Journal of Biomechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Coupled motions in human and porcine thoracic and lumbar spines

Idsart Kingma [a,*], Iris Busscher [b], Albert J. van der Veen [c], Gijsbertus J. Verkerke [b,d], Albert G. Veldhuizen [b], Jasper Homminga [d], Jaap H. van Dieën [a]

[a] Dept. of Human Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam Movement Sciences, Amsterdam, The Netherlands
[b] University Medical Center Groningen, Groningen, The Netherlands
[c] VU University Medical Center, The Netherlands
[d] University of Twente, Enschede, The Netherlands

ARTICLE INFO

Article history:
Accepted 26 November 2017
Available online xxxx

Keywords:
Facet joints
Thoracic spine
Lumbar spine
Arthrokinematics

ABSTRACT

Coupled motions, i.e., motions along axes other than the loaded axis, have been reported to occur in the human spine, and are likely to be influenced by inclined local axes due to the sagittal plane spine curvature. Furthermore, the role of facet joints in such motions is as yet unclear. Therefore, this study aimed at assessing coupled motions in multiple spine sections *in vitro*, before and after removal of posterior elements. Six elderly human and 6 young porcine spines were sectioned in four segments (high thoracic, mid thoracic, low thoracic and lumbar), each consisting of four vertebrae and three intervertebral discs. Segments were loaded along each of the three axes, and three-dimensional rotations of the middle segment were quantified. Subsequently, posterior elements were removed and the protocol was repeated. To avoid mixed loading between Axial Rotation (AR) and Lateral Bending (LB), in contrast to other studies, local axes at the vertebrae were defined as aligned with the loading device prior to each load application.

Expressed as a percentage of motion in the loaded direction, coupled motions were on average larger in human (22.7%, SD = 2.2%) than in porcine (11.9%, SD = 1.2%) spines ($p < .001$). Largest coupled motions were obtained in AR loading of the lumbar spine segments, with mean magnitudes averaged over coupling axes for human L2-L3 joints of 48.9% (SD = 13.2%), including somewhat more LB (56.4%, SD = 18.6) than FE (41.4%, SD = 14.1%) coupling. For porcine L3-L4 joints average coupling in AR loading was 29.3% (SD = 8.2%). In human segments removal of posterior elements only had substantial effects in the lumbar spine segments, where posterior element removal decreased coupled motion during AR loading, averaged over LB and FE coupling, from 48.9% (SD = 13.2%) to 27.7% (SD = 6.1%), mainly through increased motion in the loaded direction.

The present results indicate that coupled motions were largest in the lumbar spine. In human spines, posterior elements only contributed to coupled motions in lumbar axial rotation loading.

1. Introduction

During intended uni-axial *in vivo* motions, the human spine has been shown to generate substantial so-called coupled motions in the thoracic (Fujimori et al., 2012; Fujimori et al., 2014) as well as the lumbar (Fujii et al., 2007; Gercek et al., 2008; Li et al., 2009; Ochia et al., 2006; Shin et al., 2013) spine. These coupled motions suggest that loading about a single axis causes rotations about more than one axis. Moreover, enhanced *in vivo* lumbar coupled motions have been associated with low back pain (Cheng et al., 2013; Lund et al., 2002) and degenerative disc disease (Li et al., 2011), and could thus be indicative of spine problems. However, a difficulty in interpreting *in vivo* data in terms of kinematic coupling is that, when asked to perform a uni-axial motion, subjects, and maybe especially patients, may not apply pure uni-axial loads to their spine (Grabiner et al., 1992; Shirazi-Adl, 1994b).

In vitro as well as in modelling, pure uni-axial moments can be applied, which allows for a more direct interpretation of anatomically-induced kinematic coupling. *In vitro* experiments have also shown coupled motions in the thoracic (Mannen et al., 2015; Panjabi et al., 1976) and lumbar (Oxland et al., 1992a; Panjabi et al., 1989, 1994) spines and the thoracolumbar junction (Oxland et al., 1992b). Facet joints have been suggested to play an important role in this coupling (Oxland et al., 1992a; Panjabi et al., 1989).

* Corresponding author at: Department of Human Movement Sciences, Vrije Universiteit, Van der Boechorststraat 9, 1081 BT Amsterdam, The Netherlands.
E-mail address: i.kingma@vu.nl (I. Kingma).

https://doi.org/10.1016/j.jbiomech.2017.11.034
0021-9290/© 2017 Published by Elsevier Ltd.

However, even *in vitro*, where the loading direction can be controlled, interpretation of data requires consideration. In most studies referenced above (Oxland et al., 1992a; Panjabi et al., 1989, 1994), sections of multiple spine segments were loaded. Subsequently, unlike modelling work where vertebral motions were expressed in global axes (Shirazi-Adl, 1994a,b), local axes systems were constructed on vertebrae and motions of vertebrae were expressed relative to their neighbour. While the latter seems appropriate from an anatomical perspective, a problematic aspect is that the local axes are not necessarily aligned with the loading direction. This alignment problem has been acknowledged as well in previous *in vitro* work (Oxland et al., 1992a; Panjabi et al., 1989), and, through modelling work, has been shown to partly explain *in vitro* findings (Cholewicki et al., 1996). To clarify the problem, Fig. 1 shows axes systems in a lordotic spine alignment, which is normal for the lumbar spine. This figure shows that with inclined local axes, moments along the lateral bending or axial rotation axis of a loading device can project on local axial rotation or lateral bending axes, respectively. This projected moment differs in sign between the upper and lower vertebra if they are inclined in opposite directions. Indeed, coupled motions reported from tests on multi-segmented lumbar spines (Oxland et al., 1992a; Panjabi et al., 1989, 1994) are generally consistent with such projections due to tilting of vertebrae resulting from a normal lumbar lordosis. In this respect, Oxland et al. (1992a) and Cholewicki et al. (1996) distinguished postural and structural/mechanical coupling. The alignment problem might lead to interpretation problems if elderly subjects, or subjects with low back pain have a more pronounced spinal curvature, because in that case coupled motions expressed in local axes are expected to be larger. To avoid moment projections being interpreted as (mechanical/structural) kinematic coupling, one could argue that local axes should, prior to loading, be aligned with the loading device.

Following this line of reasoning, the current study set out to assess coupled motions in human thoracic and lumbar spine sections *in vitro*, with local axes at onset of loading aligned with the loading device. We hypothesized that coupled motions would be smaller after posterior element removal, and differ between lumbar and thoracic spine sections. In addition, animal models such as porcine spines are commonly used as a proxy for human spines. Similarities as well as substantial differences with human spines have been noted for both anatomy (Busscher et al., 2010a) and biomechanical behaviour in the loaded direction (Wilke et al., 2011). As coupled motions have not yet been compared between human and porcine spines, we additionally assessed to what extent coupled motions in porcine spines are roughly similar to elderly human spines.

2. Materials and methods

2.1. Specimen and specimen preparation

Fresh frozen spines of six human and six porcine cadavers were used in this study. The human spines were harvested from six cadavers obtained from the Department of Anatomy of the University Medical Center Groningen, The Netherlands. Mean age of the subjects at the time of death was 72 years (range 55–84 years). The porcine spines (from about 40 kg domestic pigs) were obtained from a local abattoir. All spines were dissected from T1-S1 and all musculature was carefully removed, while leaving the ligaments, facet joints, and joint capsules intact. At both sides of the spine, approximately 3 cm of the ribs was preserved, including the costotransverse and costovertebral articulations. CT scans of the spines showed normal porcine spines and mildly degenerated but otherwise normal human spines (Busscher et al., 2009).

The spines were divided into high-, mid-, low-thoracic, and lumbar segments, each containing 4 vertebrae and 3 intervertebral discs. The porcine spines had 15 or 16 thoracic and 6 lumbar vertebrae, compared to 12 and 5, respectively, in the human spines. The porcine spines were dissected in T2-T5, T7-T10, T12-T15, and L2-L5. The human spines were dissected in T1-T4, T5-T8, T9-T12, and L1-L4.

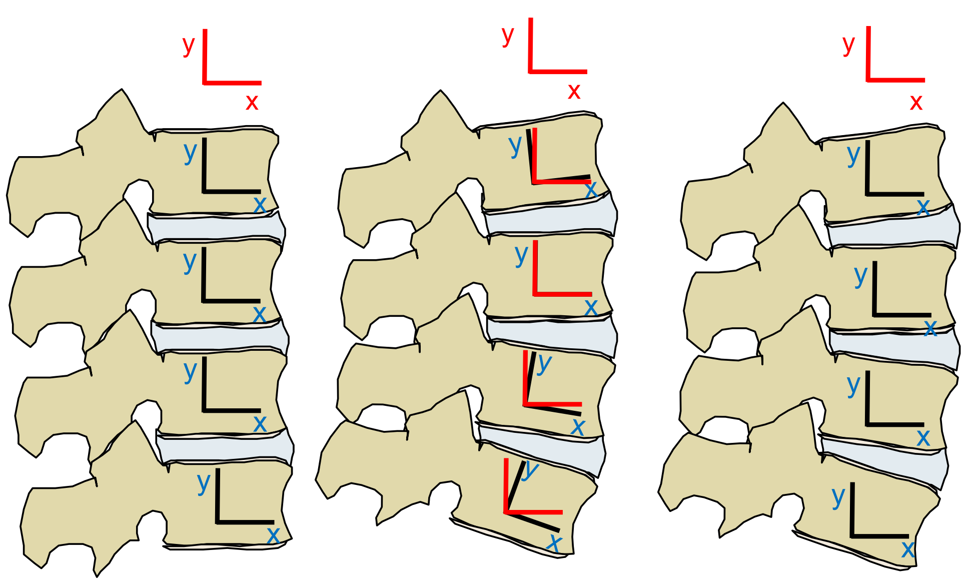

Fig. 1. Sagittal plane illustration alignment effects. With all vertebrae initially aligned with the loading device (A), local axes (black) coincide with those of the loading axes (red). In a lordotic spine section, local anatomy-based axes do not coincide with the loading device (B). Consequently, moments along the red x or y axis will partly project on the black y or x axis, respectively. For example, a positive (right Lateral Bending) moment along the red x would cause a negative (left Axial Rotation) moment along black y of the top vertebra, and a positive (right Axial Rotation) moment along te bottom vertebra black y. Note that in (B), dependent on Euler decomposition order, the problem is further exacerbated because the black axes of adjacent segments are also not initially aligned. In the present study, these problems are avoided by aligning local axes with the loading device prior to each load application (C). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Please cite this article in press as: Kingma, I., et al. Coupled motions in human and porcine thoracic and lumbar spines. J. Biomech. (2017), https://doi.org/10.1016/j.jbiomech.2017.11.034