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Clinical and statistical correlation of various lumbar pathological conditions

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ABSTRACT

Current clinical evaluations often rely on static anatomic imaging modalities for diagnosis of mechanical low back pain, which provide anatomic snapshots and a surrogate analysis of a functional disease. Three dimensional *in vivo* motion is available with the use of digital fluoroscopy, which was used to capture kinematic data of the lumbar spine in order to identify coefficients of motion that may assist the physician in differentiating patient pathology. Forty patients distributed among 4 classes of lumbar degeneration, from healthy to degenerative, underwent CT, MRI, and digital x-ray fluoroscopy. Each patient underwent diagnosis by a neurosurgeon. Fluoroscopy was taken as the patient performed lateral bending (LB), axial rotation (AR) and flexion-extension (FE). Patient specific models were registered with the fluoroscopy images to obtain *in vivo* kinematic data. Motion coefficients, C_{LB}, C_{AR}, C_{FE}, were calculated as the ratio of in-plane motion to total out-of-plane motion. Range of motion (ROM) was calculated about the axis of motion for each exercise. Inter- and Intra- group statistics were examined for each coefficient and a flexible Bayesian classifier was used to differentiate patients with degeneration. The motion coefficients C_{LB} and C_{FE} were significantly different ($p<0.05$) in 4 of 6 group comparisons. In plane motion, ROM_{LB}, was significantly different in only 1 of 6 group comparisons. The classifier achieved 95% sensitivity and specificity using (C_{FE}, C_{LB}, ROM_{LB}) as input features, and 40% specificity and 80% sensitivity using ROM variables. The new coefficients were better correlated with patient pathology than ROM measures. The coefficients suggest a relationship between pathology and measured motion which has not been reported previously.

1. Introduction

Low back pain (LBP) is a leading cause for physician visits in the United States, frequently ranked 2nd behind upper respiratory infections (Deyo et al., 2006, Hart et al., 1995). Costs associated with LBP exceed $100 billion annually (Katz, 2006), the majority of which are imaging expenses (Jarvik et al., 2003, Lurie et al., 2003). Numbers continue to rise as the population ages, as the prevalence of LBP increases with age (Woolf and Pfelger, 2003). It is difficult to treat LBP, as it is a non-specific symptom resulting from underlying etiologies which may be chemical, vascular, mechanical, or neural in nature.

In mechanical LBP, the symptoms are related to mechanical trauma or degeneration resulting from activities, including those of daily living. The spine is a mechanical system, with the various muscles, bones and tissues involved with motion becoming injured due to abnormal stresses leading to pain as a normal biological response to injury. Current clinical evaluations rely on static anatomic imaging modalities, which provide anatomic snapshots and a surrogate analysis of a functional disease. Clinicians are limited by the available diagnostic tools to determine treatment, including developing surgical plans based on pure anatomic imaging studies, such as CT, X-rays and MRI, showing anatomical changes which may not localize the abnormal stress and actual tissue injury. These images allow analysis at fixed moments in time, but fail to provide information regarding dynamic motion, making diagnosis of the functional problem or pain generator of the spine difficult.

Past efforts have used spinal kinematics and kinetics to understand the biomechanical factors associated with the clinical presentation of the patient. Previous methods used to quantify lumbar kinematics included ultrasound (Heneghan et al., 2009), goniometers (Lee et al., 2003), electromagnetic (Jordan et al., 1999), and optical tracking (Syed et al., 2007). Using these in vivo lumbar kinematic methods to measure the range of motion (ROM) in patients performing activities have been subject to reliability issues, and prone to errors due to placement or patient conditions. Most can be said to have questionable validity measures (Littlewood and May, 2007). More accurate optical

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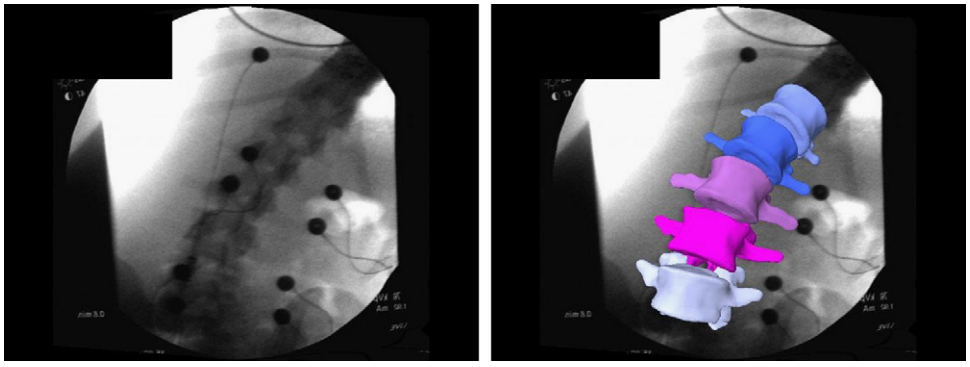

Fig. 1. Plot 2D–3D registration of patient specific vertebral models for kinematic analysis showing original fluoroscopy image (left) and models registered with image (right).

and electromagnetic tracking systems are becoming increasingly popular (Jordan et al., 2001), though these suffer from high expense and elaborate setup. In addition, while it has been shown that ROM is correlated with aging and decreased mobility (Castro et al., 2000), quantifying ROM is not a suitable measure for differentiating healthy and pathological patients (Esol, 1996, Nattrass et al., 1999). Previous results report only the motion in the direction of the activity being performed and ignore the effect of pathology on rotations and translations out of the plane of motion activity and the associated kinetics. Digital x-ray fluoroscopy offers the means to effectively track *in vivo* kinematics (Wang et al., 2008; Wong et al., 2006). Currently, it is believed tracking motion in a single plane is sufficient for kinematic diagnosis (Xia et al., 2010). However, the relationship of movement perpendicular to the sagittal plane with associated kinetics and spinal pathology has not been explored.

Our work tracks the *in vivo* kinematics of the L1–L5 vertebrae to calculate novel coefficients for differentiating between varying degrees of LBP pathology using different patient groups: healthy, healthy with LBP, degenerative and pre-operative spine patients. Our hypothesis is that motion of diseased or degenerated joints associated with low back pain is sporadic, displaying increased out-of-plane motion to minimize stresses on tissues and joints which are unable to move smoothly in the direction of the applied muscular force during motion. Using the *in vivo* kinematics of the vertebrae, the in-plane and out-of-plane motion can be quantified using a single coefficient for each activity. By examining the kinematics of various patient groups, some key measureable values may be identified which could differentiate low back pain patients with normally functioning joints, such as those with lumbar strain which will improve on its own, and those with pathological joints who need follow up medical care and treatment to address their symptoms.

2. Methods

2.1. Patient data

The study consisted of 40 patients. Each patient underwent fluoroscopic examinations as well as CT and MRI to assist in reconstructing the three-dimensional patient anatomy. Fluoroscopic examinations were performed at Vanderbilt University Medical Center. The fluoroscopic exam consisted of having the patient perform three activities, moving from the point of maximum flexion to maximum extension, lateral bending, and axial rotation. Patients were examined using a General Electric OEC 9800 or 9900 C-Arm type fluoroscopic unit (GE Healthcare, Waukesha, WI). Patients were diagnosed by a neurosurgeon. As decided by the surgeon, the patients were placed into one of four groups. The inclusion criteria for each patient group were chosen by the surgeon to represent clinically significant patient findings. The Healthy group included ten asymptomatic subjects with no radiological evidence of degeneration. The LBP group consisted of ten patients with no radiological evidence of degeneration or defects of the lumbar spine, but had reported at least one episode of LBP within a year of the evaluation. The Degenerative patient group consists of ten subjects with radiological findings of lumbar degeneration and spondylosis, experienced pain prior to evaluation, and radiologically exhibited one or more of the following conditions: Schmorl's Nodes, disc bulging both with and without canal or foraminal stenosis, disc osteophyte complexes, decreased height and fluid signal in the intervertebral disc, or facet hypertrophy. Furthermore, the degree of degeneration was not considered severe enough to require surgery. Ten additional subjects with lumbar spinal stenosis and degenerative deformities were treated surgically with a single level decompression and fusion and volunteered for participation in this study. These patients were evaluated just prior to surgery and form the fourth patient group (PreOp). Mean ages for each group were 39.7 ± 13.2 for Healthy, 42.8 ± 9.64 for LBP, 40.1 ± 9.48 for Degenerative and 48.5 ± 10.3 for PreOp. Institutional Review Board approval was obtained as well as informed consent for all patients participating in this study (IRB #7393).

2.2. Kinematics

Patient specific bone models were segmented from CT scans for the L1–L5 vertebrae. The fluoroscopic images were digitized at a resolution of 640×480 pixels for use in the kinematic analysis. The bone models were registered with the fluoroscopy frames at 0%, 33%, 66% and 100% of the motion using a previously developed 3D–2D registration technique (Mahfouz et al., 2003). While the Mahfouz et al. study focused on the knee, the method was extended to and validated for the cervical spine in a cadaveric study by Liu with accuracy of 0.5 mm and 0.5° (Liu, 1997). The validation utilized optical tracking to verify the kinematics. Fig. 1 shows an example of a fluoroscopy frame before and after registration. Local coordinate system was assigned based on the Standardization and Terminology Committee of the International Society of Biomechanics (Li et al., 2009). The relative transformations between the bone models were recorded for each frame, as well as the overall path of motion. Euler fixed angles were calculated using an N3 > –N2 > –N1 > sequence, where N1 > represents lateral bending, N2 > represents axial rotation and N3 > represents flexion-extension. The axes are oriented so that flexion-extension, axial rotation and lateral bending are defined by the Euler rotations as seen in Fig. 2. Another software package was used to interpolate for the motion between successive vertebrae, to determine the

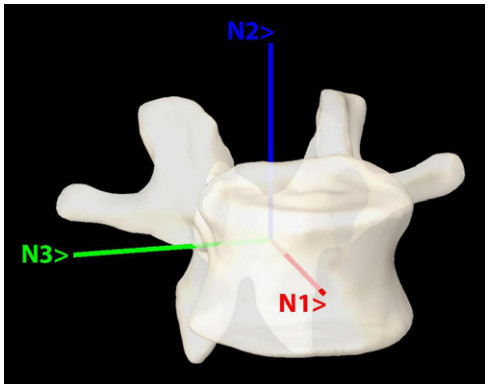

Fig. 2. Illustration of choice of axes orientation. Lateral bending is about N1 >, axial rotation is about N2 >, and flexion extension is about N3 >.