A New MRI-Based 3D Bone-marrow Model for In Vivo Spine Kinematics

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Introduction: Spinal instability has been implicated as a cause of low back pain, and it can usually be assessed by studying motion. Kinematic analyses of the spine have been recognized as an effective method for functional examination of the spine and its disorders helping to understand in-vivo 3D spinal mechanics. Imaging modalities such as Computed Tomography (CT) and MRI are suitable to obtain vertebral geometry but radiation is a clinical concern and while MRI is noninvasive, detection of bone edges especially at endplates and processes where soft tissues attach, is usually difficult. For both methods, the range of motion possible is commonly restricted to motion along or about the longitudinal axis of the body, making it ideal for torso rotation, as it constrains the body within the bore of the CT or MRI scanner. An added advantage of both imaging modalities is that they are able to capture images of large bones and organs that in the case of bony structures can be assumed to behave as rigid bodies, which is required to study kinematics. However, bone exterior contours are not always necessary for kinematics analysis of the spine as long as the image shows consistent landmarks between imaging positions. Therefore, the objective of this study was to develop a reliable and robust method for kinematics analysis of the spine using an innovative MRI-based 3D bone-marrow model.

Methods: This IRB-approved study recruited 17 patients undergoing lumbar decompression surgery to treat a single-level symptomatic herniation as part of a clinical trial for a new dynamic stabilization device (not discussed here). T1 & T2 sagittal 3T MRI scans (Magnetom Skyra, Siemens, Erlangen, Germany) were acquired as part of the pre-operative evaluation in three positions: supine and with the shoulders rotated 45° to the left and right to induce torsion of the lumbar spine by means of a bolster pillow. Commercially-available medical segmentation software (Mimics, Materialise, Leuven, Belgium) was used to create 3D bone-marrow models of L5 and S1 at the neutral and rotated positions by selecting a threshold level of the bone-marrow intensity at the bone-marrow/bone interface. Bone-marrow models were created not only from the vertebral corpus but also of the superior/inferior, transverse and spinous processes, pedicles and laminae in order to have consistent landmarks that could be used in the rotation analysis. (Fig. 1).

Kinematics Analysis: Segmental motions in 6 degree-of-freedom at L5/S1 were measured by using the validated Volume-Merge method as a 3D-3D registration technique. The Volume-Merge method was implemented through a custom-written software program in Visual C++ 2003 under Microsoft Foundation Class programming environment (Microsoft, Redmond WA) [1]. The accuracy of the Volume-
Merge method is 0.1mm in translation and 0.2° in rotation [2]. The relative motion between any two vertebral bodies was imported into the local coordinate system. After that, the model was virtually translated and rotated towards the neutral position until the algorithm converged when reaching the optimum pixel match between models. This software program calculated the translation distance and left/right rotation angles of the vertebrae. The X-axis of the local coordinate system was set in the lateral direction. The direction of left side of the body was defined as the positive direction. The Y-axis was set in the anterior-posterior direction. The posterior direction was defined as a positive direction. The Z-axis was set in the cranial-caudal direction, with the cranial direction defining the positive Z-axis [1]. When size differences between the bone-marrow models in different positions were noted, the following volume adjustment was performed: Each point consisting of the bone-marrow model was moved outwards or inwards in a direction parallel to the normal vector of each polygon surface mesh element with an increment of 0.1 mm. The Volume-Merge procedure was performed after the volume adjustment was applied. This procedure was repeated until the best 3D-3D registration was obtained.

**Results:** Based on the bone-marrow models, angular kinematics were analyzed: Segmental rotation (mean±SD) at the L5/S1 level was shown to be symmetric for both left and right motions (p = 0.149); Left: 1.04°±0.93° and Right: 1.33°±0.80°. The range of motion recorded was: left [0.05° - 3.70°] and right [0.35° - 3.25°]. These values were equivalent to previously reported values of axial lumbar rotation measured by 3D CT lumbar models [2].

**Discussion:** This study demonstrated feasibility of kinematic analyses using the 3D bone-marrow model created with clinical MRI. The bone-marrow model shows the bone-marrow/bone interface geometry - the internal structure of the vertebra rather than outside geometry usually used for kinematic analyses - that is easily and consistently detected due to its high-contrast interface MRI intensity, which does not require lengthy manual tracing of the bony contour. The bone-marrow model includes key elements of the vertebra including posterior elements and the 3D-3D registration technique used for 3D-CT model can be applied (Fig.1). This type of methodology can be used in the clinic to evaluate with sufficient accuracy subject-specific spinal kinematics without exposure to additional radiation. The MRI-based 3D bone-marrow model may also be useful for kinematic analyses of other major joints such as hip, knee, ankle and shoulder joints.

**Significance:** A new non-invasive method to analyze spinal joint motion has been developed that utilizes clinically-available imaging instrumentation. This type of analysis truly embodies translational research and can assist clinicians with taking advantage of previously unused motion parameters forgoing unnecessary exposure to ionizing radiation.
Figure 1. 3D MRI bone-marrow model (inner pink model). CT bone model (outer white model) is also shown as a reference.

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