2D/3D Intermodel Registration of Quantitative Magnetic Resonance Images

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Abstract. Quantitative Magnetic Resonance Imaging (qMRI) is backed by extensive validation in research literature but has seen limited use in clinical practice because of long acquisition times, lack of standardization and no statistical models for analysis. Our research focuses on developing a novel intermodal 2D slice to 3D volumetric pipeline for an emerging qMR technology that aims to bridge the gap between research and practice. The two-part method first initializes the registration using a 3D reconstruction technique then refines it using 3D to 2D projection method. Intermediate results promise feasibility and efficacy of our proposed 2D/3D multi-dimensional intermodal registration process.

1 Introduction

Biochemical changes often precede observable changes in morphology[3][17] and insight into these earlier asymptomatic deviations can help inform interventional and management plans. Magnetic Resonance Imaging (MRI) has been traditionally used to acquire visual insight into the anatomy, morphology and physiology of living organisms. Quantitative MRI (qMRI) can capture and express the biochemical composition of the imaged structures as quantitative, calibrated physical units [8]. Despite a historically large body of research evidence providing validation for qMRI, it has seen limited integration into routine clinical practice[7] due to obstacles such as infeasible acquisition time, insufficient standardization and a lack of statistical models for computational analysis.

The recent introduction of MR Fingerprinting (MRF), a novel technique for rapid and reproducible qMRI, has re-energized research in addressing these issues[11]. One particularly promising approach enables rapid high-resolution mapping and simultaneous mapping of multiple parameters in six 2D sections oriented around a central axis of rotation[10]. This method drastically cuts down acquisition time and has been proven to be highly reproducible[4] but it lacks any normative models to perform comparative, population-based and longitudinal analysis. This is partly owing to the novely of the data, but mostly because spatial normalization necessitates an effective 2D slice to 3D volume registration technique and multi-dimensional intermodal registration continues to be an open problem[12][5]. The specifics of the 3D volume on the other hand are less relevant since 3D/3D volume registration has several well-established and effective solutions that can be used to transform a template to a scan and vice versa[2].

This means that the novelty of our proposed technology is rooted in both the originality of our data and in the research question it aims to address.

1.1 Clinical Motivation

Symptomatic hip osteoarthritis (OA) is a degenerative joint disease that severely hinders functional mobility and impacts quality of life. It is one of the most common joint disorders in the United States[18] and the leading indication for primary total hip replacement surgeries[9]. The development of effective preventative and treatment measures necessitates the study of its causative factors.

1.2 Clinical Data

Each volunteer was scanned to collect a 3D qualitative scan of the hip and six 2D quantitative data scans acquired via incremental 30°rotations around a central axis passing through the femur bone as shown in Fig. 1. The 3D qualitative

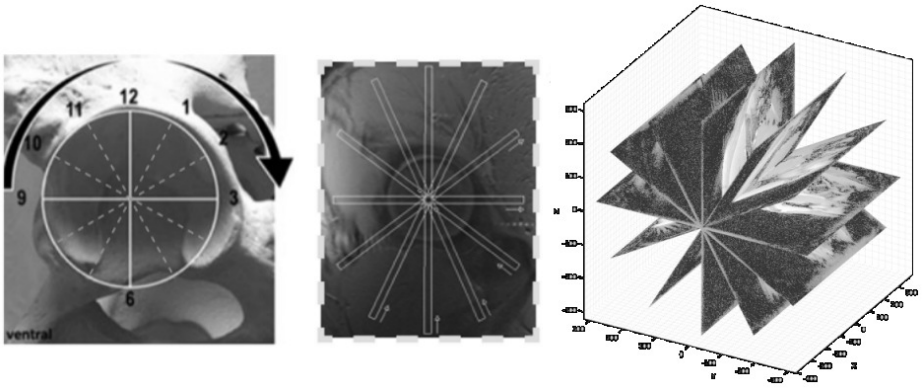

Fig. 1. Radial scans orientation(from left to right): i) superimposed over hip socket, ii) superimposed over a 2D MRI scan, iii) visualized in 3D space

scan serves as the final volume and, as previously mentioned, it is effectively interchangeable with a 3D template owing to the efficacy of current 3D/3D registration technology. To start the process, a 'localizer' plane is maneuvered over the opening of the acetabulum by the MRI technician. The axis of rotation passes through it and as a result, all acquired 2D scans are normal to while the images in Fig. 1 i) and ii) are parallel to this plane. The mechanics of MRF technology means that only the center and normal vector to this plane are accessible in the subequent DICOM images of all six qMR scans. The scans are roughly expected to appear similar to the ones in but there is no guarantee in the order or the directions of the final images. For comparison, a sequence of real scans from a volunteer can be compared to the expected orientations in the Appendix Fig. 3 and Fig. 4 respectively.

2 Method

Given the complexity of the anatomy imaged in these scans, we rely on initial segmentations of the femur and acetabulum to initialize our registrations. Different tissues express themselves differently in the modalities, however, the bony structures are easily identifiable and consistent across all scans. We use a combination of random forests trained on samples from three different modalities of the 2D scans themselves and a neural network pre-trained on a much larger dataset of shoulder joints to segment out the 2D and 3D bones respectively. Any steps in the following outline that don't explicitly mention an intensity based metric are referring to segmented label maps of the hip bones. Our proposed registration method can be broken down into two main steps. The first part includes recreating a visual hull[16] of the femur bone from the 2D slices that can then be registered to the 3D volume to estimate a reasonable initialization. The second step requires fine-tuning this registration through an iterative process of manipulation the 3D volume to 'emulate' the 2D slices, comparing these emulations to the real scans using a feature-based inter-modal similarity metric such as mutual information[15] and updating the locations accordingly.

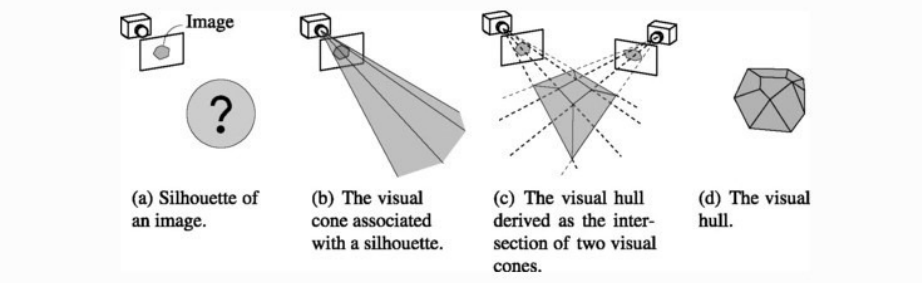

Fig. 2. [6]SFS reconstruction procedure illustrated. (a) Camera captures a silhouette (b) The silhouette defines a visual cone. (c) The intersection of two visual cones contains an object. (d) A visual hull of an object is the intersection of many visual cones

2.1 2D slice to 3D volume Reconstruction

Shape-From-Silhouette (SFS) is a 3D reconstruction technique that uses images of 2D silhouettes to produce an output termed the visual or convex hull[16]. Traditional SFS problems are posed as a 3D object surrounded by cameras that capture 2D images of the object's silhouettes from their various point of views[6]. A simple model showing the moving parts of SFS can be seen in Appendix Fig. 2. In our case, the six intersecting slices can be re-imagined as having been produced from similarly positioned external cameras surrounding the hip such that they lie within the visual cone 2 associated with the silhouette of the hip bones. Our

exact SFS-based reconstruction algorithm is still under construction itself, but we expect to share its details along with preliminary results in the next iteration of our publication. Additionally, this technique is based on the assumption that the relative locations of the 2D slices with respect to each other is accurate and known. This, as confirmed by Figures 3 and 4, is not true for our case. To address this, we preprocessed our slices by comparing them to the expected orientations and manually aligned them into their appropriate positions. This process is also expected to be automated using an appropriate similarity metric in the near future.

2.2 3D volume to 2D slice Projection

Once the location of the 2D slices has been initialized, a set of 2D scans are 'emulated' via projection of the 3D volume onto the planes where the slices intersect. A second set of emulated scans are acquired after rotating these planes clockwise and anti-clockwise by an angle of 15°. The reason for this choice of angle is to explore the space of possibilities using a binary search in logarithmic time instead of an exhaustive linear search. All the actual 2D slices are then compared to these emulated slices and cumulatively vote to move the search space to one of the two sub-regions then repeat the process using 7°rotations. Results from the binary search based optimization technique are pending the finalization of the initialization procedure, but results of the emulated scans from the 3D volumes can be seen in Appendix Figs. 5 and 6 respectively, visualized using 3DSlicer[14][13][1]

3 Discussion

Quantitative MRI technology allows earlier insight into asymptomatic morphological abnormalities and improve the likelihood of positive prognoses. Despite extensive validation in research literature, qMRI has not translated into routine clinical practice for reasons including long acquisition times, lack of standardization and an absence of statistical models for analysis. Our research aims to enable a particularly promising new qMRI technology that has reduced acquisition times to a clinically feasible range and proven to be highly reproducible over time and scanners. Our contribution aims to enable registration of these 2D qMR slices to a normative 3D volumetric space to allow performing comparative and longitudinal analysis in larger scale or longer studies. We propose an initialization method using the 2D slices to create a 3D reconstruction and a followup optimization technique that emulates the qMRI acquisition process by capturing 2D slices from the 3D volume. While method is currently under development, we have included intermediate results from its various sub-methods that show a lot of promise for the efficacy of our final 2D/3D multi-dimensional intermodal registration process.

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Appendix

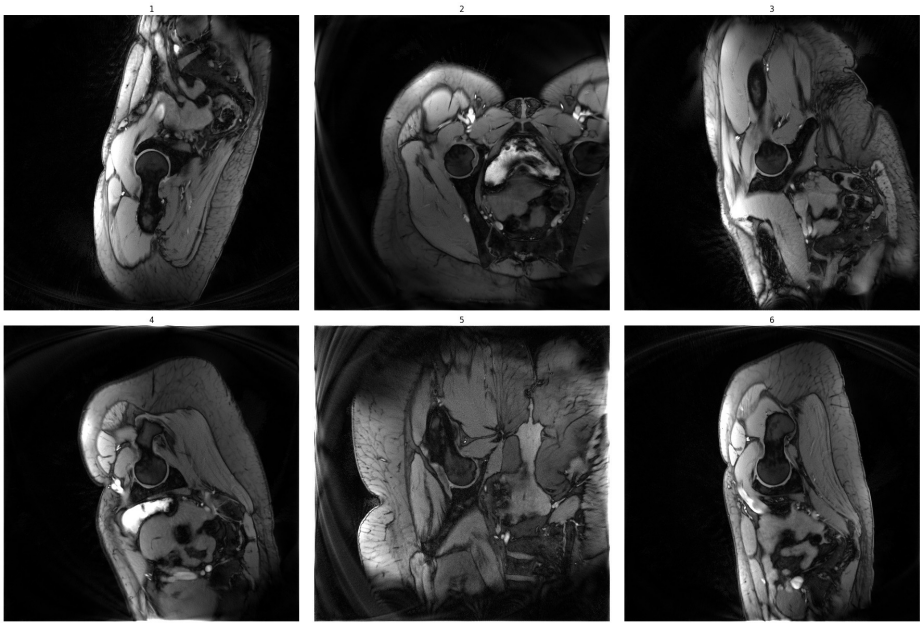

Fig. 3. Actual appearance of the six 2D qMR scans acquired from a volunteer

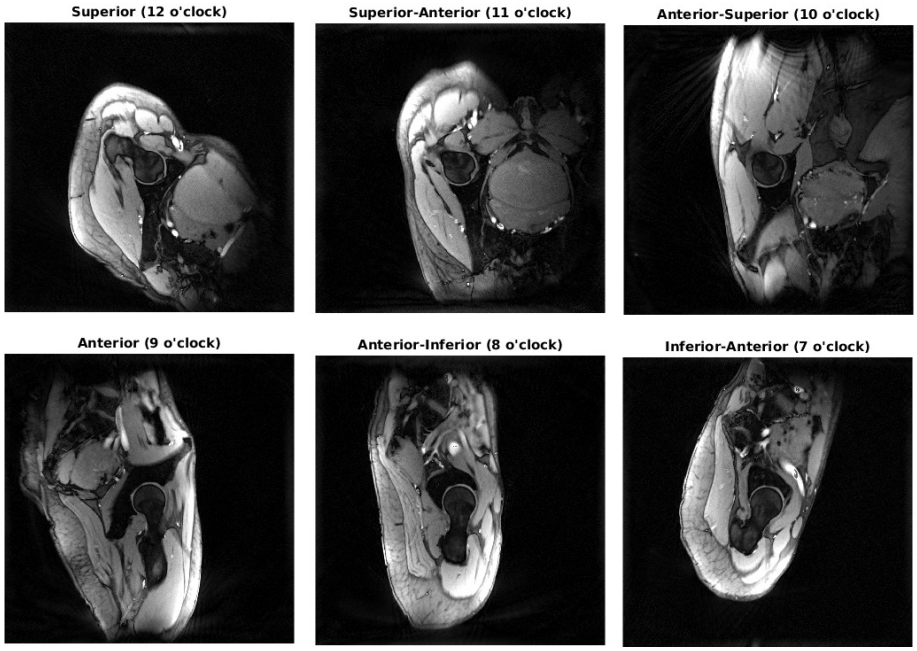

Fig. 4. Expected appearance of the six 2D qMR scans

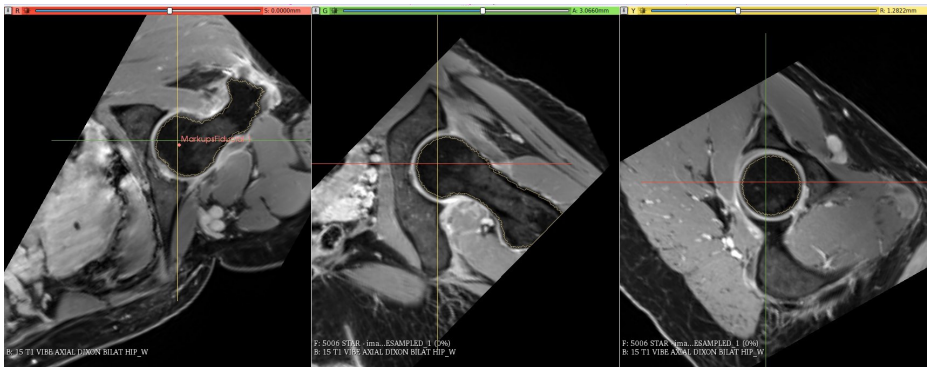

Fig. 5. The image on the far right depicts the localizer plane and so it is unchanging in both sets of emulations. The images on the center and left are captured using two planes orthogonal to the localizer plane and to each other. The initial locations of these planes was chosen arbitrarily but kept constant in both this and Fig.6. This set produced via rotation by 90°clockwise

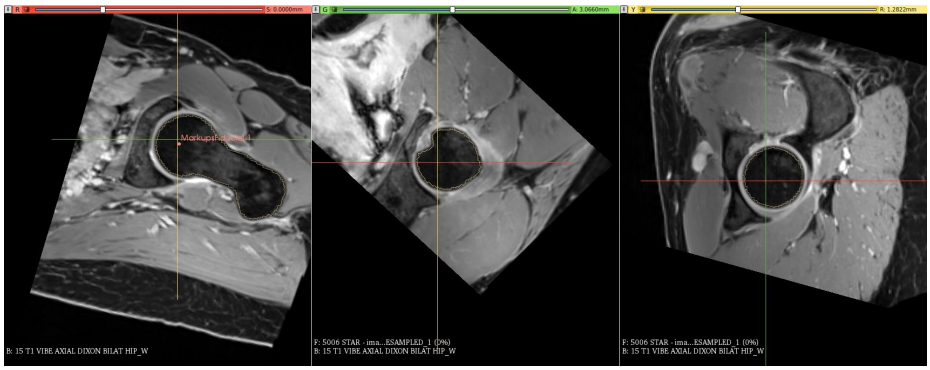

Fig. 6. The image on the far right depicts the localizer plane and so it is unchanging in both sets of emulations. The images on the center and left are captured using two planes orthogonal to the localizer plane and to each other. The initial locations of these planes was chosen arbitrarily but kept constant in both this and Fig.5. This set produced via rotation by 45°counter-clockwise