estimation and Decomposition

% This software can be used only for research purposes, you should cite ALL of
% the aforementioned papers in any resulting publication.

% Please email cn.yuanjing@gmail.com for any questions, suggestions and bug reports

% The Software is provided "as is", without warranty of any kind.

% Version 1.0
% https://sites.google.com/site/wwwjingyuan/
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% 8/5/2015
% % Sheetness Filter
idx = find (I==0);
Irand = 100*rand(size(idx));
Irand = normrnd(-121,57,1,length(idx));
I(idx) = Irand;
fprintf(' Computing Sheetness Filter ...
SF = zeros(size(I));
for SIGMA = 0.75:0.05:1
SIGMA
[SF_temp] = SheetnessFilter(I,SIGMA);
SF_temp(isnan(SF_temp)) = -1;
SFabs = max(abs(SF_temp), abs(SF));
SF = sign((SFabs==abs(SF_temp)).*(SF_temp)).*SFabs + ...
sign((SFabs==abs(SF)).*(SF)).*SFabs - (abs(SF)==abs(SF_temp)).*(SF);
end
clear SF_temp
fprintf(' DONE
')
%%% Analyze image
[nr nc np] = size(I);

%%% Input parameters
sigma = 0.2;
% Capacity of spatial flows
alpha = 0.2*ones(nr,nc,np);
alpha = SF+1.1;
% Penalty parameter in augmented Lagrangian method
C = 0.35;
% Step size for gradient descent
Eta = 0.08*0.08;
% Convergence parameters
ErrorThreshold = 1e-5;
MaxNumIter = 1000;

%%% Initialization
% Iteration number
k = 1;
C = (I>350) & (SF>0.5);
% C_t = (I < 0.3156);
C_t = (I < -50);
CC = bwconncomp(C_t);
S = regionprops(CC,'Area');
L = labelmatrix(CC);
C_t = ismember(L, find([S.Area == max([S.Area]),1,'first']));
% C_t = (I<0.3156);
% Lagrange multiplier
Lambda = zeros(size(C));
% Spatial flows
p_X = zeros(nr,nc+1,np);
p_Y = zeros(nr+1,nc,np);
p_Z = zeros(nr,nc+1);% Source flows
p_s = min(0,C_t);
% Sink flows
p_t = p_s;
clear SF
%%% Max_Flow Algorithm
divp = p_X(:,2:nc+1,:) - p_X(:,1:nc,:); ... 
p_Y(2:nc+1,:) - p_Y(1:nc,:); ... 
p_Z(:,2:np+1) - p_Z(:,1:np);
ImageNo = find(sum(sum(I)) == max(sum(sum(I))));
% ImageNo = 74;
IterError = [];
figure (1); hold on;
subplot(2,2,2);imagesc(I(:,:,ImageNo)); axis equal;
% tic
% fprintf(' Applying Continuous Max Flow ...
')
for k = 1:MaxNumIter
    %%%% Update spatial flows
    % Gradient descend
    A = divp + pt + ps = Lambda/c;
    p_X(:,2:nc,:) = p_X(:,2:nc,:) + Eta*(A(:,2:nc,:) - A(:,1:nc-1,:));
    p_Y(:,2:nr,:) = p_Y(:,2:nr,:) + Eta*(A(2:nr,:), :) - A(1:nr-1,:,:));
    % Applying |p(x)| <= alpha condition
    gk = sqrt((p_X(:,1:nc,:),).^2 + p_X(:,2:nc+1,:).^2 + ...
               p_Y(1:nr,:),).^2 + p_Y(2:nr+1,:).^2 + ...
               p_Z(:,1:np),).^2 + p_Z(:,2:np+1,:).^2)*0.5);
    gk = double(gk <= alpha) + double(~(gk <= alpha)).*(gk ./ alpha);
    gk = 1 ./ gk;
    p_X(:,2:nc,:) = (0.5*(gk(:,2:nc,:) + gk(:,1:nc-1,:))).*p_X(:,2:nc,:);
    p_Y(:,2:nr,:) = (0.5*(gk(2:nr,:), :) + gk(1:nr-1,:,:)).*p_Y(2:nr,:),
    p_Z(:,2:np) = (0.5*(gk(:,2:np) + gk(:,1:np-1,:))).*p_Z(:,2:np);
    p_X(isnan(p_X))=0;
    p_Y(isnan(p_Y))=0;
    p_Z(isnan(p_Z))=0;
    divp = p_X(:,2:nc+1,:) - p_X(:,1:nc,:);
    p_Y(2:nr+1,:,:) - p_Y(1:nr,:),
    p_Z(:,2:np+1) = p_Z(:,1:np-1);
    %%%% update the source flow ps
    ps = min(divp + pt - Lambda/c + 1/c, Cs);
    %%%% update the sink flow pt
    pt = min(-divp + ps + Lambda/c, Ct);
    %%%% update the multiplier Lambda
    LambdaError = c*(divp + pt - ps);
    Lambda = Lambda - LambdaError;
    % evaluate the average error
    IterError = [IterError, sum(abs(LambdaError(:))))/numel(I)];
    figure (1);
    subplot(2,2,[1,3]);hold on;semilogy(k,IterError(k),'.r**'); colormap jet; drawnow
    figure (1)
    subplot(2,2,4);imagesc(Lambda(:,:,ImageNo)); axis equal; colormap jet; drawnow
    % fprintf(' %d %6.2e
',k,IterError(k))
    if (IterError(k) < ErrorThresh || (isnan(IterError(k))=1)
        break;
    end
end
function [Pelvis_Matrix, Lambda] = Pelvis_Segmentation(CTnoFemur)

%% Find the Femurs
xx = CTnoFemur>350;
SE = strel('disk',10);
xx = imdilate(xx,SE);
CC = bwconncomp(xx);
S = regionprops(CC, 'Area');
L = labelmatrix(CC);
Area = sort([S{:}.Area], 'Descend');
xx = ismember(L, find([S.Area] == Area(1)));
CC = bwconncomp(xx);
S = regionprops(CC, 'BoundingBox');

%% Limit the domain to just femurs
rmin = floor(S(1).BoundingBox(2));
rmax = floor(S(1).BoundingBox(2) + S(1).BoundingBox(5));
cmin = floor(S(1).BoundingBox(1));
cmax = floor(S(1).BoundingBox(1) + S(1).BoundingBox(4));
pmin = floor(S(1).BoundingBox(3));
pmax = floor(S(1).BoundingBox(3) + S(1).BoundingBox(6));

rmin = max([rmin-10],1);
rmax = min([rmax+10],size(CTnoFemur,1));
cmin = max([cmin-10],1);
cmax = min([cmax+10],size(CTnoFemur,2));
pmin = max([pmin-10],1);
pmax = min([pmax+10],size(CTnoFemur,3));

%% Run MaxFlow Algorithm
Lambda = zeros(size(CTnoFemur));
I_temp = CTnoFemur(rmin:rmax, cmin:cmax, pmin:pmax);
[Lambda_temp] = MaxFlow3D(I_temp);
Lambda(rmin:rmax, cmin:cmax, pmin:pmax) = Lambda_temp;
clear Lambda_temp I_temp

%% Clean up the segmentation
Pelvis_Matrix = Lambda>0.7;
CC = bwconncomp(Pelvis_Matrix);
S = regionprops(CC, 'Area');
Area = [S{:}.Area];
Area = sort(Area, 'descend');
Pelvis_Matrix = bwareaopen(Pelvis_Matrix,4000);
Pelvis_Matrix = imfill(Pelvis_Matrix, 'holes');
function [Right_Pelvis_No_Sacrum, Left_Pelvis_No_Sacrum, Total_Final_Time] = Pelvis_Split()
(Pelvis_No_Sacrum, CoronalSlices, xRHTcenter, yRHTcenter, zRHTcenter, xLFTcenter, yLFTcenter, zLFTcenter, Total_Final_Time)

tic %Starting the time measurement for this section of the code
fprintf('Starting Calculations for the Sagital Plane \n');

clear x y z
% The distance between the two centers is calculated and used to make a
% vector that will be normal to the sagittal plane that pass through the
% middle point of the distance between the centers
Length = sqrt((xLFTcenter - xRHTcenter)^2 + (yLFTcenter - yRHTcenter)^2 + (zLFTcenter - zRHTcenter)^2);
NormalVector = [(xLFTcenter - xRHTcenter) (yLFTcenter - yRHTcenter) (zLFTcenter - zRHTcenter)];
D2 = [round((xLFTcenter - xRHTcenter)/2 + xRHTcenter) round((yLFTcenter - yRHTcenter)/2 + yRHTcenter) round((zLFTcenter - zRHTcenter)/2 + zRHTcenter)];
NormalVectorx = NormalVector(1); NormalVectory = NormalVector(2); NormalVectorz =
NormalVector(3);
D2x = D2(1); D2y = D2(2); D2z = D2(3);

% The coordinates for the plane in the Yslice defined by the middle point
% is calculated and stored in a vector. The thickness of the plane is
% decided as 28% of the total distance between the two centers.
t = 1:size(CoronalSlices, 1);
syms x y z
Plane = sym('(NormalVectorx*(x-D2x)) + (NormalVectory*(y-D2y)) + (NormalVectorz*(z-D2z))');
% Plane = subs(Plane);
X = solve(Plane, x);
z = t; y = D2y;
x = double(subs(X));
x = round(x); x1 = x; z1 = z;
Line = [x' z1'];
for H = 1:D2(1)-1
    x1 = x1-1;
    if x1 > 0
        Line = [Line; z1' x1'];
    end
end

% The coordinates for every point in the plane is stored in a ones matrix
% as zeros and this matrix is used as a mask for the Binary Matrix that
% represents the Pelvis
RightCutMask = zeros(size(CoronalSlices));
for Yslice = 1:size(CoronalSlices, 3)
for H = 1:size(Line,1)
    RightCutMask(Line(H,1),Line(H,2),Yslice) = 1;
end
Right_Pelvis_No_Sacrum0 = Pelvis_No_Sacrum.*RightCutMask;
LeftCutMask = ones(size(CoronalSlices))-RightCutMask;
Left_Pelvis_No_Sacrum0 = Pelvis_No_Sacrum.*LeftCutMask;

% The element with the most number of pixels is choosen to remain intact
% and the rest is deleted
cc = bwconncomp(Right_Pelvis_No_Sacrum0);
numPixels = cellfun(@(numel,cc.PixelIdxList)
    [biggest,idx] = max(numPixels);
Right_Pelvis_No_Sacrum = zeros(size(Right_Pelvis_No_Sacrum0));
Right_Pelvis_No_Sacrum(cc.PixelIdxList(idx)) = 1;
cc = bwconncomp(Left_Pelvis_No_Sacrum0);
numPixels = cellfun(@(numel,cc.PixelIdxList)
    [biggest,idx] = max(numPixels);
Left_Pelvis_No_Sacrum = zeros(size(Left_Pelvis_No_Sacrum0));
Left_Pelvis_No_Sacrum(cc.PixelIdxList(idx)) = 1;
clear z y x t z1 xl  Right_Pelvis_No_Sacrum0 Left_Pelvis_No_Sacrum0 LeftCutMask %Memory
Management
time = toc;
Total_Final_Time = Total_Final_Time+time;
fprintf('Plane fit complete in %.3f seconds\n',time);
function J = regiongrow(I, x, y, reg_maxdist)
% This function performs "region growing" in an image from a specified
% seedpoint (x,y)
% J = regiongrow(I,x,y,t)
% I : input image
% J : logical output image of region
% x,y : the position of the seedpoint (if not given uses function getpts)
% t : maximum intensity distance (defaults to 0.2)
% The region is iteratively grown by comparing all unallocated neighbouring pixels to the
% region. The difference between a pixel's intensity value and the region's mean,
% is used as a measure of similarity. The pixel with the smallest difference
% measured this way is allocated to the respective region.
% This process stops when the intensity difference between region mean and
% new pixel become larger than a certain threshold (t)
% Example:
% I = im2double(imread('medtest.png'));
% x=198; y=359;
% J = regiongrow(I,x,y,0.2);
% figure, imshow(I+J);
% Author: D. Kroon, University of Twente

if (exist('reg_maxdist', 'var')==0), reg_maxdist=0.2; end
if (exist('y', 'var')==0), figure, imshow(I,[1]); [y,x]=getpts; y=round(y(1)); x=round(x(1)); end

J = zeros(size(I));  \% Output
I sizes = size(I);  \% Dimensions of input image

reg_mean = I(x,y);  \% The mean of the segmented region
reg_size = 1;  \% Number of pixels in region

\% Free memory to store neighbours of the (segmented) region
neg_free = 10000; neg_pos=0;
reg_list = zeros(neg_free,3);

pixdist=0;  \% Distance of the region newest pixel to the region mean

\% Neighbor locations (footprint)
neighb=[-1 0; 1 0; 0 -1; 0 1];

\% Start region growing until distance between region and possible new pixels become
\% higher than a certain threshold
while(pixdist<reg_maxdist&&reg_size<numel(I))
% Add new neighbors pixels
for j=1:4,
    % Calculate the neighbor coordinate
    xn = x + neigh(j,1); yn = y + neigh(j,2);
    
    % Check if neighbor is inside or outside the image
    ins=(xn>=1)&&(yn>=1)&&(xn<=Isizes(1))&&(yn<=Isizes(2));
    
    % Add neighbor if inside and not already part of the segmented area
    if(ins&&(~J(xn,yn)==0))
        neg_pos = neg_pos+1;
        neg_list(neg_pos,:) = [xn yn I(xn,yn)]; J(xn,yn)=1;
    end
end

% Add a new block of free memory
if(neg_pos+10>neg_free), neg_free=neg_free+10000; neg_list((neg_pos+1):neg_free,:)=0; end

% Add pixel with intensity nearest to the mean of the region, to the region
dist = abs(neg_list(1:neg_pos,3)-reg_mean);
[pixdist, index] = min(dist);
J(x,y)=2; reg_size=reg_size+1;

% Calculate the new mean of the region
reg_mean= (reg_mean*reg_size + neg_list(index,3))/(reg_size+1);

% Save the x and y coordinates of the pixel (for the neighbor add process)
x = neg_list(index,1); y = neg_list(index,2);

% Remove the pixel from the neighbor (check) list
neg_list(index,:)=-neg_list(neg_pos,:); neg_pos=neg_pos-1;
end

% Return the segmented area as logical matrix
J=J>1;
function [xRHTcenter, yRHTcenter, zRHTcenter, Total_time] = Right_Center_Determination
(Yslice, AxialSlices, RightCoronalSlices, XscaleRight, Xscale, Yscale, Zscale, Xresol, Yresol, Zresol, Total_time);

% Center Determination
tic % Starting the time measurement for this section of the code

% Set the slice for selecting points to determine the center of the right
% femoral head and set the zoom on
figure(7);
x=RightCoronalSlices(:,:,Yslice);
imagesc(XscaleRight, Zscale, X); colormap(gray(256)); axis equal;
xlabel('X (mm)'); ylabel('Z (mm)');
title('{"bf\fontsize{16}Select Center of Right Femoral Head";["\fontsize{12}Coronal Slice #","num2str(Yslice)]});
zoom on
pause();
[x,z]=getpts(figure(7)); % get the X and Z points
Zslice=round(z/Zresol);
x=AxialSlices(:,:,Zslice);
imagesc(Xscale, Yscale, X); colormap(gray(256)); axis equal; axis tight;
xlabel('X (mm)'); ylabel('Y (mm)');
title('{"bf\fontsize{16}Select Center of Right Femoral Head (The one on the left)";["\fontsize{12}Axial Slice #","num2str(Zslice)]});
zoom on
pause();
[xl,y]=getpts(figure(7)); % get the X and Y points

% Avarage both measurements
xRHTcenter=round(((x+xl)/2)/Xresol);
yRHTcenter=round(y/Yresol);
zRHTcenter=Zslice;

% Display the time for this section for analysis purpose
fprintf('Center Determination complete \n');
time = toc;
Total_time = Total_time+time;
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function [SobelEdges,Total_time] = Right_Edge_Detection(Yslice,RightCoronalSlices, %
Total_time);

tic %starting the time measurement for this section of the code
fprintf('Starting Edge detection Process\n');

% Begins by analyzing Coronal Slice defined by Yslice, a slice that shows the joint line

X=RightCoronalSlices(:,:,Yslice);

% Perform Sobel Edge detection
SobelX=[-1 0 1; -2 0 2; -1 0 1];
SobelX(:,:,2)=[-2 0 2; -4 0 4; -2 0 2];
SobelX(:,:,3)=[-1 0 1; -2 0 2; -1 0 1];
SobelX=single(SobelX);
SobelY=[1 2 1; 0 0 0; -1 -2 -1];
SobelY(:,:,2)=[2 4 2; 0 0 0; -2 -4 -2];
SobelY(:,:,3)=[1 2 1; 0 0 0; -1 -2 -1];
SobelY=single(SobelY);
Sobel2=[1 2 1; 2 4 2; 1 2 1];
Sobel2(:,:,2)=[0 0 0; 0 0 0; 0 0 0];
Sobel2(:,:,3)=[-1 -2 -1; -2 -4 -2; -1 -2 -1];
Sobel2=single(Sobel2);
SobelEdges=sqrt(convn(RightCoronalSlices,SobelX,'same').^2 + convn(RightCoronalSlices,SobelY,'same').^2 + convn(RightCoronalSlices,Sobel2,'same').^2);

clear Cortical % Memory Management
% Display the time for this section for analysis purpose

time = toc;
Total_time = Total_time+time;
fprintf('Edge detection complete in %0.3f seconds \n',time);
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function [BinaryMatrix, cavg, Total_time] = Right_Ellipsoid_Calculations(AxialSlices, c, r, v, cl, r1, v1, Xresol, Yresol, Zresol, Total_time);
fprintf('Starting Right Femoral Ellipsoid Calculations\n');
tic %time measurement for this section of the code
EllipsoidX = []; EllipsoidY = []; EllipsoidZ = []; Ellipsoid = []; EllipsoidXI = []; EllipsoidYI = []; EllipsoidZI = []; EllipsoidI = [];
% Averaging the femoral head ellipsoid and the acetabular ellipsoid
cavg=(c+cl)/2;
ravg=(r+r1)/2;
vavg=(v+v1)/2;
% Defining parameters to solve the equation
A=vavg(1); B=vavg(2); C=vavg(3); D=vavg(4); E=vavg(5); F=vavg(6); G=vavg(7); H=vavg(8);
I=vavg(9);
% Defining x interval to solve the equations
X=(cav(I)-rav(I)-1):.5:(cav(I)+rav(I)+1);

% The slices for the for loop were chosen as the center plus the radius and
% a error margin for a better ellipsoid output. The number 10 showed
% to be a good value to set the ellipsoid in this procedure.
for Zslice = (round((c(3)-r(3)-10)/Zresol)): (round((c(3)+r(3)+10)/Zresol))
    Z=Zslice*Zresol;
    for K = 1:size(X,2)
        x = X(K);
        EQ2 = - (A*B*x^2 - 2*A*B*x*z + B^2*y^2 + 2*B*y^2 + 2*B*y^2 + H^2 + 2*B*y^2 + H^2)
        A*B*x^2 - 2*B*y^2 + B^2*y^2 + 2*B*y^2 + H^2 + 2*B*y^2 + H^2
        EQ3 = -(A*B*x^2 - 2*A*B*x*z + A*C*x^2 + 2*A*B*x^2 + G^2 - A*B*y^2)
        A*B*x^2 - 2*A*B*x*z + A*C*x^2 + 2*A*B*x^2 + G^2 - A*B*y^2
        end
    end
    EllipsoidX=[EllipsoidX; round(x/Xresol)];
    EllipsoidY=[EllipsoidY; round(y/Yresol) round(y1/Yresol)];
    EllipsoidZ=[EllipsoidZ; round(repmat(Z/Zresol,size(X,2),1))];
end
% Defining x interval to solve the equations
Y=(cav(2)-rav(2)-10):.5:(cav(2)+rav(2)+10);
% The slices for the for loop were chosen as the center plus the radius and
% a error margin for a better ellipsoid output. The number 10 showed
% to be a good value to set the ellipsoid in this procedure.
for Zslice = (round((c(3)-r(3)-10)/Zresol)): (round((c(3)+r(3)+10)/Zresol))
    Z=Zslice*Zresol;
    for K = 1:size(Y,2)
        y = Y(K);
        end
    end
    EllipsoidX=[EllipsoidX; round(x/Xresol)];
    EllipsoidY=[EllipsoidY; round(y/Yresol) round(y1/Yresol)];
    EllipsoidZ=[EllipsoidZ; round(repmat(Z/Zresol,size(X,2),1))];
\[ x_1 = \text{EQ3}; \]
\[ \text{EllipsoidX1} = \{\text{EllipsoidX1; round}(x/Xresol) \; \text{round}(x1/Xresol)\}; \]
\[ \text{EllipsoidY1} = \{\text{EllipsoidY1; round}(y/Yresol)\}; \]
\end{align*}
\] end
\[ \text{EllipsoidZ1} = \{\text{EllipsoidZ1; round}(z/Zresol, \text{size}(Y, 2), 1)\}; \]
\end{align*}
\] end
\[ \% \text{The results for the final ellipsoid is stored in two different vectors,} \]
\[ \% \text{one for the points stored in the coronal plane and the other for the} \]
\[ \% \text{points stored in the sagittal plane} \]
\[ \text{Ellipsoid} = \{\text{EllipsoidX EllipsoidY (, , 1) EllipsoidZ; EllipsoidX EllipsoidY (, , 2) EllipsoidZ}\}; \]
\[ \text{Ellipsoid1} = \{\text{EllipsoidX (, , 1) EllipsoidY1 EllipsoidZ1; EllipsoidX (, , 2) EllipsoidY1 EllipsoidZ1}\}; \]
\[ \text{Ellipsoid} = \text{vertcat(Ellipsoid, Ellipsoid1)}; \]
\[ \text{clear Ellipsoid1 \; \%Memory management} \]
\[ \% \text{Get rid of the imaginary numbers on the final vector} \]
\[ \text{ImagRows} = [\ ]; \]
\[ \text{for } L = 1: \text{size(Ellipsoid, 1)} \]
\[ \quad \text{if isreal(Ellipsoid(L, :)) == 0} \]
\[ \quad \text{ImagRows} = [\text{ImagRows L}]; \]
\[ \end{align*}
\] end
\[ \text{Ellipsoid(ImagRows, :)} = []; \]
\[ \text{Ellipsoid} = \text{unique(Ellipsoid, 'rows');} \]
\[ \text{clear ImagRows L \; \%Memory management} \]
\[ \% \text{A zeros matrix is created and used to store the coordinates for every} \]
\[ \% \text{point in the ellipsoid as ones} \]
\[ \text{EllMatrix} = \text{zeros(size(AxialSlices));} \]
\[ \text{for } P = 1: \text{size(Ellipsoid, 1)} \]
\[ \quad \text{EllMatrix(Ellipsoid(P, 2), Ellipsoid(P, 1), Ellipsoid(P, 3))} = 1; \]
\[ \end{align*}
\] end
\[ \text{clear Ellipsoid P \; \%Memory Management} \]
\[ \% \text{A fill command is used to fill the remaining holes in the ellipsoid matrix} \]
\[ \% \text{The ellipsoid matrix is used to create a matrix where everything is one} \]
\[ \% \text{besides the ellipsoid points} \]
\[ \text{for } p = \{\text{round}((c(3)-r(3)+10)/Zresol): (\text{round}((c(3)+r(3)+10)/Zresol)) \}
\[ \quad \text{EllMatrix}(; ; ; p) = \text{imfill(EllMatrix( ; ; ; p), 'holes');} \]
\[ \end{align*}
\] end
\[ \text{EllMatrix} = \text{imfill(EllMatrix, 'holes');} \]
\[ \text{OnesMatrix} = \text{ones(size(EllMatrix));} \]
\[ \text{BinaryMatrix} = \text{OnesMatrix-EllMatrix}; \]
\[ \text{clear OnesMatrix EllMatrix p \; \%Memory Management} \]
\[ \% \text{Display the time for this section for analysis purpose} \]
\[ \text{time} = \text{toc}; \]
\[ \text{Total time} = \text{Total time}+\text{time}; \]
\[ \text{fprintf('Femoral Ellipsoid Calculations complete in \%0.3f seconds\n', time);} \]
function [Total_Final_Time] = Right_Femur_Cloud(FinalRHTFemur, Xresol, Yresol, Zresol, ✓
Total_Final_Time)

fprintf('Starting right femur point cloud generation \n');
tic %starting the time measurement for this section of the code

% Right Femur Cloud
A2 = [];
RIGHTBF = FinalRHTFemur;

% For each slice, the .mat file is transformed into a grayscale image so the
% command bwboundaries can be used to get the pixels in the boundaries
% for each object in the image. Then, the pixels coordinates are stored
% in a vector called A2 and multiplied by de resolution.
for Yslice = 1:size(RIGHTBF,3);
    Q = RIGHTBF(:, :, Yslice);
    I = mat2gray(Q);
    [B, L, N] = bwboundaries(I);
    for k = 1:length(B),
        boundary = B{k};
        A2 = [A2; boundary(:, 2) repmat((size(RIGHTBF,3)-Yslice),size(boundary,1),1)];
        boundary(:, 1)];
    end
end
A2(:, 1) = A2(:, 1) .* Xresol; %x
A2(:, 2) = A2(:, 2) .* Yresol; %y
A2(:, 3) = A2(:, 3) .* Zresol; %z

% After the first set of points is sorted, the matrix is rotated and the
% same process is repeated so the pixels in boundaries that couldn't be
% reached in the previous code can be stored
TransversalRHTFemur = [];
for i = 1:size(RIGHTBF,3);
    TransversalRHTFemur (:, :, i) = fliplr(RIGHTBF(:, :, i));
end
Xc = num2cell(TransversalRHTFemur,[1,2]);
Xc = cellfun(@(x) rot90(x,1), Xc, 'uni', false);
TransversalRHTFemur = cat(3, Xc(:, :));
TransversalRHTFemur = permute(TransversalRHTFemur,[3,1,2]);
A3 = [];
for Zslice = 1:size(TransversalRHTFemur,3);
    Q = logical(TransversalRHTFemur(:, :, Zslice) > 0);
    I = mat2gray(Q);
    [B, L, N] = bwboundaries(I);
    for k = 1:length(B),
        boundary = B{k};
        A3 = [A3; boundary(:, 2) boundary(:, 1) repmat(Zslice, size(boundary, 1), 1)];
        end
end
clear TransversalRHTFemur Xc
A3(:,1) = A3(:,1).*xresol; %x
A3(:,2) = (size(RIGHTBF,3)-A3(:,2)).*yresol; %y
A3(:,3)= A3(:,3).*zresol; %z

% Both matrices are concatenated into one n-by-3 matrix representing the % coordinates for all the pixels in the boundaries. After that, the % repeated rows are eliminated for a better point cloud without double % points.
A3 = vertcat(A2,A3);
A3 = unique(A3,'rows');

% The file is stored as a .xyz file in the current MATLAB folder
csvwrite('RHTFemurCloud.xyz',A3)
clear A2 A3 RIGHTBF % Memory Management
time = toc;
Total_Final_Time = Total_Final_Time+time;
fprintf('Point Cloud Generation complete in %0.3f seconds\n',time);
function [MaskRHT2,RightCoronalBinaryMatrix,Total_time] = Right_Femur_Mask_Calculations
(BinaryMatrix,RightCoronalSlices,Nx,Total_time);

fprintf('Starting Right Femur Mask Calculations and Cleaning\n');
tic;
% Rotates BinaryMatrix 90 degrees and stores them as CoronalBinaryMatrix, which
% can be accessed by CoronalBinaryMatrix(:,i,a) and split it in half
CoronalBinaryMatrix=permute(BinaryMatrix,[2,3,1]);
Xc=num2cell(CoronalBinaryMatrix,[1,2]);
Xc=cellfun(@(x) rot90(x,-1),Xc,'uni',false);
CoronalBinaryMatrix=cat(3,Xc{:});
for i=1:size(BinaryMatrix,1),
    CoronalBinaryMatrix(:,i,:)=-flipdim(CoronalBinaryMatrix(:,i,:));
end
RightCoronalBinaryMatrix=single(CoronalBinaryMatrix(:,1:Nx/2+1,:));
clear CoronalBinaryMatrix

RightCoronalBinaryMatrix Xc

% Apply the threshold, fill the holes and take of the right femoral head
% using the ellipsoid
MaskRHT2 = [];
FinalMask = [];
for Yslice = 1:size(RightCoronalSlices,3),
    W = RightCoronalSlices(:,Yslice,:);
    Cortical2=W>216; % Changed to 300 for Gloria
    Threshold=double(W).*RightCoronalBinaryMatrix(:,Yslice,:);
    P=18;
    NoNoise=bwareaopen(Threshold,P);
    se=strel('disk',1);
    Dilate=imdilate(NoNoise,se,'same');
    Filled=imfill(Dilate,'holes');
    BoneShadow=imerode(Filled,se,'same');
    P=10;
    BigGroups=imdilate(bwareaopen(BoneShadow,P),strel('disk',7),'same');
    BigGroups=imerode(BigGroups,strel('disk',7),'same');
    BigGroups=imfill(BigGroups,'holes');
    BigGroups=imfill(BoneShadow,'holes');
    MaskRHT2(:,Yslice) = BigGroups.*RightCoronalBinaryMatrix(:,Yslice);
end
clear Cortical2 BigGroups BoneShadow Filled Dilate NoNoise Threshold W %Memory Management

% Display the time for this section for analysis purpose
time = toc;
Total_time = Total_time+time;
fprintf('Right Femur Mask Calculations complete in %0.3f seconds\n',time);
tic;
% The element with the most number of pixels is choose in the
% RightBinarymatrix and teh rest is deleted. This should get rid of
% everything besides the pelvis
cc = bwconncomp(MaskRHT2);

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numPixels = cellfun(@(numel, cc.PixelIdxList)
[SortedPixels, I] = sort(numPixels, 'descend');
idx = I(I);
MaskRHT2 = zeros(size(RightCoronalSlices));
MaskRHT2(cc.PixelIdxList(idx)) = 1;
imshow(MaskRHT2)
disp('Scroll through to see if femur is masked')
pause
button = questdlg('Is the femur masked?', 'Confirm Mask', 'Yes', 'No', 'Yes');
switch button
  case 'Yes'
    disp('Femur successfully masked')
  case 'No'
    idx = I(2);
    MaskRHT2 = zeros(size(RightCoronalSlices));
    MaskRHT2(cc.PixelIdxList(idx)) = 1;
    imshow(MaskRHT2)
    pause
    button = questdlg('Is the femur masked?', 'Confirm Mask', 'Yes', 'No', 'Yes');
    switch button
      case 'Yes'
        disp('Femur successfully masked')
      case 'No'
        idx = I(3);
        MaskRHT2 = zeros(size(RightCoronalSlices));
        MaskRHT2(cc.PixelIdxList(idx)) = 1;
        imshow(MaskRHT2)
        disp('Will continue as is')
        pause
    end
end

% Display the time for this section for analysis purpose
time = toc;
Total_time = Total_time + time;
fprintf('Right Side Cleaning complete in %.3f seconds \n', time);
function [c,r,α,v,cl,rl,el,vl,Total_time] = Right_Gather_Ellipsoid_Points(AxialSlices, ✓
RightCoronalSlices, SobeiEdges,xRHTcenter, yRHTcenter, zRHTcenter, Xresol, Yresol, Zresol, ✓
Total_time);

tic % Starting the time measurement for this section of the code
% Gather Ellipsoid Points
% Set scales and limits for the selection of ellipsoid points
x=[ ]; y=[ ]; z=[ ]; cupx=[ ]; cupy=[ ]; cupz=[ ];
Xlim=(xRHTcenter-50):(xRHTcenter+50);
Ylim=(yRHTcenter-50):(yRHTcenter+50);
Zlim=(zRHTcenter-50):(zRHTcenter+50);
XrhtScale=(Xlim(1)*Xresol Xlim(101)*Xresol); YrhtScale=(Ylim(1)*Yresol Ylim(101)*Yresol); ZrhtScale=(Zlim(1)*Zresol Zlim(101)*Zresol);

% Set the Yslice (based on the center), apply threshold, fill and display
% the image to the user so he can select the points for the ellipsoids
figure(7)
Yslice=yRHTcenter+16;
X=RightCoronalSlices(:, :, Yslice);
Cortical2=(X>126);
ThresholdX=Cortical2.*double(X);
P=18;
NoNoiseX=bwareaopen(ThresholdX, P);
se=strel('disk', 1);
DilateX=imdilate(NoNoiseX, se, 'same');
FilledX=imfill(DilateX, 'holes');
BoneShadowX=imerode(FilledX, se, 'same');
P=50;
BigGroupsX=imdilate(bwareaopen(BoneShadowX, P), strel('disk', 7), 'same');
BoneEdgesX=SobeiEdges(:, :, Yslice).*BigGroupsX;
imagesc(XrhtScale, ZrhtScale, BoneEdgesX(Xlim, Xlim));
colorbar(gray(256)); axis equal; axis tight; xlabel('X(mm)'); ylabel('Z(mm)');
title('title');
[xl, zl]=getpts(figure(7));
x=[xl; xl]; z=[zl; zl]; y=[y; y]; repmat(Yslice*Yresol, size(xl, 1), 1);

title('title');
[xl, zl]=getpts(figure(7));
x=[cupz; xl]; z=[cupz; zl]; y=[y; y]; repmat(Yslice*Yresol, size(xl, 1), 1);

% Set a new Yslice (based on the center), apply threshold, fill and display
% the image to the user so he can select the points for the ellipsoids
Yslice=yRHTcenter+16;
X=RightCoronalSlices(:, :, Yslice);
Cortical2=(X>126);
ThresholdX=Cortical2.*double(X);
P=18;  %Value can be adjusted. Larger for removing larger noise, smaller for allowing more noise
NoNoiseX=bwareaopen(ThresholdX,P);
se=strel('disk',1);
DilateX=imdilate(NoNoiseX,se,'same');
FilledX=imfill(DilateX,'holes');
BoneShadowX=imerode(FilledX,se,'same');
P=50;  %Value can be adjusted. Larger for removing larger bodies, smaller for allowing more bodies
BigGroupsX=imdilate(bwareaopen(BoneShadowX,P),strel('disk',7),'same');
BoneEdgesX=SobelEdges(:,Yslice).*BigGroupsX;
imagesc(XrhtScale, YrhtScale, BoneEdgesX(Xlim,Xlim));
colormap(gray(256)); axis equal; axis tight; xlabel('x(mm)'); ylabel('y(mm)');
title('Select Points On Right \bfFemoral Head';'\fontsize{12}Coronal Slice\ #',num2str(Yslice));
[x1,z1]=getpts(gcf);
x=[x1;1]; z=[z1;1]; y=[y;1]; repmat(Yslice*Yresol,size(x1,1),1]);

title('Select Points On Right \bfAcetabular Cup';'\fontsize{12}Coronal\ Slice\ #',num2str(Yslice));
[x2,z2]=getpts(gcf);
cupx=[cupx;z2]; cupz=[cupz;z2]; cupy=[cupy;1]; repmat(Yslice*Yresol,size(x2,1),1));

% Set a Zslice(based on the center for the ellipsoid), apply threshold,
% fill and display the image to the user so he can select the points for
% the ellipsoid
Zslice=ZsliceCenter+16;
X=AxialSlices(:,Zslice);
Cortical2=(X>126);
ThresholdX=Cortical2.*double(X);
P=18;
NoNoiseX=bwareaopen(ThresholdX,P);
se=strel('disk',1);
DilateX=imdilate(NoNoiseX,se,'same');
FilledX=imfill(DilateX,'holes');
BoneShadowX=imerode(FilledX,se,'same');
P=50;
BigGroupsX=imdilate(bwareaopen(BoneShadowX,P),strel('disk',7),'same');
for i=1:256
    AxialSobelSlice(:,i)=SobelEdges(Zslice,i,:);
end
BoneEdgesX=AxialSobelSlice.*BigGroupsX(:,1:256);
imagesc(XrhtScale, YrhtScale, BoneEdgesX(Xlim,Xlim));
colormap(gray(256)); axis equal; axis tight; xlabel('x(mm)'); ylabel('y(mm)');
title('Select points on Right \bfFemoral Head';'\fontsize{12}Axial Slice\ #',num2str(Zslice));
[x1,y1]=getpts(gcf);
x=[x1;1]; y=[y1;1]; z=[z;1]; repmat(Zslice*Zresol,size(x1,1),1));
title('Select Points On Right \bfAcetabular Cup';'\fontsize{12}Axial Slice\ #',num2str(Yslice));
[x2,y2]=getpts(figure(7));
cupx=[cupx;x2]; cupz=[cupz;repmat(Zslice*Zresol,size(x2,1),1)]; cupy=[cupy; y2];

% Set a new Zslice (based on the center for the ellipsoid), apply threshold,
% fill and display the image to the user so he can select the points for
% the ellipsoid
Zslice=ZTHcenter-16;
X=AxialSlices(:,:,Zslice);
Cortical2=(X>126);
ThresholdX=Cortical2.*double(X);
P=18;
NoNoiseX=bwareaopen(ThresholdX,P);
se=strel('disk',1);
DilateX=imdilate(NoNoiseX,se,'same');
FilledX=imfill(DilateX,'holes');
BoneShadowX=imerode(FilledX,se,'same');
P=50;
BigGroupsX=imdilate(bwareaopen(BoneShadowX,P),strel('disk',7),'same');
for i=1:256
    AxialSobelSlice(:,:,i)=SobelEdges(Zslice,i,:);
end
BoneEdgesX=AxialSobelSlice.*BigGroupsX(:,1:256);
imagesc(XrhtScale, YrhtScale, BoneEdgesX(Ylim,Xlim));
colormap(gray(256)); axis equal; axis tight; xlabel('x(mm)'); ylabel('y(mm)');
title('Select points on Right \bfFemoral Head';'
num2str(Zslice)));
[x1,y1]=getpts(figure(7));
x1=[x1;x1]; y1=[y1;repmat(Zslice*Zresol,size(x1,1),1)]; y1=[y1;y1];
title('Select Points on Right \bfAcetabular Cup';'
num2str(Yslice)));
[x2,y2]=getpts(figure(7));
cupx=[cupx;x2]; cupz=[cupz;repmat(Zslice*Zresol,size(x2,1),1)]; cupy=[cupy; y2];

% Apply the function ellipsoid_fit to fit an ellipsoid to both set of
% points
[c,r,e,v]=ellipsoid_fit([x,y,z]);
c1,r1,e1,v1=ellipsoid_fit([cupx,cupy,cupz]);

% Output:
% * center - ellipsoid center coordinates [xc; yc; zc]
% * ax - ellipsoid radii [a; b; c]
% * evcs - ellipsoid radii directions as columns of the 3x3 matrix
% * v - the 9 parameters describing the ellipsoid algebraically:
%     Ax^2 + By^2 + Cz^2 + 2Dxy + 2Exz + 2Fyz + 2Gx + 2Hy + 2Iz = 1
% Display the time for this section for analysis purpose
close all

time = toc;
Total_time = Total_time+time;
fprintf('Gather Ellipsoid Points for the Right Femur complete \n');
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function [Total_Final_Time] = Right_Pelvis_Cloud(Right_Pelvis_No_Sacrum,Xresol,Yresol,Zresol,Total_Final_Time)

fprintf('Starting pelvis right side point cloud generation \n');
tic %starting the time measurement for this section of the code

% Right Pelvis Cloud
A1 = [];
Pelvis = Right_Pelvis_No_Sacrum;

% For each slice, the .mat file is transformed into a grayscale image so the
% command bwboundaries can be used to get the pixels in the boundaries
% for each object in the image. Then, the pixels coordinates are stored
% in a vector called A1 and multiplied by de resolution.
for Yslice = 1:size(Pelvis,3);
    Q = logical(Pelvis(:,1,:));
    I = mat2gray(Q);
    [B,L,N] = bwboundaries(I);
    for k=1:length(B),
        boundary = B(k);
        A1 = [A1; boundary(:,2) repmat((size(Pelvis,3)-Yslice),size(boundary,1),1)]
        boundary(:,1)];
    end
end
A1(:,1) = A1(:,1).*Xresol; %x
A1(:,2) = A1(:,2).*Yresol; %y
A1(:,3) = A1(:,3).*Zresol; %z

% After the first set of points is sorted, the matrix is rotated and the
% same process is repeated so the pixels in boundaries that couldn't be
% reached in the previous code can be stored
TransversalPelvis = [];
for i=1:size(Pelvis,3),
    TransversalPelvis(:,i)=fliprl(Pelvis(:,i));
end
Xc=num2cell(TransversalPelvis,[1,2]);
Xc=cellfun(@(x) rot90(x,1),Xc,'uni',false);
TransversalPelvis=cat(3,Xc(:));
TransversalPelvis=permute(TransversalPelvis,[3,1,2]);
A4 = [];
for Zslice = 1:size(TransversalPelvis,3);
    Q = logical(TransversalPelvis(:,2,:));
    I = mat2gray(Q);
    [B,L,N] = bwboundaries(I);
    for k=1:length(B),
        boundary = B(k);
        A4 = [A4; boundary(:,2) boundary(:,1) repmat(Zslice,size(boundary,1),1)];
    end
end
end
end

A4(:,1) = A4(:,1).*Xresol; \%x
A4(:,2) = (size(Pelvis,3)-A4(:,2)).*Yresol; \%y
A4(:,3) = A4(:,3).*Zresol; \%z

\% Both matrices are concatenated into one n-by-3 matrix representing the
\% coordinates for all the pixels in the boundaries. After that, the
\% repeated rows are eliminated for a better point cloud without double
\% points.
A4 = vertcat(A1,A4);
A4 = unique(A4,'rows');

\% The file is stored as a .xyz file in the current MATLAB folder
csvwrite('Right_Pelvis_No_Sacrum.xyz',A4)
clear A1 A4 Pelvis Xc \% Memory Management
time = toc;
Total_Final_Time = Total_Final_Time+time;
fprintf('Point Cloud Generation complete in %0.3f seconds\n',time);
 function [PelvisRHT,Total_time] = Right_Side_Pelvis(MaskRHT2,RightCoronalSlices,
    RightCoronalBinaryMatrix,SobelEdges,Total_time);
 tic
 % With the Final Mask created, the mask is dilated and multiplied by the
 % ellipsoid matrix again. This is used to make sure we got every point in
 % the pelvis and don't get any point of the femur. Finally, the image is
 % multiplied by the edge detected image and output the final result for the
 % right side
 PelvisRHT = [];
 for Yslice = 1:size(RightCoronalSlices,3)
     Dilate = imdilate(MaskRHT2(:,Yslice),strel('disk',2),'same');
     FemurMaskRHT(:,Yslice) = Dilate.*RightCoronalBinaryMatrix(:,Yslice);
     PelvisRHT(:,Yslice) = FemurMaskRHT(:,Yslice).*SobelEdges(:,Yslice);
 end

 % Display the time for this section for analysis purpose
 clear Dilate FemurMaskRHT MaskRHT
 time = toc;
 Total_time = Total_time+time;
 fprintf('Pelvis Right Side complete. Time elapsed %0.3f seconds\n',Total_time);
% Confidential - University of Cincinnati

function [Total_Final_Time] = Sacrum_Cloud(Sacrum,Xresol,Yresol,Zresol,Total_Final_Time)

fprintf('Starting Sacrum point cloud generation \n');
tic %starting the time measurement for this section of the code

% Sacrum Cloud
A1 = [];

% For each slice, the .mat file is transformed into a grayscale image so the
% command bwboundaries can be used to get the pixels in the boundaries
% for each object in the image. Then, the pixels coordinates are stored
% in a vector called A1 and multiplied by de resolution.
for Yslice = 1:size(Sacrum,3);
    Q = logical(Sacrum(:,Yslice)>0);
    I = mat2gray(Q);
    [B,L,N] = bwboundaries(I);
    for k=1:length(B),
        boundary = B(k);
        boundary(:,1) = boundary(:,1)*Yresol;
        A1(:,1) = A1(:,1).*Xresol;
        A1(:,2) = A1(:,2).*Yresol;
        A1(:,3) = A1(:,3).*Zresol;
    end
end

% After the first set of points is sorted, the matrix is rotated and the
% same process is repeated so the pixels in boundaries that couldn't be
% reached in the previous code can be stored
TransversalPelvis = [];
for i=1:size(Sacrum,3);
    TransversalPelvis(:,i)=flipud(Sacrum(:,i,:));
end
Xc=num2cell(TransversalPelvis,[1,2]);
Xc=cellfun(@(x) rot90(x,1),Xc,'unif',false);
TransversalPelvis=cat(3,Xc(,,:));
TransversalPelvis=permute(TransversalPelvis,[3,1,2]);
A4 = [];
for Zslice = 1:size(TransversalPelvis,3);
    Q = logical(TransversalPelvis(:,Zslice)>0);
    I = mat2gray(Q);
    [B,L,N] = bwboundaries(I);
    for k=1:length(B),
        boundary = B(k);
        A4 = [A4; boundary(:,2) boundary(:,1) repmat(Zslice,size(boundary,1),1)];
    end
end
end
A4(:,1) = A4(:,1).*Xresol; % x
A4(:,2) = (size(Sacrum,3)-A4(:,2)).*Yresol; % y
A4(:,3) = A4(:,3).*Zresol; % z

% Both matrices are concatenated into one n-by-3 matrix representing the
% coordinates for all the pixels in the boundaries. After that, the
% repeated rows are eliminated for a better point cloud without double
% points.
A4 = vertcat(A1,A4);
A4 = unique(A4,'rows');

% The file is stored as a .xyz file in the current MATLAB folder
csvwrite('Sacrum.xyz',A4)
clear A1 A4 Sacrum Xc % Memory Management
time = toc;
Total_Final_Time = Total_Final_Time+time;
fprintf('Point Cloud Generation complete in %0.3f seconds\n',time);
1/24/17 2:16 PM  F:\Ortho-Specific\Ma...\Sacrum Plane Fit.m  1 of 2

% Confidential - University of Cincinnati

function [Pelvis_No_Sacrum,Sacrum,Total_Final_Time] = Sacrum_Plane_Fit(Pelvis_Matrx,
CoronalSlices,xRHTcenter,yRHTcenter,zRHTcenter,xLFTcenter,yLFTcenter,zLFTcenter,
Total_Final_Time)

tic %starting the time measurement for this section of the code
fprintf('Starting Calculations for the Plane \n');

clear x y z
% The distance between the two centers is calculated and used to make a
% vector that will be normal to the sagittal plane that pass through the
% middle point of the distance between the centers
Length = sqrt((xLFTcenter - xRHTcenter)^2 + (yLFTcenter - yRHTcenter)^2 + (zLFTcenter -
            zRHTcenter)^2);
NormalVector = [(xLFTcenter - xRHTcenter) (yLFTcenter - yRHTcenter) (zLFTcenter -
                zRHTcenter)];
D2 = [round((xLFTcenter - xRHTcenter)/2 + xRHTcenter) round((yLFTcenter - yRHTcenter)/2 +
            yRHTcenter) round((zLFTcenter - zRHTcenter)/2 + zRHTcenter)];

NormalVectorx = NormalVector(1); NormalVectory = NormalVector(2); NormalVectorz =
NormalVector(3);
D2x = D2(1); D2y = D2(2); D2z = D2(3);

% The coordinates for the plane in the Yslice defined by the middle point
% is calculated and stored in a vector. The thickness of the plane is
% decided as 28% of the total distance between the two centers.
t = 1:round(D2(3));
syms x y z
Plane = sym('((NormalVectorx*(x-D2x)) + (NormalVectory*(y-D2y)) + (NormalVectorz*(z-
            D2z)))^2');
% Plane = subs(Plane);
X = solve(Plane,x);
z = t; y = D2y;
x = double(subs(X)); x1 = x; z1 = z;
Line = [z' x'];
for H = 1:round(0.2*Length) % Changed from 0.28 to 0.2
    x = x+1;
    Line = [Line; z' x'];
end
for H = 1:round(0.2*Length) % Changed from 0.28 to 0.2
    x1 = x1-1;
    Line = [Line; z1' x1'];
end

% The coordinates for every point in the plane is stored in a ones matrix
% as zeros and this matrix is used as a mask for the Binary Matrix that
% represents the Pelvis
NoSacrum = ones(size(CoronalSlices));
for Yslice = min(yLFTcenter,yRHTcenter):size(CoronalSlices,3)  
    for H = 1:size(Line,1)  
        NoSacrum(Line(H,1),Line(H,2),Yslice) = 0;  
    end  
end  
Pelvis_No_Sacrum0 = Pelvis_Matrix.*NoSacrum;  

% The element with the most number of pixels is chosen to remain intact  
% and the rest is deleted  
cc = bwconncomp(Pelvis_No_Sacrum0);  
numPixels = cellfun(@numel,cc.PixelIdxList);  
[biggest,idx] = max(numPixels);  
Pelvis_No_Sacrum = zeros(size(Pelvis_No_Sacrum0));  
Pelvis_No_Sacrum(cc.PixelIdxList{idx}) = 1;  
clear z y x t zl xl %Memory Management

Sacrum0 = ones(size(CoronalSlices)) - Pelvis_No_Sacrum;  
Sacrum = Sacrum0.*Pelvis_Matrix;  
clear Sacrum0  
time = toc;  
Total_Final_Time = Total_Final_Time+time;  
fprintf('Plane fit complete in %0.3f seconds\n',time);  

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% Confidential - University of Cincinnati

function [SF] = SheetnessFilter(I,SIGMA)

% Ref: Krcah, M., Székely, G., Blanc, R.: Fully automatic and fast segmentation of the
% femur bone from 3D-CT images with no shape prior. 2011 IEEE International Symposium
% Biomedical Imaging: From Nano to Macro (2011).
% clear all
% close all
% clc

%Parms
parms.k = 10;
parms.SD = 1;
parms.alpha = 0.5;
parms.beta = 0.5;
parms.gamma = 0.25;

%Unsharp filter
tic
[g3,g3x,g3y,g3z]=Gaussian3(1,3);
IU = I + parms.k * (I - convn(I,g3,'same'));

%Sheetness filter (May need to modify this based on the paper)
[g3,g3x,g3y,g3z]=Gaussian3(SIGMA,ceil(3*SIGMA));

LX = convn(IU,g3x,'same');
LY = convn(IU,g3y,'same');
LZ = convn(IU,g3z,'same');

LXX = convn(LX,g3x,'same');
LXY = convn(LX,g3y,'same');
LXZ = convn(LX,g3z,'same');
LYY = convn(LY,g3y,'same');
LYZ = convn(LY,g3z,'same');
LZZ = convn(LZ,g3z,'same');

%Trace of Hessian
T = LXX + LXY + LZZ;

%Eigenvalues of Hessian
[11,12,13] = eigenvaluefield33( LXX(:,), LXY(:,), LXZ(:,), LYY(:,), LYZ(:,), LZZ(:,));

l = [11 12 13];
clear LX LY LZ LXX LXY LXZ LYY LYZ LZZ 11 12 13

[lambda,pos] = sort(abs(l),2,'ascend');

%Sorted Eigenvalues |L1| <= |L2| <= |L3|
L1 = (l (sub2ind(size(l),1:size(l,1),pos(:,1))'));
L2 = (1 (sub2ind(size(L),1:size(L,1),pos(:,2)))
L3 = (1 (sub2ind(size(L),1:size(L,1),pos(:,3)))
L1 = reshape(L1,size(T));
L2 = reshape(L2,size(T));
L3 = reshape(L3,size(T));
clear l lambda pos

% size(T)
% Calculate Sheetness Filter (SF)
Rsheat = abs(L2) ./ abs(L3);
Rtube = abs(L1) ./ (abs(L2).*abs(L3));
Rnoise = (abs(L1)+abs(L2)+abs(L3)) ./ T;

SF = -slog(L3) .* exp(-Rsheat.^2/parms.alpha^2)...
   .* exp(-Rtube.^2/parms.beta^2)...
   .* (1-exp(-Rnoise.^2/parms.gamma^2));
function [cs, index] = sort_nat(c, mode)
% sort_nat: Natural order sort of cell array of strings.
% usage: [S, INDEX] = sort_nat(C)
%
% where,
% C is a cell array (vector) of strings to be sorted.
% S is C, sorted in natural order.
% INDEX is the sort order such that S = C(INDEX);

% Natural order sorting sorts strings containing digits in a way such that
% the numerical value of the digits is taken into account. It is
% especially useful for sorting file names containing index numbers with
% different numbers of digits. Often, people will use leading zeros to get
% the right sort order, but with this function you don’t have to do that.
% For example, if C = {'file1.txt', 'file2.txt', 'file10.txt'}, a normal sort
% will give you
% {'file1.txt' 'file10.txt' 'file2.txt'}
% whereas, sort_nat will give you
% {'file1.txt' 'file2.txt' 'file10.txt'}
% See also: sort

% Version: 1.4, 22 January 2011
% Author: Douglas M. Schwarz
% Email: dmschwarz-ieee.org, dmschwarz-urgrad@rochester.edu
% Real_email = regexpreg(Email, ['^','^'],'^','^'))

% Set default value for mode if necessary.
if nargin < 2
    mode = 'ascend';
end

% Make sure mode is either 'ascend' or 'descend'.
modes = strcmpi(mode, {'ascend', 'descend'});
is_descend = modes(2);
if ~any(modes)
    error('sort_nat:SortDirection...',
    'sorting direction must be 'ascend'' or '''descend''.');
end

% Replace runs of digits with '0'.
c2 = regexprep(c, '\d+', '0');

% Compute char version of c2 and locations of zeros.
s1 = char(c2);
z = s1 == '0';
% Extract the runs of digits and their start and end indices.
[digruns,first,last] = regexp(c, '\d+', 'match', 'start', 'end');

% Create matrix of numerical values of runs of digits and a matrix of the
% number of digits in each run.
num_str = length(c);
max_len = size(a1,2);
num_val = NaN(num_str,max_len);
um_digit = NaN(num_str,max_len);
for i = 1:num_str
    num_val(i,z(i,:)) = sscanf(sprintf('s ',digruns{i}),'%f');
    num_digit(i,z(i,:)) = last[i] - first[i] + 1;
end

% Find columns that have at least one non-NaN. Make sure activecols is a
% 1-by-n vector even if n = 0.
activecols = reshape(find(~all(isnan(num_val))),1,[]);
if ~any(activecols)
    n = length(activecols);
end

% Compute which columns in the composite matrix get the numbers.
umcols = activecols + (1:2:2^n);

% Compute which columns in the composite matrix get the number of digits.
n_digit = numcols + 1;

% Compute which columns in the composite matrix get chars.
charcols = true(1,max_len + 2^n);
charcols(numcols) = false;
charcols(n_digit) = false;

% Create and fill composite matrix, comp.
comp = zeros(num_str,max_len + 2^n);
comp(:,charcols) = double(a1);
comp(:,numcols) = num_val(:,activecols);
comp(:,n_digit) = num_digit(:,activecols);

% Sort rows of composite matrix and use index to sort c in ascending or
% descending order, depending on mode.
[unused,index] = sortrows(comp);
if is_descend
    index = index(end:-1:1);
end
index = reshape(index,size(c));
comp = c(index);
Appendix II: Cadaver Series Sample Surgical Plan

Surgical Plan for Total Hip Arthroplasty with Patient-Specific Instrumentation

<table>
<thead>
<tr>
<th>Procedure ID Number</th>
<th>Fresh Cadaver 7-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT CD ID Number</td>
<td>38229[170]</td>
</tr>
<tr>
<td>CT ID Number</td>
<td>008 pre op</td>
</tr>
<tr>
<td>Cadaver ID</td>
<td></td>
</tr>
<tr>
<td>Date of Procedure</td>
<td>4/6/16</td>
</tr>
<tr>
<td>Surgeon</td>
<td>Dr. Todd Kelley</td>
</tr>
<tr>
<td>Side</td>
<td>Right</td>
</tr>
</tbody>
</table>

**Acetabulum Measurements**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cup Size</td>
<td>48mm</td>
</tr>
<tr>
<td>Vertical Inclination</td>
<td>36.63°</td>
</tr>
<tr>
<td>Anteversion</td>
<td>19.47°</td>
</tr>
<tr>
<td>Offset from COR</td>
<td>2mm</td>
</tr>
</tbody>
</table>

**Femur Measurements**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem Size</td>
<td>4</td>
</tr>
<tr>
<td>Stem Length</td>
<td>93.50mm</td>
</tr>
<tr>
<td>Stem Base Offset</td>
<td>41.75mm</td>
</tr>
<tr>
<td>Stem Leg Adjustment</td>
<td>32.00mm</td>
</tr>
<tr>
<td>Stem Neck Length</td>
<td>36.00mm</td>
</tr>
<tr>
<td>Neck Angle</td>
<td>130°</td>
</tr>
<tr>
<td>Coating Angle</td>
<td>45°</td>
</tr>
<tr>
<td>Femoral Head Size</td>
<td>30mm</td>
</tr>
<tr>
<td>Anteversion</td>
<td>16.7°</td>
</tr>
</tbody>
</table>

**Screw Measurements**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>25mm</td>
</tr>
<tr>
<td>Screw hole</td>
<td>Either</td>
</tr>
</tbody>
</table>

**Notes:**
Hand segmentation methods were used

X-axis is normal to Sagittal Plane, Positive is Left
Y-axis is normal to Coronal Plane, Positive is Posterior
Z-axis is normal to Transverse Plane, Positive is Superior

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### Cup Alignment

<table>
<thead>
<tr>
<th>Coronal View</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image_url" alt="Coronal View Image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vertical Inclination 36.6°</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image_url" alt="Vertical Inclination Image" /></td>
</tr>
<tr>
<td>Coronal View</td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td><img src="image1.png" alt="Coronal View" /></td>
</tr>
<tr>
<td>Femoral Resection</td>
</tr>
<tr>
<td><img src="image4.png" alt="Femoral Resection" /></td>
</tr>
</tbody>
</table>
Appendix III: Cadaver Series Data
*Yellow cells indicate a failure and the data was not included in analysis

<table>
<thead>
<tr>
<th>Cadaver</th>
<th>Computer Folder</th>
<th>Sex</th>
<th>Cadaver Type</th>
<th>CT Label</th>
<th>Date</th>
<th>Acetabular PSI Design</th>
<th>Reamer Handle Design</th>
<th>Segmentation Method</th>
<th>CAD Creation Method</th>
<th>Cup Material</th>
<th>PSI Material</th>
<th>Side</th>
<th>Surgical Plan Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>002 Fresh Cadaver</td>
<td>Female</td>
<td>Fresh</td>
<td>002</td>
<td>9/16/2015</td>
<td>T-Slot</td>
<td>T-Slot</td>
<td>Matlab</td>
<td>SolidWorks</td>
<td>Crumble</td>
<td>ABS</td>
<td>Right</td>
<td>002</td>
</tr>
<tr>
<td>2</td>
<td>003 Fresh Cadaver</td>
<td>Female</td>
<td>Fresh</td>
<td>003</td>
<td>9/30/2015</td>
<td>T-Slot</td>
<td>T-Slot</td>
<td>Matlab</td>
<td>SolidWorks</td>
<td>Bronze</td>
<td>ABS</td>
<td>Right</td>
<td>004</td>
</tr>
<tr>
<td>3</td>
<td>004 Fresh Cadaver</td>
<td>Female</td>
<td>Fresh</td>
<td>004</td>
<td>10/14/2015</td>
<td>Single Pin</td>
<td>Angled Arms</td>
<td>Matlab</td>
<td>SolidWorks</td>
<td>SST</td>
<td>ABS</td>
<td>Right</td>
<td>006</td>
</tr>
<tr>
<td>4</td>
<td>005 Fresh Cadaver</td>
<td>Female</td>
<td>Fresh</td>
<td>005</td>
<td>11/4/2015</td>
<td>Single Pin</td>
<td>Angled Arms</td>
<td>Matlab (Scaled wrong)</td>
<td>Rhino</td>
<td>SST</td>
<td>ABS</td>
<td>Right</td>
<td>008</td>
</tr>
<tr>
<td>5</td>
<td>006 Fresh Cadaver</td>
<td>Female</td>
<td>Fresh</td>
<td>006</td>
<td>12/2/2015</td>
<td>Single Pin</td>
<td>Angled Arms</td>
<td>F-Matlab (Scaled wrong), P-Amira</td>
<td>Rhino</td>
<td>SST</td>
<td>ABS</td>
<td>Right</td>
<td>010</td>
</tr>
<tr>
<td>6</td>
<td>007 Fresh Cadaver</td>
<td>Female</td>
<td>Fresh</td>
<td>007</td>
<td>3/23/2016</td>
<td>Single Pin</td>
<td>Angled Arms</td>
<td>Amira</td>
<td>Rhino</td>
<td>Nylon</td>
<td>Nylon</td>
<td>Right</td>
<td>012</td>
</tr>
<tr>
<td>7</td>
<td>008 Fresh Cadaver</td>
<td>Female</td>
<td>Fresh</td>
<td>008</td>
<td>4/6/2016</td>
<td>Single Pin</td>
<td><em>Faulty</em></td>
<td>Amira</td>
<td>Rhino</td>
<td>SST</td>
<td>Nylon</td>
<td>Right</td>
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</tr>
<tr>
<td>8</td>
<td>009 Fresh Cadaver</td>
<td>Female</td>
<td>Fresh</td>
<td>009</td>
<td>4/27/2016</td>
<td>Single Pin</td>
<td>Angled Arms</td>
<td>Amira</td>
<td>Rhino</td>
<td>Nylon</td>
<td>Nylon</td>
<td>Right</td>
<td>016</td>
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<tr>
<td>9</td>
<td>010 Fresh Cadaver</td>
<td>Female</td>
<td>Fresh</td>
<td>010</td>
<td>6/8/2016</td>
<td>Single Pin</td>
<td>Double Hooks</td>
<td>Amira</td>
<td>Rhino</td>
<td>SST</td>
<td>Nylon</td>
<td>Right</td>
<td>018</td>
</tr>
<tr>
<td>10</td>
<td>011 Fresh Cadaver</td>
<td>Male</td>
<td>Fresh</td>
<td>011</td>
<td>7/13/2016</td>
<td>Single Pin</td>
<td>Double Hooks</td>
<td>Amira</td>
<td>Rhino</td>
<td>SST</td>
<td>Nylon</td>
<td>Right</td>
<td>020</td>
</tr>
<tr>
<td>Calculated Diameter</td>
<td>Natural Cup Inclination</td>
<td>Natural Cup Version</td>
<td>Natural Femoral Version</td>
<td>Cup Size</td>
<td>Stem Size</td>
<td>Femoral Head</td>
<td>Pin Location Med to Lat</td>
<td>Pin Location A to P</td>
<td>Pin Location S to I</td>
<td>Pin Angle Inclination</td>
<td>Pin Angle Anteverision</td>
<td>Cup Inclination</td>
<td>Cup Anteverision</td>
</tr>
<tr>
<td>---------------------</td>
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<td>----------------</td>
<td>-------------------</td>
<td>---------------------</td>
<td>----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>42.5118</td>
<td>54.36</td>
<td>24.75</td>
<td>18.89</td>
<td>46</td>
<td>2</td>
<td>28</td>
<td>[74.41, 67.32]</td>
<td>[5.78, -9.58]</td>
<td>[161.76, 162.62]</td>
<td>N/A</td>
<td>N/A</td>
<td>45</td>
<td>20</td>
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<tr>
<td>42.6396</td>
<td>56.35</td>
<td>23.62</td>
<td>15.58</td>
<td>46</td>
<td>2</td>
<td>28</td>
<td>[119.13, 113.06]</td>
<td>[-4.82, 14.42]</td>
<td>[161.71, 152.95]</td>
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<td>N/A</td>
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<td>20</td>
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<tr>
<td>52.4078</td>
<td>44.26</td>
<td>16.82</td>
<td>6.85</td>
<td>52</td>
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Todd commented that the cup looked too retroverted in surgery.

No pictures because Lica was needed to hold retractors etc.
Appendix IV: Cadaver Series Achieved vs Planned Overlays

*Red indicates the planned position, blue indicates the achieved position, and orange represents the PSI guide.

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Right

004  
Left

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