Dual Ultrasound Can Measure Kinematic Motion and Intervertebral Disc Deformation of Cervical Spine

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Introduction: Neck pain is a common occupational health complaint associated with cervical spine intervertebral disc (IVD) degeneration, the result of acute and/or chronic injury sustained in the work place. Laborers exposed to repetitive loads and vibrations are at highest risk. Currently there are no methods to evaluate the dynamic motion of the cervical spine in individuals working in extreme environments. Imaging technologies such as plain radiography, computed tomography and Magnetic Resonance Imaging are limited by the large size and power requirements of the equipment. Our overarching goal is to demonstrate that clinical ultrasound (US) can provide a portable imaging modality capable of quantifying cervical spine IVD motion in individuals working in extreme environments. In our previous work, we validated that clinical ultrasound (US) is capable of quantifying cervical spine IVD deformation in human cadaveric vertebrae at frequencies <6 Hz with an overall error of ±0.148 mm. The purpose of current study is to develop a dual US system capable of measuring C-spine kinematics stereographically. This system hardware and software were validated using PMMA phantoms at frequencies 1-8 Hz and ex-vivo using human cadaveric C-spine.

Methods: PMMA Phantom Tracking Validation: The precision of US tracking software was validated using phantom tests to track rigid body motion over a range of frequencies. We developed a least sum of square difference (LSSD), error-correcting, acoustic signal tracker with subsample estimation. To validate the tracking algorithm, a PMMA cylinder acoustic phantom was manufactured and known displacements applied which were then compared to the displacements measured using the dual US system.

Cadaveric Dynamic Validation: 5 Human cervical C6-C7 FSUs were submerged in 0.9% saline at 37°C physiological conditions. Each FSU was subjected to sinusoidal compressive/distractive loads from -90N to 90N at frequencies ranging 1-8Hz. Continuous, real-time, synchronized B-mode US acoustic signals were captured during load application using a custom designed dual US system (Terason T3200, 15L4 linear array, 50 frames per second; Teratech, Burlington, MA). Consistent anatomic landmarks were identified on each of the imaged vertebrae to standardize C6-7 FSU kinematics and IVD displacement measurements in response to the applied load (Figure 1). The vertebrae were modeled as rigid bodies, attributing the motion of the FSU to deformation of the IVD. Regions of interest (ROI) corresponding to distinct vertebral landmarks were specified by the user on the initial B-mode US image and subsequently tracked automatically using a block matching operation on the radio frequency (RF) image data.
generated during dynamic loading. The dynamic motion of the FSU derived using this US algorithm was compared to direct measurements using a linear variable differential transformer (LVDT).

**Cadaveric Mechanical Creep Test:** After defrosting, the trachea, esophagus, and skin were removed from 5 contiguous human cadaveric, fresh frozen, cervical spines, C2-T1, ages 54 - 67 years (Medcure, Portland, OR). The surrounding paracervical muscles and adipose tissue were retained. Each spine was subjected to 150N compressive creep test. Using minimally invasive technique, uniaxial, 5 mm diam. titanium pedicle screws were placed into the vertebral bodies under fluoroscopic guidance. Steel rods were used to fix C2-C4 FSUs and C5-T1 FSUs. Change in the height of the C4-C5 IVD measured by US was correlated with the real-time load measurement. C4-C5 level is commonly affected by degenerative disease, presumptively as a consequence of chronic overloading. Stiffness and damping coefficient of C4-C5 FSU were derived from standard Voigt model and compared to IVD hydration level in MRI Images.

**Results:**

**Phantom Validation:** For applied frequencies from 1 - 8 Hz, the mean absolute error (MAE) between US tracking and LVDT measurements for each frequency ranged from 0.0227 to 0.0508 mm. The overall average MAE of US measurements was ±0.041 mm.

**Cadaveric Validation:** Dynamic IVD deformation measured by US was consistent with the IVD deformation measured directly by the LVDT. Coefficients of determination for linear regressions between the IVD deformations measured by US vs that measured directly were plotted as a function of the applied frequency (Figure 2). C6-7 IVD deformation derived from US using the RF algorithm accounted for ~92% of the variation in FSU motion compared to that measured directly using the LVDT for frequencies up to 6Hz and 77% at 8Hz (R²=0.77).

**Mechanical Behavior of C4-C5:** In compressive creep test, the stiffness of a specimen was affected its Pfirrmann Grade while the damping coefficient was not (Table 1). Younger specimens with integral disc tends to be more compliant in creep test analysis compared to older specimens.

**Discussion:** The phantom study quantified the technical limits of our US based system for measuring cervical spine kinematics and IVD deformation. In cadaveric specimen tests, the accuracy of US tracking accounted for >90% of the variation in IVD deformation at frequencies ≤6Hz. At high frequency of FSU motion, the accuracy is lower (77%) at 8Hz possibly due to the irregular shape of bone-tissue boundary (compared to a cylinder phantom) which may distort the sound echo at higher rates of motion.

As this was conducted as a feasibility study, the number of samples analyzed was low and our preliminary findings must be viewed with some caution. Analysis of additional samples will allow us to validate our preliminary results. But the correlation between stiffness and IVD hydration is consistent with the observation that the “health” and integrity of the IVD affects the mechanical performance of the FSU. Our US system may provide a cost-effective clinical tool to evaluate the integrity and performance of the IVD by applying low amplitude traction and compressive loads to the head and neck in-vivo.

**Significance:** We demonstrate that clinical ultrasound can provide a portable, low cost imaging modality capable of quantifying cervical spine IVD displacement and the mechanical compliance of a functional spinal unit in response to applied forces. Our study establishes the feasibility of using two synchronized clinical US to stereographically measure dynamic FSU motion in response to applied loads in real time up to 8 Hz. This technology allows the in-vivo evaluation of cervical spine mechanical behavior in dynamic environments where MRI and CT cannot be used. As treatments to reconstitute degenerated IVD
become available, quantitative analysis of IVD mechanics will be necessary to determine which patients will be appropriate for these treatments and to monitor their response.

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ORS 2015 Annual Meeting
Poster No: 1096