# Application of Ultrasound in Spine Kinematic Determination: A Systemic Review

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## Abstract

Spine kinematic determination is required to diagnose or rehabilitate back pain due to spinal instability. Ultrasound imaging, as a less harmful and cost-effective method, has been recently applied to kinematic analysis. This study reviews all available published articles to see how much progress has been made in spine kinematic measurement by ultrasound. In this regard, we searched PubMed, Scopus, and Google Scholar among all available studies until 2021, using keywords such as ultrasound, spine, kinematics, rotation, twist, flexion, and bending. Finally, after identifying and scanning 183 articles, only nine articles were included, which analyzed spine kinematics by ultrasound. Among these nine articles, three reported axial displacements, three reported flexion/extension, and three reported axial rotation. Although ultrasound is a suitable alternative to other kinematic measurement methods, very little research and progress have been made in this area. Today, this method is still not used practically for spine kinematic measurement because the bone scans via ultrasound imaging are challenging to understand, and no three-dimensional kinematic measurement technique has been reported. However, recent advances in converting ultrasound images into three-dimensional images can pave the way for further improvements.

**Keywords:** Back pain, flexion, intervertebral kinematic, rotation, spine kinematics, ultrasound

## Introduction

Spinal instability is one of the most practical reasons for severe back pain, more prevalent among the elderly.[1-3] An accurate understanding of spine kinematics is beneficial in diagnosing and rehabilitating spinal instability. Today, several methods are employed for kinematic determination, including X-ray imaging,[4,5] magnetic resonance imaging (MRI),[6] and optical tracking systems.[7,8] However, there are apparent obstacles through the introduced methods. For example, X-ray imaging is ionizing and deleterious for the tissue, MRI is expensive and imposes a high cost on the health system, and optical tracking devices based on external markers lead to measurement error due to soft tissue movements.[9] Although internal fixation of markers into the bone minimizes errors, it is not welcomed because of invasiveness.

However, ultrasound is a less-harmful method,[10,11] which recently has been applied as a practical musculoskeletal imaging modality.[12,13] In this regard, ultrasound imaging has had several applications in the spine, such as facilitating spinal anesthesia,[14] identifying deformities,[15-18] and spine kinematics determination. This study intends to analyze the results and methods of spine kinematic measurement via ultrasound to see: How much progress has been made? Where does this method stand now? Have the existing studies and advances been enough to make this method practical in medical centers?

## Methods

### Protocol of the study

The study was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses program.[19]

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Moreover, a recently printed systemic review paper[20] was used as a sample format.

### Studies search and selection

The sources in this study are published articles in English and were selected from PubMed, Scopus, Google Scholar, and references list of the cited articles. The keywords including spine, ultrasound, kinematics, rotation, twist, flexion, and bending were used [the search strategy of keywords combination in each database has been provided in Supplementary Material] regardless of the type of article and from 2000. The search period for this study was August 2021.

### Inclusion and exclusion criteria

Studies were included if they (1) analyzed any *in vivo* and/or *in vitro* study of spine kinematics and (2) applied a two-dimensional (2D) ultrasound imaging device as the primary method of kinematic measurement.

On the other hand, the following studies were excluded: (1) analyzing anatomy of the spine; (2) determination of spine deformity; and (3) applying ultrasound tracking systems instead of imaging.

### Quality assessment

Joanna Briggs Institute checklists[21] were used to evaluate the studies' quality. It provides robust checklists for the appraisal and assessment of most types of studies.

### Data extraction

One author did the data extraction from studies, and another author verified all exclusion. The articles were thoroughly analyzed, and all the data obtained from them were carefully recorded, including the ultrasound machine, statistical, comparing, and validation methods.

## Results

After all identification, the abstracts of 183 articles [Figure 1] were reviewed. Then, 39 articles were included for scrutiny. However, 30 articles were removed from the final list due to lack of spinal examination, experimental results, and kinematic study. Finally, nine articles were eligible. The diagram of the inclusion is shaped in Figure 1.

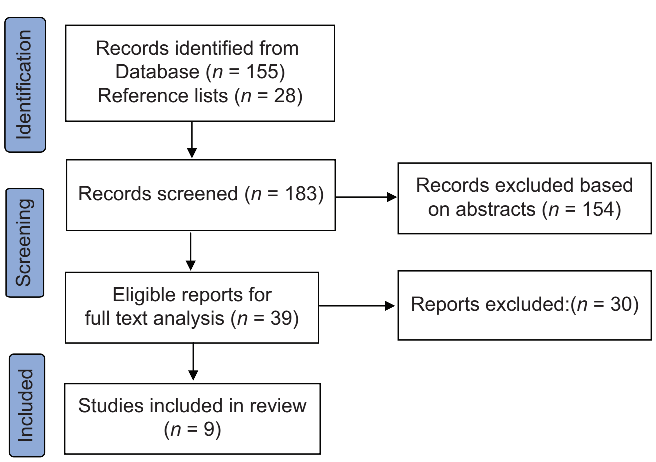


**Figure 1:** Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 flow diagram for new systematic review

Among the final list, three articles[22-24] examined kinematic in vertical displacements such as standing position *(in vivo)* or axial traction and compression (*in vitro*), three articles studied flexion/extension movements,[25-27] and three articles investigated axial rotation.[28-30] Information about the type of studies is summarized in Table 1. In addition, detailed data about the type of ultrasound machine, transducer, frequency, and the number of samples are provided in Table 2.

### Data report

The final reports are divided into three categories according to the types of experiments.

#### *Vertical displacement*

To date, only three intervertebral vertical displacement measurements have been reported by Zheng *et al*.[22-24] In the *in vitro* studies, they applied 1 mm frequency motions of 1–8 Hz in the C4–C5 and first compared the one-transducer ultrasound results with optical tracking methods and showed an accuracy of ±0.148 mm at frequencies <6 HZ, then compared the dual-transducer ultrasound results with linear voltage differential transformers, and showed 90% accuracy in frequencies <6 HZ. Moreover, in the *in vivo* studies, they designed a jumping test for participants and measured intervertebral compression using one transducer and dual transducer. Not enough numerical results have been reported in their studies, and only the high accuracy of ultrasound has been declared.

#### *Flexion/extension*

Chleboun *et al*.[27] measured the axial distance between the spinous processes of L1–L5 in the neutral supine, lumbar flexion, and lumbar extension postures via ultrasound and MRI. In the 1–6 mm range of spinous processes distances, the average MRI results were 1.3 mm higher than the ultrasound. Besides, the coefficient variation of MRI was 9%, and the coefficient variation of ultrasound was 12%. Next, van den Hoorn *et al*.[25] first in an *in vitro* study introduced two measurement techniques (direct angle measuring, indirect angle measuring) for flexion/extension of L5–S1 via ultrasound and then compared the results with a digital camcorder. The mean errors between ultrasound and digital camera were about 0.715° in 20%–100% of range of motion (RoM, 2.8°–14.1°). Furthermore, the explained variances between the ultrasound and digital camera results were 97% and 77% in two different measurement techniques. Then, in an *in vivo* study, they replaced the digital camera with a fluoroscope. The explained variance between the ultrasound and fluoroscopy in the first technique was 93.8% and for the second technique was 95%. Plus, for the first technique, the corresponding linear regression was 0.995, with an absolute prediction error of 2.1°. Concerning the second technique, the corresponding linear regression was 0.997, with an absolute prediction error of 1.7°.

In the third article, Cuesta-Vargas[26] combined ultrasound and electromagnetic sensors to measure the mean composite range

**Table 1: The method of studies in included records**

| Study name | Condition for kinematic test | Type of study | Sample size |
|---|---|---|---|
| Zheng *et al.*[22] | Vertical displacement | *In vitro* (human) | 5 |
| Zheng *et al.*[23] | Vertical displacement | *In vitro* (human) | 4 |
| | | *In vivo* (human) | 5 |
| Zheng *et al.*[24] | Vertical displacement | *In vivo* (human) | 9 |
| Van Den Hoorn *et al.*[25] | Flexion/extension | *In vitro* (human) | 1 |
| | | *In vivo* (pig) | 1 |
| Cuesta-Vargas[26] | Flexion/extension | *In vivo* (human) | 5 |
| Chleboun *et al.*[27] | Flexion/extension | *In vivo* (human) | 6 |
| Mckinnon and Callaghan[29] | Axial rotation | *In vitro* (pig) | 12 |
| Heneghan *et al.*[28] | Axial rotation | *In vivo* (human) | 24 |
| Mckinnon and Callaghan[30] | Axial rotation | *In vivo* (human) | 16 |

**Table 2: The types of the employed ultrasound machine**

| Study name | Ultrasound machine | Transducer | Frequency range (MHz) |
|---|---|---|---|
| Zheng *et al.*[22] | Treason T3000 | - | - |
| Zheng *et al.*[23] | Treason T3200 | Linear array | - |
| Zheng *et al.*[24] | Treason T3200 | Linear array | 4-15 |
| Van Den Hoorn *et al.*[25] | Logiq 9 | Linear array | 7-10 |
| | Acuson SC2000 | | |
| Cuesta-Vargas[26] | M-turbo | Linear array | 6-13 |
| Chleboun *et al.*[27] | My lab 25 | Curvilinear array | 6 |
| Mckinnon and Callaghan[29] | M-turbo | Linear array | 6-13 |
| Heneghan *et al.*[28] | Sono 5500 | Linear array | 3-11 |
| Mckinnon and Callaghan[30] | M-turbo | Linear array | 6-13 |

of L4–L5 during the full flexion, which was 15.5° ± 2.04°, the standard error of the mean was 0.54°, and the coefficient of variation was 4.18% in a single trial. Moreover, reliability was excellent for both within days (0.995–0.999) and between days (0.996–0.999).

### Axial rotation

In an *in vitro* study,[29] the rotations of several C3–C4 and C5–C6 were measured via ultrasound and optical tracking system in three positions of neutral, flexion (5.58° ± 1.18°), and extension (2.37° ± 1.72°). The maximum rotation was 3.5° in flexion and about 3.2° for neural and extension. Therefore, the correlation between the two systems was higher than 0.903, and the absolute system error across all flexion/extension was 0.01° ± 0.05°.

Moreover, Heneghan *et al.*[28] combined ultrasound and motion tracking sensors to measure the C7 rotation in maximal upper body rotations of participants. The mean range of axial rotation was 85.15°. The intraclass coefficient correlation was "excellent" for within days (0.89–0.98) and "good/excellent" for between days (0.72–0.94).

Finally, McKinnon *et al.*[30] investigated the effect of maximum external thoracopelvic angle (41.1° ± 6.8°) on the lumbar segmental axial rotation angle. The results in 25% of RoM were L1 = 3° ± 2.4°, L2 = 2.6° ± 2.6°, L3 = 1.4° ± 1.9°, L4 = 1.2° ± 2.0°, L5 = 1.1° ± 1.4°, S1 = −0.2° ± 1.1°; in 50% of RoM were L1 = 7.4° ± 2.3°, L2 = 6.9° ± 2.9°, L3 = 4.7° ± 2.8°, L4 = 4° ± 3.2°, L5 = 3.8° ± 2.3°, S1 = 1.8° ± 2.8°; and in 75% of RoM were L1 = 12.4° ± 4°, L2 = 11.7° ± 3.3°, L3 = 8.4° ± 2.5°, L4 = 7.9° ± 2.7°, L5 = 6.9° ± 3.4°, S1 = 6.9° ± 3.4°.

A summary of the strengths and weaknesses of different methodologies is summarized in Table 3.

## Discussion

Diagnosing spinal instability and the related rehabilitation requires accurate kinematic determination. Accordingly, it needs extensive researches to facilitate the measurement process. Today, several methods have been applied, while they are associated with various drawbacks. At the same time, ultrasound as a convenient system may help compensate for the shortcoming. Still, the image quality of bone scans via ultrasound has led to less attention paid to spinal kinematic. However, nine articles have analyzed the spine kinematic and are included in this study. Regarding the years of publication, Heneghan *et al.* [28] are the first group that analyzed spine kinematics using ultrasound in 2009. They combined ultrasound and electromagnetic sensors to measure C7-T1 axial rotation (85.15°), which their results were very similar to earlier declared reports (85°).[31] Three years later, in 2012, Chleboun *et al.*[27] recorded lumbar spine intervertebral flexion/extension based on the axial distance between spinous processes and reported significantly similar results compared to MRI. Next, in 2013 and 2014, Zheng *et al.*[22-24] applied intervertebral vertical frequent motions to compare the measurement accuracy of one

**Table 3: Assessment of applied methodology**

| | Strengths | Weaknesses |
|---|---|---|
| Heneghan *et al*.[28] | First spine kinematics measurement in an RoM study<br>Designing the novel method of combination of ultrasound with motion tracking sensors | No image processing<br>No coordinate transform system<br>No compare with other methods |
| Chleboun *et al*.[27] | First intervertebral study<br>Comparing the results with MRI | The method was only for supine position<br>Small sample size<br>Applied for only discrete kinematic |
| Zheng *et al*.[22] | Kinematic measurement in a dynamic movement<br>Comparing ultrasound results with optical tracking motion<br>Both in vivo and in vitro tests | Only vertical intervertebral motion analysis<br>No ability to be developed for other kinematic measurements<br>Probability of probe movement in dynamic studies<br>Small sample size |
| Zheng *et al*.[23] | Kinematic measurement in a dynamic movement<br>Applying a novel dual-ultrasound technique as a more accurate method<br>Comparing results with linear voltage differential transformers | Only vertical intervertebral motion analysis<br>Employing a similar test procedure to the last study |
| Zheng *et al*.[24] | Kinematic measurement in a dynamic movement<br>Applying the dual-ultrasound method for an in vivo study | Only vertical intervertebral motion analysis<br>Employing a similar test procedure to the last studies<br>No comparing with other methods<br>Probability of probes instability while dynamic movement<br>Small sample size |
| Cuesta-Vargas[26] | Develop the method of combining ultrasound and motion tracking sensors<br>Employing coordinate transform system<br>Employing a novel image processing method | Small sample size<br>No compare with other methods<br>Applied for only limited postures |
| van den Hoorn *et al*.[25] | Introduced a novel method of indirect angle measurement | Obscurity of landmarks<br>Complexity of movement<br>Not applicable for shorter RoM |
| Mckinnon and Callaghan[29] | Evaluating the transducer measurement angle<br>Comparing with a motion capture system<br>Employing coordinate transform system | |
| Mckinnon and Callaghan[30] | Develop the previous methods for RoM measurement | Limitation in the experimental setup<br>Applying only passive motions |

RoM: Range of motion, MRI: Magnetic resonance imaging

ultrasound with optical tracking systems and dual ultrasound with linear voltage differential transformers. They showed about 90% accuracy in low-frequency motion.

After that, in 2015, Cuesta-Vargas[26] developed the previously introduced technique of combined ultrasound and electromagnetic sensors to measure the mean composite range of L4–L5 (15.5° ± 2.04°) during the full flexion and reported the similar results of earlier published direct pin-based records (16.87° ± 4.74°).[32]

Then, in 2016, Zheng *et al*.[21] used the dual-ultrasound method again in an *in vivo* jump test and showed high accuracy in intervertebral vertical displacement. No more numerical results have been provided in their studies. Moreover, in the same year, van den Hoorn *et al*.[25] used two different ultrasound imaging techniques to measure intervertebral flexion/extension and showed high accuracy and reliability compared to digital cameras and fluoroscopes.

Finally, in the most recent studies, in 2019 and 2021, Mckinnon *et al*.[29,30] first showed a high correlation between ultrasound results and optical tracking systems measuring cervical axial rotation. As well, the reported error (0.1° in 3° RoM) was lower in comparison to the obtained results in the older record (2.1° in 14° RoM). Second, they measured lumbar segmental vertebrae axial rotations and showed significant similarity to earlier publications.[32]

A review of existing articles shows that very few studies have applied ultrasound in spine kinematic determination; therefore, much progress has not been made yet. Although available examinations have been reported high accuracy and reliability of ultrasound results, all have been limited to 2D measurements, and no practical technique for 3D measurement has been introduced. As a result, this method is currently not clinically used by therapists. If enough advancement is made in this field, the advantages of ultrasound will place it as an ideal alternative. It seems that recently developed spine 3D modeling via ultrasound images[33] can help future studies record spine kinematics in 3D models. This method converts 2D ultrasound images to 3D ones, thanks to the image processing techniques. As a result, the location of the bony landmarks gets more visible. Then, the displacement of these landmarks in any direction on three anatomical plates could be accurately recorded. By improving this technique, the real-time intervertebral 3D kinematics is measurable.

## Conclusion

Studies showed that spine kinematic measurement via ultrasound is still a toddler who needs much upbringing. High-accuracy 2D spine kinematic determination via ultrasound has been reported to date, while they are not enough because spine kinematics need to be analyzed 3D. The recently developed 3D spine modeling helps further progress of ultrasound to compete with other imaging methods such as CT scans and MRI. By producing accurate 3D data, other benefits of ultrasound, such as portability and being real-time, which is functional for *in vivo* studies, make it superior to different systems.

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### Conflicts of interest

There are no conflicts of interest.

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## Supplementary Material

**Natural Sciences and Engineering Research Council**

**Supplementary Material:** Strategy of keywords combination

("Spine" AND "Ultrasound")

AND

("Kinematics" OR "Rotation" OR "Twist" OR "Flexion" OR "Bending")

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