**Khallaghi2010 - Registration of a Statistical Shape Model of the Lumbar Spine to 3D Ultrasound Images:**

* Introduces prevalence of back pain, the importance of its proper management, and risks associated with prevailing methods
* Proposes method for registration of L3 atlas model to patient’s 3D US volume
* Generated atlas by selecting one L3 segmentation as a template, rigidly registering other training segmentations, then deformably registering segmentations, and finally performing PCA
* US images were simulated from the shape atlas, and the model rigidly then deformably registering the atlas (reinstantiating by updating its shape parameters) to optimize the Linear Correlation of Linear Combinations metric between real and simulated US volumes
* 3 CT volumes were used to construct phantom models. These models were used for validation, where experienced ultrasonographers located 5 landmarks on the registered atlas, US volume, and CT volume (3 sets?) and the TRE was measured as the average distance between landmarks.

**Gill2012 – Biomechanically constrained groupwise ultrasound to CT registration of the lumbar spine:**

* Extensive introduction discussing prevalence and importance of back pain injections, and also mentions screw placement
* Describes feature-based registrations methods as having difficulties resulting from dependence on US bone segmentation quality
* They use an intensity-based method for the US image based component of their registration process, incorporating bone shadow information
* The other component of the registration process consisted of biomechanical model based registration constraint
* Lumbar vertebrae were manually segmented from 5 CT scans and both used to simulate US images for the registration process and as models to be registered
* To assess the capability of rigid-registration (as a benchmark comparison), a “gold standard” fiducial-based rigid method was used to register the CT models to US volume. They also imposed vertebra-wise translations on the CT model to test rigid registration on cases where the inter-modality images do not correspond perfectly.
* Their group-wise registration started with a known misalignment and iteratively updated each vertebra’s 6 pose parameters to maximize the Linear Correlation of Linear Combination metric between real and simulated US images, while minimizing the inter-vertebral spring energy in the registered model
* Tests were performed on human-based phantom models, one phantom with 4o of transverse curvature, and a sheep cadaver.
* The method was evaluated based on the TRE defined by CT-visible markers placed at the corners of vertebral bounding-boxes

**Hacihaliloglu2014 - Local Phase Tensor Features for 3-D Ultrasound to Statistical Shape+Pose Spine Model Registration:**

* Starts with the importance of injection therapy for back pain, and the advantages US has over fluoroscopy and CT
* Difficulties in interpreting US images, hence the lack of widespread adoption
* Describes CT-US registration as dependent of CT segmentation and US image quality
* Mentions several point-based CT-US registration methods but describes them as being limited by dependence on US brightness/intensity, algorithm parameters and machine settings
* Introduces several local phase-based image processing methods as redressment to the intensity dependence of other pre-registration image processing methods
* Proposes the use of a gradient energy tensor (GET) filter to extract the local phase tensor (LPT) metric, and the use of this metric with a shape+pose model for improved statistical shape model registration
* Their method uses a band-pass (Log-Gabor) filtered image as input to the GET filter, requiring an exhaustive search for optimum filter center frequency, frequency bandwidth, and standard deviation parameters
* Landmarks manually chosen from SPs, and superior and inferior articular processes (not injection sites) were used for TRE-based assessment of their method
* Their method (GET/LPT) produced substantial quantitative (TRE) and qualitative (visualization) improvements in the subsequent registration compared to phase-symmetry and feature-symmetry filtering methods

**Rasoulian2015 - Ultrasound-guided spinal injections: a feasibility study of a guidance system:**

* Because of radiation, fluoroscopy should not be used as a guidance modality for spinal injections
* US based methods are proposed and undergoing research but are not yet adopted due to difficulty in interpretation
* Mentions CT based methods but says such scans are usually unavailable and result in radiation
* They use a statistical, mulit-vertebral model with separate shape and pose analysis of each vertebra for registration-based navigation visualization (see Rasoulian2013 for model and registration details)
* They constructed 3D volumes from tracked US scans using 3 scanning patterns to which they registered their statistical model, which was constructed from the CT scans of 32 patients
* Pose statistics were represented as similarity (rigid + scale) transforms which form a Lie group, which had to be projected into linear space with a logarithmic mapping
* Separate PCAs were performed on pose and shape modes of variability for the entire lumbar spine
* Before registration, US images were enhanced with the dynamic programming approach from Foroughi2007
* They validated the three stages of their method: US acquisition and registration accuracy were validated against prior CTs, where available, and guidance accuracy was validated by comparing needle position known from fluoroscopy to its position measured in the US mode

**Nagpal2015: - A multi-vertebrae CT to US registration of the lumbar spine in clinical data:**

* Proposes method for multi-vertebral pre-operative CT segmentation to intra-operative US registration using a global image intensity based step, a global point-based step, and a multi-vertebral point-based step.
* The CTs were preprocessed with a Log-Gabor quadrature local phase filter, and then raytracing to segment the pixels of the posterior surface of the spine, i.e. the pixels expected to be visible in US.
* US images were also pre-processed with local phase filters, in this case, using Hacihaliloglu2013’s method, and raytracing to remove bright pixels corresponding to soft-tissue posterior to the spine surface.
* The global intensity-based step uses the BRAINS module in Slicer to maximize mutual information between imaging modalities with a rigid registration
* The Coherent Point Drift algorithm is used for the second step, the global point-based registration. Presumably the points are those segmented in pre-processing.
* An inter-vertebral spring model was used with a CPD variant (modified to accommodate the multi-body registration) to penalize large relative transformation between adjacent vertebrae. The coefficient weighting the importance of the biomechanical model was determined experimentally
* The method was validated quantitatively based on the ability of the method to realign digital marker points placed on the laminae in US images, which were assumed to be optimally aligned after registration, and therefore to correspond to such points on CT. The CT vertebrae models with the markers points were perturbed, and the TRE computed based on how closely re-registered points matched the original locations.
* Qualitative evaluation was also performed on the basis of whether points added to the dura between vertebrae remained in this region after perturbation and re-registration.

**Behnami2016 - Joint registration of ultrasound, CT and a shape+pose statistical model of the lumbar spine for guiding anesthesia:**

* Starts with the difficulty, prevalence, and risk of lumbar spine injections (facet joint and epidural)
* Lists fluoroscopy as standard of care
* Research done on ultrasound based visualization/navigation, but methods have not been adopted due to difficulty of interpreting ultrasound
* Methods which register CT segmentation to US are labor intensive for manual segmentation, and inaccurate for automatic segmentation
* Atlas registration errors “vary in magnitude and location”, therefore there is a need to improve and assess the accuracy of such models (their proposed method).
* Their method involves the joint registration of CT and US, edge detection in CT, phase-based bone probability measurement in US, and shape+pose statistical model registration
* Registration improvements mainly in SPs, and TrPs to some extent, when compared with atlas-US registration

**Koo2016 - Hierarchical CT to Ultrasound Registration of the Lumbar Spine: A Comparison with Other Registration Methods:**

* Deals with CT-US registration of spinal models for the sake of deformation assessment rather than visualization/navigation
* Proposes a “hierarchical” CT-US registration method and compares it with other methods in a dry-bone human phantom, and porcine cadaver
* Describes their intensity-based registration as an improvement on feature-based methods which rely on extracting bone surfaces from US, despite the fact that they locate voxels corresponding to bone in US with simple “backward ray tracing” threshold edge detection, assuming the brightest pixels correspond to bone
* Patient-specific models are constructed “semi-automatically” using a threshold, and each vertebra is rotated (presumably manually) to match the orientation in the US images
* The first step of their registration method is landmark-based for an initial guess. They use the SPs and TrPs of each vertebra for initial alignment.
* Voxels corresponding to the posterior bone surface in the CT are extracted using another raytracing method
* They state that two stepwise intensity-based registration steps are then used (although the distinction is not clear, both are apparently described in the same paragraphs and use the same objective functions). The objective function used for intensity-based registration finds transformations which maximize the mutual intensity between the posterior CT voxels, and their nearest neighbors (as per the “nearest-neighbor algorithm”) in the US dataset
* Vertebrae were each registered separately, and for speed, the US image sequences were manually under-sampled by inspection
* Four fiducial markers were attached to each vertebra to enable the computation of ground-truth, apparently created by registering a model to these landmarks, rather than locating and examining these corresponding landmarks on their proposed registration method’s results, or CT-ing their phantom/cadaver models
* Used inter-voxel distances to (incorrectly?) define their target registration error

**Brudfors2015 - Towards real-time, tracker-less 3D ultrasound guidance for spine anaesthesia:**

* Proposes a method for navigation in spinal injections where a statistical model (atlas) is continuously registered to a 3D US stream
* Used Foroughi’s method to generate bone probability maps from US images
* Registration optimizes model translation and rotation to match bone probability map, and if the error between the previous model and latest non-rigid registration is greater than a threshold, the optimization finds new shape and pose coefficients for a new non-rigid registration
* Registration is considered successful if the mean surface error of two subsequent models is less than a threshold
* Method was evaluated in vivo on 12 volunteers by measuring the distance between injection sites on the models registered onto US images, and in the real US images themselves as judged by an experienced ultrasonographer
* The error for epidural localization was considered acceptable at 3mm, while facet joint localization error was 7mm, exceeding the acceptable error of 5mm