The Concavity Index: A Novel Approach for Quantifying Intervertebral Disc Degeneration

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Low back pain (LBP) is one of the most common musculoskeletal disorders facing the working world. Most LBP studies focus on exposure to physical risk factors in the workplace such as lifting, pushing, pulling and awkward postures. Unfortunately, many of these studies do not consider personal risk factors. Several studies have observed that personal characteristics such as age and gender are predictive of LBP. However, studies that focus on MRI characteristics of the disc structure and the relationship between lumbar discs and personal characteristics are very rare. For this study, T2-weighted MRI scans were obtained from 50 subjects (25 females & 25 males) whose age ranged from 20-40 years (mean 31.12 years, SD ± 5.4) without any self-reported chronic episodes of low back pain. The MRI scans contain the sagittal profile of lumbar endplates (L2-S1). Each examiner measured the height and the concavity levels of the lumbar discs. These measures were used to calculate a Concavity Index (CI; concavity level divided by vertebral body height). CIs were compared to Pfirrmann IVD grading scores to evaluate their agreement and compare their respective inter-observer reliabilities. A higher CI is hypothesized to be indicative of spinal degradation and subsequent low back pain. Gender differences were observed for CIs at all levels, particularly for the L5-S1. A linear relationship between average CI and corresponding Pfirrmann classification was observed. While overall agreement among Pfirrmaann raters was high, 10% of ratings disagreed by two or more categories. CIs had an average coefficient of variation of just 0.95% across all participants and lumbar regions. This work presents an alternative method for quantifying intervertebral disc degeneration that appears to have advantages over the traditional Pfirrmann grading scale.

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INTRODUCTION

MSDs are the leading cause of disability in the United States and represent 48 percent of all self-reported chronic medical conditions (BMUS, 2011). According to the U.S. Bureau of Labor Statistics, the overall incidence rate of nonfatal occupational injury and illness cases requiring days away from work to recuperate was 109.4 cases per 10,000 full-time workers in 2013 (BLS, 2014). The economic burden of LBP to society, due to the large number of workdays lost by a small percentage of patients with chronic LBP, expensive medical costs, and productivity losses is enormous (Maetzel and Li, 2002).

The annual prevalence of LBP in the United States has been estimated at more than one-quarter of the U.S. population (Deyo et al., 2006). Subsequently, pain can be costly to the nation because it requires medical treatment, complicates medical treatment for other conditions, and hinders people's ability to work and function in society (Gaskin & Richard, 2012). Each year there are approximately 149 million lost workdays resulting from LBP and 68.5% of them are work-related (Maetzel and Li, 2002). More than 44.4 million healthcare visits were due to back pain in 2006 (BMUS, 2011). This is why interest in biomedical models of the spine as well as detailed knowledge of spinal morphometry and the relationships between geometrical dimensions of the vertebrae and the intervertebral discs has been increasing.

There is growing evidence that the majority of LBP is associated with intervertebral disc (IVD) degeneration (IVDD) (Wei et al., 2014: Torrie et al., 2015; Takatalo et al., 2011; Hancock et al., 2012). IVDD is known to increase with age (Weiler et al., 2012). Nearly 40% of people who are under 30 years and 90% of people, who are older than 50 years of age, are faced with IVD problems (Cheung et al., 2009; Torrie et al, 2015).

Larsen et al. (1985) evaluated the superior and inferior vertebral margins in order to obtain information on the degrees of curvature the lumbar bodies. Larsen explained it as "a horizontal concavity was always found in L1-L3, in L5 a posterior convexity was prevailing, and L4 occupied an intermediate position." They argued that deformation of the vertebrae was caused by the contents of the spinal canal and vertical load of the body weight.

In a morphometric study, Berry et al. (1987) measured selected human vertebrae to provide data for surgical implant designs. For this purpose, 27 dimensions were measured from thoracic (T2, T7, T12) and Lumbar (L1-L5). These authors observed:

> "vertebral body height increases caudally except posteriorly where, after an initial increase, it decreases in the lower lumbar region. Major and minor body diameters and the major spinal canal diameter slightly increase caudally, whereas minor spinal canal diameter exhibits little or no change".

Semaan et al. (2002) analyzed 160 lumbar vertebrae. The mean height of the pedicle was almost 16 mm for L1 to L4 and 21 mm for L5. Pedicle width was 7mm for L1 and L2 then rapidly widened to reach 10 mm for L5. For these measurements, subjects who were over 40 years of age were selected in order to observe more degenerative spines. They observed that transpedicular vertebral depth is a constant feature of the lumbar spine, which is measured in between 40

Xand 56 mm for 95% of the population. The authors further claimed,

> "The dimensions of the pedicle are particularly important: the width must be known to determine the size of pedicle screws; it measured between 7 and 12 mm in 95% of the population. The largest mean cross section of the pedicle was found for L5 (82mm), but measured less than 60 mm in 10% of the vertebrae, suggesting predisposition to spondylolysis."

Dai (2001) studied 53 patients (32 women and 21 men with age ranged of 42-73 years). All of the patients had degenerative spondylolisthesis at the L4-L5 level. They found that

> "Patients with degenerative spondylolisthesis had more sagittal orientated facet joints ($P<0.01$) and more significant facet joint tropism ($P<0.05$) than normal control subjects. For patients with degenerative spondylolisthesis, the facet joint tropism was significantly correlated with the degree of disc de-generation ($P<0.05$). The results suggest that morphological abnormalities of the lumbar facet joints are a pre-disposing factor in the development of degenerative spondylolisthesis."

The degree of disc degeneration can be evaluated using T2-weighted MRI images with the five-grade Pfirrmann classification system (Pfirrmann et al., 2001). The Pfirrmann grading system is related to the height of the intervertebral discs. It is widely used as an accredited standard in both research and preliminary clinical applications (Niu et al., 2011; Niinimaki et al., 2009; Rajasekaran et al., 2004; Watanebe et al., 2007; Perry et al., 2006; Trattnig et al., 2010; Blumenkrantz et al., 2010; Marinelli et al., 2010; Nguyen et al., 2008). This grading system facilitates relatively easy assessment of IVD morphological health (Ellingson et al., 2013). According to the scoring system, Grades I and II have normal disc height and have a healthy structure when compared with other levels. Grade III and IV demonstrate some height changes (becoming narrower) relative to other discs and the disc's structure also begins to change. The last step is Grade V where the distinction between disc nucleus and annulus is completely lost and the disc space has collapsed. These grades are illustrated in Figure 1 and show the progression from a healthy disc to a severely compromised disc (Pfirrmann et al., 2011).

Despite the strengths of the Pfirrmann classification system, the method lacks a means to quantify the reduction in disc height. The Pfirrmann grading system is a subjective method and it may differ between examiners. However, it can provide a semi-quantitative assessment of IVD health (Niu et al., 2011; Niinimaki et al., 2009; Trattnig et al., 2010; Blumenkrantz et al., 2010; Marinelli et al., 2010). The Pfirrmann scoring system (from 1 to 5) is based on the MRI signal intensity, clarity of the transition zone between the annulus fibrosus (AF) and nucleus pulposus (NP), and a visual assessment of disc height (Pfirrmann et al., 2001; Ellingson et al., 2013). The objective of this study was to investigate quantitative methods for evaluating disc morphology and bony changes using MR imaging techniques with the aim to develop a new mathematical method for quantifying IVD health rather than relying on a subjective, 5-point ordinal scoring system.

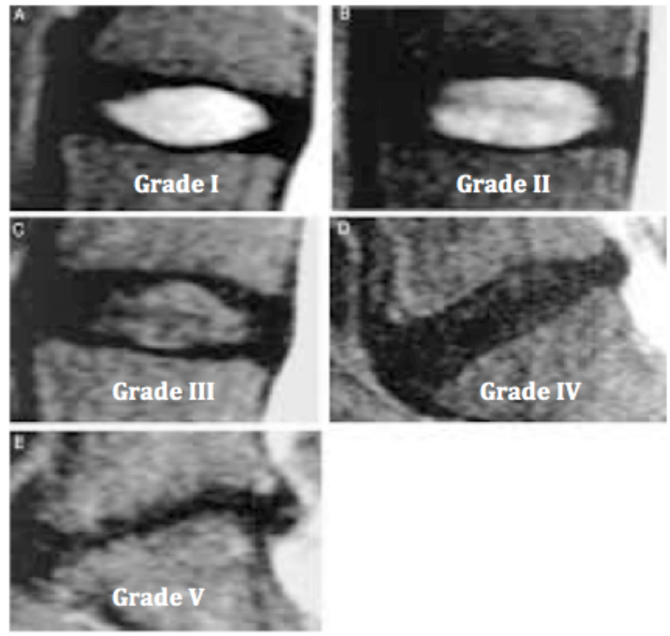

Figure 1. Pfirrmann Grading Scores

METHODS

Participants

Fifty subjects (25 male and 25 female) aged 20-40 (mean 31.12 years, SD ± 5.4) without current or chronic episodes of LBP were examined on a whole body 3T Magnetic Resonance Imaging machine (Siemens Verio open-bore). All imaging was performed in the supine position. A T2-weighted sequence was used for the morphological evaluation of intervertebral discs. A sagittal T2 sequence was applied for the evaluation of the lumbar spine. MRI was performed on the intervertebral discs L2/L3, L3/L4, L4/L5 and L5/S1. Institutional review board (IRB) approval was obtained before the examination of subjects and all subjects consented to participate in this study.

Data Collection

The lumbar spine is the largest segment of the vertebral column (Gray, 2012) and is responsible for supporting much of the body's weight. Comprised of five vertebrae (L1-L5), the lumbar vertebrae are larger than the thoracic and cervical vertebrae and allow for more motion than the thoracic spine. Each vertebrae consists of two essential parts – an anterior solid segment or body, and a posterior segment or arch (which is formed by two pedicles and two laminae, supporting seven processes which include four articular, two transverse, and one spinous) (Gray, 2012). In between each vertebrae is an intervertebral disc that absorbs pressure and stress. When the intervertebral disc compresses or degenerates, pressure and stress on the vertebrae can increase and contribute to LBP.

Image Analysis

T2-weighted MRI scans of the sagittal profile of the participant's lumbar endplates (L2-S1) were evaluated by three trained examiners. Each examiner measured the height and the concavity levels of the lumbar discs (L2/L3, L3/L4, L4/L5 and L5/S1) as well as Pfirrmann scores for each lumbar disc. The CIs were compared to their corresponding Pfirrmann classifications and respective intre-observer reliabilities were evaluated for each method. Specifically, OsiriX software (version 4.0, Figure 2) was used to measure the vertebral height and the level of concavity. Direct measurements of the following two parameters and their ratios were taken from each vertebral body: anterior vertebrae body height in the mid-sagittal plane and concavity level of the superior vertebral body.

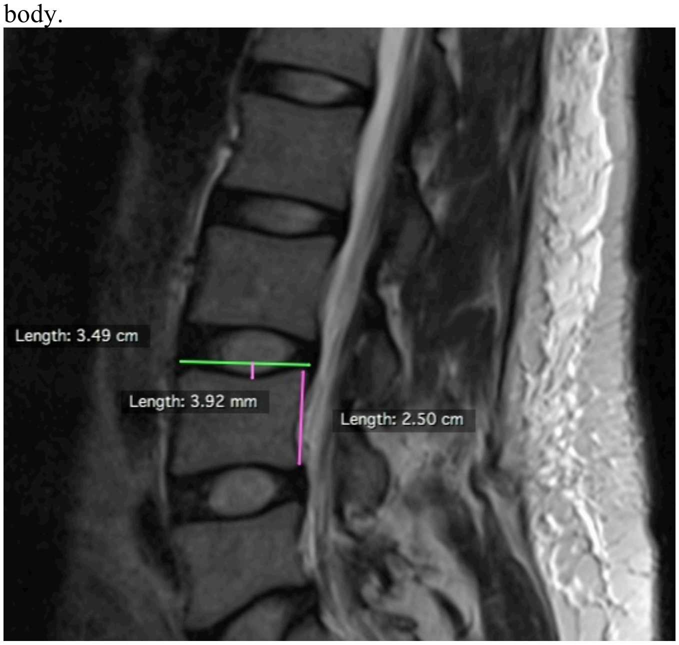

Figure 2. Measurement of Concavity Index

Concavity level was measured as follows: superior vertebral body lengths, which are the distances in the sagittal plane between anterior and posterior borders of the vertebral body, were traced first. Then, the perpendicular distance between this length and the vertebral body was measured and defined as level of concavity. Dividing concavity level by vertebral body height (CL/DH) created a Concavity Index (CI).

Vertebral Analysis

Several quantitative studies have investigated the external geometry of the vertebrae and intervertebral discs of different regions of the human spine.

Morphometric studies typically use one of two primary methods: 1) using cadaveric vertebrae and 2) using medical images such as magnetic resonance imaging (MRI) or computed tomography (CT).

Statistical Analysis

Descriptive statistics were performed to describe subject personal characteristics as well as morphological measurements such as vertebrae height and concavity level. Coefficient of Variation (CoV) was obtained for CIs for all participants and across all lumbar regions. Regression analysis was used to explore the relationship between CI and Pfirrmann IVD Grading. Pearson correlations were also used to evaluate agreement among observers for both CIs and Pfirrmann IVD grading.

The repeatability of both CIs and Pfirrmann grading was investigated using three different observers. Each observer was blinded to other observers' data analysis. They all evaluated discs using Pfirrmann grading and measured CIs for the adjacent vertebral bodies.

RESULTS

Gender differences were observed for CIs at all levels, particularly for the L5-S1. While L3/L4 CIs showed little difference, other lumbar regions (L2/L3, L4/L5, L5/S1) show more dramatic differences that appear to be related to gender.

A strong linear relationship was observed between CI and Pfirrmann score. As the Pfirrmann score increases, so do the CIs (shown in Figure 3). However, the CI is a more objective, repeatable measure than the Pfirrmann score and may be more predictive as well as an earlier indicator of LBP since it is a continuous rather than discrete measure.

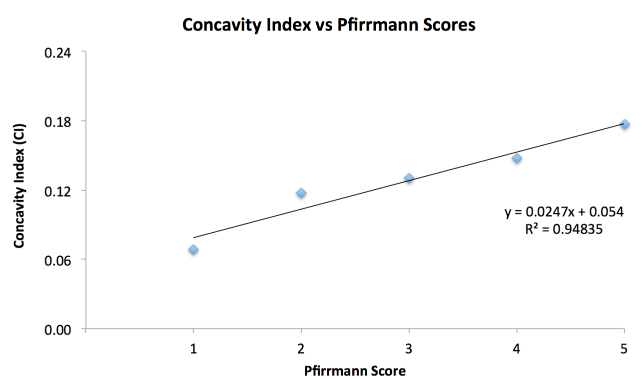

Figure 3. Relationship between Concavity Index and Pfirrmann Score

The repeatability analysis indicated that the highest level of absolute agreement between any two observers for the Pfirrmann score was 66%. However, two of three observers disagreed by 1 or more categories 80% of time. For CIs, the agreement was much higher. For example, the lowest correlation between CI measures was .96 (range of .96 - .99).

DISCUSSION

The overall objective of this study was to develop a new mathematical method for quantifying IVD health rather than relying on a subjective scoring system. Specifically, we investigated the relationship between Pfirrmann score and CI as well as the inter-rater reliability of each method. An anatomic study of morphometric measurement was performed for lumbar vertebrae. Results suggest that the CI method shows promise for objectively quantifying low back health and predicting future low back pain. The measure also allows for relative comparisons because it is a continuous measure rather than an ordinal scale. Relating LBP to CI may also provide guidance for surgeons to describe end states for low back corrective surgery. The CI should be validated directly with subject ratings of LBP and studied pre- and post-operation for surgical interventions.

Accurate knowledge of normal and degenerative lumbar intervertebral discs is very important for both surgeons and radiologists. Using the CI, medical professionals can potentially make more accurate diagnostic interpretations and, subsequently, more precise surgical interventions regarding the lumbar discs. The Pfirrmann grading system is considered a reliable method for evaluating the health of the lumbar discs and is an established method. However, as can be seen from this analysis, Pfirrmann scores varied significantly among observers. In this regard, CI may be an improved measure for reliably describing disc health.

Over the last 20 years, vast improvements in MRI technology have led to the development of quantitative imaging techniques (Stelzeneder et al., 2011). These techniques offer more accurate results and can be performed in any anatomical plane. Recent improvements in the resolution of MRI have provided even better visualization of the detailed spinal structures such as disc material, vertebral bodies and neural structures [Kimura et al., 2001; Danielson, et al., 1998; Fennell et al., 1996; Hamanishi, et al., 1993; Okada et al., 1994; Willen et al; 1997]. Transverse relaxation time (T2) mapping has increasingly been applied to the spine and has the potential to better quantify deterioration of the molecular composition and structural integrity of intervertebral discs (Perry et al., 2006). These technology improvements coupled with the CI show great promise for surveillance of low back pain and objectively measuring low back health.

FUTURE WORK

More work is needed to explore the full potential of the CI for improving the diagnosis and treatment of LBP. This work should include further inter- and intra-rater reliability studies with a greater number of raters and, ideally, with medical professionals familiar and proficient with the Pfirrmann rating system. In addition, the CI ranges related to each Pfirrmann score should be determined and tabulated for use by medical personnel. Larger sample sizes and a more diverse subject population would allow investigation of other personal characteristics such as age and medical history.

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