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Real-Time Evaluation of Lumbar Instability Using Dynamic MRI: A Commentary on Current Approaches and Developmental Opportunities

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Abstract

This brief commentary presents the current approaches and challenges concerning the use of dynamic magnetic resonance imaging (MRI) to evaluate lumbar instability in real time. In a continuum of using end-of-range static imaging to detect and quantify lumbar instability, this commentary outlines current approaches, limitations, and potential developmental opportunities of using MRI to quantify dynamic intervertebral displacements for investigating mechanistic underpinnings of back pain.

Keywords

- degrees of freedom
- displacements
- low back pain
- neutral zone
- vertebral segment

Background

Lumbar instability, static (measured at the end-of-range) and dynamic (quantified during movements from the neutral position), has been implicated in low back pain and in listhetic nerve root impingements.[1] Conventional diagnostic imaging to detect and quantify lumbar instability has predominantly revolved around quantifying intervertebral displacements (translations and rotations) measured on static, end-of-range, flexion–extension sagittal radiographic images of the lumbar spine.[2] Two-dimensional (2D) imaging used to evaluate spine kinematics is also unable to detect anomalous coaxial (coupled) movements of vertebral segments resulting from vertebral instabilities.[3–5] On the other hand, biomechanical studies have demonstrated that spine segments are comparatively more vulnerable to larger displacements around the neutral position within the range of motion (ROM) of a vertebral segment when the safety net of paraspinal muscle activation is minimally initiated (occurring at the initiation of segmental movements).[6–8] Although experimental and diagnostic use of X-ray-based approaches (orthogonal fluoroscopy, positional X-rays, computed tomography [CT] scans) and other techniques such as ultrasound to detect anomalous segmental motion have evolved over time, the application of multiplanar dynamic magnetic resonance imaging (MRI) to investigate in vivo real-time vertebral instability remains underexplored.[2]

The use of diagnostic MRI in back pain has mainly focused on identifying structural degeneration and pathological anomalies in the spine (vertebral morphology, evidence of intervertebral disk degeneration, soft-tissue injuries, spinal canal or foraminal stenosis).[9] Additionally, conventional spine MRI acquired in the supine position limits its ability to detect the effects of physiological spine loading in an upright weight-bearing position.[10] Several studies have reported additional diagnostic benefits of upright spine MRI and with or without additional axial spine loading protocols.[11] On the other hand, experimental use of advanced MRI sequences that can selectively suppress or enhance certain tissue-specific signal intensities has opened up possibilities of studying soft-tissue (e.g., disk, ligament) deformations with positional imaging.[4,12,13] Moreover, the

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use of orthogonal imaging has enabled quantification of coupled displacements with the application of coordinate matching, volume rendition, and three-dimensional (3D) modeling techniques.[14] However, while these approaches can potentially yield clinically corroborative information, such techniques are still limited in being quasi-dynamic and based on static imaging, which are also limited by associated prolonged scan times.

Dynamic Spine Magnetic Resonance Imaging

Experimental dynamic imaging of diarthrodial joints, specifically the knee joint, has shown distinct advantages over static 2D MRI in detecting joint subluxation or functional joint instability.[4,13,15] However, the scope for the use of dynamic MRI sequences is challenged by issues of image quality and resolution, on the one hand, and by limitations of performing requisite movements inside the gantry setup to yield detectable structural (and functional) instability, unless being performed inside high-resolution, weight-bearing open MRI systems, on the other. Studies attempting dynamic MRI to capture intervertebral displacements and deformations in real time report mixed results, with some major limitations of these approaches being cited as issues related to resolution, measurement accuracy, and longer scan times. The limitations of voxel-based imaging further reduce the ability to detect displacements in 3D and in all degrees of freedom. Additionally, constrains in acquiring simultaneous orthogonal images limits the power to analyze or interpret clinically crucial information on coupled (axial rotation-induced sagittal/coronal linear/angular) displacements with this approach.

Advanced dynamic MRI sequence mapping movements of articular elements in joints use bursts of impulses to track proton spins in real time within a given space requiring a much-reduced computation time using spine-echo or gradient-echo approaches.[5,13,16] Currently, real-time images can mostly be acquired in a single plane. However, the choice of acquiring images with different slice thickness (and volumes), with coordinate algorithms that help align and register customized presegmented vertebral models to a series of dynamically acquired images may be used to navigate some of the current limitations of dynamic MR to investigate intervertebral displacements (►**Fig. 1**). A major reason for existent gaps in the literature correlating mechanistic associations between back pain and vertebral instability is the lack of nonionizing imaging techniques that could allow accurate in vivo high-resolution mapping of segmental displacements. Moreover, clinical use of supine MRI to diagnose vertebral instability continues to limit our ability to appreciate the association between dynamic vertebral motion and its relationship with nociceptive triggers in back pain around the neutral zone.[7]

Scope of Advancement

Several opportunities exist for developing and improving techniques and approaches for the assessment of spine kinematics, which can be briefly summarized as the following:

- Improving animation-based assessment of 3D spine displacements that can facilitate tracking of coupled spine motion in six degrees of freedom. For example, development of faster multislice, multiplanar or volumetric imaging assisted by morphology-based coordinate registering algorithms to match anatomical landmarks may help more accurate assessments.[16–18] Such an approach may circumvent time constraints and motion artefact limitations encountered with voxel and volume-based 3D reconstructions.
- Moment-associated quantitative assessments of loading may be achieved by using MRI-compatible mechanical load testing to standardize motion-specific, deformation-stress-torque patterns using fresh cadaveric spine segments to generate and validate the database for such experimental models. This information could then be applied to frames of dynamic spine motion images to correlate vertebral stress patterns in 3D, in all degrees of freedom.[9,19]

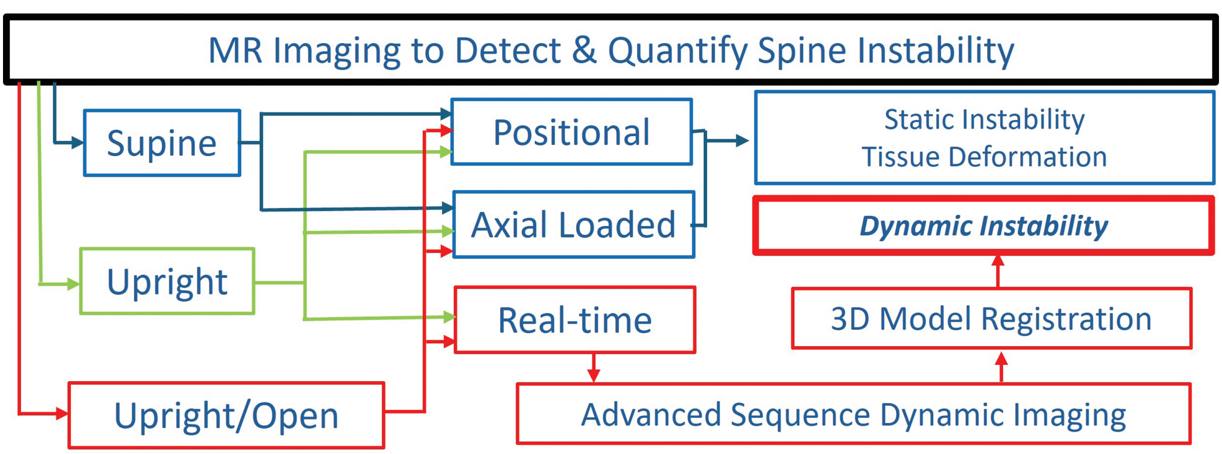

Fig. 1 Workflow schema of magnetic resonance imaging (MRI) based imaging approaches to quantify segmental instability and soft-tissue deformations and to evaluate loading characteristics of the spine using static and dynamic paradigms.

- Availability of faster sequences validated for dynamic weight-bearing imaging may further provide real-time quantifications alongside supplementary postimaging techniques. Use of open MRI systems may facilitate weight-bearing imaging that may potentially uncover unexpected segmental behavior secondary to physiological/secondary axial loading.[20] In the future, availability of MRI-compatible electromyographic (EMG) systems can be used to detect instability-induced muscle activation patterns in paraspinal muscles to correlate deformation-stress-torque data.[21]
- Additionally, improvement in automated segmentation, digitization, registration algorithms, and techniques for using 3D model registration with kinematic MRI can facilitate quantification of real-time spine motion.

Discussion

About more than of back pain patients may not appear to present any detectable structural/functional cause for their back pain or overt instability of their spine segments as determined by 2D, supine MRI. These vast number of back pain patients are grouped as the "nonspecific" mechanical back pain population. Due to unavailability of high-fidelity dynamic spine imaging sequences, determining outcomes of spine stabilization exercise protocols or outcomes of surgical interventions restoring spine stability become challenging. Also, despite the existence of evidence for association between degenerative disk disease and vertebral instability (and spine pain), the etiological relationship between radiologic segmental instability and back pain becomes hard to establish given the static and supine approach of imaging.[22] Thus, the importance of developing newer MRI-based approaches for evaluating dynamic intervertebral motion cannot be overemphasized. Improvements in voxel-based imaging methods, automated creation, and superimposition of 3D models (reconstructed from postacquisition volume rendition of multiple isotopically scanned images) to ensure adequate spatial resolution could be achieved by acquiring morphology selective anisotropic image slices in a single or select orthogonal planes.[23,24] Further, 3D rendition may be circumvented and the number of image slices used for volume registration can be substantially minimized by selecting image slices based on morphological determinants to register slice elements to dynamic MRI frames, thereby reducing overall scan time and enhancing the reliability of image quantification without compromising resolution.[15,16] Additionally, using presegmented morphology-specific models and motion analysis algorithms may further help detect conjunct-adjunct (adjacent segment)[25] motion and soft-tissue deformation in scanning protocols tailored to capture progressive axial and/or rotational stress applied to position-dependent changes in the spine.[26,27] Current literature on the topic shows that clinical and experimental imaging research communities have made considerable advancements in the last decade to enhance MR-based techniques as potential tools to detect dynamic instability in spine segments to quantify pathological soft-tissue stress–deformation relationships.[4,15,28]

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Conflict of Interest
None declared.

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