3D ultrasound for accurate guidance of arthroscopic femoroacetabular impingement osteoplasty: a phantom model validation study

Buchan LL¹, Hacihaliloglu İ², Ellis RE³, Gilbart MK², Wilson DR²

¹Biomedical Engineering, University of British Columbia, Vancouver, Canada
²Department of Orthopaedics, University of British Columbia, Vancouver, Canada
³School of Computing, Queen's University, Kingston, Canada

lawrence.buchan@alumni.ubc.ca

Introduction: Femoroacetabular impingement (FAI) is characterized by abnormal contact within the hip at extremes positions in its range of motion and widely thought to be a leading cause of hip osteoarthritis [1]. FAI is generally caused by a deformity of the femoral head/neck (cam impingement) or acetabulum (pincer), and often both; surgical correction of FAI by resection of the bony deformities has become widely used to delay the onset of osteoarthritis and improve hip range of motion. However, achieving an accurate arthroscopic osteoplasty in the hip joint can be challenging due to a small available field of view. Recently, image-based navigation using a preoperative plan for arthroscopic osteoplasty of FAI has been shown to improve the accuracy of post-surgery bone surface contours [2].

The current standard for intraoperative monitoring, three-dimensional (3D) X-ray fluoroscopy, is accurate at the initial registration step to within 0.8±0.5mm [3], but exposes patients and surgeons to radiation. Alternative imageless methods that use digitized depth probes are limited in achievable accuracy, with initial registration error of 5.6±4.1mm [3]. Intraoperative 3D ultrasound (US) is a promising alternative for providing real-time, 3D visual feedback during FAI osteoplasty and can be registered with a high-resolution preoperative plan based on a computed tomography (CT) image. The utility of the 3D US approach depends critically on the accuracy of registration between US and CT-based volumes and has not yet been investigated in the hip.

Objective: The objective was to determine the accuracy with which 3D US can be used to visualize surgical progress according to a CT-based preoperative plan and to compare 3D US to fluoroscopic methods.

Methods: The evaluation protocol included the following steps:

- Create a preoperative plan from a CT image of a femur model
- Automatically extract an accurate bone surface from a 3D US
- Perform a fiducial-based reference registration from US to C
- Randomly misalign and re-register multiple 3D US scans to CT in order to quantify achievable registration accuracy
- Create a post-operative model and provide a sample measure of surgical accuracy using 3D US to CT registration

The model was a thermoplastic left femur phantom with a cam deformity. Thirty metal 1mm diameter fiducial markers were placed on the US-accessible anterior and lateral surfaces of the femur. A CT image was acquired (Xtreme CT #HRpQCT, Scanco, Wayne, PA, USA) with 0.246mm isotropic voxel size and segmented and reconstructed into a 3D model (Mimics 15.0, Materialise, Leuven, Belgium). A
preoperative plan for resection of the cam deformity was created with input from an orthopaedic surgeon experienced in hip arthroscopy, and also reconstructed into a visual 3D model.

Fig. 1. A) Preoperative ultrasound (US) surface in yellow and computed tomography (CT) model in white, with fiducial markers in red, in their respective native coordinates; B) US surface after registration with the CT model; C) US surface visualized with the preoperative plan; D) a new “post-op” US surface registered with the preoperative plan.

Twenty-two sets of 3D US data were gathered from the phantom using a clinical ultrasound machine and 3D RSP5-12 transducer (GE Voluson 730 Expert, General Electric, Waukesha, WI, USA) with 0.21mm isotropic voxels while the phantom was submerged in water. Each scan was obtained from slightly different regions on the anterior/lateral surfaces of the femur with at least four fiducials visible in the volume. US surfaces were extracted using a recently proposed phase-symmetry algorithm [4]. Fiducial markers in the US volume were manually registered to the corresponding CT fiducials in order to provide a gold standard reference registration. Resulting distance error between corresponding fiducials was
measured and reported as fiducial registration error (FRE). Average surface error of each gold-standard registration was defined as the average Euclidean distance from each US voxel to the closest CT voxel and reported as target registration error (TRE).

After fiducial-based spatial initialization, each US surface was randomly misaligned in three directions (rotations ±15°, translations ±80 voxels or 10mm) and re-registered using a coherent point-drift algorithm [5]. Average distance error between US and CT was reported as surface registration error (SRE).

Finally, a plastic physical model of the preoperative plan (cam deformity resection) was manufactured to represent a sample “post-op” model using a 3D printer (University of British Columbia Rapid, Vancouver, Canada). Five US scans were acquired of the “post-op” model from the resection area near the femoral head/neck. Each US scan was initialized by selecting three reference points, randomly misaligned 20 times to replicate point picking variability, then registered using the coherent point drift algorithm. The surgical outcome accuracy was reported using final surface registration error (fSRE).

**Results:** Average FRE for all 22 scans was 0.41±0.19mm representing minor distance error between corresponding CT and US fiducials following manual point registration. The TRE was 0.46±0.26mm (average distance between surfaces following the gold-standard fiducial registration) indicating accurate extraction of the US bone surface. The average SRE (distance between surfaces following misalignment and re-registration) for all 2200 automated registration trials was 0.39±0.17mm. Each registered US surface was visualized in its native coordinates (Fig. 1A) and then superimposed on both the original CT data (Fig. 1B) and preoperative plan (Fig. 1C).

Lastly, five US scans of the post-operative model with 20 trials yielded an average fSRE (distance between surfaces following automated registration) of 0.58±0.07mm. Post-operative scans were superimposed on the pre-operative plan (Fig. 1D). Qualitative results showed good matching from preoperative and both post-operative registration.

**Discussion:** Initial registration between intraoperative 3D US and preoperative CT is critical in establishing accurate visualization of surgical progress during FAI osteoplasty. The results show that, given a spatial initialization, the achievable registration accuracy of 3D US to CT is an average surface distance error of 0.39±0.17mm which is well within the current fluoroscopy standard of 0.8±0.5mm [3]. The next step will be to expand the study group to include soft tissue, cadavers, and ultimately in vivo validation. The results to this point suggest strong potential for ultrasound to guide computer-assisted arthroscopic hip osteoplasty for cam FAI deformities.

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**References**