In Vivo Dynamic Lumbar Vertebral Motion and Disc Deformation During Lifting

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Abstract

Low back disorders (LBDs) remain one of most prevalent, debilitating, and costly occupational health problems in the United States. Mechanical loading on the lumbar spine is a central factor in the causation and prevention of occupational LBDs. The existing knowledge and methodological bases for evaluating mechanical forces on the lumbo-sacral (L5-S1) inter-vertebral disc were largely developed from static and/or in vitro cadaveric studies, or from in vivo dynamic studies that did not determine the internal vertebral movement or disc deformation. They are limited in their applicability in assessing the low back disorder or injury risks associated with dynamic work activities such as manual load lifting. The objective of this exploratory study was to characterize the relationships between dynamic responses of the lumbar spine and lifting dynamics defined by the load and lifting kinematics (i.e., dynamic postures), and begin to develop an improved model for evaluating the low back mechanical stress associated with manual tasks. Our overarching hypothesis was that more accurate understanding of the dynamic responses of lumbar spine during load-lifting will lead to more effective prevention and control of LBDs.

This R21 project has taken advantage of a recently developed technique to acquire true 3D lumbar vertebral kinematics, in vivo, during a functional load-lifting task. The technique uses a state-of-art dynamic stereo-radiography (DSX) system coupled with a volumetric model-based bone tracking procedure, offering unprecedented accuracy in lumbar kinematics measurement. Twelve asymptomatic participants (7 male, 5 female) with no self-reported history of low back pain performed weight-lifting tasks, while the DSX system imaged their lumbar motions. A model-based tracking procedure then determined the 3D lumbar kinematics, followed by kinematic and statistical analysis/modeling procedures to explore the hypothesized effects and gender differences. Results revealed motions occurring simultaneously in all the intervertebral joints as functional units of the lumbar, including substantial translations, and largely equitable contributions to overall lumbar motion from individual segments or joints. We identified significant gender differences and some effects of the magnitude of load handled on various aspects of the lumbar intervertebral motions. We also discovered that the there is substantial migration of the instantaneous centers of rotation (ICR) for the segmental motions.

This study achieved a milestone technical success by demonstrating the feasibility of capturing continuous 3D in vivo lumbar intervertebral kinematics during functional tasks. The data acquired from this exploratory study, though preliminary in nature, provide updated knowledge regarding lumbar spine function and related influencing factors, and challenge some of the existing assumptions or understanding and tools and methods thus derived. The technical ability established in this study, and the kind of data and knowledge it can generate, will allow more accurate assessment of the mechanical stresses experienced by the low back and more effective recognition and intervention of the risks, thus leading to potentially a profound long-term impact on low back injury prevention and control.

Highlights/Significant Findings

This NIOSH exploratory research (R21) grant was the first study to our knowledge that directly and successfully measured *in vivo* how lumbar vertebrae (i.e., underlying bone) movement during dynamic functional lifting tasks. The measurement technique we used, namely, dynamic stereo-radiographic imaging, offers sub-millimeter (in translation) and sub-degree (rotation) accuracy. We found and recorded substantial intervertebral translations that numerous previous studies have failed to discern or chosen to ignore. We also found largely equitable contributions by individual segmental motions (L2-L3, L3-L4, L4-L5, L5-S1), both in rotation and translation, to the overall L2-S1 lumbar motion. We identified and quantified significant gender differences and some effects of the magnitude of load handled on various aspects of the lumbar intervertebral motions. Additionally, we revealed the migrating nature of instantaneous centers of rotation for the intervertebral motion and documented their paths during lifting acts.

Translation of Findings

Collectively, the research findings from this study advanced the knowledge of lumbar spine movement during functional dynamic activities. They challenged the existing methods and their knowledge bases, such as those developed from static and/or in vitro studies, for assessing mechanical loads on the low back and the risk of low back disorder associated with occupational tasks. Specifically, the substantial intervertebral translations observed may translate into a new emphasis on the shear strain and stress on the intervertebral discs being more important, possibly dominant factors (than the conventional compressive strain and stress) for injury-causing exertions. The findings regarding the gender differences in segmental motion response are important in that they can be used to improve the gender-specific guidelines for safe load-lifting limits such as NIOSH Lifting Guide, which currently does not consider the gender differences the lifting mechanics.

Outcomes/Relevance/Impact

The proposed project was a first attempt to investigate the truly dynamic and in vivo mechanical behavior of the lumbar spine during lifting activities. It has paved the way for developing much improved capabilities to more accurately assess or predict low back mechanical stress during dynamic manual lifting. It also affords a unique opportunity to establish new criteria (e.g., in vivo strain-based instead of stress-based, gender differences in lifting mechanics) for evaluating lumbar disc tissue tolerance/failure. This work, along with a series of systematic studies that would naturally follow, will lead to a new body of knowledge and next-generation guidelines, models, and tools for better recognition, evaluation, and reduction of the risk of occupational low back disorders. Beyond the occupational health and ergonomics field, a broader impact is also foreseeable in terms of new baseline data for spine function and disorder diagnosis and new knowledge and tools for designing or planning spine surgeries that can better restore normal spine function.

Scientific Report

Background

Low back disorders (LBDs) remain one of most prevalent, debilitating, and costly occupational health problems in the United States. It has been estimated that LBDs account for 16-19% of all worker compensation claims, and 33-41% of all worker compensation costs (Spengler, Bigos et al., 1986; Webster & Snook, 1994). Manual load lifting is a major cause of work-related low back disorders (Bigos, Spengler et al., 1986; Snook, 1978). The underlying risk factor is the excessive mechanical loading on the lumbar spine during such work activities. More specifically, compressive and shear forces inflicted upon the lumbar spinal discs are considered as the most relevant measures of mechanical stress. The compressive force on the lumbo-sacral (L5-S1) disc, in particular, was used to define the biomechanical criterion for the NIOSH lifting equation as part of the *Work Practices Guide for Manual Lifting* (Waters, Putz-Anderson et al., 1993). Accurate assessment of these forces is key to identifying the high-risk acts or individuals and effectively controlling the incidence of LBDs associated with manual lifting.

With the current technology, it is not yet feasible to directly measure in vivo the L5-S1 compressive or shear forces incurred during load handling tasks (nor is it ethical for any setting). Instead, they are predicted from a description of the work, work methods, and worker characteristics, by biomechanical models (Chaffin, 1969; Granata & Marras, 1993, 1995; Hughes & Chaffin, 1995; Nussbaum, Chaffin et al., 1995; Schultz, Andersson et al., 1982). These models varied mainly in their approaches to estimating the trunk muscle forces. Regardless of the specific model used, one common piece of knowledge required in determining the disc compressive and shear forces is the lumbar vertebral kinematics—how the lumbar vertebrae move during the work and associated changes in the disc orientation and deformation. Because the model-based predictions of the compressive and shear forces are highly sensitive to the assumed lumbar vertebral kinematics, the accuracy of this information is critical. Without confidence in this fundamental piece of knowledge, the choice of biomechanical model for force or stress prediction is a much less meaningful issue.

The existing knowledge on lumbar vertebral kinematics is insufficient for accurate and complete evaluations of the mechanical stress experienced by the low back during occupational activities. Such knowledge was acquired using static medical imaging and/or surface-based kinematics measurement systems. For example, a number of studies have used X-ray systems to measure lumbar spine segmental orientation and geometry and related them to external, photo- or video-graphically measurable body postures (Anderson, Chaffin et al., 1986; Chaffin, Schutz et al., 1972; Chen & Lee, 1997; Lee & Chen, 2000; Sicard & Gagnon, 1993). In particular, Anderson et al.(Anderson, Chaffin et al., 1986) studied the L5-S1 orientation for a number of static lifting postures with systematically varied trunk and knee angles, and developed regression models allowing prediction of the L5-S1 disc orientation from body posture measures. These studies laid the foundation for determining the forces on L5-S1 disc from static posture and loading measurements. However, the body of knowledge generated from these studies, though based on the best science and technology available at the time, is limited in that it cannot be readily extrapolated to dynamic settings.

Dynamic factors such as velocity and acceleration in load lifting can significantly affect the mechanical response of lumbar spine (Zhang, Xiong et al., 2003) and increase the associated risk of LBD (Bigos, Spengler et al., 1986). Dynamic lumbar motions have been measured using surface-marker-based motion capture systems (Gracovetsky, Newman et al., 1995; Zhang & Xiong, 2003; Zhang, Xiong et al., 2003) and an exoskeleton device Lumbar Motion Monitor (Marras, Fathallah et al., 1992). While these approaches can provide surface-based lumbar kinematics data, they can only at best infer the underlying vertebral body movements (Zhang & Xiong, 2003) and cannot ascertain the inter-vertebral disc deformation. Of note here is that an externally measured flexion angle change from 0-10 degrees does not mean that the disc changes from a flat disc to a 10-degree wedge.

An additional limitation in the current way the L5-S1 compressive forces are predicted is that the dynamic response of the inter-vertebral disc itself is not considered. The discs deform substantially and non-uniformly, as evidenced by recent studies (Kanayama, Tadano et al., 1995; Wang, Xia et al., 2009) and our own pilot work. An apparent dynamic relationship between the L5-S1 disc deformation and compressive forces is not taken into account in any existing biomechanical model for the force prediction. Finite element models have been developed to describe the mechanical response of the lumbar discs to external loads (Goel, Monroe et al., 1995; Guan, Yoganandan et al., 2006; Moramarco, Perez del Palomar et al., 2010). However, they were constructed and validated based on in vitro cadaveric testing data. Because of limitations such as arbitrary non-physiological loading and absence of active muscle forces in cadaveric testing, these models offer little insight into the actual disc force-deformation relationship and risk of failure in vivo or under "real-world" settings.

Recent technology advancement has allowed internal lumbar spine kinematics to be measured in vivo with high accuracy. The reported project was a unique endeavor, empowered by the latest dynamic stereo-radiographic imaging technology for acquiring skeletal motion data, to fill the above-mentioned critical knowledge gaps. This project was intended to pave the way for developing much improved capabilities to assess or predict low back mechanical stress during dynamic manual lifting, leading to a new body of knowledge and next-generation guidelines, models, and tools for more effective prevention and control of occupational low back disorders. Engineering Controls, Musculoskeletal Disorders, and Prevention through Design are the specific NIOSH cross-sector programs being addressed in the proposed research.

Specific Aims

Our long-term goal is to develop a new body of biomechanical science knowledge along with a set of practical tools for better evaluation, recognition, and reduction of the risk of occupational LBDs. **Our overarching hypothesis** is that more accurate assessment of the dynamic responses of lumbar spine during load lifting activities will lead to more effective prevention and control of LBDs. **The objective of this exploratory study** was to elucidate the relationships between dynamic responses of the lumbar spine and lifting dynamics defined by the load and lifting kinematics (i.e., dynamic postures), and begin to develop an improved model for evaluating the low back mechanical stress associated with manual tasks. We sought to advance two specific aims by examining the in vivo dynamic responses including both the lumbar vertebral kinematics and disc deformation during lifting tasks:

Specific Aim 1: Characterize the relationship between lumbar vertebral kinematics and dynamic lifting posture and the effect of load lifted on the relationship. This Aim tested the following two hypotheses:

Hypothesis 1A: The relationship between lumbar vertebral kinematics and lifting posture determined from our dynamic study is significantly different from those determined in previous static studies.

Hypothesis 1B*:* The above relationship is significantly affected by the magnitude of load lifted.

Specific Aim 2: Explore gender differences in intervertebral motion during load lifting. This Aim was driven by the following hypothesis:

Hypothesis 2: There are significant differences in lumbar intervertebral segmental motion and disc motion characteristics (that are not due to anthropometric differences).

Methodology

Subjects

With Institutional Review Board (IRB) approval, 8 healthy male subjects (age: 24 ± 2 years old; height: 178 ± 7 cm; weight: 78 ± 9 kg; BMI: 25 ± 3) and 5 health female subjects (age: 25 ± 2 years old; height: 170 ± 6 cm; weight: 61 ± 8 kg; BMI: 21 ± 3) were recruited to participate the study. None had prior history of spinal disorders (based on self-reporting) and none had waist size greater than 89 cm (35 inches) (83 ± 5 cm for the males and 73 ± 9 cm for the females). All participants provided written informed consent.

Lifting Task

The experimental task consisted of lifting an object loaded with three different weights – 4.55 kg (10 lb), 9.1 kg (20 lb), and 13.65 kg (30 lb) – from a starting, trunk-flexed (~ 75° flexion) position to a final, upright position in a sagittally symmetric manner. The object was a radiolucent wooden dowel rod symmetrically loaded with weights on both sides (Figure 1). The dowel was positioned at an approximate height of 35 cm from the floor and about 30 cm away horizontally from the upright body position. Handles were affixed onto the dowel perpendicular to its length and approximately shoulder width apart (38 cm). Participants were instructed to perform the lift primarily with trunk extension and without bending the knee (i.e., as a back-lift rather than a leg-lift strategy). Aural pulses generated by a metronome at one-second intervals guided the participants in pacing the lifting task. Once participants had assumed the starting position for the lift, the metronome was turned on. X-ray generators were turned on at this time, but not triggered. After a few pulses, a countdown was begun (3, 2, 1, GO), which was timed to the cadence of the metronome. The participant was instructed to begin the lift on "GO". The X-ray cameras and the data acquisition were also triggered on "GO". This protocol allowed synchronization between the participant, the investigator in the room giving the instructions and triggering the X-ray cameras, and the operator for the X-ray generators and the data acquisition system. Prior to the X-ray trial, participants practiced the lifting technique with the instructions in order to prepare themselves for the task. In addition to the dynamic trial, a static trial was conducted, where participants were asked to hold the weight statically in the upright position.

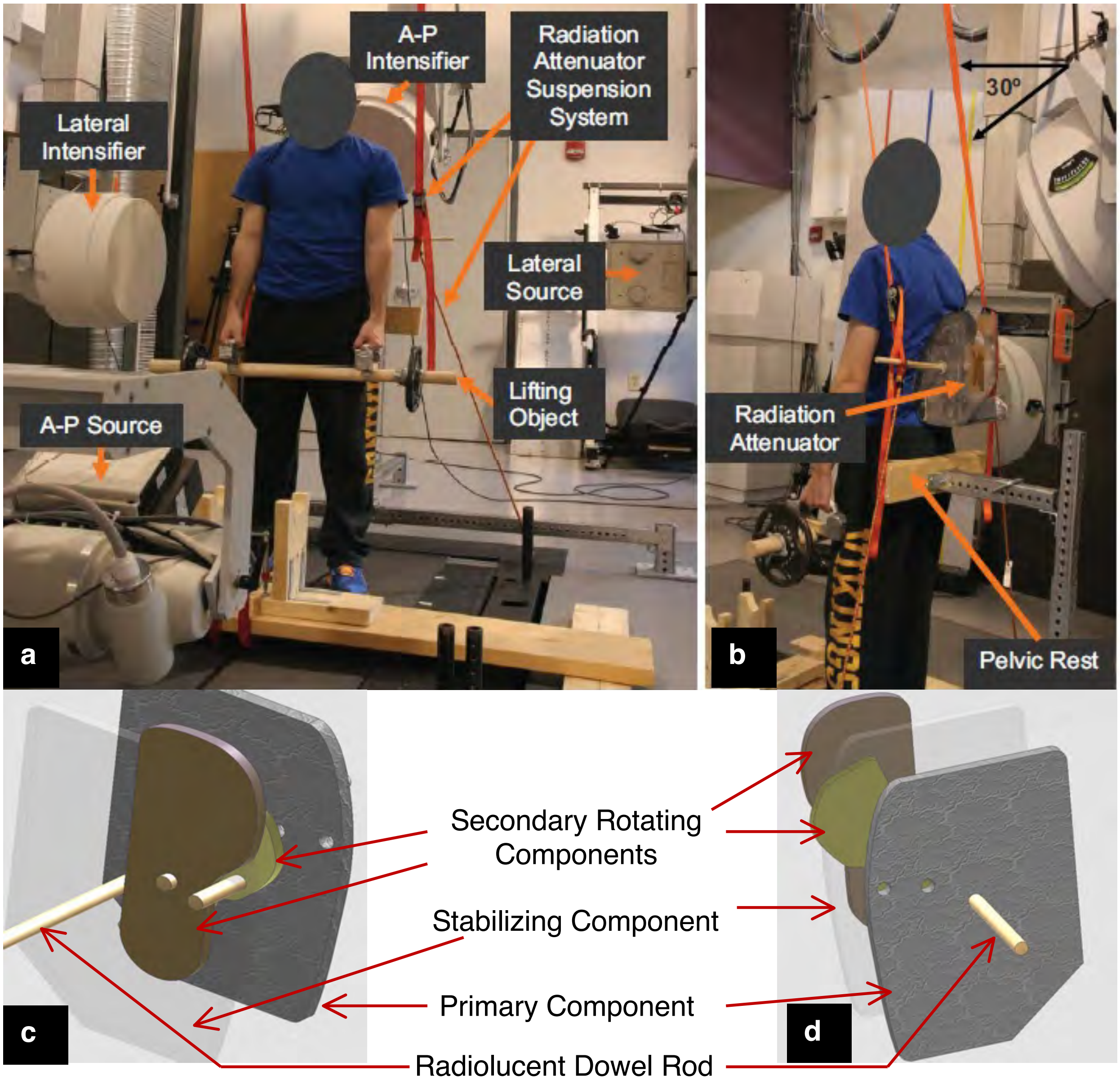


Figure 1. (a) Dynamic stereo radiography (DSX) system configured for the functional lifting task; (b) Lateral view shows positioning of the Pelvic Rest and Radiation Attenuator; (c & d) Detailed views of the Radiation Attenuator.

Data Acquisition

Participants were positioned with their lumbar region centered within the DSX system. The system comprised of two cardiac-cine angiography generators (EMD Technologies, CPX-3100CV), two 0.3/0.6 mm focal spot X-ray tubes, two 16-inch Thalus image intensifiers, and two high-speed digital cameras (4 mega pixel Phantom v10, Vision Research). One pair of X-ray source and camera along with image intensifier was configured in the medial-lateral (ML) direction, while the other was placed in the anterior-posterior (AP) direction (Figure 1). The AP camera and intensifier were angled at +/-30^{o} respectively with regard to the horizontal plane to obviate excessive attenuation of X-rays by the upper body, particularly in the initial stages of the motion, and improve the imaging of all lumbar vertebrae. A prior study (Zhang & Xiong, 2003) has shown that it takes on average less than two seconds to complete a lifting task; hence data were recorded for two seconds per trial. X-rays were generated at 30 fps (4 ms exposure time, 70-80 kV, 320-630 mA) by high-speed cameras from the 16-inch image intensifiers and mapped to images of dimensions 1800 x 1824 pixels resulting in a pixel size of approximately 0.22 mm. Down-sampling to 512 x 512 pixel resolution produced images of approximately 0.8 x 0.8 mm^2 pixel size. Within the excitation voltage and current ranges specified, voltage and current levels were customized for each participant depending on attenuation by surrounding soft tissue to obtain the best contrast for identifying the vertebrae. Following testing, a CT scan of each participant's lumbar spine was obtained *(GE LightSpeed Pro 16, GE Medical Systems, Waukesha, WI. Excitation voltage = 120 kV; slice thickness = 1.25 mm; field of view =12.8 cm; image size = 512x512; voxel volume = 0.25x0.25x1.25 mm^3).* Individual vertebrae were segmented in Mimics 14.0 (*Materialise Inc., Ann Arbor, MI*) to create 3D bone models.

AP pelvic motion during the lifting task can hinder data collection as the lumbar spine moves in and out of the (ML) X-ray system's field of view. This motion was limited by having participants maintain light but constant contact between their pelves and a *Pelvic Rest* (*PR)* throughout the lifting task (Figure 1b). Completely preventing backward motion of the pelvis while bending forward from an erect position, however, could result in a tendency to fall forward. In order to avoid this, participants were asked to position themselves for the task with their feet slightly forward. Participants were then encouraged to align their feet as closely with the hips as possible without feeling they would fall over if they bent forward. Hence participants were almost, but not completely erect when they attained the final "upright" position at the end of the lifting task. The semi-rigid construction helped to limit, but not entirely prevent the backward motion of the pelvis as the participants performed the lifting task.

A *Radiation Attenuator (RA)* was developed (Figure 1c&d) in order to minimize radiation white-out – an over-exposure of the X-ray image intensifier due to large areas of unattenuated radiation causing a "washing out" of the images acquired from the (ML) system. The *RA* and accompanying flexible suspension system were designed to follow the motion of the participant's back without adding significant loads or constraints and minimize the obstruction to X-ray and motion analysis camera system view paths. The *RA* comprised of one primary convex-shaped piece made up of a lead sheet sandwiched between two polycarbonate pieces, and a secondary, stabilizing polycarbonate piece of similar shape, but without the lead sheet. The two pieces were mounted on a wooden dowel rod (diameter = 1 cm) about 10 cm apart. Acetal ball bearings allowed unconstrained rotation about the rod. The dowel rod itself was maintained in a horizontal position behind the participant's back by the flexible suspension system. Additional components could be mounted directly onto either the primary or secondary piece on small wooden dowel pins to fill any gaps left uncovered by the primary attenuating piece. Unconstrained rotation of the additional components about the dowel pins helped to account for the changing curvature of the back during the movement and to be guided out of the X-ray beam path as the participant progressed towards the final upright position.

Model-Based Tracking

Figure 2 provides a graphical representation of the volumetric model-based tracking process. Briefly, custom software generates a virtual DSX system proportionally and configurationally identical to the experimental setup. A 3D vertebral model reconstructed from CT is placed within the virtual system. Digitally reconstructed radiographs (DRRs) of the vertebral model are created using a ray-tracing algorithm and registered to the experimental DSX dataset. The correlation between the DRRs and DSX images is maximized using a volumetric image-matching algorithm to ascertain the 3D pose of the bone for each frame of collected data. The process is repeated for each lumbar vertebra and the sacrum. The software suite then outputs 3D kinematics (three rotations and three translations) of the lumbar vertebrae and sacrum. More detailed descriptions are available elsewhere (Anderst, Zauel et al., 2009; Anderst, Baillargeon et al., 2011; Bey, Zauel et al., 2006; Martin, Greco et al., 2011) .

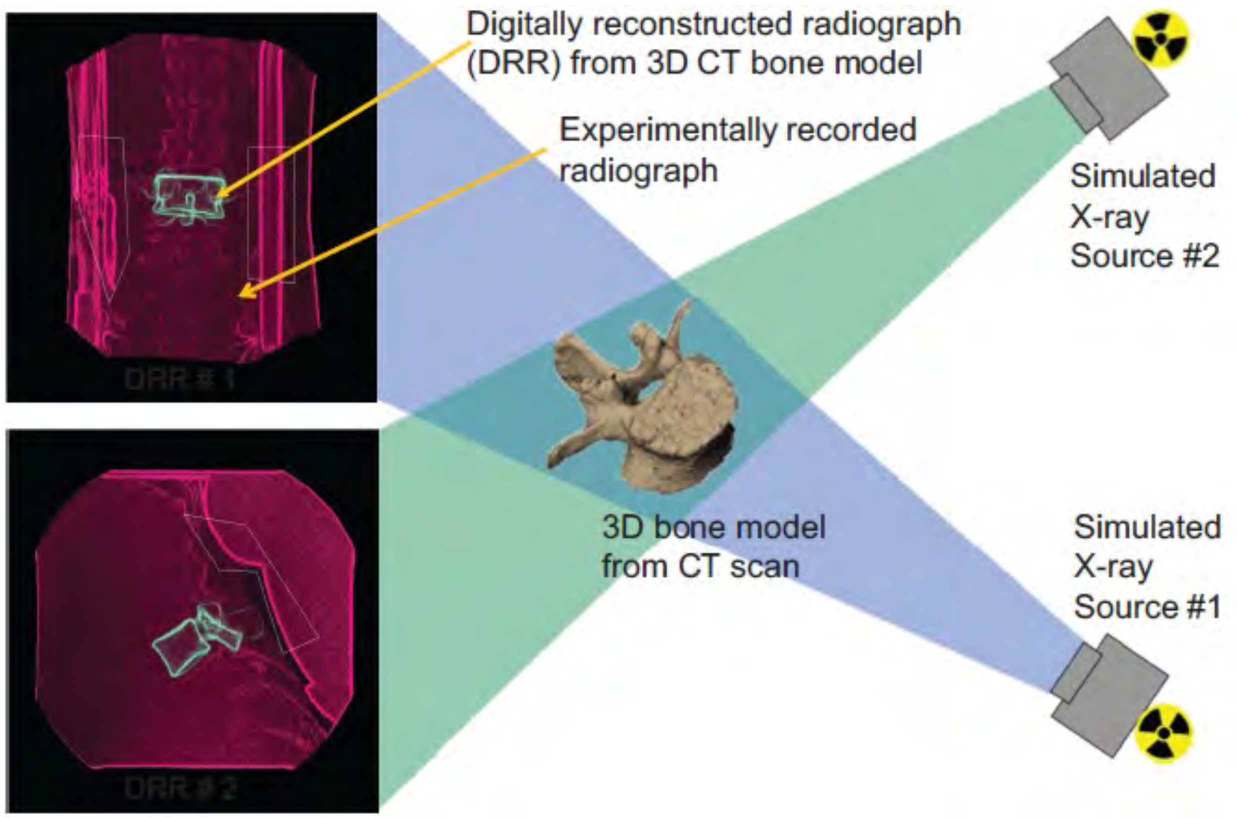


Figure 2. Volumetric model-based bone tracking for determining the 3D position and orientation of the vertebras from the recorded DSX images.

Kinematic Analysis

Anatomical coordinate systems (ACS) (Wu, Siegler et al., 2002) were defined for each vertebra by three mutually orthogonal axes – AP, ML and superior-inferior (SI) – and located in the center of the vertebral body (Figure 3). Ordered body-fixed rotations (Kane, Likins et al., 1983) and translations were extracted from homogenous transformation matrices relating frame-by-frame position of the superior vertebral ACS relative to the inferior vertebral ACS. Segmental (L2-L3, L3-L4, L4-L5 and L5-S1) motion was expressed as the motion of the superior vertebra relative to the inferior vertebra. Segmental extensions and AP translations were plotted with respect to each individual's L2-S1 extension. The following data processing steps were applied in order to standardize representation of the motion across participants. L2-S1 extension accomplished by each participant at each frame was first expressed as a percent of his own upright L2-S1 posture from the static trial, which represented the ideal final position and was defined as 100%. The initial position was defined as 0%. This step standardized the X-axis (0-

100% of L2-S1 extension) for all participants and allowed for time– and frame– independent normalization. The frame-wise segmental extensions and AP translations of each participant were then plotted with respect to their normalized L2-S1 extension.

Figure 3. Vertebral anatomical coordinate system with origin located at the center of the vertebral body. Origin is defined as the mean of the eight landmark (red) points. $Axis_1$ is defined as the vector connecting the anterior and posterior points on the superior endplate. Temporary Axis is defined as the vector connecting the two lateral points. Vertical axis ($Axis_2$) is defined as the cross product ($Axis_1$ x Temporary Axis). $Axis_3$ is then defined as the cross product ($Axis_1$ x $Axis_2$).

Data were then interpolated to obtain segmental extensions and AP translations for each percentage point increment of the individuals' L2-S1 range of motion (ROM). While the magnitude of segmental motion is an important parameter, the contribution of each segment to the overall lumbar motion at any given instant is an equally important characteristic of lumbar kinematics. Thus, in order to elucidate the apportionment of total lumbar motion across the segments, rotational data were further reorganized to extract the fractional contribution of each segment to the overall lumbar (L2-S1) extension. Percent contribution of each segment to the instantaneous lumbar (L2-S1) motion was computed at every percentage point increment of L2-S1 ROM in order to assess differences in segmental contribution to overall lumbar motion. Additionally, data from the two superior intervertebral segments—L2 – L3 and L3 – L4, denoted as L2 – L4— and two inferior intervertebral segments—L4 – L5 and L5 – S1, denoted as L4 – S1— were averaged to contrast the contrast contribution of the two superior segments with the contribution of the two inferior segments. This was done separately for the male and female datasets in order to explore potential sex differences in segmental motion. 95% confidence intervals (CI_{95}) for the mean segmental rotation, and the percent segmental contributions for the combined superior (L2 – L4) and L5 – S1) segments were calculated at every percent of L2-S1 ROM to enable qualitative observations of the differences in segmental contribution. All data are plotted as continuous curves (mean values) with the variously color-shaded regions depicting the respective ± CI_{95} ranges. Statistical significance in the differences between segments were assessed based on the extent of overlap (or lack thereof) between the ± CI_{95} curves.

Helical Axis Analysis

Helical axes of rotation were computed using the finite helical axis (FHA) method. The three-dimensional FHA, representing the motion of the superior vertebra with respect to the adjacent inferior vertebra, were computed at 1° increments of the respective segmental extension. Instantaneous centers of rotation (ICR) were defined according to the method of (Spoor & Veldpaus, 1980). The L2-S1 extension, and consequently the percent L2-S1 ROM, corresponding to the end frame of each 1° increment for that particular FHA computation step were noted. ICRs for each intervertebral segment were then interpolated to obtain ICR values at every 10^{th} percentile of L2-S1 ROM. Furthermore, the A-P and S-I coordinates of the ICRs were normalized to the depth and height of the inferior bone for each segment respectively. These normalization steps were implemented in order to enable comparison across all segments, participants and weight levels and visualize the segmental ICRs simultaneously for all the segments in the lumbar spine.

Where available, data from both trials for each participant and weight level were averaged into a single dataset to be used for subsequent analysis. Datasets with ICR ranges in A-P and S-I directions more than 250% of bone width or height respectively were excluded from the analysis. Mean segmental ICR location along the A-P (bone depth) and S-I (bone height) directions and their respective ± 95% confidence interval (CI_{95}) values were computed for each weight level at every 10^{th} percent increment (from 20% – 80%) of L2-S1 ROM across participants to enable qualitative observations of differences across segments and across weight levels.

Statistical Modeling and Analysis

We expressed individual segmental motions (rotations and translations) against total lumbar (L2-S1) rotation. Initial verification showed this representation resulted in largely linear relations (see Results below), which allowed us to employ simple linear statistical models. Differences in slopes of segmental rotations versus the L2-S1 rotation were analyzed using one-way analysis of variance (ANOVA) to detect possible different segmental contributions to the overall lumbar rotation. Tests were conducted at a significance level of $\alpha = 0.05$. Additionally, 95% confidence intervals (CI) for the mean segmental contributions were calculated at every 10^{th} percent of L2-S1 ROM to enable qualitative observations of the differences in segmental contribution.

To investigate the gender differences in the segmental rotations and AP translations in handling loads of varied weight magnitude, linear mixed-effects models were first introduced to fit the data separately for the female and male groups. The mixed-effects model combines both fixed effect (load effect) and random (subject) effect. The mean and 95% confidence intervals (CI) of the segmental rotations and translations at different load levels for the male and female groups were estimated from the fitted models. To account for the size variability, the segmental AP translations were normalized by the AP length of the upper vertebral body. The gender differences were then analyzed by analysis of covariance (ANCOVA) for different segmental levels, where the percentages of L2-S1 ROM were used as covariates. Within the same-gender groups, the load effects were also examined using ANCOVA for different segmental levels, where the percentages of L2-S1 ROM were used as covariates.

Results and Discussion

While this was an exploratory study, we conducted a pilot test and proceeded prudently in order to minimize the number of subjects that were exposed to imaging (CT, MRI, or Dynamic X-ray) but did not generate usable data. We were able to limit that number to 1. So data collection for the first participant was not complete; however this pilot test helped to optimize the configuration and X-ray settings for subsequent participants.

We also tracked and examined the first six male participants' raw data, which we reported in a methodological paper published in Journal of Biomechanical Engineering (Aiyangar et al., 2014). When the individual intervertebral segmental extensions and translations were plotted against the total lumbar (L2-S1) motions (Figure 4), linear relations were revealed. This justified the use of linear mixed models for the subsequent statistical analyses of the effects as described above in Statistical Modeling and Analysis.

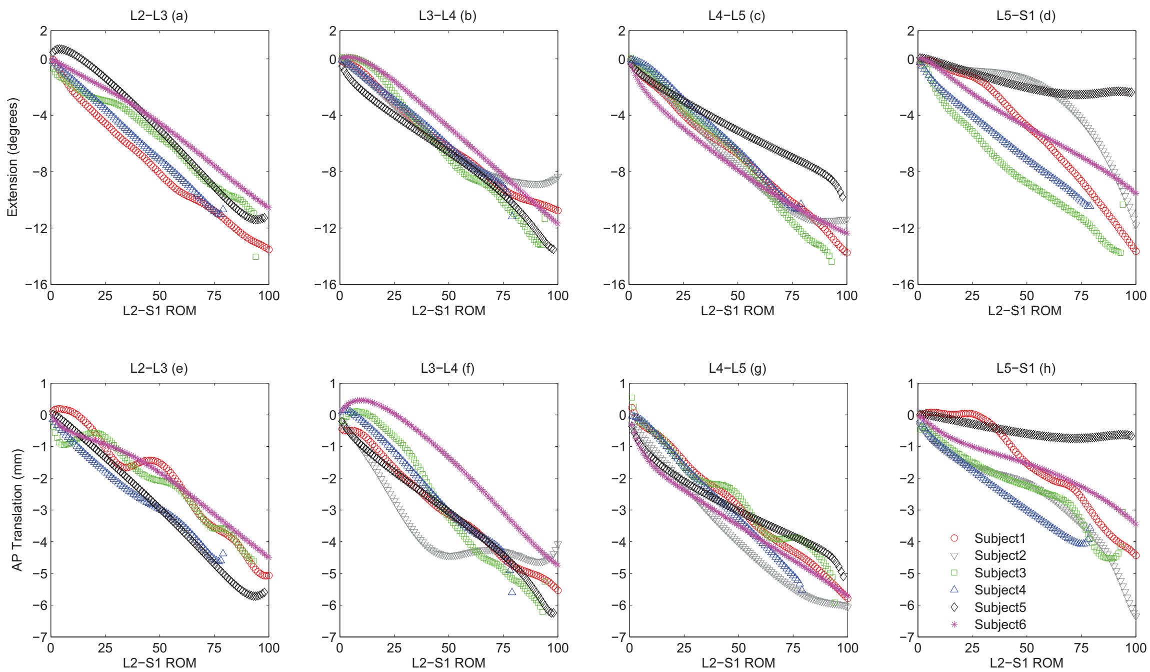
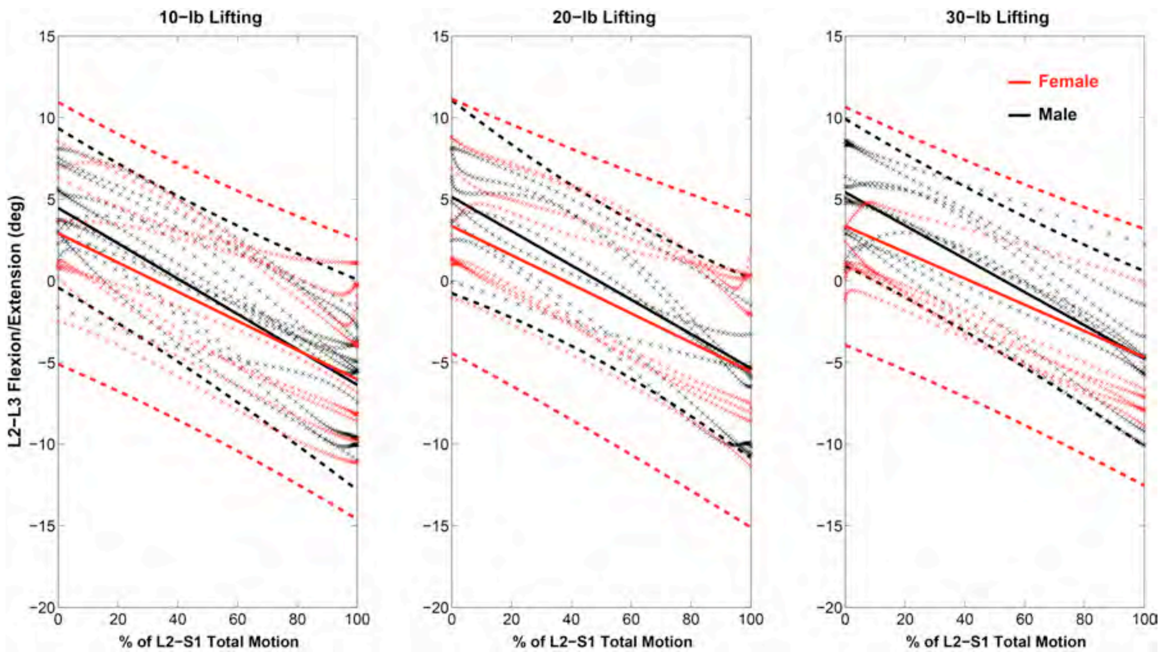


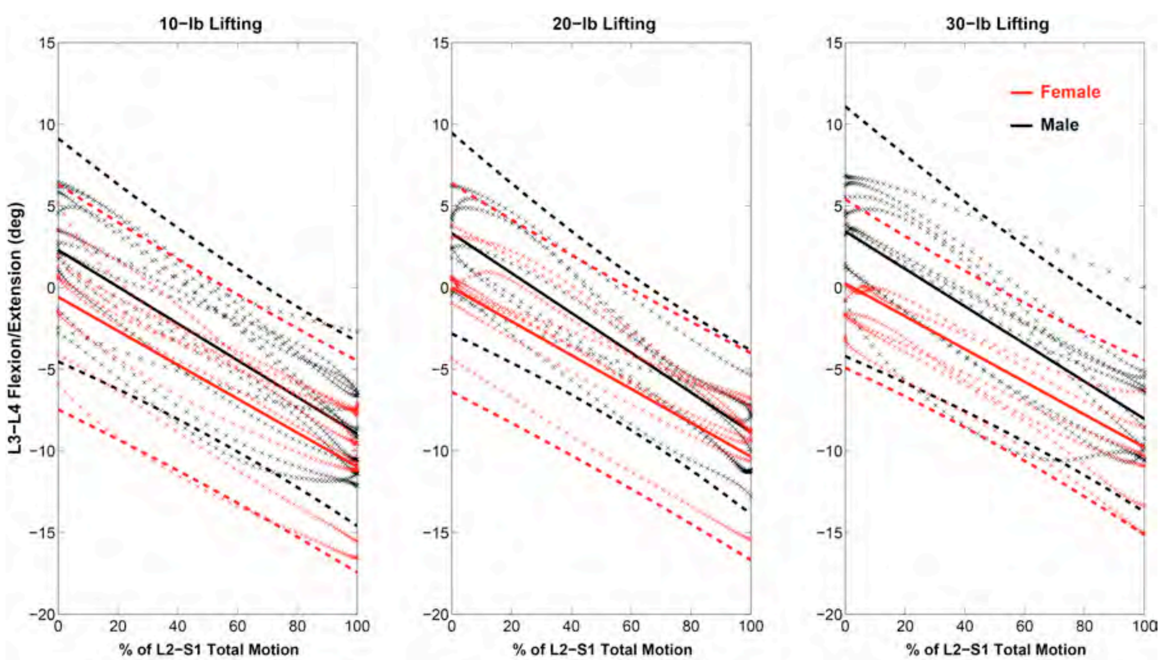
Figure 4. Continuous extension (a-d) and AP translation (e-f) data for first six participants during the lifting task. Intervertebral segmental motion is plotted against L2-S1 ROM. Each participant's L2-S1 ROM is normalized to the upright posture recorded during the static test (100%), with the initial position in the lifting task set as 0%.

Gender and Load Effects on Segmental Rotations

For the heavy-weight lifting trials (30-lb load), the gender differences were found in both the intercept (the initial offset of the segmental extensions) and the slope (the extension changes with respect to the percent increments of L2-S1 total motion) ($p<0.05$; Figure 5). For the light- and moderate-weight lifting trials (10- and 20-lb loads), the gender differences in the intercept were found at the lower levels of the lumbar (L3-L4, L4-L5 and L5-S1) ($p<0.05$; Figure 5b, c and d); the gender differences in the slope were found at upper levels (L2-L3 and L3-L4) ($p<0.05$; Figure 5a and b). For both female and male groups, the load magnitude significantly affected the offset of the segmental extensions (the intercepts) at all the segmental levels ($p<0.05$). In the male group, the load magnitude significantly affected the slopes (the extension changes with respect to the percent increments of L2-S1 total motion) for all the levels except for L4-L5 level; while in the female group, the weights affected the slopes only for the lower levels (L4-L5 and L5-S1) ($p<0.05$).



(a)



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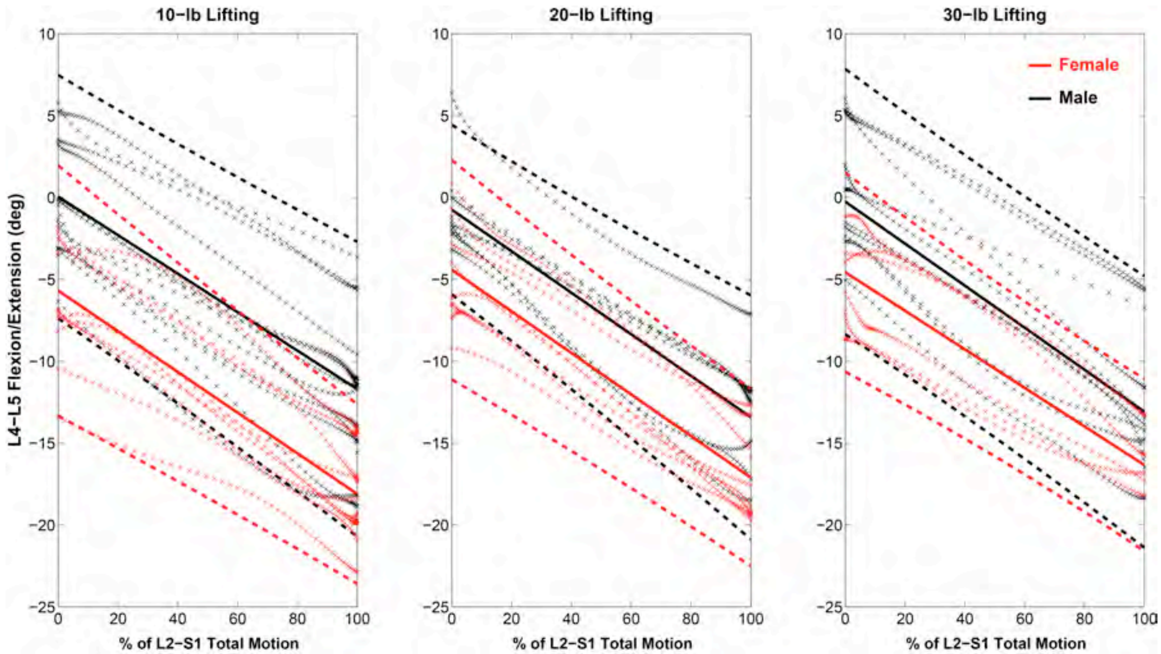
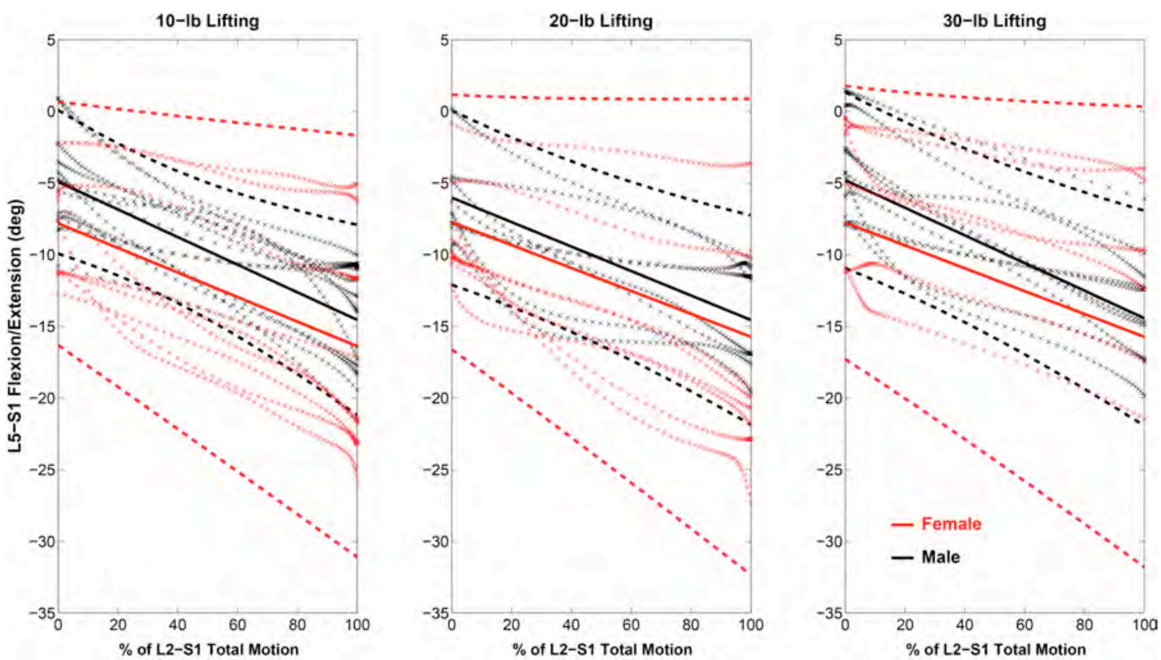


(c)

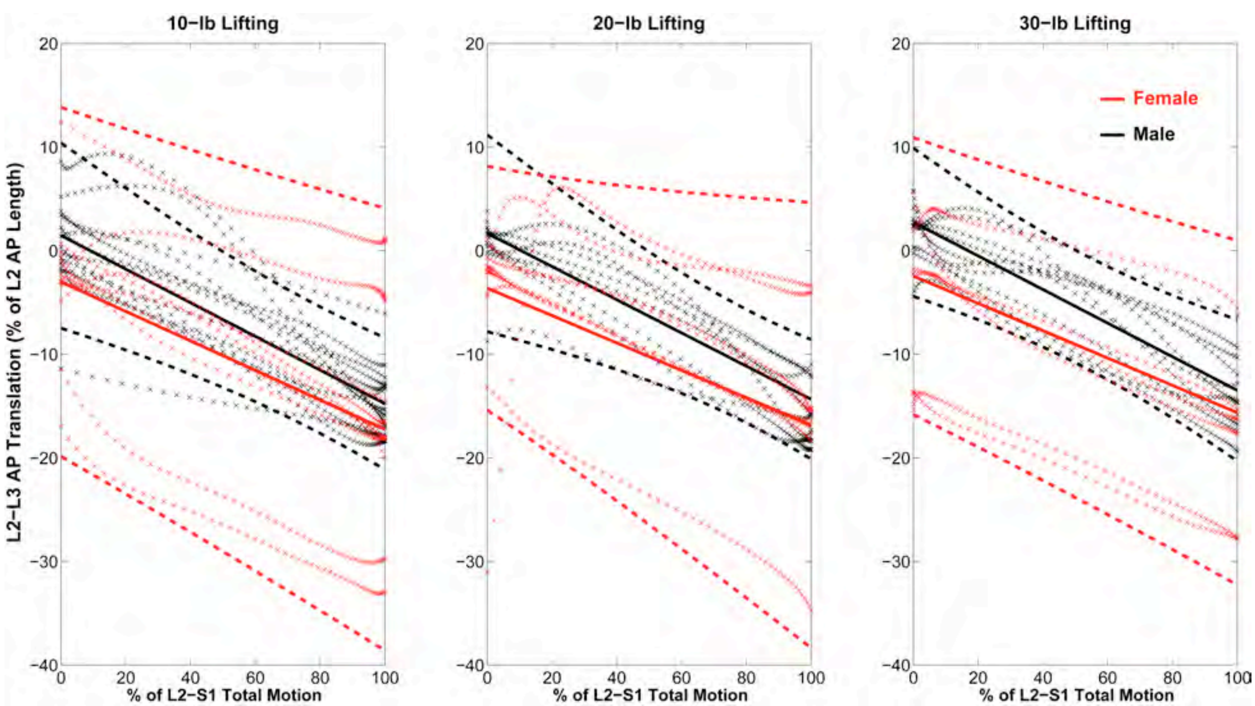


(d)

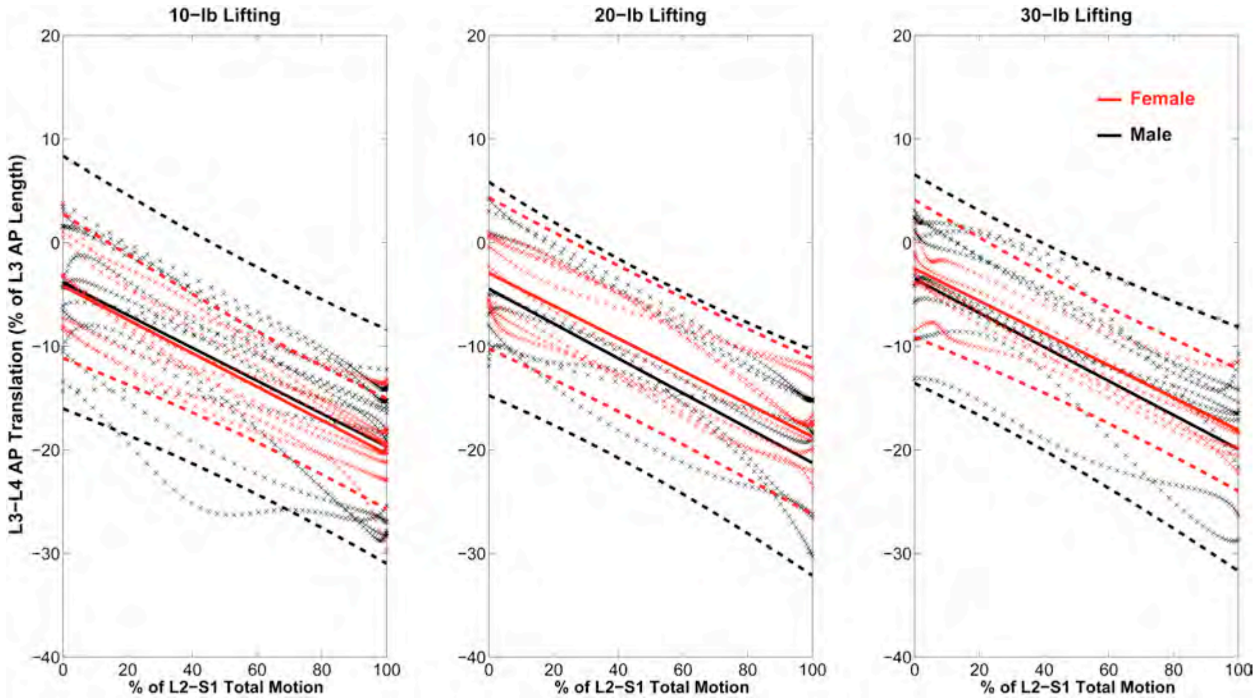
Figure 5. Intervertebral segmental extensions at L2-L3 (a), L3-L4 (b), L4-L5 (c), and L5-S1 (d) levels against total L2-S1 motion during lifting of different weights. The observed data for the individual subjects (thin dashed lines), and the predicted mean (thick solid lines) and 95% confidence intervals (thick solid lines) from the mixed-model analysis were color-coded (red: female; black: male).

Gender and Load Effects on Segmental AP Translations

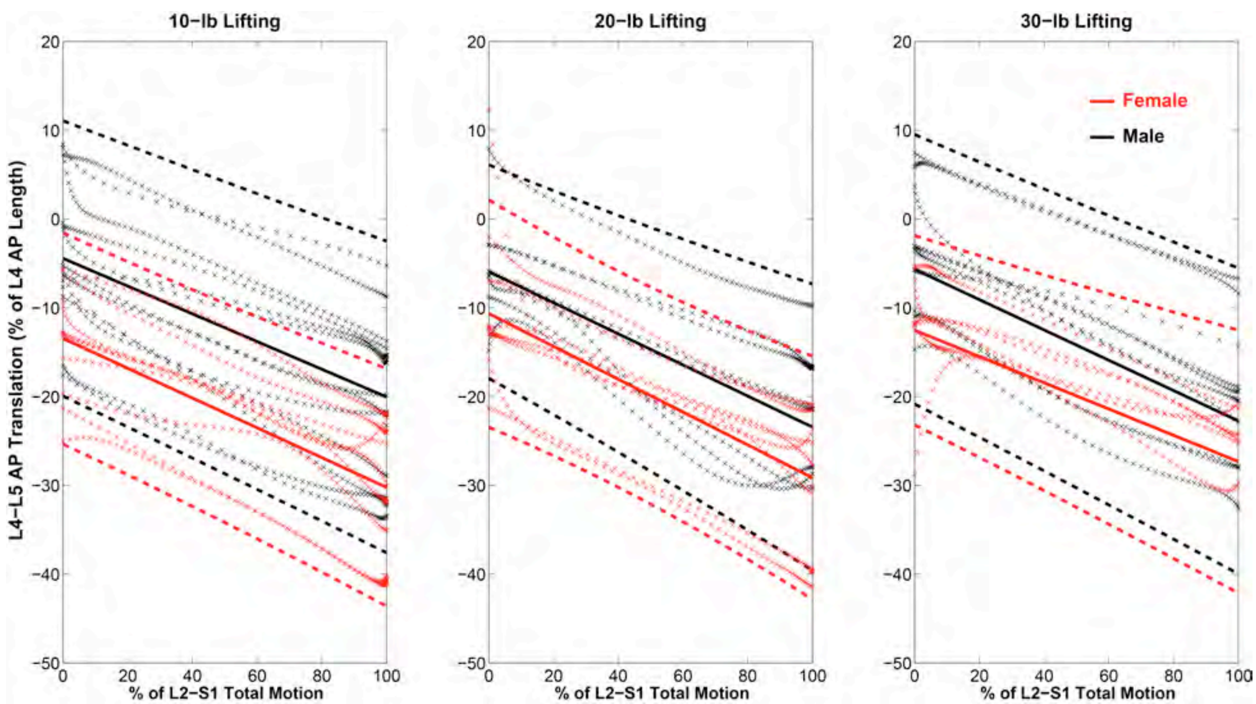
In the heavy-weight lifting trials (30-lb load), significant gender differences in the offset of the normalized AP translation (the intercept) were found at all the four lumbar segmental levels, while the gender differences in the slope (the changes of the AP translations with respect to the percent increments of the L2-S1 total motion) were only found in lower levels (L4-L5 and L5-S1) ($p<0.05$**;** Figure 6**)**. In the light lifting trials (10-lb load), the gender differences in the intercept were only significant in the L2-L3 and L4-L5 levels ($p<0.05$; Figure 6a and c), and the gender differences in the slope were only significant in the L2-L3 and L5-S1 levels ($p<0.05$; Figure 6a and d). In the moderate-weight lifting trials (20-lb weight), the gender differences in the intercept were found in the upper levels (L2-L3, L3-L4 and L4-L5) ($p<0.05$; Figure 6a, b and c), and the gender differences in the slopes were found in the L2-L3 and L4-L5 levels ($p<0.05$; Figure 6a and c). For both female and male groups, the load magnitude significantly affected the offset of the segmental AP translation (the intercept) at all the segmental levels ($p<0.05$). The load magnitude only affected the slopes (the changes of the AP translations with respect to the percent increments of the L2-S1 total motion) in L4-L5 levels for the female group ($p<0.05$), and had no effect for the male groups at any of the intervertebral level.



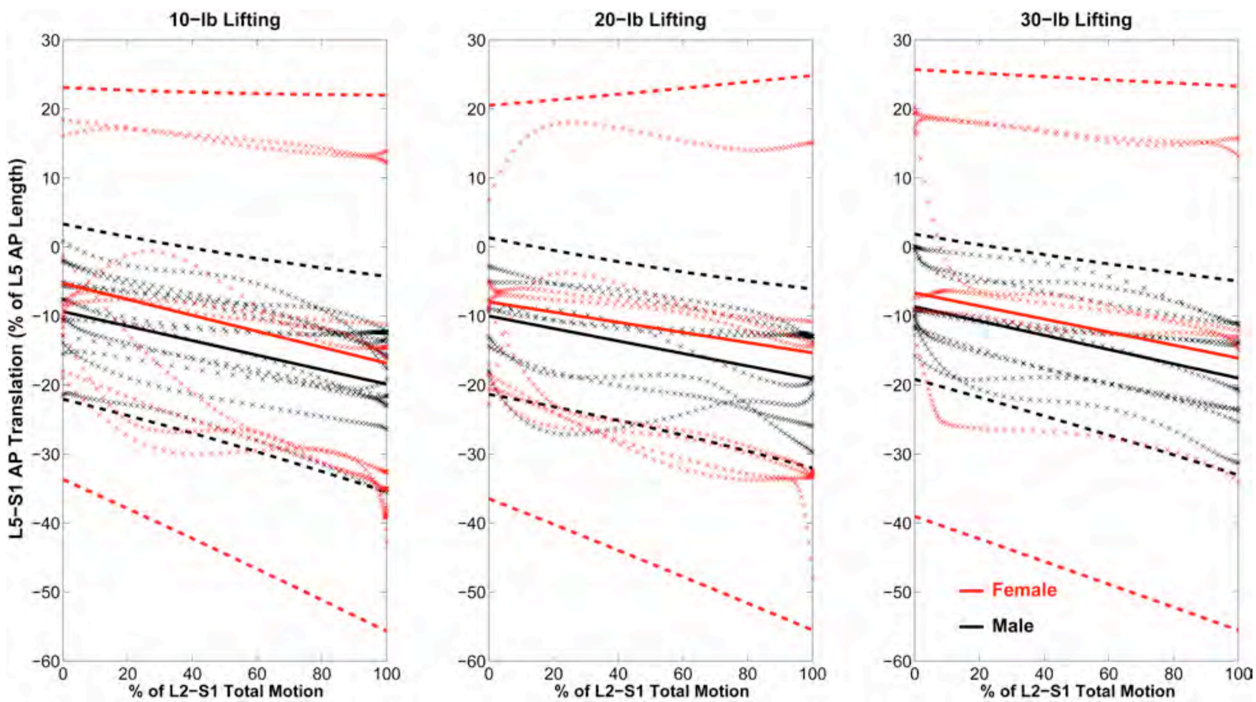
(a)


10−lb Lifting
20−lb Lifting
30−lb Lifting
Female
Male
L3−L4 AP Translation (% of L3 AP Length)
% of L2−S1 Total Motion

(b)


10−lb Lifting
20−lb Lifting
30−lb Lifting
Female
Male
L4−L5 AP Translation (% of L4 AP Length)
% of L2−S1 Total Motion

(c)

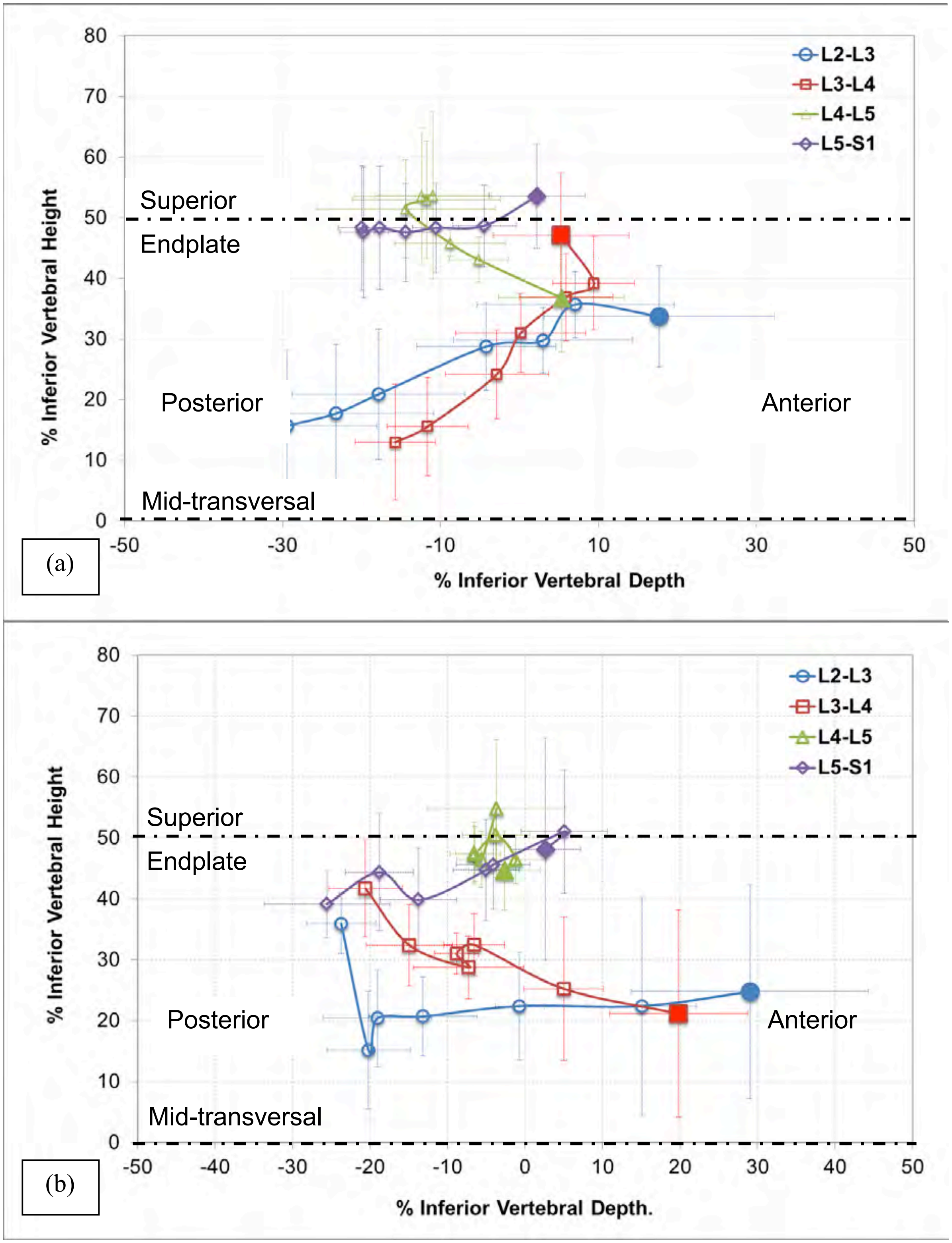


(d)

Figure 6. Intervertebral anterior-posterior translation (normalized by the AP length of the upper vertebral body) at L2-L3 (a), L3-L4 (b), L4-L5 (c), and L5-S1 (d) levels against total L2-S1 motion during lifting of different weights. The observed data for the individual subjects (thin dashed lines), and the predicted mean (thick solid lines) and 95% confidence intervals (thick solid lines) from the mixed-model analysis were color-coded (red: female; black: male).

Instantaneous Center of Rotation Characteristics

The ICR representation has been the standard way to characterize the spinal segmental motion and mobility, mostly based on static X-ray images(Panjabi, Chang et al., 1992; White & Panjabi, 1978) or surface-based motion captures (Zhang & Xiong, 2003). The ICR results from our finite helical axis (FHA) analysis based on the in vivo kinematics data would serve as the new "benchmark" reference data. We found a substantial migration of the instantaneous center of rotation (ICR) during the motion (Figure 7). ICRs appeared to generally lie between the mid-transverse plane and the upper endplate of the bottom vertebra of each intervertebral functional spinal unit, e.g., between the top endplate and the mid-transverse plane of the L3 vertebra for the L2-L3 intervertebral joint. Furthermore, the ICRs appeared to move closer to the endplate with increasing magnitude of weight being lifted (from 10 lb to 30 lb) and with decreasing vertebral level (i.e. from L2-L3 towards L5-S1).


L2-L3
L3-L4
L4-L5
L5-S1
Superior
Endplate
Posterior
Anterior
Mid-transversal
% Inferior Vertebral Height
% Inferior Vertebral Depth
(a)
L2-L3
L3-L4
L4-L5
L5-S1
Superior
Endplate
Posterior
Anterior
Mid-transversal
% Inferior Vertebral Height
% Inferior Vertebral Depth.
(b)

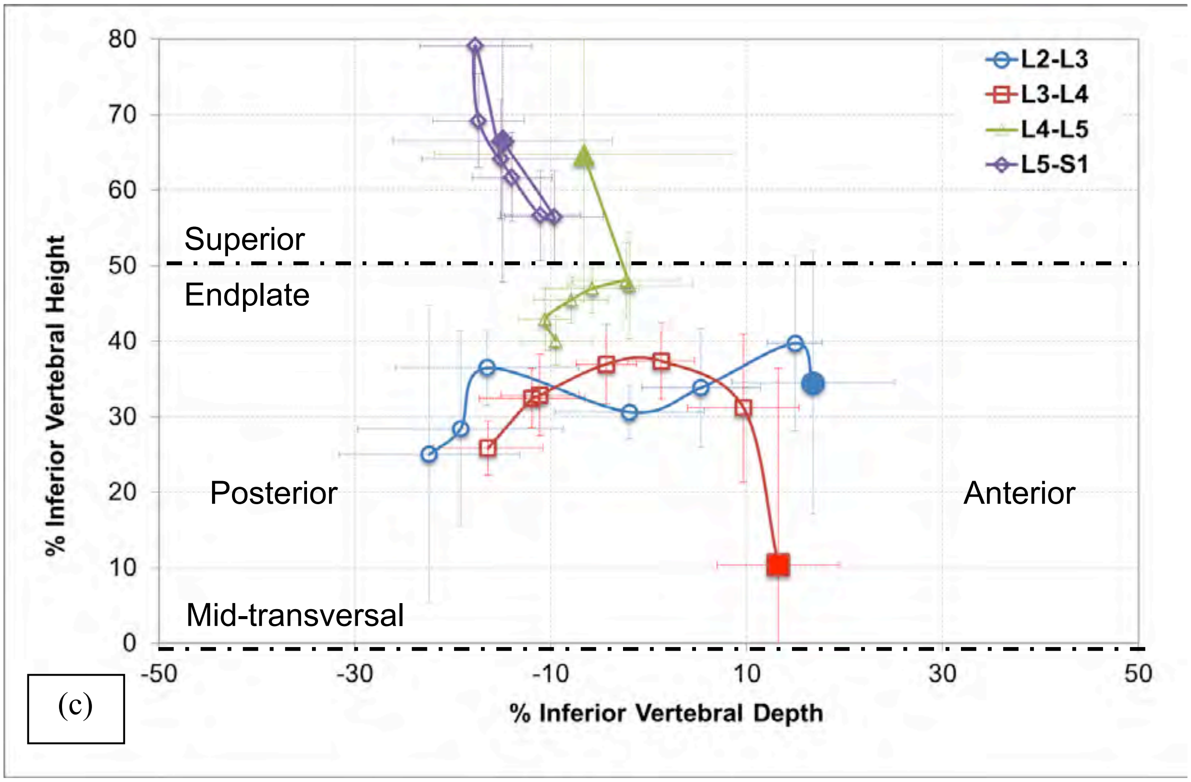


Figure 7. Location of the ICRs for each intervertebral segment during the lifting task, relative to the inferior bone size for three weight levels: (a) 10 lb; (b) 20lb; (c) 30lb. Each data point shown is the ICR computed at a decile of total lumbar (L2-S1) ROM. Solid filled data points indicate the ICR computed at 20% of L2-S1 ROM for each segment. Each subsequent data point indicates the computed ICR at the consecutive decile of L2-S1 ROM. Data are shown from 20% to 80% of L2-S1 ROM. 100% ROM is the assumed upright position of each participant. Error bars indicate ± 95% confidence intervals.

A better visualization of where ICRs are generally located and how they migrated during lumbar extension incurred in lifting activities is presented in Figure 8. In general, the ICRs of relative intervertebral rotations (superior to inferior, or upper to lower) are located in the top half of the inferior vertebra near the endplate and migrate from anterior to posterior during lumbar extension. The load effects are also illustrated and appear to be small.

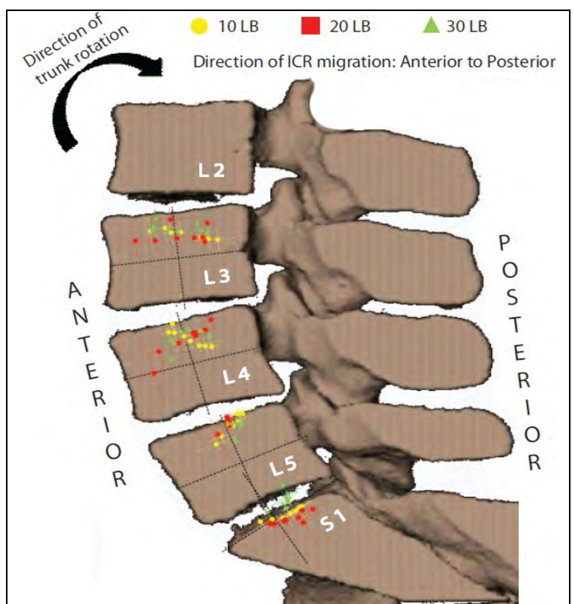


Figure 8. ICRs for lumbar inter-vertebral motions.

Limitations

A number of limitations of the study are acknowledged. A limitation of this study was the restriction to participants with waist size no greater than 89 cm (35 in.), which excluded a large portion of the population. This was deliberate, as we initially hoped to develop the methodology using lean participants prior to evaluating larger participants. However, success in acquiring images while maintaining a low level of radiation exposure will enable to us to relax this constraint in future studies. Second, while radiation exposure from DSX was low, the overall radiation exposure for the participants was still high owing to the large dose from CT scans. The CT data were used primarily for generating the 3D bone models used in the tracking process. Developing bone models from MRI could eliminate the high radiation exposure associated with CT, and an investigation exploring this approach is ongoing. Self-reporting of lumbar spinal health by participants was another limitation. Using self-reported status of the spine was considered reasonable since the study was restricted to participants who were less than 30 years of age. Age-related disc degeneration is of low incidence in this age group. However, it is possible that a participant could have had asymptomatic pathological conditions. The sample size in this study was small; hence results presented are considered preliminary in nature and quantitative assessments should be interpreted with caution. Finally, strong, statistically significant differences regarding differences in segmental contribution, differences in the ICR paths and patterns across the segments, the effects of the different weight levels used for the lifting tasks or differences between male and female subjects could not be determined. This could very well be attributed to the small sample size of this exploratory study. However some interesting trends were revealed, which could be further investigated within the context of a larger study.

Conclusion

In conclusion, this exploratory study successfully demonstrated the ability to directly record three-dimensional vertebral motion, in vivo, during functional lifting tasks using a novel imaging system known as dynamic stereo radiography (DSX). The study showed all the lumbar segments studied contributed substantially to the movement of the lumbar in lifting acts with no clear statistical differences between them. The study also found substantial AP translation occurring in all the intervertebral joints. Individual AP translation curves exhibited greater nonlinear behavior compared to flexion rotation. The substantial translations across all the segments coupled with the nonlinear patterns emphasizes the importance of acquiring continuous motion data. It is evident that, given the substantial translations, the ICR is not fixed, as has been assumed in many lumbar spine biomechanical models for estimating low back forces or stresses. This was, indeed, revealed in the substantial migration of the ICRs, which at times spanned more than 50% of the inferior bone depth. Gender differences in lumbar intervertebral motions were identified: females tended to be more extended, particularly in the higher lumbar vertebral levels, and be more posteriorly translated (superior vertebra relative to the inferior) than males throughout the lifting. The load magnitude was found to significantly affect some aspects of the lumbar motion, mostly the rates of segmental extensions (i.e., the slopes).

The study thus demonstrated the success of a technical capability that allows us to address the knowledge gaps in lumbar kinematics and to provide the most accurate kinematic data input to biomechanical models. This would in turn enable more accurate estimation of the mechanical stress inflicted upon the low back and more effective recognition and prevention of low back disorders.

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Aiyangar A, Zheng L, Anderst W, Tashman S, Zhang X: [2014] Capturing Three-Dimensional *In Vivo* Lumbar Inter-Vertebral Joint Kinematics Using Dynamic Stereo-Radiographic Imaging. Journal of Biomechanical Engineering 136: 041004-1-8.

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Zhang X: [2014] Advancing the Occupational Biomechanical Science Base Through New Measurement and Modeling Approaches. Proceedings of the 7th World Congress of Biomechanics, Boston, MA (**Keynote Lecture**).