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● *Original Contribution*

DEVELOPMENT AND VALIDATION OF A METHOD TO MEASURE LUMBOSACRAL MOTION USING ULTRASOUND IMAGING

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Abstract—The study aim was to validate an ultrasound imaging technique to measure sagittal plane lumbosacral motion. Direct and indirect measures of lumbosacral angle change were developed and validated. Lumbosacral angle was estimated by the angle between lines through two landmarks on the sacrum and lowest lumbar vertebrae. Distance measure was made between the sacrum and lumbar vertebrae, and angle was estimated after distance was calibrated to angle. This method was tested in an *in vitro* spine and an *in vivo* porcine spine and validated to video and fluoroscopy measures, respectively. R^2, regression coefficients and mean absolute differences between ultrasound measures and validation measures were, respectively: 0.77, 0.982, 0.67° (*in vitro*, angle); 0.97, 0.992, 0.82° (*in vitro*, distance); 0.94, 0.995, 2.1° (*in vivo*, angle); and 0.95, 0.997, 1.7° (*in vivo*, distance). Lumbosacral motion can be accurately measured with ultrasound. This provides a basis to develop measurements for use in humans. (E-mail: w.vandenhoorn@uq.edu.au) © **2016 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Spine motion, Ultrasound, *In vitro* model, *In vivo* model.**

INTRODUCTION

Intervertebral motion can be measured accurately with radiologic techniques (Breen et al. 1989; Dvorák et al. 1991a; 1991b; Pearcy 1985; Pearcy and Whittle 1982). However, repeated exposure to ionizing radiation poses health risks. Alternative methods using markers attached to the skin to represent intervertebral motion (Lee et al. 1995; Mörl and Blickhan 2006; Vanneuville et al. 1994) are not ideal because movement of the skin relative to the vertebral body means that markers may not reflect true intervertebral motion. Although this problem can be overcome by attachment of markers directly to spinous processes (Steffen et al. 1997), this is invasive and impractical for widespread use. Accurate measurement of intervertebral motion in clinical settings requires a method, which is non-invasive, easy to use and readily available.

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Measurement of intervertebral motion could help to explore the relation among muscle dysfunction, reduced proprioception and low back pain, and could therefore direct rehabilitation. There is accruing evidence that control of motion at a single segment may be relevant for low back pain (Breen et al. 2012). For example, function of deep erector spinae muscles is affected at a single segment by low back pain (MacDonald et al. 2010) and spinal injury (Hodges et al. 2006) and atrophy and inhibition of these muscles might affect segmental motion (Quint et al. 1998). Reduced segmental motion would affect proprioception (Burke et al. 1978), and lower back proprioception is affected in people with low back pain (Brumagne et al. 2000). A non-invasive method to measure intervertebral motion is necessary to investigate the relation between low back pain and dysfunctions in clinical practice and in large cohorts.

Ultrasound imaging allows direct and accurate imaging of vertebral structures (from reflection of the ultrasound beam at the periosteum) and surrounding soft tissues, is readily available in clinical settings and has the potential to measure intervertebral motion accurately and non-invasively. Anatomic landmarks of the sacrum and lumbar vertebrae can be visualized reliably

with ultrasound (Zieger and Dörr 1988). We proposed that a set of anatomic landmarks could provide the basis to estimate intervertebral motion with ultrasound imaging.

The aim of the current investigation was to develop techniques using ultrasound imaging to accurately and non-invasively measure intervertebral motion of the lumbosacral spine in the sagittal plane. A second aim was to compare these techniques against measurement of intervertebral motion made either with a video when the technique was applied to an *in vitro* spine model, or fluoroscopy when the technique was applied *in vivo* using an anesthetized pig.

MATERIALS AND METHODS

Traditionally, angle between two segments is defined by two anatomic landmarks identified on each segment (Morrissy et al. 1990). Lines can be drawn through these pairs of anatomic landmarks and the angle between the two lines used as a representation of the angle between these segments. This technique was tested using two points identified on the L5 vertebra and sacrum in a single image. An alternative method to estimate intervertebral angle change may be based on one anatomic landmark per segment when it is difficult to accurately track two points on two structures as the structures move relative to each other. This technique is based on the assumption that the distance between bony landmarks on adjacent segments changes with spinal movement in the sagittal plane and, when calibrated against a known angle change, a change in distance between posterior elements of adjacent vertebra could be used to estimate intervertebral movement. Both methods were evaluated in two separate experiments. In the first experiment, lumbosacral motion of an *in vitro* spine model was measured with ultrasound imaging and digital photography. In the second experiment, motion measured with ultrasound imaging was compared with measures made *in vivo* with fluoroscopy in an anesthetized pig.

EXPERIMENT 1: MEASUREMENTS OF INTERVERTEBRAL MOTION USING AN *IN VITRO* SPINE MODEL

Experimental set-up

A synthetic anatomic model of the spine (3B Scientific, Lumbar Spinal Column, Hamburg, Germany) was used to simulate lumbosacral motion. The model was modified by placing a one-degree-of-freedom hinge at the position of the approximate instantaneous axis of rotation (approximately one third of the distance from the dorsal aspect of the vertebral body) (Pearcy and Bogduk 1988). The hinge allowed motion in the sagittal plane (Fig. 1a). With the sacrum fixated, L5 could be moved manually (approximately 4°/s) through a physiologic range of motion (ROM) of 14° (White and Panjabi 1978).

The model was placed in a water-filled tank to facilitate coupling for ultrasound imaging (Fig. 1b). The transducer (7–10 MHz linear array) of the ultrasound system Logiq 9 (GE Healthcare, Little Chalfont, Buckinghamshire, UK) was submerged and held

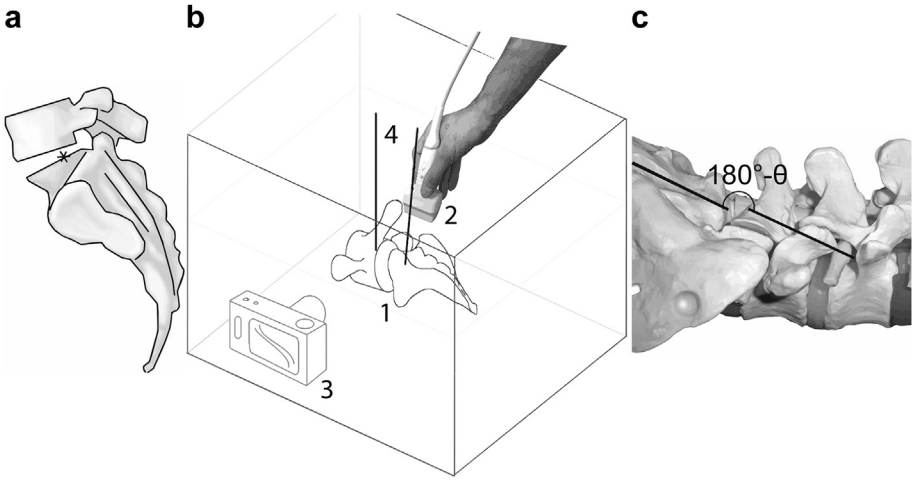

Fig. 1. Experiment 1 set-up. (a) Sagittal plane image of the spinal model used, * indicates the estimated position of the axis of rotation of L5. (b) The spinal model (1) was submerged in a water filled tank for ultrasound coupling. The ultrasound transducer was held manually. Motion of L5 in relation to the sacrum was recorded simultaneously by the ultrasound transducer (2) and digital camera (3). The angle between the sacrum and L5 estimated from the ultrasound measures were compared to the angle between the rods (4) inserted into L5 and the sacrum. (c) Angle between a line drawn through two prominent landmarks of the sacrum and a line drawn through the lamina and mammillary process of L5 used in the ultrasound measure (experiment 1, method 1).

manually approximately 50 mm above the model to record the relevant anatomic landmarks of the sacrum and L5 (see below).

For validation of the measures, motion of L5 was recorded simultaneously with a digital camera (Kodak V530; Eastman Kodak Company, Rochester, New York, USA) (Fig. 1b). To facilitate accurate measurement of the angle change from the digital images, metal rods (length = 80 mm) were inserted into the sacrum and L5 (Fig. 1b). Two points on each rod were visually identified, and the angle between the lines through the points was calculated.

Measurement technique 1: Direct measurement of angular change

The lamina and mammillary process of L5 and two points on the surface of the sacrum immediately lateral to the dorsal processes (Fig. 1c) served as bony landmarks to estimate lumbosacral movement. This is referred to as a "direct" technique, as an angle is directly calculated from the ultrasound images. To enable simultaneous visualization of the four landmarks, the ultrasound transducer was held at an angle in the frontal plane of approximately 25° relative to the longitudinal axis of the spine (Fig. 2a).

Measurement technique 2: Indirect measurement of angular change

The change in the distance between the lamina of L5 and the cranial edge of the dorsal aspect of the sacrum during spinal movements was used to estimate lumbosacral angle. To visualize these landmarks, the ultrasound transducer was held parallel to the spine (Fig 2b). To estimate an angle change from a distance change, knowledge about the relation between a change in distance and

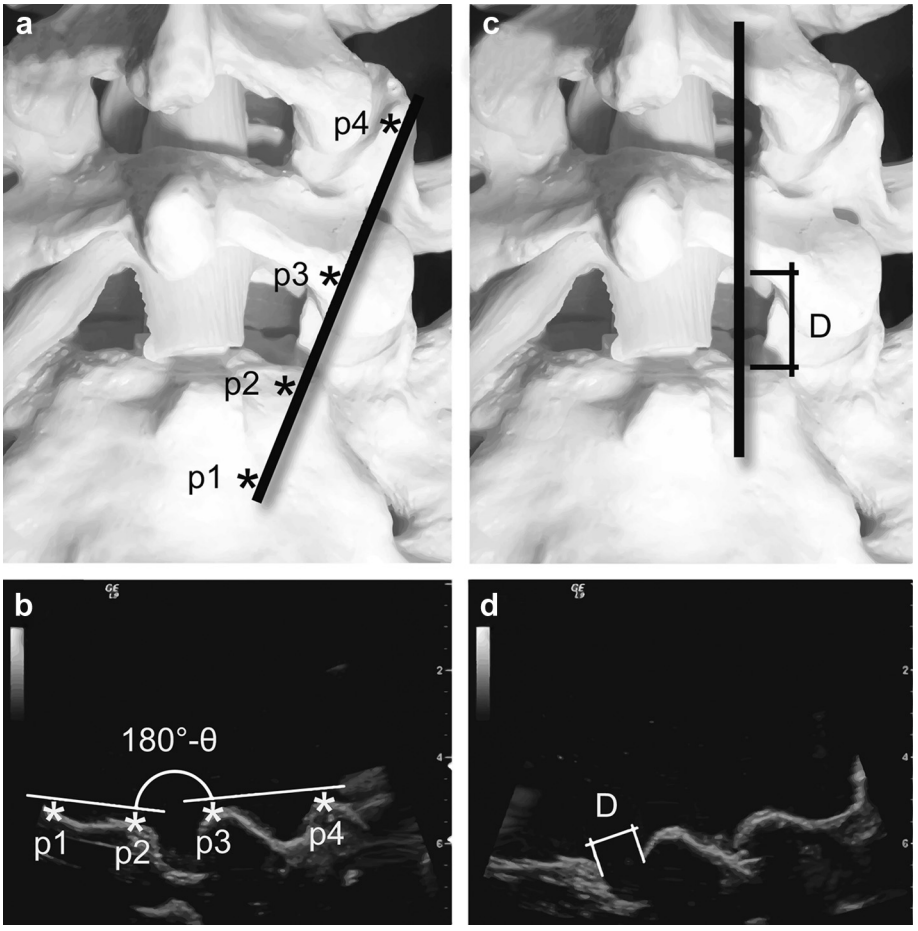

Fig. 2. (a) Position of the ultrasound transducer to visualize two prominent landmarks of the sacrum; dorsal aspect (p1) and the cranial edge of the dorsal aspect of the sacrum (p2) and L5; the lamina (p3) and mammillary process (p4). (b) Ultrasound image obtained with the ultrasound transducer positioned as in (a). The angle ($180°-\theta$) between a line through p1 and p2 and a line through p3 and p4 depicts an anatomic angle between the sacrum and L5. (c) Position of the ultrasound transducer to visualize the cranial edge of the dorsal aspect of the sacrum and L5 lamina, where D displays the distance between the sacrum and L5 points. (d) Ultrasound image obtained with the ultrasound transducer positioned as in (c), where D displays the distance between the sacrum and L5 points.

a change in angle is required. To establish this relation, data from measurement technique 1 were used, as both distance and angle information were available in ultrasound images using that technique. The distance change from when the ultrasound transducer was held parallel to the spine was then transformed to an angle change. We refer to this as an "indirect" technique, as the change in angle is estimated from a change in distance.

Data analysis

The digital video and ultrasound movie frames were converted into JPEG images and imported into MATLAB (The MathWorks, Inc., Natic, MA, USA). To correct for sampling rate differences (ultrasound: 29 fps; camera: 30 fps), images were synchronized to the first and last frame in which movement of the L5 vertebra could be visually determined. To reduce bias from sequential presentation of the images, images were analyzed in random order. To ensure a large enough angle change between frames during the slow movement of the spinal model, every 20th digital video frame was analyzed. Data were recorded for 1 min of repeated movement between the extremes of ROM (approximately 16 cycles).

Measurement technique 1. Because the ultrasound transducer was placed approximately 25° oblique (β) to the spine to visualize the bony landmarks in measurement technique 1, and because motion of L5 occurred in the sagittal plane, the calculated angle (θ) from the ultrasound was corrected for the out-of-plane movement using eqn (1).

$$\theta_{\text{corrected}} = \frac{1}{\cos(\beta)}\theta \tag{1}$$

Where $0° \leq \beta < 90°$.

Measurement technique 2. Because the available range of lumbosacral movement used for calibration of the distance data may be smaller than 14° in real life situations, intervertebral angle change was also estimated with calibration ratios calculated for smaller ROM. This enabled assessment of the degree to which calibration range affected the accuracy of the indirect technique (11.2° [80% of 14°]; 8.4° [60%]; 5.6° [40%]; and 2.8° [20%]). Calibration ratios to convert distance change (Δd) to angular change ($\Delta\varphi$) were determined for each range of motion using eqn (2).

$$\Delta\varphi = \frac{\Delta\theta_{\text{ROM}}}{\Delta d_{\text{rom}}}\Delta d \tag{2}$$

Where *ROM* relates to 11.2°, 8.4°, 5.6° and 2.8°. As the ultrasound transducer was placed at approximately a 25° angle in the frontal plane relative to the longitudinal axis during the calibration measurements, the measured distance change was adjusted by multiplication of the values by cos(25°). Although the projected distance between the two points measured should approximate a sin function of the angle, a linear estimation of the distance was used, as there were only small changes in angle.

EXPERIMENT 2: *IN VIVO* MEASUREMENTS USING AN ANESTHETIZED PIG

Experimental set-up

A 4-mo-old domestic pig (Swedish Landrace), weighing 45 kg, was used. Ethical approval was obtained from the institutional ethics committee. The animal was sedated by a 30-mg/kg intramuscular injection of ketamine (Ketalar, Pfizer, New York, NY, USA), and after 10 min, anesthetized intravenously with 20 mg/kg of propofol (Rapinovet, Shering-Plough, Kenilworth, NJ, USA). Maintenance doses were given as required. The animal was placed prone on a table. Although the pig is a quadruped, its lumbar spine approximates the human lumbar spine in size, shape and biomechanics (Smit 2002).

Fluoroscopy and ultrasound recordings of intersegmental motion were made simultaneously during lumbopelvic movements. The lumbar spine was moved by changing the orientation of the rear legs and pelvis (Fig. 3). Ultrasound images were recorded with an Acuson SC2000 7–10 MHz linear array transducer (Siemens Healthcare, Malvern, PA, USA).

Measurement technique 1: Direct measurement of angular change

An angle was calculated between the lines fitted parallel to the sacrum and parallel to the L6 spinous process of the last lumbar vertebrae (L6) to represent the angle between these two structures. The ultrasound transducer was placed in the midsagittal plane to image the cranial aspect of the sacrum and the caudal aspect of the dorsal processes of L6 (Fig. 4a, 4b). Two points could be identified on each of these structures for orientation of the lines for calculation of angle change.

Measurement technique 2: Indirect measurement of angular change

To assess whether the change in linear distance between the cranial edge of the dorsal aspect of the sacrum and lamina of L6 could be used to quantify lumbosacral motion, the same indirect method was used as in experiment 1, with the exception that the lamina of L6 was visualized in the pig.

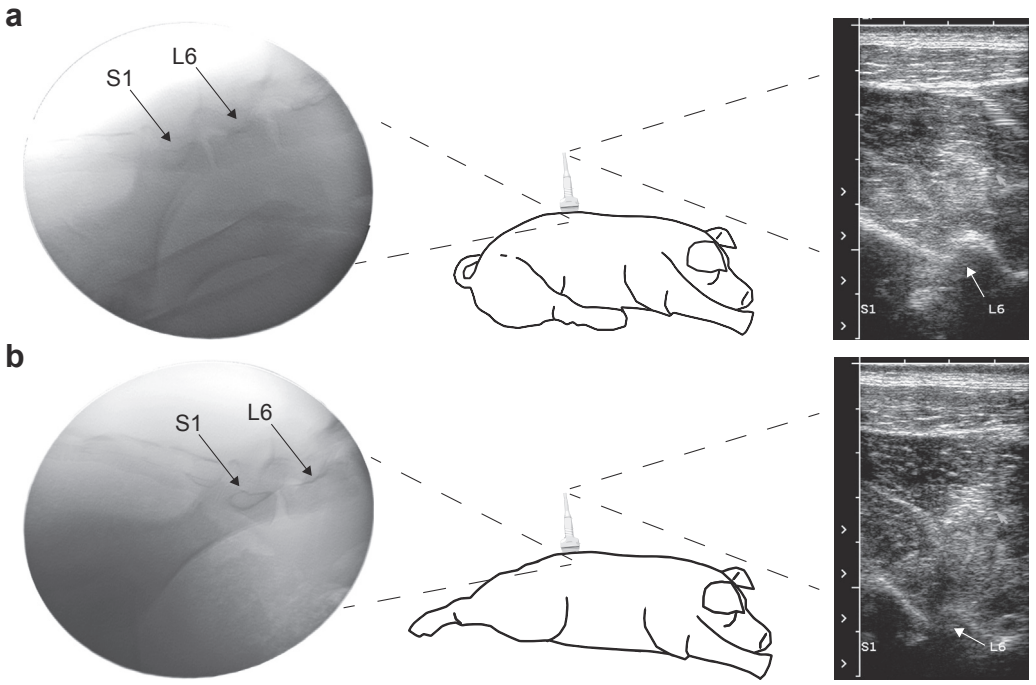

Fig. 3. Experiment 2 set-up. The lumbar spine of the pig was extended in small steps. The lumbar spine at the extremes of flexion (a) and extension (b) are shown. The left side shows the corresponding fluoroscopic images and the right side shows the corresponding ultrasound images. The sacrum (S1) and the sixth lumbar vertebrae (L6) are highlighted in both fluoroscopic and ultrasound images.

Data analysis

The change in angle between the sacrum and L6 was analyzed by overlaying consecutive fluoroscopy images (Cakir et al. 2006). For technique 2, the distance measure could not be calibrated as it had been in experiment 1, because it was difficult to obtain an accurate estimation of distance and angle from the same image in technique 1. To be able to estimate angle change from a distance change, the angle information extracted from the fluoroscopy images was used. To calibrate a distance change to an angle change, the linear relation between distance measured from ultrasound and angle measured from fluoroscopy was determined by estimating the linear regression coefficients. The linear regression coefficients were then used to transform distance measured from ultrasound to angle.

STATISTICAL ANALYSIS

Statistical analyses were performed using MATLAB (The MathWorks, Inc.). To investigate the relationship between the angles and distances estimated from the ultrasound images, and the angles measured either from the digital images (experiment 1) or fluoroscopy (experiment 2) linear regressions were calculated with the intercept forced through zero. Regression coefficients and explained variance (R^2) were extracted. A regression coefficient smaller than one indicates that the ultrasound measure tends to underestimate the lumbosacral angle compared to the measure used for validation. To determine error, the mean absolute differences between the measures made with ultrasound, and the respective technique used for validation, were calculated.

RESULTS

Experiment 1: In vitro *measurements*

For technique 1, the explained variance between the lumbosacral angles measured by digital photography and ultrasound was 97%. The corresponding linear regression coefficient was 0.992. The mean absolute prediction error was 0.82°. For technique 2, the explained variance between the lumbosacral angles measured by digital photography and ultrasound was 77%. Table 1 summarizes the comparison between measures made from photography and ultrasound when distance was calibrated at different ranges of movement. When the distance change was calibrated to the angle change at 60% range (8.4°) of the total range of technique 1, the mean error of the estimated angle change was the lowest, and the regression coefficient was the closest to one. When range used for calibration was reduced to 20% (2.8°) of the total range, the mean error of the estimated angle change was the highest, and the regression coefficient

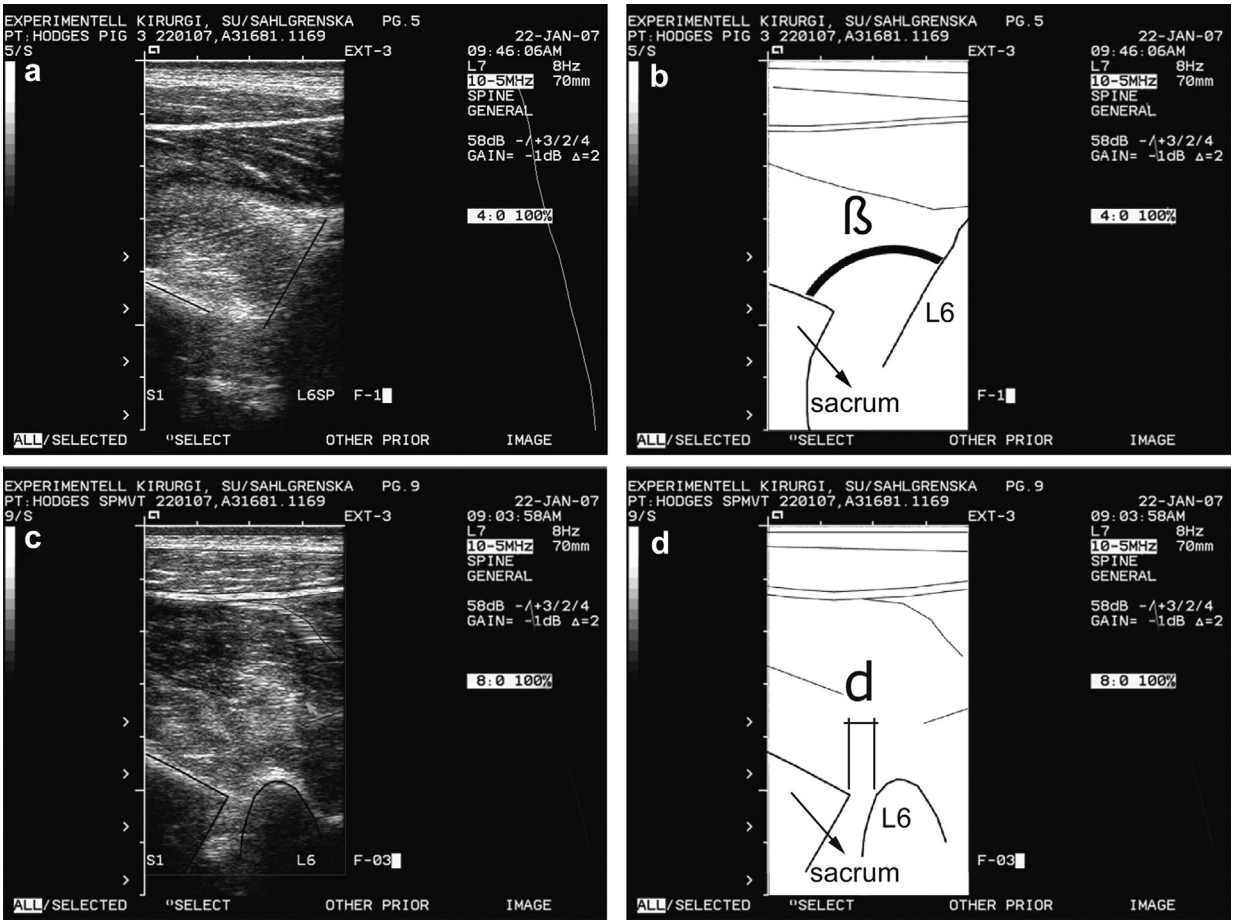

Fig. 4. Angle (a, b [β]) and distance (c, d [D]) between the sacrum and L6 calculated from the ultrasound images of the animal (pig) experiment.

was the furthest from one. Figure 5 shows an example of the estimated and observed angle change when the available range was 60% (8.4°) of the total range.

Experiment 2: In vivo *measurements*

The explained variance between the lumbosacral angles measured by fluoroscopy and ultrasound (technique 1) was 93.8% (Fig. 6). The corresponding linear regression coefficient was 0.995. The mean absolute error was 2.1°. When estimating changes in lumbosacral angle from changes in distance between the cranial edge of the dorsal aspect of the sacrum and the lamina of L6 (technique 2), the explained variance was 95.0% (Fig. 6). The corresponding linear regression coefficient was 0.997. The mean error was 1.7°.

Table 1. Statistical results for estimated angle change between the sacrum and L5

ROM	14.1° (100%)	11.3° (80%)	8.5° (60%)	5.6° (40%)	2.8° (20%)
Mean error	0.710°	0.696°	0.663°	0.709°	0.801°
Regression coefficient	1.024	1.019	0.982	0.850	0.789
R^2	0.774	0.774	0.774	0.774	0.774
Calibration ratio	0.4801	0.4752	0.4603	0.3987	0.3697

ROM = range of motion used for calibration.

DISCUSSION

This study aimed to develop and validate techniques to measure lumbosacral motion with ultrasound imaging. The findings of *in vitro* and *in vivo* experiments demonstrated the viability of ultrasound to estimate lumbosacral movement.

Measurement technique 1: Direct measurement of angular change

The results demonstrate that the amplitude of lumbosacral motion measured from the angle between a line drawn through two prominent landmarks on the sacrum and a line drawn through the lamina and mammillary processes of L5 was highly correlated with the angle measured with digital photography. This confirms the accuracy of the technique. The same principle is

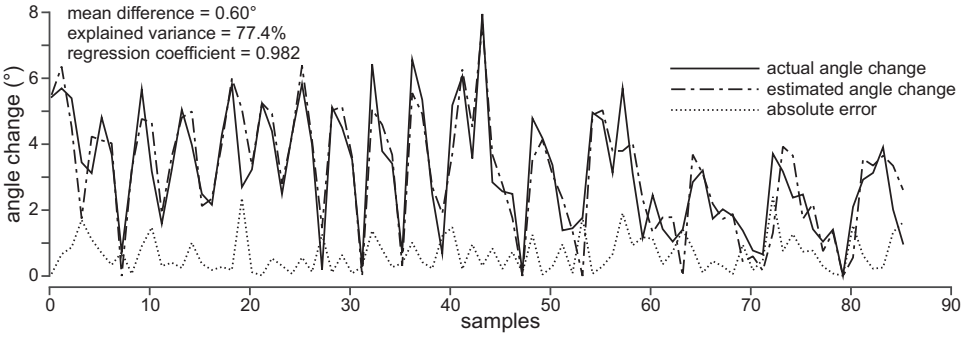

Fig. 5. Comparison between the angular data in the *in vitro* spinal model using the distance between the cranial edge of the dorsal aspect of the sacrum and L5 lamina (dashed black line) after angle change was calibrated with the 60% (8.2°) range of motion calibration with the angles calculated from the digital camera (solid black line). The dotted grey line shows the absolute errors.

commonly used in X-ray analysis where the angle between lines that go through anatomic landmarks on adjacent vertebrae represents a segmental angle (Breen et al. 1989; Pearcy 1985; Pearcy and Whittle 1982). The quality of the ultrasound images was very good in the *in vitro* model as a result of the absence of soft tissues, and is most likely better than the quality that could be expected *in vivo*. However, the 93.8% explained variance between fluoroscopy and ultrasound angle from the animal study indicated that angles measured with ultrasound can be used to accurately measure an angle between the sacrum and an adjacent vertebra *in vivo*. The average error of the estimated angle was greater in the *in vivo* than in the *in vitro* experiment (2.10° vs. 0.82°). A larger error in the *in vivo* experiment could be related to reduced clarity of the landmarks of the sacrum and L6, or be a result of

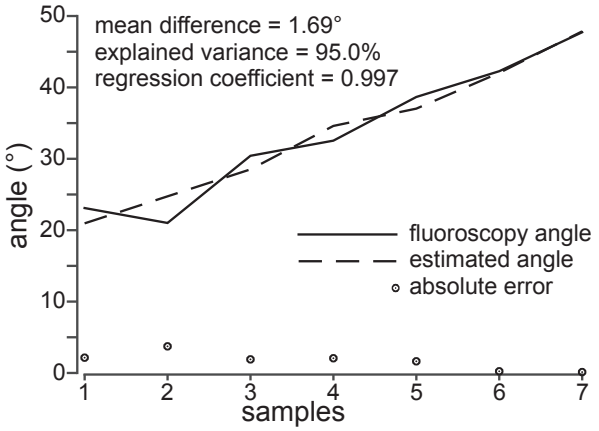

Fig. 6. Comparison between the angular data in the *in vivo* pig model using the distance change between the cranial edge of the dorsal aspect of the sacrum and L6 lamina (dashed black lines) and fluoroscopy images (solid black lines). The black dots show the absolute errors.

greater complexity of motion (combined translation and rotation), as motion in the *in vitro* model was limited to a single degree of freedom. Furthermore, the ultrasound measures were compared to angles calculated from fluoroscopy images, which probably has larger errors compared to the angles measured from the digital camera images. Regardless, the errors are relatively small considering the total lumbosacral ROM (approximately 25°) available in the porcine spine.

In the *in vitro* experiment the ultrasound transducer was held at an angle in the frontal plane of approximately 25° relative to the longitudinal axis of the spine to allow visualization of anatomic landmarks used for a direct lumbosacral angle measure. Deviations of the ultrasound transducer from 25° could introduce an error in lumbosacral angle calculation, as the ultrasound transducer was held manually throughout the experiment. Because the ultrasound transducer angle was not measured during the experiment, however, potential error can be calculated. With knowledge of real lumbosacral angle change (measured with the video camera) and the actual orientation angle of the ultrasound transducer, the error can be calculated using eqn (3).

$$\text{Error} = \theta \frac{\cos(\gamma)}{\cos(\varepsilon)} - \theta \tag{3}$$

Where θ is the real lumbosacral angle change, γ is the real ultrasound transducer angle and ε is the erroneous ultrasound transducer angle. For example, a deviation of the ultrasound transducer of 5° toward the longitudinal axis of the spine from 25° (*i.e.,* 20°) with a lumbosacral angle change of 5° (observed from the video camera) would give an overestimation error of 0.18° (3.7%); a deviation of the ultrasound transducer of 5° away from the longitudinal axis of the spine from 25° (*i.e.,* 30°) with a lumbosacral angle change of 5° (observed from the video camera) would give an underestimation error

of -0.22° (4.4%). Although the ultrasound transducer was held as still as possible, small errors could have been introduced by small changes in ultrasound head orientation. Accurate control of ultrasound transducer orientation can avoid additional errors in the measurement of lumbosacral angle.

It is likely to be challenging to image four anatomic landmarks simultaneously to calculate the lumbosacral angle because of muscle contraction and body contour changes during movement of a human spine, and there is increased potential for operator error with this technique. For these reasons we also investigated a simpler technique to evaluate if a change in distance between posterior elements of adjacent vertebrae can be used to estimate intervertebral movement.

Measurement technique 2: Indirect measurement of angular change

Change in the distance between landmarks on adjacent vertebrae is related to a change in intervertebral angle and can be converted to an angle *via* calibration with a known angle change. Distance between the cranial edge of the dorsal aspect of the sacrum and lamina of L5 measured with ultrasound was highly correlated with the angle calculated from the digital camera and could be used to estimate lumbosacral angle change. However, the error of the angle calculated from the distance change was slightly larger when calibrated at smaller ROMs. This may have consequences when this method is applied in clinical situations, for example, if lumbosacral range of motion is reduced in people with lower back pain. This would limit the largest possible angle available for calibration. The error in the *in vitro* experiment suggests that angle changes smaller than 0.66° cannot be detected reliably. However, this error is relatively small in relation to the total ROM of 14° of the lumbosacral spine, set to represent average ROM in humans.

In vivo flexion and extension movements in the lumbar spine involve rotational and translational components (Ogston et al. 1986). Both components are tracked by the path of the instantaneous axis of rotation. In our spine model, the axis of rotation was fixed by a hinge, and therefore, translational components were restricted. It is possible that in *in vivo* situations, the distance can change through a pure translation, which would erroneously be reported as an angle change. However, small distributions of instantaneous axes of rotation in healthy people have been reported *in vivo* (Pearcy and Bogduk 1988). Although Ogston et al. (1986) reported larger distributions of the instantaneous axis of rotation, they did not normalize for vertebral size. Given that the instantaneous axis of rotation changes little *in vivo*, this supports the use of a single instantaneous axis of rotation for validation of our method in our *in vitro* model. Furthermore, the *in vivo* animal experiment showed that ultrasound distance related well to angle measurement with fluoroscopy. This suggests that a change in instantaneous axis with sagittal motion did not influence the measurement of the distance between the sacrum and last lumbar vertebrae. However, this can only be assumed, as we did not measure the position of the instantaneous axis of rotation in experiment 2. Another option to reduce the effect of translation on the calculation of distance and related error in the estimated angle change is to use only the caudal-cranial distance component. This would reduce the error in the angle estimation, as the translational component does not contribute to the distance calculation. In addition, in older patients, spondylosis and related osteophytes could hamper reliable identification of two landmarks on L5 in the same image, which is required to calibrate distance change to angle change. The extent to which this affects our measures should be explored in future studies.

Both experiments indicate that a change in distance between adjacent segments can be used to estimate angle change. In theory, it does not matter which two anatomic landmarks are used as long as they can be followed reliably during motion. Thus, this technique is potentially very adaptable. More superficial landmarks such as the dorsal processes could be used to detect change in distance between segments with motion in the sagittal plane, and has been explored by Chleboun et al. (2012) and in a more recent paper by Cuesta-Vargas (2015) between lumbar segments in humans.

CONCLUSION

The results show that ultrasound can be used to measure intervertebral motion in an *in vitro* and in an *in vivo* model. The ultrasound method has a potential to provide a measure of intervertebral motion in clinical conditions without invasive procedures or exposure to ionizing radiation using real time ultrasound imaging. In a logical next phase of this research, the reliability of the developed methods needs to be examined in humans.

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