DE GRUYTER Current Directions in Biomedical Engineering 2019;5(1):347-350

Martin Weidling*, Christian Voigt, Toni Wendler, Martin Heilemann, Michael Werner, Jan-Sven Jarvers and Christoph-E. Heyde

Kinematics of the Lumbo–Pelvic Complex under Different Loading Conditions

Abstract: The lumbo-pelvic complex is a highly complex structural system. The current investigation aims to identify the kinematics between interacting bone segments under different loading conditions. A specimen of the lumbo-pelvic complex was obtained from a human body donor and tested in a self-developed test rig. The experimental setup was designed to imitate extension, flexion, right and left lateral bending and axial rotation to the left and to the right, respectively. The vertebra L3 was firmly embedded and load was introduced via hip joints. Using a digital image correlation (DIC) system, the 3D motions of 15 markers at different landmarks were measured for each loadcase under cyclic loading. For each loadcase, the kinematics were analyzed in terms of three-dimensional relative movements between L3 and the sacrum. The usefulness of the experimental technique was demonstrated. It may serve for further biomechanical investigations of relative motion of sacroiliac and vertebral joints and deformation of bony structures.

Keywords: range of motion, pelvis, spine, bone kinematics, experimental biomechanics.

https://doi.org/10.1515/cdbme-2019-0087

1 Introduction

With growing numbers of elderly patients, the number of cases with degenerative diseases is also increasing. Osteoporotic fractures of the spine and pelvis are a major area of concern [1]. Screw-rod systems have proven successful in the thoracic and lumbar spine. In the region of lumbo-sacral transition, however, high loosening rates and implant fractures occur frequently with these systems [3].

The lumbo-pelvic complex is comprised of the lumbo-sacral transition and the pelvic ring, including various bones, ligaments and intervertebral discs. Further improvement of implant fixation requires knowledge about the load transfer from the spine to the hip region, which is, therefore, a major field of biomechanical investigation. However, studies in the literature usually investigated only single directional loadcases [2, 4]. To deepen our understanding how these components interact during load transfer, the current study aims for identification the kinematics of the interacting bone segments under different loading conditions.

This requires the development of an experimental setup that can imitate near-realistic movements of the lumbo-pelvic complex while maintaining simple and well defined boundary conditions. Measurement equipment has to be customized, to capture the 3D motion of the individual bone segments with high accuracy. Knowledge of the kinematics and load situation is substantial for advancement of implant design.

2 Materials and Methods

Preparation of specimen

From a male body donor (67 years at death) the compound of lumbar vertebrae L3-5 and pelvis was dissected and muscle tissue was removed from the specimen, while preserving intervertebral discs, facet joints and ligament structures. After dissection the specimen was fresh frozen. On the day of the experiment the specimen was thawed under time and temperature control. Pathologies were excluded by CT examination. Furthermore, osteoporosis could be excluded by bone density scan (T-score: -0.4).

***Corresponding author: Martin Weidling:** Center for Research on Musculoskeletal Systems (ZESBO), Faculty of Medicine, University of Leipzig, Semmelweisstrasse 14, Leipzig, Germany, e-mail: martin.weidling@medizin.uni-leipzig.de
Christian Voigt, Toni Wendler, Martin Heilemann: Center for Research on Musculoskeletal Systems (ZESBO), Faculty of Medicine, University of Leipzig, Leipzig, **Michael Werner:** Fraunhofer Institute for Machine Tools and Forming Technology IWU, Dresden, Germany, **Jan-Sven Jarvers and Christoph-E. Heyde:** Department of Orthopaedic, Trauma and Plastic Surgery, University Hospital Leipzig, Leipzig, Germany

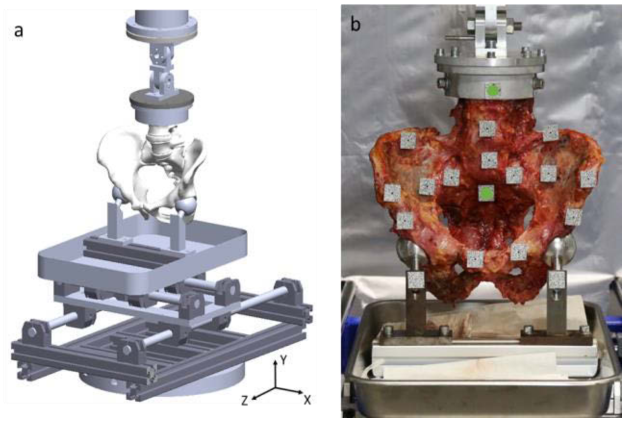

Figure 1: Experimental setup: a – CAD-concept of the experimental setup; b – Human bone and soft tissue specimen including measurement markers at anatomical landmarks, evaluated markers of the current study are indicated with a green dot.

The specimen was embedded with the L3 inside a mounting socket using polyurethane casting resin RenCast® (Huntsman Int. LLC, USA), while aligning the intervertebral joint L3/L4 parallel with the rim and the base plate of the mounting socket. Prior alignment of the specimen in the mounting socket allows for positioning the specimen corresponding to an upright body posture, when the socket is mounted horizontally [6]. Care was taken to ensure that the mobility of the L3/L4 joint, especially at the facet joints and the intervertebral disc, remained undisturbed by the embedding material.

Experimental setup

The self-developed test rig was set up in a DYNA-MESS testing machine (Type 2082/000, built-in test modes: tensile, compression, torsion, DYNA-MESS, Aachen, Germany). The working axis of the testing machine is its central vertical axis, specified as Y-axis in the experimental coordinate system (Figure 1a). A locking hinge, which can be pre-set to different angular positions, was incorporated to fix the mounting socket with the specimen to the upper frame of the testing machine. Congruent spheres, made of aluminium, were inserted into the acetabula of the pelvis and checked for smooth mobility to represent intact physiological hip joints. The spheres were installed on posts which were sitting upright on a cross slide, which allowed them to freely move in the horizontal plane. The cross slide was mounted to the actuator driven base plate of the testing machine. In summary, the specimen was suspended with boundary conditions of rigid fixation at the upper end (L3) and of low friction sliding and vertical loading on the lower end (acetabula) while the Y-axis was the axis of all load applications.

Pins were inserted into the specimen at anatomical landmarks. Measurement markers in the shape of small plates with black and white speckle patterns were attached to these pins (Figure 1b). The markers were captured during movement in 3D space using a digital image correlation (DIC) system with a three-camera-setup (Q400, LIMESS Messtechnik und Software GmbH, Krefeld, Germany).

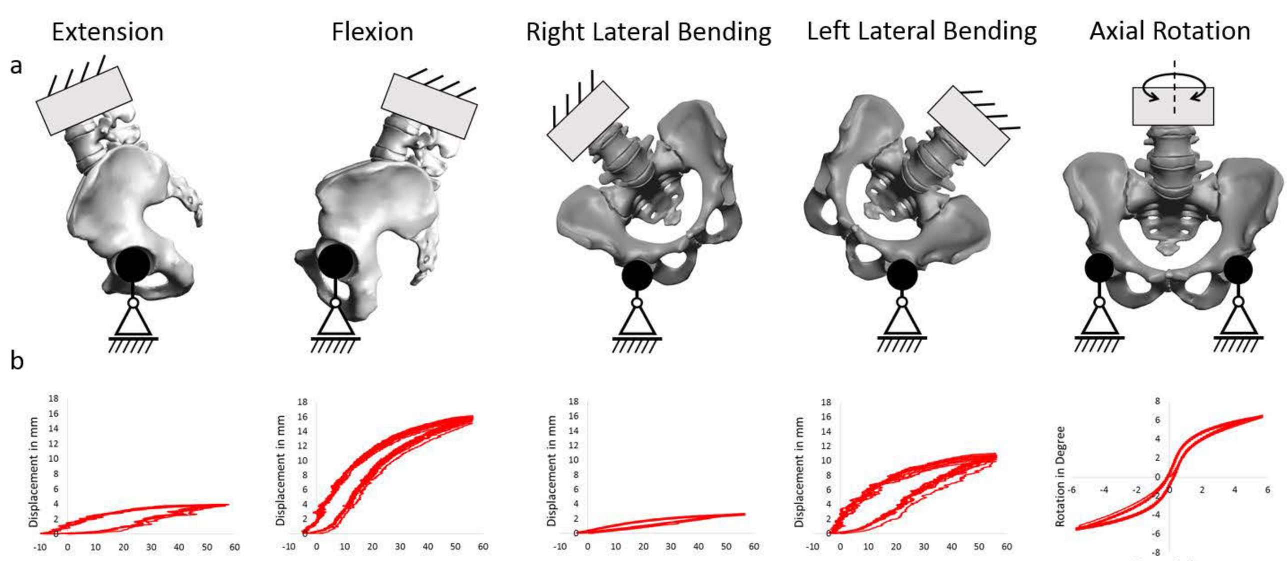

Figure 2: Tested loadcases: a – pictograms of loading scenario; b – evaluated cyclic force-displacement diagrams of complete specimen during each loadcase.

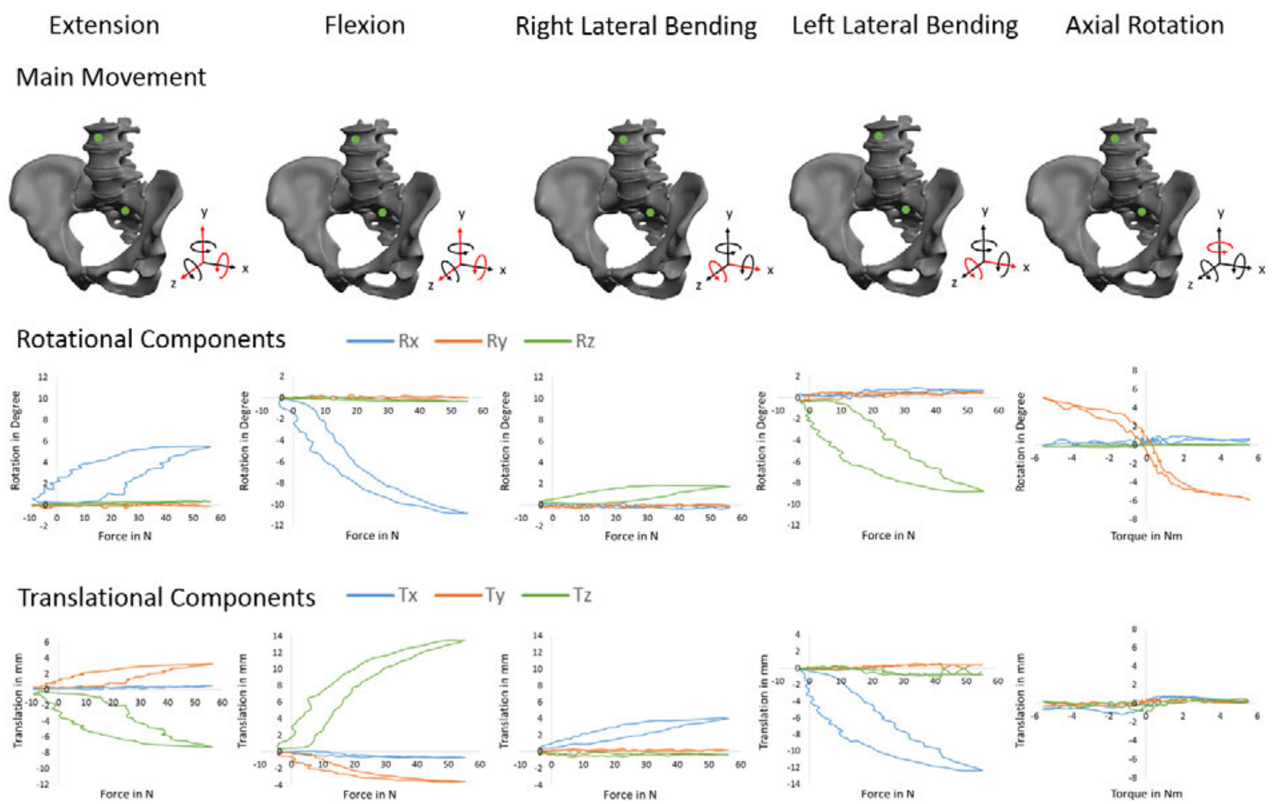

Figure 3: Kinematic results of relative motion between L3 und sacrum for all tested loadcases. Above – Loadcase specific main components of relative motion are shown in anatomical body coordinate system and indicated in red; Middle – Rotational components of 3D relative motion; Below - Translational components of 3D relative motion.

Experimental procedure

The loading scenarios are shown in Figure 2a. Extension, flexion, right and left lateral bending motion are each tested individually. To examine extension and flexion, the locking hinge was pre-set to 20° anterior/posterior tilt with regard to the horizontal plane (XZ), respectively (Figure 2a). In right and left lateral bending, the locking hinge was pre-set to 45° right/left lateral tilt with regard to the horizontal plane (XZ), respectively (Figure 2a), while the cross slide (XZ) was locked in the Z-direction to allow only lateral movement. Thereby, only one acetabulum was engaged, which is corresponding to the body posture of one-legged stance. The specimen was loaded at a rate of 1 mm/s along the Y-axis. Ten cycles with a maximum compression force of 56.25 N were recorded.

During axial rotation, the specimen was fixed in neutral position so that the mounting socket and, thereby, the intervertebral joint L3/L4 were orientated parallel to the horizontal plane. The torque actuator of the testing machine is located at the upper fixture of the machine. Therefore, the load was introduced into the specimen via the L3 as a rotation around the Y-axis. Five cycles of rotation from left to right and reverse were tested at a rate of 1°/s with a maximum torque of 5.625 Nm, respectively. To balance out the weight of the hanging specimen, the base plate actuator was set to apply a constant counter-acting support force in Y-direction during the test procedure, equal to the previously measured weight of the specimen.

Experimental procedures lasted not more than 20 hours at room temperature (23°C, 50% humidity), during which the specimen was kept moist at all times [6].

Evaluation

Image data were recorded over the entire motion sequence and analysed with the image correlation software Istra 4D V4.4.4, Dantec Dynamics, Skovlunde, Denmark. 3D coordinates analysed at measurement points on each marker had to be translated to the underlying landmark on the bone surface. Therefore, coordinates were shifted by the free standing length of the attached pin, respectively. The relative motion between two bony landmarks was then evaluated in all six degrees of freedom (Matlab R2015b, MathWorks, Natick, MA, USA).

For more intuitive readability, the final results were transferred to the anatomical body coordinate system (xyz), which is commonly used to describe an orientation with regard to an upright body posture. Hence, the xy-plane is congruent with the frontal plane and the xz-plane is congruent with the transverse plane (Figure 3).

3 Results

The loads applied by the testing machine and the analysed kinematic reactions of the complete specimen are shown for all investigated loading cycles in Figure 2b in the experimental coordinate system (XYZ). After a few cycles an almost constant hysteresis curve is obtained. Only one cycle was chosen for further consideration (3rd cycle for axial rotation, 7th cycle for all other loadcases).

The relative motion between L3 and sacrum was evaluated for all tested loadcases which is shown in Figure 3 in the anatomical body coordinate system (xyz). In Figure 1b, the segments whose relative kinematics were evaluated are marked with a green dot. In the upper part of Figure 3, the axes that make up the characteristic components of relative motion are highlighted in red. The three components of the rotational motion and the three components of the translational motion are shown in the diagrams below.

4 Discussion and Conclusion

In the literature in vitro studies of the lumbo-pelvic complex under near-realistic loading conditions are rare. In most cases, loads are applied in only one direction of motion [4, 5]. These movements are often measured on the surface of the specimen using only few tactile displacement meters [4] or glued-on markers [2]. The underlying soft tissue can induce inaccuracies of measurement. In the present study, an experimental technique is proposed as a solution for these problems. Thus, the lumbo-pelvic complex is loaded in different directions in a simple and defined way, corresponding to common body postures and movements of extension, flexion, lateral bending and axial rotation. The kinematics of bone segments can be determined by a full set of markers. Moreover, the markers are connected to the bone by pins to account for bone movement rather than soft tissue movement.

The analysed relative movements between L3 and sacrum comply with the expected directions of movement for each loadcase. In addition, they can be precisely quantified as a function of the load.

With the presented method, biomechanical investigations of the relative motion of individual intersegmental joints as well as the overall deformation of bones can be conducted for different loading scenarios. A better understanding of the biomechanical behaviour of the lumbo-pelvic complex can be useful for development of advanced implant fixation techniques.

Acknowledgements
The authors wish to thank Christoph Oefner for his support during the experiments and Florian Metzner for his segmentation of the CT scan.

Author Statement
Research funding: Federal Ministry for Economic Affairs and Energy of Germany within “Zentrales Innovationsprogramm Mittelstand” (KF2036726AK4). Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent was not required as no individuals were involved in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board.

References

[1] Alnaib M, Waters S, Shanshal Y, Caplan N, Jones S, St Clair Gibson A, Kader D (2012) Combined pubic rami and sacral osteoporotic fractures. A prospective study. J Orthop Traumatol 13(2):97–103. doi:10.1007/s10195-012-0182-2

[2] Hammer N, Scholze M, Kibsgård T, Klima S, Schleifenbaum S, Seidel T, Werner M, Grunert R (2019) Physiological in vitro sacroiliac joint motion. A study on three-dimensional posterior pelvic ring kinematics. J Anat 234(3):346–358. doi:10.1111/joa.12924

[3] Kasten MD, Rao LA, Priest B (2010) Long-term results of iliac wing fixation below extensive fusions in ambulatory adult patients with spinal disorders. J Spinal Disord Tech 23(7):e37-42. doi:10.1097/BSD.0b013e3181cc8e7f

[4] Vleeming A, van Wingerden JP, Dijkstra PF, Stoeckart R, Snijders CJ, Stijnen T (1992) Mobility in the sacroiliac joints in the elderly. A kinematic and radiological study. Clinical Biomechanics 7(3):170–176. doi:10.1016/0268-0033(92)90032-Y

[5] Wang M, Dumas GA (1998) Mechanical behavior of the female sacroiliac joint and influence of the anterior and posterior sacroiliac ligaments under sagittal loads. Clin Biomech (Bristol, Avon) 13(4-5):293–299

[6] Wilke HJ, Wenger K, Claes L (1998) Testing criteria for spinal implants. Recommendations for the standardization of in vitro stability testing of spinal implants. Eur Spine J 7(2):148–154. doi:10.1007/s005860050045